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Forensic geotechnical investigation of cracks in buildings around Gubi and environs, Bauchi, Northeast Nigeria

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ABSTRACT

The study aims to undertake a geoforensic investigation of the major causes of cracks in buildings in Gubi and its environs. To achieve this, geophysical and geotechnical approaches were adopted to characterize the soil properties and subsurface rocks. Five vertical electrical soundings (VES) were purposively carried out using Schlumberger's configuration to characterize the geoelectrical properties of the soil. In addition, 10 disturbed soil samples were collected for geotechnical laboratory analyses. The indices analyzed are natural moisture content (NMC), particle size distribution, Atterberg limits, free swell index, linear shrinkage, and specific gravity. Three geoelectrical layers comprising topsoil, weathered layer, and bedrock basement were delineated within the study area. The resistivity values (10.8–42.8 Ωm) suggest that the top and weathered layers of VES 1 and VES 2 are incompetent clay material. The results of the geotechnical tests, however, revealed that the site is underlain by poorly graded clay sand to sand clays with low to medium plasticity, specific gravity (2.2–2.7), liquid limit (25.8%–39.0%), plastic limit (18.8%–35.1%), NMC (7.10%–25.0%), and linear shrinkage limit (2.8%–11.3%). The result generally shows that the soils in the northeastern parts have NMC, linear shrinkage, and free swell value above the permissible limit for a foundation. It was concluded that the differential settlement of the incompetent subsoil material is responsible for the failure of the foundation material and building walls.

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1. Introduction

Cracks in buildings are gradually becoming a global engineering problem faced worldwide. Cracks are the consequence of excessive stresses in the components of buildings and other structures (Rajabather, 2016). Stress in a building is attributable to external forces such as earthquakes, winds, and foundation settlement. Conversely, stress can be internally generated by variation in temperature and moisture contents (leading to soil swelling or shrinkage). Cracks undermine the stability and safety of engineering structures, thereby increasing their susceptibility to failure and eventual collapse. However, timely investigation of such cracks and their underlying causes becomes paramount. Although cracks in concrete cannot be prevented entirely they can be controlled by using adequate material and the technique of construction and considering design criteria (Rajabather, 2016). The rate of buildings failure in Nigeria has increased in recent times, resulting in the loss of lives (Oyedele, 2009). Furthermore, there are several cases of cracking of walls that have led to collapsed buildings and

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these have been linked to poor foundation and inadequate site investigation (Alhassan et al., 2015).

Other sources ascribe the cause of a building's collapse to a combination of factors, including bad building material and weak underlying soils (Egwuonwu and Sule, 2012; Oyedele, 2009). Unfortunately, in this region of the world, one critical component that is frequently overlooked is the lack of appropriate knowledge on the characteristics of subsurface material before structures are built. Buildings founded on hidden geological structures, like faults, karst regions, and expansive clays, are bound to fail due to heaving or settlement of subsurface soils (Egwuonwu and Sule, 2012). The mineral composition of the soils has a great influence on their geotechnical properties and the primary considerations and concepts in just about all practical soil use are the appraisals of the material's strength and compressibility characteristics (Christodoulias, 2015). As a result, a thorough understanding of soil geotechnical characteristics is critical in addressing geotechnical issues like soil swelling and shrinkage, which are primarily responsible for the considerable development of cracks in houses, pavement foundations, and other civil engineering buildings.

Geoforensic investigation entails the application of the principles and knowledge of earth sciences to real-life problems (Ruffell and McKinley, 2005) while incorporating technological capability, inventiveness, and experience to tackle geotechnical problems. In line with Delatte and Rens (2002), some of the investigations deployed in geoforensic geotechnical studies include chemical tests, electrical resistivity studies, X-ray diffraction, and scanning electron microscopy. Different techniques have been deployed by different authors to address engineering problems in different parts of the world. These include mineralogical (Christodoulias, 2015), geotechnical (Bello, 2007), integrated geophysical, and geotechnical approaches (Cosenza et al., 2006). Although geophysical surveys are often ignored when investigating sites for construction purposes, the geophysical and geotechnical approaches remain the preferred geoforensic techniques for foundation investigation because they can give useful information on the geotechnical qualities of the foundation soils in a timely and economic manner (Oyedele, 2009).

This study has been conducted against the backdrop of the widespread development of cracks in buildings in parts of the Gubi Campus of the Abubakar Tafawa Balewa University, Bauchi, and surroundings which have raised concerns on the consequence to human life and property occasioned by increased occupancy level. Studies have reported the issue of cracking of building walls in parts of Bauchi and neighboring states (Lawal and Ahaji-unanka, 2020; Orazulike, 1992). According to these studies, soils in parts of Bauchi area are rich in expansive clays, like illite and montmorillonite, which cause the soils to shrink and swell intermittently with seasonal change in the water table. It is, however, worth noting that the abovementioned researches were based on chemical data and index engineering properties of the soils.

To further investigate this engineering problem, the present study deployed an integrated forensic geotechnical technique, and the geoelectrical studies used vertical electrical sounding (VES) to map the subsurface layering of the causative soils and evaluate the geotechnical cause of building cracks in Gubi and environs in Bauchi, in the northeastern part of Nigeria, to forestall the loss of lives and public properties. The significance of this research cannot be overemphasized in this area considering the sad incident of a bridge collapse that occurred in the Gubi campus about 2 years ago which claimed some lives.

1.1. Location and geology of the study area

The study area lies within latitudes N10°26'13" and N10°29'00"and longitudes E90°48'45" and E90°50'24" (Fig. 1). The area falls within the southeastern part of Bauchi State and it is accessible via a main route that connects Bauchi and Kano and several minor roads linking it to Abubakar Tafawa Balewa University. The area also has numerous footpaths that serve as access roads to the study area's remote sections. The terrain is distinguished by low- and high-level outcrops, majority of which show conical shape and reach 693 m above sea level. The drainage system is dendritic, with minor streams in the area which appears to be structurally controlled, emptying their water into the Gubi River. The climate of the study area consists of a wet rainy season which extends from May/June to October with a temperature range of 25ºC–37ºC (NIMET, 2008) and a dry season, characterized by the Harmattan from November/December to April/May as with a temperature range of 29°–45° (NIMET, 2008). The vegetation type is Savannah and comprises scattered trees, shrubs, and mostly flat-lying grasses that generally become dry and leave bare ground during the dry season; trees shed their leaves but quickly develop leaves during the rainy season.

The Bauchi area is underlain by crystalline rocks of the Nigerian basement complex, mostly Precambrian to early Paleozoic (Oyawoye, 1972) and Chad formation. The rocks suites in this complex are the

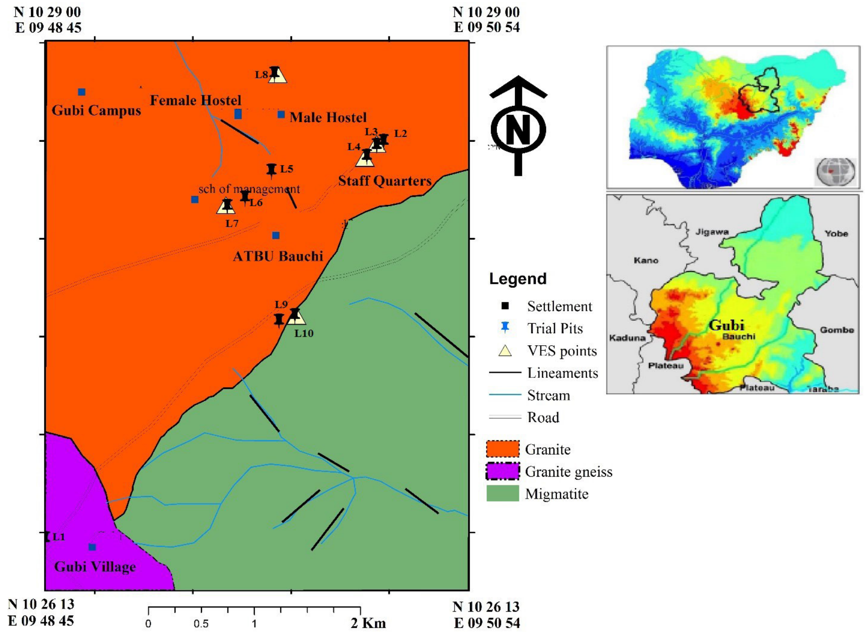

Figure 1. Geological map of the study area with inset map of Nigeria and Bauchi State.

migmatite–gneiss–quartzite complex, the schist belt, the younger granite, and the older volcanics. The older granite suites are presumably porphyritic biotite granite or biotite hornblende granite. The granite–gneiss occurs in the southern zone of the state, comprising the southwestern part of Bauchi, some parts of Ganjuwa and Tafawa Balewa area. It is a fine- to medium-grained biotite-rich granitic rock. In general, they have a uniform appearance and are relatively constant in composition. These rocks are composed of white plagioclase and some microcline quartz and fairly abundant biotite. Hornblende is also present in varying amounts.

Locally, based on field research and petrographic analysis, the Gubi area is underlain by granites, granite–gneisses, and migmatite–gneisses (Rufai et al., 2017). The granites are high-K calc-alkaline granitoids which have similitude with the Late Neoproterozic granitoids of Nigeria (Ferre and Caby, 2007). According to Ferre and Caby (2007), the area is part of a metamorphic rock setting that consists primarily of monotonous granite—high-grade gneisses and migmatite—that is cross-cut by humongous Neoproterozoic monzogranite magmas that occur as either elongate intrusive bodies and run parallel to general structural trends or as circular plutons molded by country rock structures.

3. Materials and Methods

The geoforensic investigation adopted for this study entailed the following: (i) reconnaissance and crack monitoring survey, (ii) geoelectrical sounding, (iii) soil sampling, and (iv) geotechnical laboratory analyses.

3.1. Reconnaissance and crack monitoring

The reconnaissance survey took the form of field traversing during which the rocks, drainages, road network, security, and other important information concerning the study were determined. The reconnaissance also entailed observation of affected structures and inspection of the nature, type, and level of severity of cracking, as well as the spatial distribution of the cracks (Fig. 2). The severity of a crack was assessed by observing the crack's orientation or direction on the affected wall. Foundation movement is usually indicated by vertical and diagonal fissures in concrete walls. When a vertical crack expands at the bottom or top, it is an indication of heaving or settling, which can cause difficulties (Joshi et al., 2013). Furthermore, the observation of the width and propagation of the cracks to ascertain their level of development is a vital aspect of the forensic geotechnical investigation.

3.2. Geoelectrical sounding

Geoelectrical sounding is one of the techniques for geoforensic investigation and its strength lies in the fact that it provides relevant information about the physical properties of subsurface materials (Delatte and Rens, 2002). For this study, five VES were purposively distributed across the area to have an idea of the underlying lithology, the degree of saturation,

Figure 2. Observation of building cracks in the study area.

and fracturing. While some of the VES points were undertaken in the problematic zones where cracks are manifested on buildings (locations L2, L3, L4, and L6), others were deployed in areas without any manifestation of fractures to serve as a control (locations L1, L5, L7, L8, L9, and L10). For the VES, the Schlumberger configuration was deployed to a maximum current separation of 100 m using an ABEM SAS 3000 BC terameter. The chosen array was to probe greater depths not covered by the geotechnical sampling (1.5 m) and to reveal deeper zones of weakness. The results of the VES were interpreted with the IPI2WIN software, through the forward modeling technique that is considered a vital tool in analyzing different survey arrays and geological scenarios where comparison are to be made between the acquired field data and synthetic results (Loke, 2002). To probe the soils further, their index and other engineering characteristics were determined through a geotechnical investigation.

3.3. Geotechnical field sampling

Ten disturbed soil samples were collected from predetermined locations in the study area. Excavations were made to a depth of about 1.5 m, following the BS standards for site investigation. The samples were collected manually and the equipment used included a shovel, digger, measuring tape, and GPS for measuring sampling coordinate. 3–4 kg of samples were obtained and placed inside polythene bags before they were transported to the soil laboratory for further investigations.

3.4. Geotechnical laboratory analyses

The laboratory analyses were carried out at the soil laboratory of the department of civil engineering, ATBU, Bauchi, using standard procedures specified in BS 1337-2 (1990). The laboratory tests carried out include the natural moisture content (NMC) test, Atterberg limit (liquid and plastic) test, specific gravity test, grain size distribution, swelling test, and shrinkage test. For the granulometric analysis, 200 g of disaggregated sample was mechanically sieved using the BS 200 sieve and the retained soil was air-dried and ran through a set of standard sieves. The liquid limit and plastic limit tests were carried out on air-dried samples passing 0.425 mm sieve in line with the specification in BSI 1377-2 (1990). About 100 g of sample passing BS sieve no. 400 was mixed at the liquid limit to fill the shrinkage mold and thoroughly leveled after the mold has been oiled. The sample was oven-dried for a period of 24 hours, the variation in the size of the sample due to the shrinkage was measured, and L_s was expressed in percentage.

3.5. Calculations

The mathematical formulation of some of the index and engineering test conducted on the samples are elucidated below.

3.5.1. Natural moisture content (NMC)

The moisture content of the cool sample could be calculated as a percentage of the dry soil mass, from the following equation:

$$\text{Moisture content } (W) = \frac{m^3}{m^3 - m^3} \times 100\ \% \qquad (1)$$

where
m^1 = mass of the container (g);
m^2 = mass of the container and wet soil (g);
m^3 = mass of the container and dry soil (g).

3.5.2. Specific gravity

The specific gravity values were calculated using the following equation:

$$\text{Specific gravity } (G_s) = [(w^2 - w^1)/(w^4 - w^1)\text{-}w^3 - w^2] \qquad (2)$$

where
G_s = specific gravity;
w^1 = weigh of dry bottle + stopper;
w^2 = weigh of soil + bottle and stopper;

w^3 = weigh of bottle + stopper and soil + water;
w^4 = weigh of bottle + stopper + water content.

3.5.3. Linear shrinkage

The variation in the size of the sample due to the shrinkage was measured and L_s was expressed in percentage using the following equation:

$$L_s = S - \frac{S_0}{S} \times 100 \qquad (3)$$

where
L_s = linear shrinkage;
S = length of wet soil;
S_o = length of dry soil sample.

4. Results and Discussion

Preliminary investigations revealed that the area under study is underlain by three rock units: charnokites (70% of the area), granite gneiss (10%), and migmatite (20%). The crack monitoring exercise revealed the spatial distribution of the affected buildings (Fig. 3) and suggested that the cracks developed on buildings in the Gubi area appeared to be structural cracks that are detrimental to the safety and stability of buildings, judging by their vertical to diagonal propagation (Min, 2006). Unlike the structural cracks (Fig. 3), the nonstructural crack is perfectly innocuous to engineering structures. The outcome of other investigations aimed at further unraveling the cause of this engineering failure, which is elucidated under the subsequent subsections.

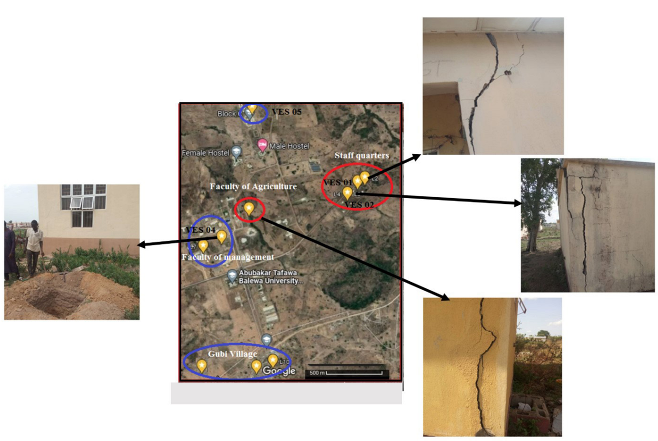

Figure 3. Results of the visual inspection of the buildings in the study area with a Google Earth inset map; red circles show the problematic zones and the blue circles show the unaffected areas.

4.1. Result of geoelectrical sounding

The results of the preliminary interpretation of the VES data (geoelectrical type curves) are shown in Figure 4, while the primary geoelectrical parameters are presented in Table 1. The competence rating for subsurface soils proposed by Idornigie et al. (2006) was adopted for interpretation (Table 2). According to Figure 4, the study area is characterized by three-layer H-type curves which suggest $p^1 > p^2 < p^3$, implying that the arrangement of the three layers are such that a low conductive layer (weak) is sandwiched between two relatively resistive material (topsoil and bedrock unit).

The resultss of the primary geoelectrical parameters (p and h) revealed the presence of three geoelectrical layers, which include topsoil, weathered layerm and fresh basement. The topsoils have resistivity values between the range 42.8 and 642 Ωm, with thickness ranging from 0.5 to 10.6 m (Table 1). The resistivity of the intermediate weathered layer ranged from 10.8 to 355 Ωm, with thickness ranging from 5.4 to 10.6 m. The resistivity of the fresh basement, however, varies between 642 and 1,537 Ωm. The observed geoelectric parameters were subsequently interpreted using a lithological competence scheme based on apparent resistivity, in line with Idornigie et al. (2006) (Table 2). Based on this classification scheme, the area's topsoil is classified as competent clayey sand (p-values between 350 and 750 Ωm) as suggested by VES 3, 4 and 5. VES 1 and 2, however, indicated incompetent clays (p-values between 0 and 100 Ωm) and moderately competent sandy clays (p-values between 100 and 350 Ωm), respectively. In terms of the thickness, VES 3, 4, and 5 showed thicknesses of 1.3, 1.5 and 1.4 m, respectively, while VES 1 and 2 are generally less than 1 m (Table 2). The second layer in the study region, however, revealed sand clays (VES 4 and 5), clays (VES 1 and 2), and clayey sand in VES 3. By implication, the amount of clays in the overburden appeared to increase with depth and this could be detrimental to the bearing capacity of the soils considering that clays increase cohesion and reduce shearing resistance in the soils. The clay minerals that make up the clay soils are also a source of concern in that expansive clay-bearing argillaceous materials tend to swell and shrink, resulting in consequential damage to engineering structures placed on them. One major limitation of the resistivity method is its inability to detect the mineralogy of clays or their shrinking or swelling tendencies. Hence, the integration with the geotechnical approach is vital in ascertaining vital index and geotechnical properties of soil materials.

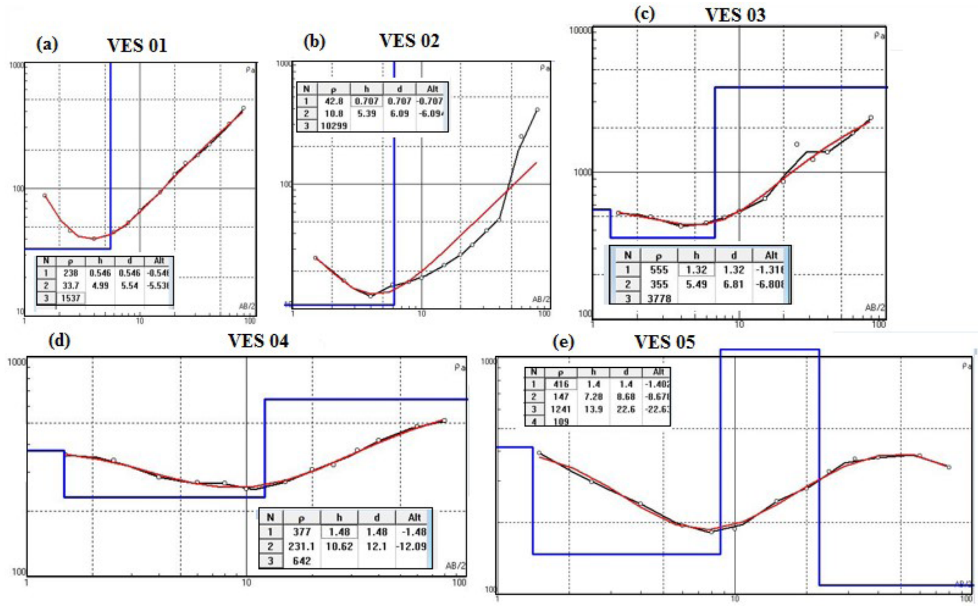

Figure 4. Observed type-curve at (a) VES 01, (b) VES 02, (c) VES 03, (d) VES 04, and (e) VES 05.

Table 2. Lithological competence rating in terms of apparent resistivity value (after Idornigie et al., 2006).

Resistivity (Ωm)	Lithology	Competence rating
0 <100	Clay	Incompetent
100–350	Sandy clay	Moderately competent
350–750	Clayey sand	Competent
>750	Sand/Laterite/Bedrock	Highly competent

Based on the above premise, it can be summarized that VES 1 and 2 are underlain by incompetent clays, which could be detrimental to the engineering structures emplaced on them, while VES 3, 4, and 5 are underlain by clay sand materials of high competence. It is important to note, however, that the subsoils in the area generally became clayey with increasing depth. To further investigate the engineering properties of the studied soils, a geotechnical laboratory analysis was undertaken.

4.2. Result of geotechnical laboratory analyses

The geotechnical test results (Table 3) indicated the percentage of soil passing the No. 200 (0.075 mm) sieve range from 2.63% to 6.62% and averages 4.6%, indicative of coarser-grained soils based on the Unified Soil Classification System (USCS). Furthermore, from the grain size distribution curves (Fig. 5), the estimated values of coefficient of uniformity (C_u) and coefficient of curvature (C_c) range from 2 to 4.5 and 0.8 to 1.3, respectively, based on the fact that C_u value greater than 4–6 is classified as well-graded soils, while C_u less than 4 indicates poorly graded. The soil in the study area can be classified as poorly graded except sample 10, with C_u of 4.5, which is well-graded (Lawal and Ahaji-unaka, 2020). C_c values also conformed to the result C_u, as C_c less than 1 typifies poorly graded soils and a good number of the samples revealed C_c values of less than 1–1. The significance of the soil grading and sorting in the engineering context lies in the fact that these parameters give insight into the permeability characteristics of the material. While well-graded soil is characterized by low permeability and causes water logging due to poor drainage properties of the soil, poorly graded soils, however, would generally be more permeable and exhibit good drainage conditions.

The liquid limit, plastic limit, and plasticity index ranged between 20% and 38%, 0% and 24.3%, and 7.5% and 30%, respectively. The implication of the Atterberg limits can best be explained using a Casagrande plasticity chart (Fig. 6), which is very instrumental in classifying the fine fractions of soil

Table 3. Summary of the geotechnical laboratory test results.

Pit no.	1	2	3	4	5	6	7	8	9	10
% passing	6.11	2.79	4.47	2.63	3.26	3.26	3.44	6.62	5.02	4.47
C_u	2	2.5	2.5	2.3	2.5	2.7	2.1	3.7	2.14	4.5
C_c	0.9	1	1	0.8	0.9	1.1	1	1.3	0.9	1.3
LL (%)	30	32	28	38	25	32	20	25	22	23
PL (%)	0	21.3	19.1	24.3	0	23.1	15.6	17.5	0	0
PI (%)	30	10.7	8.9	13.7	25	8.9	4.4	7.5	22	23
L_s (%)	3.5	9.9	9.2	11.3	3.5	11.3	3.5	2.8	4.9	6.3
FS (%)	0	12.1	14.2	11.1	0	13.2	0	0	0	0
NMC (%)	9.7	23.26	20.2	25	10.1	22.4	7.1	8.6	11.6	12.1
G_s	2.61	2.48	2.6	2.55	2.59	2.53	2.61	2.58	2.61	2.62

C_c = Coefficient of curvature, C_u = Coefficient of uniformity, NMC = Natural moisture content, LL = Liquid limit, PL = Plastic limit, PI = Plasticity index, L_s = Linear shrinkage, FS = Free swell

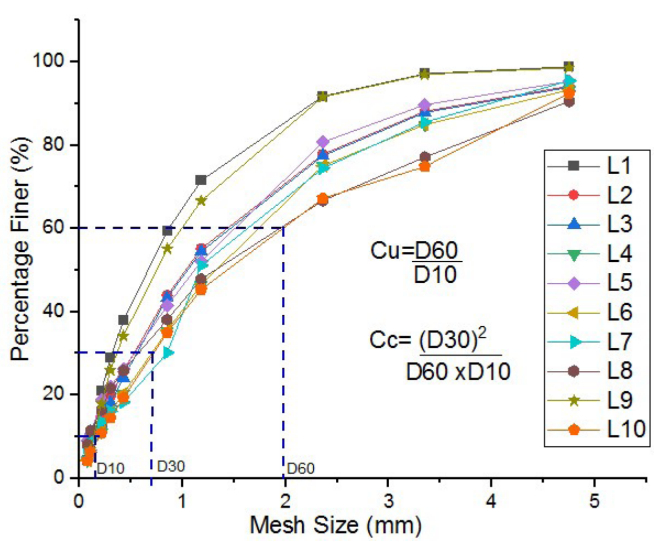

Figure 5. Results of the granulometric analysis showing D10, D30, and D60, and the expressions for C_u and C_c.

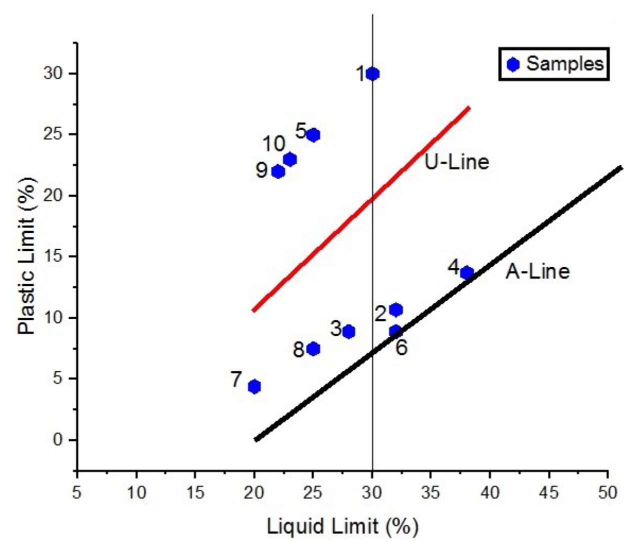

Figure 6. Casagrande plasticity chart showing the distribution of samples: A-line and U-line.

into silt, clays, or silty clays. The plasticity chart is used together with the granulometric analysis in naming the soil based on the USCS soil classification scheme. As shown by the chart, all the soils fell above the A-line, indicating that the soils are clayey. Soils below the A-line are silty in nature, while soils with PI of between 5 and 7 are silty clays. Furthermore, samples from pits 3, 5, 7, 8, 9, and 10 revealed liquid limit percent of between 0 and 30, which typifies low plasticity clays, whereas samples 1, 2, 4, and 6 showed liquid limit values of between 30% and 50%, an indication of clays of medium plasticity.

The moisture content of the samples ranges from 7.1% to 23.5%, which suggests that some of the soil samples have a high tendency to hold water during the wet season and the expulsion of the water during the dry season could cause serious shrinkage problems. Samples L2, L3 L4, and L6 showed the highest amounts of NMC, which could be detrimental to the foundation of buildings emplaced on them. Also, increasing water contents would reduce the cohesion of the soils and the effective stress within the soil grains which will, in turn, decrease the strength of the foundation supporting soils (Lawal and Ahajiunanka, 2021). According to Altmeyer (1955), linear shrinkage values >8 are reflective of critical and unsuitable foundation soils. The linear shrinkage of the soil in the study area range from 2.8% to 11.3%, and this implies that samples L2, L3 L4, and L6 have critical linear shrinkage limit, and hence the affinity to swell when in contact with water and shrink

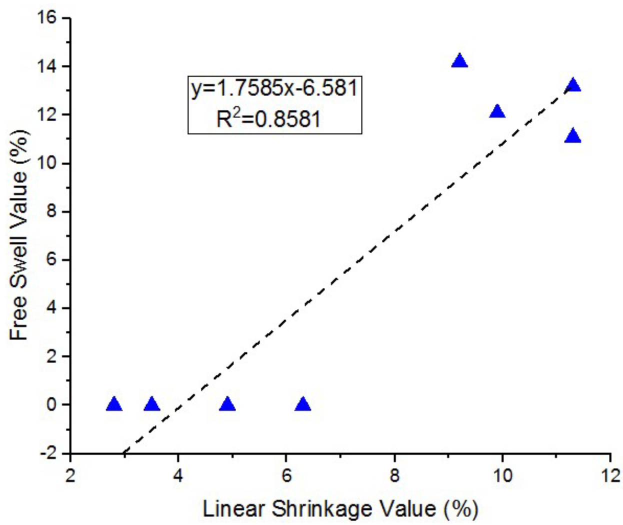

Figure 7. Relationship between free swell value and linear shrinkage.

when dried. In addition, the free swell value of the studied soil samples is another important geotechnical parameter used to estimate the degree of expansion of the expansive soils (Prakash and Jain, 2002). Similarly, the abovementioned sample locations also indicated high amounts of the free swell ratio, which generally varied from 0% to 14.2% in the studied soils. Samples L2, L3, L4, and L6, however, revealed free swell values of between 11.1% and 14.2%, suggesting that the samples exhibit some swelling tendencies. Conversely, other soils samples showed free swell ratios of zero, suggestive of the fact that the clays are better suited for foundation and road materials, owing to their negligible free swell values. Although there are no standardized ratings for free swell value (Holtz and Gibbs, 1956), a significant positive correlation exist between the free swell value and the linear shrinkage, judging by the high R^2 value shown by the linear regression line in Figure 7.

The specific gravity of the soil samples varied between 2.48 and 2.62. According to Bowles (2012), the standard range of values for specific gravity lies between 2.60 and 2.80 for sands, silty sands, and inorganic clays, while organic clays have a specific gravity of < 2.60, which make them unsuitable and detrimental to the foundation of structures. Based on the above premise, only samples L1, L3, L7, and L10 fall within the expected range, samples L2, L4, L5, L6, and L8 all fell short of the acceptable threshold, and this could be the reason for the failure of foundation and cracking of building walls in the area. This is because specific gravity is consequential in determining the efficacy of soils in engineering construction. According to Prakash and Jain (2002), greater amounts of specific gravity give rise to better pavement systems and competent foundations.

Based on the result of geotechnical data analysis conducted, it can be surmised that the soils in the area are clayey sand (SC) of low to medium plasticity, some of which exhibit high NMC which could affect the structural strength and stability of these soils. It can, however, be concluded that samples L2, L3, L4, and L6 are somewhat problematic owing to their higher moisture content, higher swelling index, higher shrinkage, and low specific gravity values, which are detrimental to the foundation of structures emplaced on them.

4.3. Data synthesis

The result obtained from the geoforensic geophysical and geotechnical investigation showed a significant level of agreement. The geophysical survey of the study area reveals that the study area is largely covered by the clayey sand soil type which conforms to the USCS nomenclature derived from the granulometric analysis and Casagrande plasticity chart of the studied soils. Furthermore, as revealed by the geoelectrical sounding, VES 1 and 2 are underlain by incompetent clays which could be detrimental to the engineering structures emplaced on them, while VES 3, VES 4, and VES 5 are underlain by competent clayey sand. Similarly, the result of the geotechnical investigation revealed that the subsoil of L2, L3, L4, and L6 are incompetent, and hence cannot support a good foundation due to their higher moisture content, higher swelling index, higher shrinkage, and low specific gravity. However, other locations (L1, L5, L7, L8, L9, and L10) indicated competent subsoil with good bearing capacity attributable to their good engineering properties.

5. Conclusion

The geoforensic investigation of the failure of buildings in the Gubi area using integrated geotechnical and geoelectrical methods has proved to be very effective. Based on the result of this research, the cracks developed in parts of the Gubi area are attributable to the incompetent soil materials which constitute the foundation of the buildings. Visual inspection of the affected structures indicates that the direction of cracks is vertical to diagonal, which confirms that the structural damage is caused by soil heaving and settlements. The results of VES show that the soils underlying the staff quarters and the Faculty of Agriculture in the northeastern part of the study area are of low resistivity (<50 μm) and constitute incompetent engineering soils. The results of the geotechnical investigation which are in tandem with the geophysical results revealed that locations L2, L3, L4, and L6 (northeastern parts) are underlain incompetent engineering materials with high moisture content, high swelling index, and linear shrinkage value, as well as low specific gravity. However, locations L1, L5, L7, L8, L9, and L10 indicated competent subsoil with good bearing capacity, as revealed by their favorable geotechnical properties. It is, therefore, recommended that detailed site investigations should be necessitated before erecting buildings and other engineering structures, especially in the northeastern part of the area. These would allow for timely interventions, which could take the form of chemical stabilization or removal and replacement of the affected soil material with more competent materials.

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