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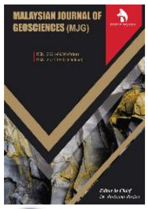

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RESEARCH ARTICLE

EVALUATION OF FOUNDATION FAILURE USING INTEGRATED METHODS: A CASE STUDY OF BAUCHI METROPOLIS, NORTHEASTERN NIGERIA

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ABSTRACT

Assessment into the source of building failure was conducted within the Bauchi metropolis, northeastern Nigeria. Recently, the loss of lives and properties in the area was due to building failures. Geotechnical, geochemical, mineralogical, and geophysical methods of investigations were employed to test likely features responsible for this anomaly. Results from sieve analysis showed that the proportion amount of clay ranges from 1.0 – 70.0%, Optimum Moisture Content (OMC) ranges from 9.3 - 15.3%, Liquid Limit (LL) 25.8 - 43.2%, Plastic Limit (PL) 20.8 - 34.2%, Plasticity Index (PI) 4 - 14%, Maximum Dry Density (MDD) 1605 - 2005 kg/cm^3, specific gravity (SP) range from 2.7 to 2.8%, permeability (k) 2×10^{-5} to 21×10^{-5} m/s. Triaxial test result also shows high cohesion values of 81.30105.00 kPa, and low angle of internal friction in the range of 11.75^0 - 20.46^0, with a low bearing capacity of 35-209 KNm2. Clay mineral predominates the studied soil as smectite shown by X-Ray Diffraction (XRD). Results from Vertical Electrical Sounding (VES) revealed a three-layered formation, comprise of Topsoil, with resistivity values ranging from 64.13 to 352 Ωm, and a weathered layer (saprolite), with resistivity of 11.99 to 118 Ωm and fresh Basement. Hence, a significant amount of smectite with high swelling and shrinkage potential, low permeability, and low resistivity among others as factors responsible for the basis of building failure experienced in the study area. These make the soils unsuitable for siting of a building. Thus, the need for stabilization and improvement before building construction.

KEYWORDS

Building, Geotechnical, Constructions, Geophysical, Smectite

1. INTRODUCTION

All engineering structures can be divided into two major parts; the exposed upper part is called the superstructure and the unexposed parts connect the superstructure, and the adjacent underlying zone of the soil or rock is known as the foundation (Arora, 2008). The foundation constitutes the supporting part of a structure, and it is not restricted to the concrete or reinforced concrete member that transmits the superstructural load to the earth. It encompasses the soil and rock beneath the foundation. The basic function of a foundation is to sufficiently transmit the load of the building to the underlying material with limited stress. It is also worthy of note that for a civil engineering structure to stand safely, two consequential factors must be met. The underlying soil must not fail by shearing and should be devoid of excessive settlement (Arora, 2008). Cracking of walls of buildings and eventual damage to the building occurs when these conditions are not met, resulting in loss of lives and properties. In most developing countries, geotechnical investigations which are supposed to be a prerequisite for every civil engineering structure have been relegated to the background and this has led to the collapse of buildings, bridges, dams, and loss of lives and properties (Ayedun et al., 2012; Matawal, 2012).

Building collapse refers to the structural failure of a building to send the structure's weight to the ground. This can also mean the inability of the ground to bear the weight of a building. Moreover, this happens when the building's weight exceeds the ground's bearing capacity which leads to uneven settlement. Consequently, huge economic losses of millions of naira are mostly associated with building collapse (Ayedun et al., 2012; Matawal 2012). Thus, suggests that soil surveys need to be conducted to determine the soil's capacity to consolidate and compress as well as its bearing capacity (McCarthy, 1999). Since the stability of engineering structures is largely dependent on certain inherent soil properties and the underlying geological formation, subsurface characterization and determination of soil strengths are prerequisites for the foundation design of important civil engineering structures (Sudha et al., 2009). However, such investigations could take diverse forms; mineralogical, geotechnical, geophysical, or even an integrated approach depending on the availability of resources, structural designs/load, and existing geological conditions. Earlier studies carried out on the mineralogical properties of clays in Bauchi state reported the occurrence of expansive clays in parts of the state (Orazulike, 1988,1992). Most investigations have continued to adopt integrated approaches for better and more reliable subsurface investigations because an integrated approach helps to increase the accuracy of an investigation and reduce the bias associated with most

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standalone techniques (Srinivasa and Jugran 2003), it remains the most economical method of obtaining subsurface information, especially within large area. The researcher have worked on the application of geophysical and geotechnical analysis in engineering site evaluation in Nigeria (Oyedele and Bankole, 2009; Olorunfemi and Fatoba, 2004; Akintorinwa and Adeusi, 2009). The study also employed the used of geotechnical properties in assessing the implication of soils in Otukpo area of Ogbadibo, Benue State (Peter et al., 2018). Furthermore, used integrated geotechnical and geophysical investigation techniques to study recurrent building collapse in Akpugo, part of southeastern Nigeria (Una et al., 2015). The occurrence of cracks in buildings has been observed in different buildings within the study area by the researchers. despite many attempts made by locals using different building specifications, the problem persists probably because detailed attention has not been given to the geotechnical, geophysical, geochemical, and mineralogical properties of the soils. Hence, this research aims to integrate these techniques at a time to eexamine and correlate the consequence, which will help determine in detail the engineering properties of the soil in the study area. (Fig. 1)

Figure 1: Mitigation measures on cracked building

2.The Study Area

The area is situated within the geographical coordinates of 10o 21I 36IIN to 10o 81I 0II N and 9o 50I 24II E to 9o 53I 24II E. Bauchi area is bounded to the southeast by Alkaleri, to the west by Tafawa Balewa, and the north by Ganjuwa. It is easily accessible by several roads; like the Bauchi to Jos Road, Bauchi to Kano Road, and Bauchi to Maiduguri link road, while the study area is slightly laid out from the Bauchi metropolis, accessed through a federal highway that links Bauchi to Maiduguri to the east of Bauchi metropolis, and several primary roads and footpaths and a railway track. The climate in the area is tropical and is usually characterized by dry and dusty northeasterly trade wind, which originates from the Sahara Desert (Harmattan) dry dust-bearing wind. The area is categorized by two main seasons: the rainy and the dry season. The rainy season is normally experienced between April to September and the dry season is from October to March. The area is characterized by mean annual rainfall of about 700-1300 mm (BSADP, 1983). The Harmattan is usually experienced between December and February. The highest humidity and rainfall are recorded in August and September (Mustapha and Adamu, 1991). The vegetation is the Savannah type, composed of scattered trees, which grow near water sources, shrubs, and mainly flat-lying grasses. The plants in such a setting are mostly xerophytes and can adapt to long periods of the dry season

2.1 The Geology

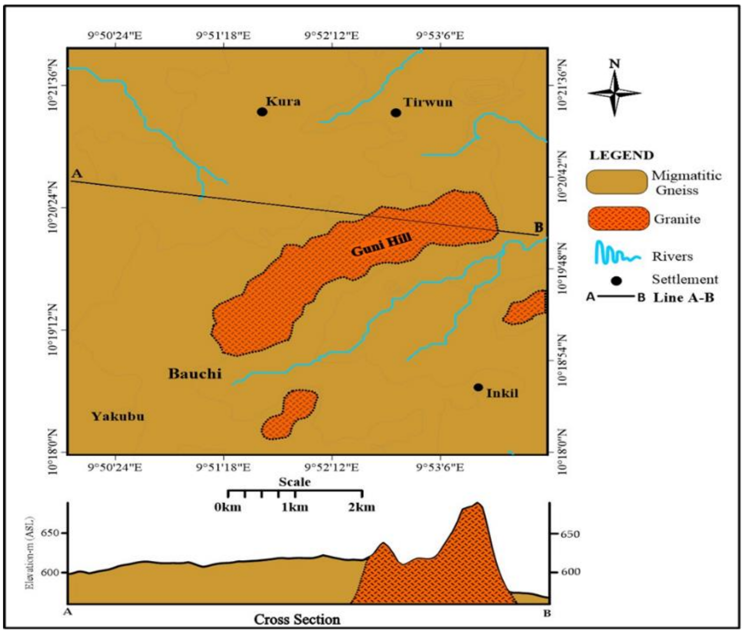

Figure 2: The geologic map of the area study

The area studied is underlain by rocks of the Precambrian crystalline Basement Complex of Nigeria. The major lithologic units are the Bauchite (Fayalite-quartz-monzonite); the biotite-hornblende-granite; the porphyroblastic biotite-granites, granulites and undifferentiated migmatites and gneisses (Ferre and Caby, 2007). In most parts of the area, these rocks are covered by unconsolidated weathered overburden materials consisting of laterites, clays, sands, and gravels, which constitute the foundation soils for buildings and subgrades for pavement. Exposed by erosion, the soil profile consists of laterite topsoil underlain by a clay horizon. which is underlain by weathered parent rock materials. From the observation, it was found that at higher altitudes these sediments are coarse-grained and fine towards the low-lying plains. Exposures of fayalite-quartz-monzonite (Bauchite) and Biotite hornblende-granite occur at almost all the locations (Fig. 2). Fayalite – Quartz – Monzonites (Bauchite) Fayalite – bearing quartz monzonites have been described in Bauchi area (Oyawoye, 1970). It contains quartz (72%), K- feldspar (14-72%), and plagioclase (4-52%). This unit is characterized by an almost equal amount of alkali feldspars and plagioclase. It has dominant accessory minerals such as biotite and hornblende. In others, augites are present and are normally accompanied by hypersthene and olivine. The K-feldspars in monzonite are usually orthoclase (rarely microcline). Quartz occurs in minor amounts. The Biotite-Hornblende-Granite is a rock unit whose dominant minerals are biotite and hornblende. Other minerals found associated with them are muscovite, augites, sodium-rich amphiboles, pyroxenes, and minor quartz or olivine. The biotite is often dark-coloured, and the hornblende is green-coloured. Outcrops of these rocks show that they have been fractured due to tectonism. The prominent fractures trend towards the NE-SW and N-S zones (Oyawoye, 1970). The host rocks are weathered to varying degrees with depths. The undifferentiated Migmatite and Gneisses are mixed rocks of mainly two sources – the pre-existing host rock and a rather indefinite diffusion of other rock materials that are granitic in composition through the host rock. The host rock is usually the meta-sedimentary schists, and the intruded materials include mostly granites, pegmatites, and quartzite. They occur also mostly around the northwestern and southeastern portions and are less weathered than the schist.

3. Research Methodology

Field geological mapping was carried out which entailed ground traversing of the whole area, where rocks of different types and structures were identified and samples were collected for further analysis. Structural measurement of strike and dip, geographical coordinates, and elevation of sample locations in the study area were documented. Some of the materials/equipment used include a Geographic positioning system (GPS), compass clinometer, geologic hammer, measuring tape, camera, field notebook, sample bag, and base map (extracted from a topographic map of Bauchi, sheet 149 NE). Geophysical analysis was employed which aimed at acquiring information on the sub-surface geology to be able to predict the nature and thickness of geoelectric layers. The geophysical investigation adopted was the Electrical Resistivity method employing the Schlumberger Configuration of Vertical Electrical Sounding (VES). The locations were traversed, and ten (10) points were sounded with AB/2 at a maximum spread from 100 m. The MN/2 was varied at a maximum of 20 m. Apparent Resistivity values were calculated from the field resistance readings by multiplying the Di-electric constant (K). The product in Ohm-m was then used as plots against the current distance spread (AB/2) m to generate a curve on a bi-log graph paper. The curves so plotted were interpreted by curve matching with a standard curve. The interpretation is finally confirmed by using the computer interpretation software IPI2win. The software produces modelled curves, adjusts field data, and interprets geo-electric layers.

Soil samples were randomly and carefully selected and analysed for particle size, using the Unified Soil Classification System (USCS), Specific Gravity, Atterberg Limits (for clayey materials), Compaction, Triaxial Tests, and California Bearing Ratio (CBR) tests. For details about these geotechnical methods see (Arora, 2008). The x-ray diffraction (XRD) analysis was done in the XRD laboratory of the National Geoscience Research Laboratory (NGRL) a subsidiary of the Nigerian Geological Survey Agency (NGSA), Kaduna. The samples were sun-dried and pulverized. By placing the pulverized sample inside the XRD machine's sample holder, the sample was then scanned with x-rays of a specified wavelength, where the intensity of the reflected radiation was recorded Bish, D. L., Reynolds, R. C., and Post, J. E. (1989); Moore and Reynolds 1997). A search and match method were used to analyse the pattern displayed on the detector. Results of the geophysical, geotechnical, and geochemical methods combined would be modelled, which will reflect the vertical variation in the soil properties. (Fig. 3)

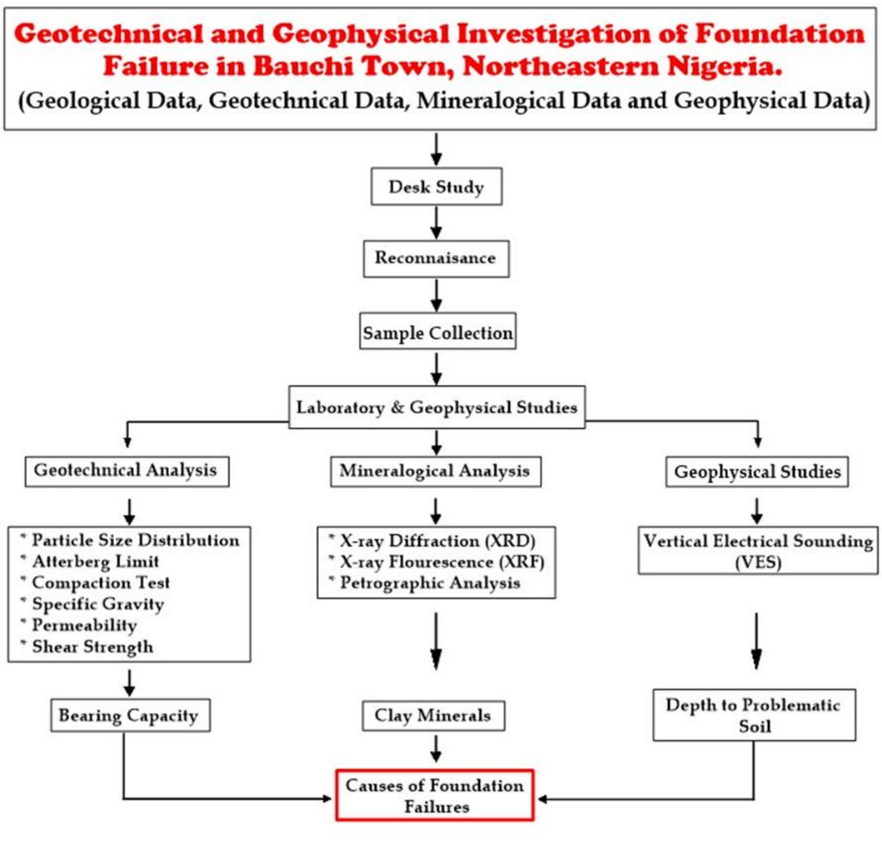

Figure 3: Study workflow

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4. Results And Discussion

Table 1: Summary of VES Analysis

VES Points	Layers Number	Resistivity (Ohm`s)	Thickness (m)	Depth (m)	Curve Types	Lithology
1	1	209	0.897	0.897	H	Top Soil
	2	34.9	7.653	8.55		Weathered Zone (Sandy-Clay)
	3	8148	∞	∞		Fresh Basement
2	1	330.6	0.9125	0.9125	H	Top Soil
	2	41.07	11.9675	12.88		Weathered Zone (Sandy-Clay)
	3	782.1	∞	∞		Fresh Basement
3	1	129	2.53	2.53	H	Top Soil
	2	11.99	2.194	4.724		Weathered Zone (Sandy-Clay)
	3	33614	∞	∞		Fresh Basement
4	1	352.3	0.6207	0.6207	H	Top Soil
	2	59.33	5.1083	5.729		Weathered Zone (Sandy-Clay)
	3	479	∞	∞		Fresh Basement
5	1	64.13	1.315	1.315	A	Top Soil
	2	35.19	6.542	7.857		Weathered Zone (Sandy-Clay)
	3	448.8	∞	∞		Fresh Basement
6	1	150	2.25	2.25	H	Top Soil
	2	42.4	7.39	9.64		Weathered Zone (Sandy-Clay)
	3	403	∞	∞		Fresh Basement
7	1	183.4	1.338	1.338	H	Top Soil
	2	40.35	6.618	7.956		Weathered Zone (Sandy-Clay)
	3	244.6	∞	∞		Fresh Basement
8	1	119.1	0.6389	0.6389	A	Top Soil
	2	24.22	1.8081	2.447		Weathered Zone (Sandy-Clay)
	3	83.15	16.1369	17.945		Weathered Zone (Sands)
	4	1603	∞	∞		Fresh Basement
9	1	206	0.585	0.585	H	Top Soil
	2	76.4	5.605	6.19		Weathered Zone (Sands)
	3	1194	∞	∞		Fresh Basement
10	1	115	3.93	3.93	A	Top Soil
	2	118	11.67	15.6		Weathered Zone (Sands)
	3	41513	∞	∞		Fresh Basement

Results from VES carried out as shown in Table 1, revealed that most of the sounding curves obtained from the study area were majorly the H - A type curves, where three (3) distinctive layers were mostly delineated viz; the topsoil, regolith (weathered clay) layer, and crystalline (fresh) Basement. The resistivity of the topsoils ranged between 64.13 Ωm and 352.3 Ωm, with thicknesses of between 0.5 m and 3.93 m. The weathered layer (clay) has resistivity starting from 11.99 Ωm and 118 Ωm, with thicknesses of between 1.81 m and 11.97 m to a depth that ranges from 2 to 6 m. The bedrock layer resistivity also ranges between 403 Ωm and 8148 Ωm, with thickness from 5 to 10 m, to an infinite depth. In this study both the topsoil and weathered layers fall within the clay category, with resistivity values less than a 100 Ωm. These were modelled and geoelectric layers were inserted which gives a better display. In summary, the first and the second geoelectrical layers are generally incompetent as engineering materials, according to resistivity classification by Sherrif (1991). However, the fresh Basement layers are competent for most parts of the study locations. (Fig. 4)

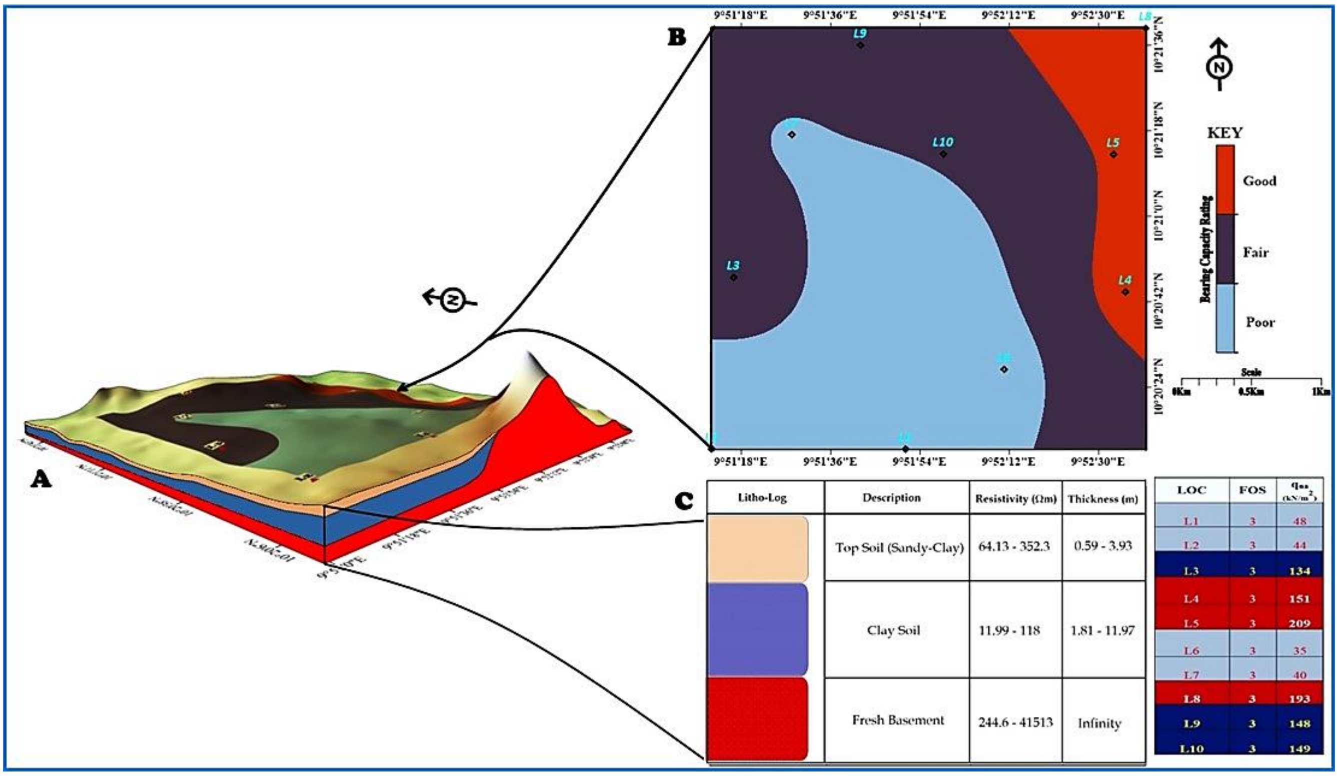
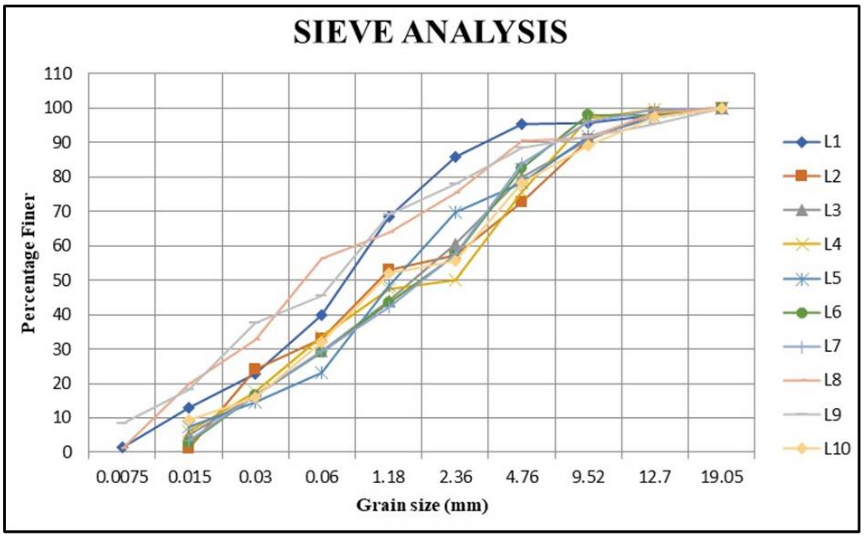


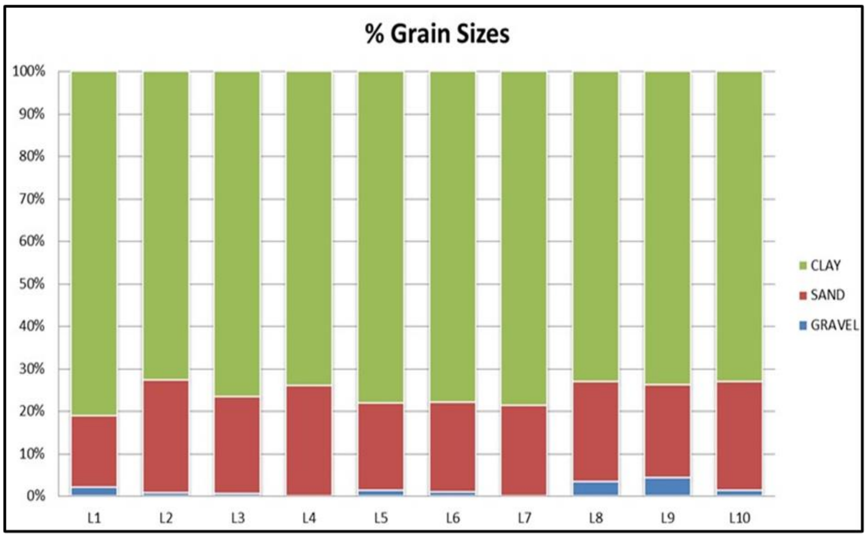
Figure 4: (a) A Digital Elevation Model Map of the area. (b) Allowable Bearing Capacity rating map of the area. (c) A geo-electric section of various layer found within the studied area

Table 2: Summary of Sieve analysis and Atterberg limits test results											
Parameter	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	Max
Gravel %	2.03	0.7	0.55	0.15	1.3	1	0.15	3.3	4.33	1.3	4.33
Sand %	16.73	26.43	22.8	25.83	20.13	20.8	20.83	23.37	21.53	25.57	26.43
Clay %	**80.73**	**72.23**	**76.28**	**73.88**	**76.63**	**77.03**	**77.13**	**72.45**	**72.6**	**72.65**	**80.73**
CU	9.28	3.7	39	8.4	0.9	3.5	16.8	0.4	5.5	40	40
CC	0.5	0.3	1.1	1.4	4.7	1.3	0.1	47	1.2	0.7	47
DEPTH (M)	1.6	1	1.8	1.5	1.8	1.5	1.5	1.5	2.0	1.5	1.57
LL%	25.8	31.9	26.5	34.2	34.2	26.1	40.3	29.7	42	43.2	33.39
PL%	20.8	27.9	22.3	28.2	29.8	26.1	32.9	29.7	34.2	29.2	28.11
PI%	5.0	4.0	4.2	6.0	4.4	0.0	7.4	0.0	7.8	14.0	5.28

*NB: According to (Arora 2008), well graded soil ranges from coefficient of uniformity **(Cu) > 6** and coefficient of curvature **(Cc) = 1 to 3.***

Summarized in Table 2, are the results of grain size distribution analysis. This analysis is vital in determining the significance of the soil's strength (Samtani and Nowatzki, 2006). The results show the ratio amount of gravel fraction in the studied soils ranged from 4.33 to 0.7%, the Sand fraction ranged from 26.43 to 16.73% and the Clay ranged from 80.73 to 72.6. Standard specification by the Unified Soil Classification Scheme (USCS) requires foundation soils to possess less than 35% number of fines (clay), while the reverse is the case in the study area. A comparison of the obtained results with the FMWH 1974, specification indicates that all soil samples did not meet up the specification by (Ameh et al., 2017). There is a strong correlation between high soils fines and clay predominance, which has a dominating influence on the soil mass behavior, causing it to be unsuitable or unfit. It can also be inferred from the results that the soils are vulnerable to recurrent shrinkage and swelling potentials during climate variations. This suggests that the soils are of fair to poor quality as far as the foundation of the building is concerned. (Fig. 5)





Clay = (72.6%-80.73): **Sand = (16.73-26.43%)**: **Gravel = (0.15-4.3%)**

Figure 5: (a) A chart showing plots of grain size distribution curves. (b) Histogram chart portraying the percentage of grain size distribution

Atterberg limits analysis results summarized in Table 2, disclosed that the Liquid Limit range from (25.8–43.2%), the Plastic Limit from (20.8–34.2%), and the Plasticity Index (33.4, 28.1) with mean values of 5.30. Sowers and Sowers (1970), state that the Plasticity Index (PI>31) should be considered high, which in turns indicates high content of expansive clay, most probably smectite which is detrimental to foundation soils. Based on LL and PI standards, the soils sample are classified as inorganic clays of high plasticity. Such soils usually retain substantial volumes of moistness and is usually susceptible to high compressibility (Sowers and Sowers, 1970). An increase in PI signifies a loss in strength, and plastic soils decrease in load-bearing capacity as moisture increases (Emesiobi, 2000). On the Casagrande's plasticity chart remains a very valuable tool in classifying the plasticity of soil materials (Amadi et al., 2015). The studied soil samples largely plot above the U-line and are classified as low compressibility clay soils (CL-group) belonging to the low plasticity clays (CL). As said through that soil samples with low, medium and excessive plasticity may have low, medium, and excessive compressibility respectively (Casagrande, 1947). Based on the result of the gradational analysis and the Atterberg limits the studied soils can be classified as CL. This could explain the mechanism of severe crack initiation in the studied area.

Table 3: Results of Coefficient of Permeability and compaction Test

LOCATIONS	Loc 1	Loc 2	Loc 3	Loc 4	Loc 5	Loc 6	Loc 7	Loc 8	Loc 9	Loc 10	LOCATIONS
DEPTH (M)	1.6	1	1.8	1.5	1.8	1.5	1.5	1.5	2.0	1.5	**DEPTH (M)**
PM (Hazen's 1893) K=100 $(d10)^2$ cm/s ($\times10^{-3}$)	7×10^{-5}	21×10^{-5}	8×10^{-5}	7×10^{-5}	27×10^{-5}	2×10^{-5}	2×10^{-5}	14×10^{-5}	2×10^{-5}	7×10^{-5}	**PM (Hazen's 1893) K=100 $(d10)^2$ cm/s ($\times10^{-3}$)**
NMC (%)	1.5	5.4	2.5	6	3.8	2.2	3.2	2.4	2.1	7.7	**NMC (%)**
OMC	13.4	12.5	9.3	11.6	15.3	11.6	10.5	12.8	11.2	14.1	**OMC**
MDD	1950	2005	2000	1995	1940	1930	1697	1945	1605	1645	**MDD**

The coefficient of permeability test (K) result summarized in Table 3, recorded lower K-values in the soils found within the study area. Which range from 1.58 × 10−3 to 2.68 × 10−2 m/sec. The low coefficient of permeability could be because of high clay content which impedes drainage. The study reported that soil's saturation ratio is inversely proportional to its saturation (Arora, 2008). The infiltration capacity of soil depends on the permeability, degree of saturation, vegetation, and amount and duration of rainfall (Todd, 1980). This also implies that excess pore water pressure will develop, thereby reducing the effective stress and thus, decreasing shear strength upon loading. However, when these soils encounter water, the soils will retain water and lead to rapid weakening due to poor drainage. The result implies that the study area is waterlogged during the rainy season because of its low permeability values, which makes the soils unsuitable as foundation soils. Hence, the soils (clay) should be excavated and backfilled with cohesionless, non-expansive soils and compacted, or partially replaced with granular soils (sands and gravel) as it will increase drainage, effective stress, and thus, increase shear strength.

Table 4: Results of Triaxial (Shear Strength parameter)

LOCATION	Loc 1	Loc 2	Loc 3	Loc 4	Loc 5
C (kPa)	73.000	81.30	65.00	67.00	105.0
ϕ (°)	15.87	11.75	19.19	20.46	19.17

The results of the undrained triaxial test and the Mohr plot for all samples as presented in Table 4. Results revealed that cohesion (C) for the different soils ranges from 65 kPa and 105 kPa, and angle of internal friction (Ø) values range between 11.750 and 20. 460. The soils showed a relatively mild cohesion but a low angle of internal friction. This is directly related to the binding forces within the pores of clays relative to its low frictional contact, high water content reduces the angle of internal friction This result indicates lower shear strength, and bearing capacity loss, which in turn makes a site poor for engineering construction (Una et al., 2015). Also postulated research the strength of any rock or soil that has inadequate permeability will decrease when hydrostatic pore pressure builds up within it when loaded because the void cannot drain water (Blyth and de Feritas, 1984). This research also found that soil shear strength decreases with an increase in excess pore pressure. On this account, soil samples are likely to experience shear reduction at the peak of rains or moisture influx if heavily loaded (Igwe and Fukuoka, 2014). The soil strength may, however, be increased by increasing the compaction effort.

The compaction test results and curves of the studied soils are shown in Table 3. The Optimum Moisture Content (OMC) varied between 9.3% to 15.3%, at a Maximum Dry Density of 1.61 to 2.01 g/cm3 respectively. The compaction result revealed that Optimum Moisture Content (OMC) is high in the studied samples, due to the high proportion of clay. This agrees with analysis that OMC is higher in fine-grained soils and lesser in coarse-grained soils (Arora, 2008). Principally, a decrease in Maximum Dry Density (MDD) is an indicator of soil weakness (Eltaif and Gharaibeh 2008). This revealed that soils in the study area can be classified as poor-fair foundation materials based on compaction grading. Thus, before laying a foundation, soils within this area should be compacted on the wet side of optimum moisture content, as this will increase shear strength and minimize swelling potentials (Emesiobi, 2000).

Also, the result of mineralogical analysis using X-Ray Diffraction (XRD) techniques was employed on the soil samples to aid in the identification of clay minerals which are known to influence the expansive nature of the foundation soils in the study area. Analysis revealed that smectite occurred as a major clay mineral. The area study revealed the abundance of smectite clay minerals. Smectite expands about 300% of its original volume when drained (Farmer 1973). As a result of the swelling of smectite during the rainy season and subsequent shrinkage during the dry season, differential settlement of buildings results in cracks and collapse of structures (Arora 2008). Consequently, the presence of these minerals in soil indicates a high compressibility, a high plasticity index, and a low strength index. To further support the XRD result, expansive clay soils in the field can be easily recognized in the dry season by the deep cracks, in roughly polygonal patterns, on the ground surface. As a result of expansive clays, buildings in the study area have major cracks that lead to their collapse.

5. Conclusion

Geotechnical, geochemical, and geophysical investigations have been carried out in some parts of Bauchi, Northeastern Nigeria. Results obtained from geotechnics revealed that the soils found within the studied area are majorly clayey. The soils are classified as A-6 (11) and CL, which is reflective of fair to poor foundation materials, rated by the American Association of State Highway and Transportation Officials (AASHTO M 145-2012) soil classification system. Results of the geophysical investigations revealed low resistivity and incompetent saturated clay underlying foundation in the area. From the investigations carried out, it is evident that the buildings in the study area are situated on an unstable expansive clay (Smectite) with high cohesion and low angle of internal friction which indicates lower shear strength and bearing capacity loss, therefore makes a poor foundation material. Geologically, the study area is comprised of predominant migmatite gneiss and granite, which when subjected to weathering activities played a key role in the formation of clay (smectite), which in turn led to foundation failure because of its shrink and swelling potential. Therefore, it recommended that detailed foundation studies should be carried out within the area before the commencement of any civil work, partial replacement of clay soils with granular soils (sands and gravel) can be used to improve when subject to stabilization measures, water should be prevented from the foundation by the provision of adequate surface drainage, and also a further structural study of the bedrock using aeromagnetic data is also recommended in future works in the area. This would give a true picture of the structural disposition of the bedrock in the area.

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