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GEOTECHNICAL CHARACTERIZATION AND FOUNDATION SUITABILITY ASSESSMENT: CASE STUDY OF GANDU, LAFIA, NORTH-CENTRAL NIGERIA

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ABSTRACT

This study presents an integrated geotechnical characterization of subsurface soils in Gandu, Lafia, north-central Nigeria, to evaluate their suitability for foundation support. Laboratory analysis (particle size distribution (PSD) and Atterberg limits) and in-situ test (standard penetration test (SPT)) were conducted on five (5) test pits (PT1-PT5). The PSD results show that the soils are predominantly fine-grained, with coefficients of uniformity ($C_u \approx 2.7–2.9$) and curvature ($C_c \approx$ 0.8–0.9) suggesting uniformly graded fine soils and poor gradation. Atterberg limits analysis exhibited Liquid Limit (LL) of 28.7 – 35.0 %, Plastic Limit (PL) of 12.9 –24.8 %, and resultant plasticity indices (PI) of 7.7 – 22.1 %. Casagrande plasticity chart classification placed PT1 within the CL zone (clay of low plasticity) and PT2–PT5 in the ML–CL region (silty clay or clayey silt). The SPT N-values indicate an increase in stiffness with depth, signifying the effect of natural consolidation and overburden pressure. Soils with high PI exhibited lower penetration resistance, thereby establishing a clear relationship between plasticity and strength. Strong agreement was observed among PSD, Atterberg limits, and SPT results, which confirms the suitability of the combined index and in-situ testing for soil characterization and preliminary engineering assessment. Overall, the subsurface soils are characterized by moderate strength, low permeability, and moderate compressibility, making them suitable for lightly loaded structures with a well-designed foundation. However, if high-rise or heavier structures are desired, ground improvement or deep foundation systems may be required.

Keywords: Foundation support, Atterberg limit, Particle size distribution, Bearing capacity

INTRODUCTION

A foundation is an integral part of a structure that is responsible for distributing and transferring all applied loads to the underlying soil mass (Adekeye *et al*., 2021; Lollo, 2016). Foundation systems are primarily classified into two major types, namely shallow foundations and deep foundations. The shallow foundation is a type of foundation that transmits the structural load to near-surface soils. The depth of the ground in a shallow foundation varies from 1.5 to 3 m (Magar *et al*., 2020). The foundation that transfers structural loads to deeper, competent strata, typically at a depth exceeding 3 m (Magar *et al*., 2020). In general, soil support is what all foundations ultimately rely on. Hence, a comprehensive site investigation is essential before engineering design to characterize soil properties and stratification (Islam *et al*., 2020). Geotechnical data obtained from site investigations informs the selection and design of suitable foundation systems. For optimal performance, the subsoil must possess sufficient bearing capacity to prevent shear failure while exhibiting settlements that remain within the structure's tolerable limits (Bowles, 1996).

A considerable number of works have been undertaken to investigate the engineering parameters of subsurface soil before the placement of any structure. For instance, Akintorinwa and Adeusi (2009); Ishola *et al*. (2022); Adewuyi and Philips (2019) and Oyedele and Oladele (2015) conducted geophysical and geotechnical investigations for proposed sites to determine the competency of the areas for the placement of engineering structures. The swelling and or shrinkage potential of subsoils where quantified using geotechnical techniques (Arthur *et al*., 2021; Kelly, 2021; Zhou *et al*., 2021).

Among the geotechnical methods used for soil investigations, sieve analysis, Atterberg limits, Standard Penetration Test (SPT) and Cone Penetration Test CPT are mostly employed because of their wide coverage in terms of the engineering properties (Lollo, 2016). The first three methods have also been adopted for this study. Sieve analysis stands as a conventional geotechnical approach for classifying coarse-grained soils such as gravels andsands. The Atterberg limits are a key measure of soil behavior, representing the specific water contents at which a remolded fine-grained soil passes from one physical state to another (Briaud, 2023). As shown in Figure 1, the Liquid Limit (LL) marks the transition from a liquid to a plastic state; the Plastic Limit (PL) from a plastic to a semi-solid state; and the Shrinkage Limit (SL) from a semi-solid to a solid state.Testing is conducted on the portion of a soil sample finer than a No. 40 sieve (0.425 mm opening). The standard penetration test is one of the oldest in-situ tests used for estimating settlement and bearing pressure for shallow and deep foundations (Briaud, 2023).

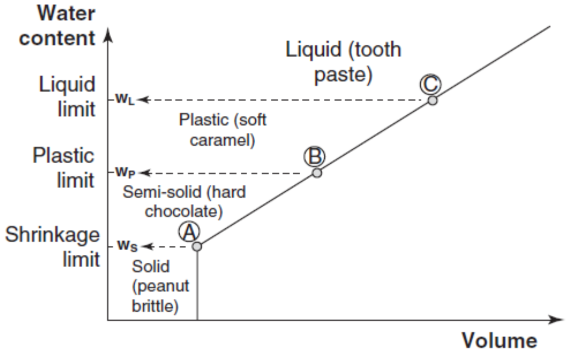

Figure 1: States of consistency and Atterberg limits (Briaud, 2013)

Over the years, the study area (Gandu) has experienced rapid infrastructural development due to the establishment of the Federal University of Lafia. So many structures have been built to accommodate the influx of students. However, there is evidence of structural defects that could lead to the collapse of buildings in the area. To forestall or mitigate the aforementioned problem, it became necessary to gain subsurface soil information for a solid foundation design. Hence, the need for this study.

Geology and Hydrogeology of the Area

The study area is underlain by Late Turonian-Early Santonian sediments of the Awgu Formation within the Middle Benue Trough, Nigeria. Lithologically, the area is made up of ferruginous siltstone, ferruginous sandstone, and shale (Figure 2). Shale is the dominant lithology, covering about 95 % of the area. The shale is divided into two lithofacies: grey shale and carbonaceous shale. The grey shale is fine-grained, with a smooth texture dominated by shiny micas. It is fissile and feels smooth to the touch; however, the presence of finely dispersed silty materials gives it a slightly gritty texture. Oxidation of iron oxide and other iron-bearing minerals results in reddish colouration in the grey shale layers. The carbonaceous shale appears dark grey, indicative of the presence of organic matter. It is fine-grained, fissile, and more friable than the grey shale (Nwajide, 1990).

The study area and environs posed serious hydrogeological challenges due to the nature of its prospective aquifers. The aquifers are of small size, thinly developed with intermittent clay and shale interbedding that are not too porous and permeable, and in some locations, are highly indurated, which only become aquiferous through secondary voids generated by fractures and joints (Umar *et al.*, 2025). The Awgu Formation comprises carbonaceous and calcareous shales, occasionally interspersed with limestone, and a medium- to coarse-grained, permeable, water-bearing sandstone layer. However, the limited thickness and lateral extent of the sandstone reduce the overall groundwater potential of the study area (Nwajide, 1990).

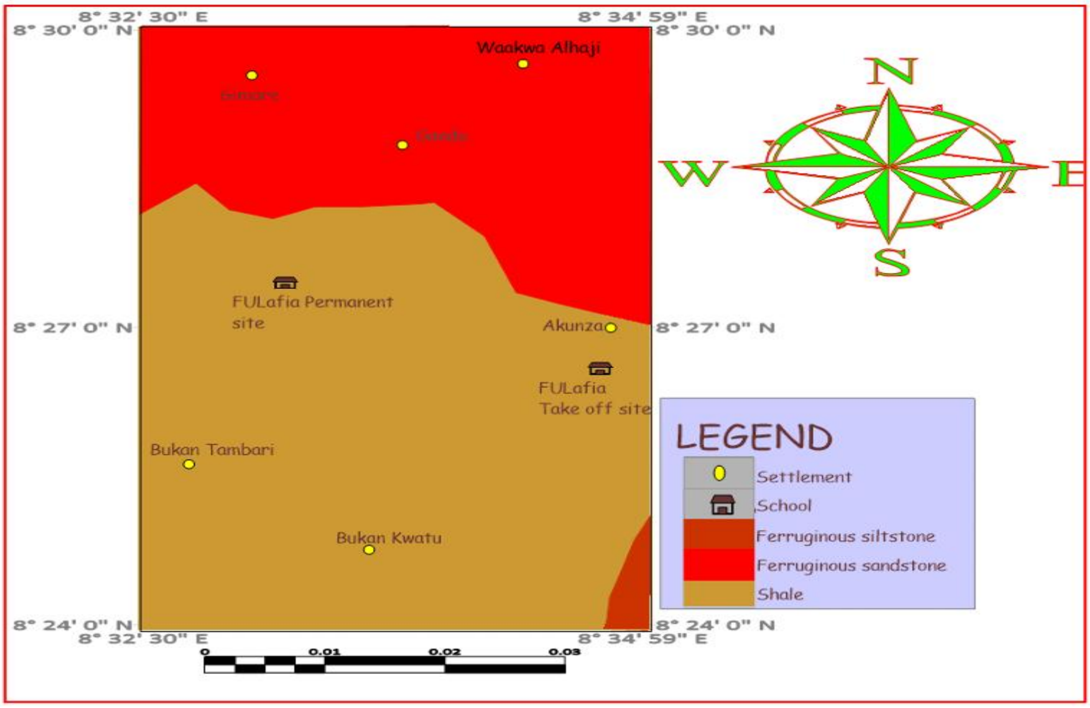

Figure 2: Geological map of the study area

MATERIALS AND METHODS

Soil sampleswere obtained from a hand-excavated test pit at a depth of 3 m. Disturbed samples, collected with a split spoon sampler, were analyzed in the laboratory for index properties, including Atterberg limits and particle size distribution (via sieve analysis). The procedures for these laboratory tests and the in-situ test (SPT) are detailed in the following subsections.

Atterberg Limits

The Atterberg limits,which encompass the Liquid Limit (LL) and Plastic Limit (PL) were determined in compliance with ASTM D4318 (2023) and BS 1377-2 (1990) standards. Air-dried soil samples were first pulverized and sieved through a 0.425 mm sieve to obtain the fine fraction used for testing. The Casagrande cup method was used for the liquid limit determination. The soil paste was placed in the cup, to groove and induce the impacts, at a two blows per second until closure on alength of 13 mm. This procedure was repeated for varying moisture contents, each corresponding to a given number of blows. The moisture content was plotted against the logarithm of the number of blows, and the liquid limit was identified as the moisture content at 25 blows on the flow curve.
For the plastic limit, soil was rolled into 3 mm diameter threads. Rolling was continued until the threads crushed at that diameter, suggestinga plastic-to-semi-solid state transition. The moisture content at this stage was determined and recorded as the plastic limit. The Plasticity Index (PI), defining the range of water content within the plastic state, was subsequently calculated as the numerical difference between the Liquid and Plastic Limits (Equation 1);

$$PI = LL - PL \qquad (1)$$

The results were finally used to classify the soils on the Casagrande Plasticity Chart, identifying whether each sample behaved as clay or silt of low or high plasticity.

Particle Size Distribution

Particle size distribution (PSD) is a laboratory method for separating a soil sample into distinct fractions of particles according to their sizes. The procedure involves initially washing the sample over a 75 µm (No. 200) sieve to remove the fine particles sticking to coarse grains. The retained fraction is then oven-dried, and a dry sieve analysis is performed. The resulting data, percentage finer by weight versus particle size, is plotted on a semi-logarithmic graph, where particle size is represented on a logarithmic scale to accommodate the wide range of grain sizes. The graph is called the PSD curve, which is used to calculate the coefficient of uniformity (C_u), a key parameter for classifying soil gradation as well-graded or poorly-graded. The C_u is defined mathematically as in Equation 2;

$$C_u = \frac{D_{60}}{D_{10}} \qquad (2)$$

The parameter D_{10} represent the particle size at which 10 % of the sample is finer. Similarly, D_{60} is the diameter at which 60 percent is finer.

Another parameter used for classifying soil gradation is the coefficient of curvature (C_c), which describes the general shape of the e particle size distribution curve and is defined by Equation 3

$$C_c = \frac{(D_{30})^2}{D_{60} \times D_{10}} \qquad (3)$$

Where D_{30} is the particle size for which 30 percent amount of soil has particles which are finer than this size.

It has been established that for a soil to be well graded

$$C_u > 4 \quad \& \quad 1 < C_c < 3 \quad well\ graded\ Gravel$$
$$C_u > 6 \quad \& \quad 1 < C_c < 3 \quad well\ graded\ Sand$$

If any of the above conditions are not met, the soil will be classified as poorly graded.

Standard Penetration Test

The Standard Penetration Test (SPT) is a widely adopted in-situ testingmethod used to evaluate the geotechnical properties(strength and consistency) of subsurface soils. In accordance with BS 1377, the SPT is classified as a dynamic test that provides a quantitative measure of subsurface soil characteristics (Bery & Saad, 2012). The test is conducted by driving a standard split-spoon sampler into the soil at the bottom of a borehole using repeated blows from a 623N hammer falling through a standard height. After an initial seating penetration of 75 mm, the number of blows required to drive the sampler through the next 300 mm (in three successive 75 mm intervals) is recorded. The sum of the blows for this 300 mm penetration is reported as the SPT N-value, which provides an indication of soil density or consistency and is commonly used to estimate bearing capacity, compressibility, and strength characteristics of the soil. The first measurement is taken at 1 m depth, and subsequent measurements are taken at an increment of 0.5 m for the investigated depth of 3 m.

RESULT AND DISCUSSION

Particle Size Distribution (PSD)

The Particle size distribution PSD curves for samples PT1- PT5 (Figure 3) show the majority of mass passing the larger sieves and concentrated in the fine fraction. This is an indication that the material is dominated by silt and clay-sized particles rather than coarse sand or gravel. Hence, the PSD is typical of silty or clayey soils rather than well-graded sands. This observation is consistent with the low D_{10} and small spread between D_{10} and D_{60}. The values for D_{10}, $D_{30,}$ and D_{60} are obtained from the interpolation of the PSD curves, as in Table 1.

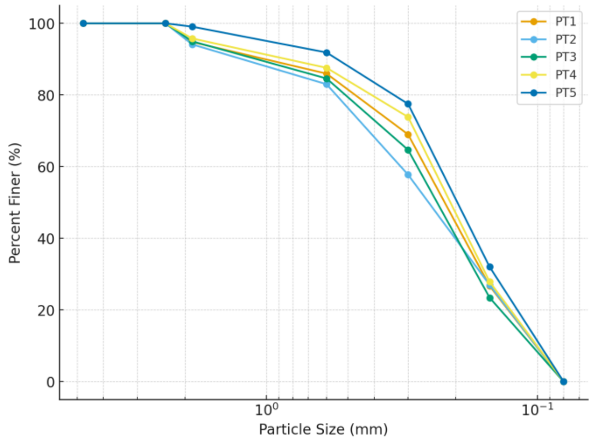

Figure 3: Particle size distribution curves

Table 1: Estimated values of D_{10}, D_{30}, and D_{60}

Sample	D_{10} (mm)	D_{30} (mm)	D_{60} (mm)
PT1	0.13	0.20	0.37
PT2	0.14	0.22	0.39
PT3	0.13	0.19	0.36
PT4	0.12	0.19	0.33
PT5	0.14	0.21	0.40

Table 2: Estimated values of the coefficient of uniformity (C_u) and curvature (C_c)

Sample	C_u	C_c	Classification (Based on Gradation)
PT1	2.85	0.84	Poorly graded (uniform fine)
PT2	2.79	0.89	Poorly graded
PT3	2.77	0.84	Poorly graded
PT4	2.75	0.91	Poorly graded
PT5	2.86	0.79	Poorly graded

These values are used to determine the coefficient of uniformity and curvature. Using equations 2 and 3, the two coefficients are obtained, respectively, as in Table 2.

It was observed that the calculated $C_u \approx 2.7 - 2.9$ (< 4) and $C_c \approx 0.8 - 0.9$ (< 1) which indicates poorly graded/uniformly graded fine material (i.e., not well-graded). This is in line with the standard sieve-based classification rules for sands ($C_u \geq 4$ and $1 \leq C_c \leq 3$ indicate well-graded sands) Although it does not strictly apply to predominantly fine/silty materials (Pizzati *et al.*, 2023). The low C_u and C_c values imply the distribution is narrow and concentrated in a small size range. Also, low C_u signifies a limited range of particle sizes, which often produces lower permeability and more homogeneous deformation behavior under load (James, 2024; Zhang *et al.*, 2022).

Atterberg Limit Analysis

From Figure 4, the liquid limit (LL) obtained ranges from 29-35 %. The plasticity Index (PI) values were obtained using equation 1, approximately 8-22 % indicate a low-to-medium plasticity fine soil overall, as shown in Table 3. According to the Casagrande classification (Figure 5), PI and LL ranges place most samples in the ML–CL region (silty soils to low-plasticity clays); specifically, PT1 (PI ≈ 22 %, LL ≈ 35 %) plots above the A-line which implies more clay-like (CL), while PT2-PT5 (PI ≈ 7-9 %, LL ≈ 29-33 %) plot at or below the A-line implies more silt-like (ML or CL-ML). The LL test plots were linear on semi-log blow scale, indicating correctly performed flow-curve behaviour (Zhou *et al.*, 2021). The PT1's higher PI (≈22 %) relative to the others suggests a higher clay mineral fraction or more active clays in that sample. This is consistent with well-known relationships between clay fraction and Atterberg limits: increasing clay content (and especially presence of active clay minerals) raises LL and PI (Polidori, 2007).

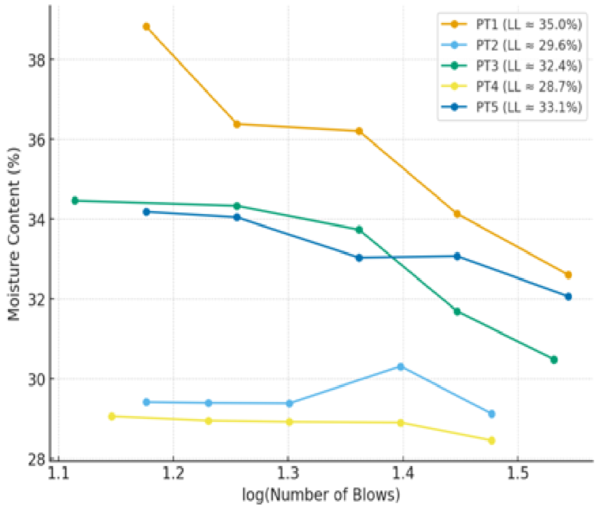

Figure 4: Flow curves for liquid limit determination

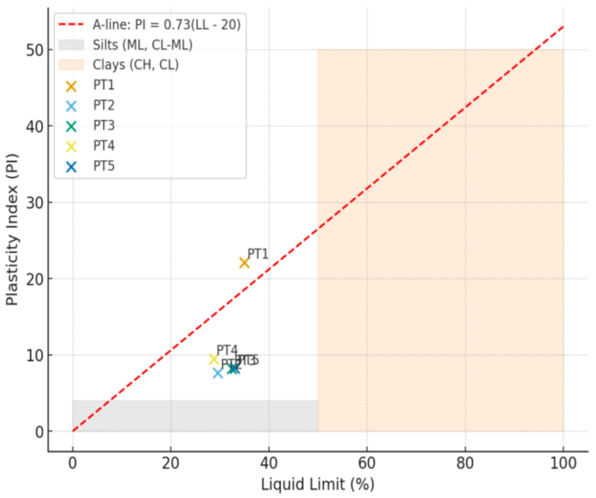

Figure 5: Casagrande plasticity chart

Table 3: Computed values of plasticity index

Sample	Liquid Limit (LL) %	Plastic Limit (PL) %	Plasticity Index (PI) %
PT1	35.0	12.9	**22.1**
PT2	29.6	21.9	**7.7**
PT3	32.4	24.2	**8.2**
PT4	28.7	19.2	**9.5**
PT5	33.1	24.8	**8.3**

Standard Penetration Test SPT

Thestandard penetration test (SPT) results for pits PT1-PT5 are presented in Table 4. Adopting the Standard SPT-based consistency correlations for fine-grained soils established by Skemton, (1986) as depicted in Table 5. It is observed that the N-values range from 3 to 13 within the investigated depth of approximately 3 m, indicating a transition from soft to stiff soil conditions. For shallow depths (1.0 m), the N-values appear to be low (3-5), suggesting soft to medium-stiff soils, while deeper layers reveal higher resistances up to 'N' values of 11-13, suggesting medium-stiff to stiff soils. This increase in penetration resistance with depthis attributed to natural consolidation of the fine-grained soilsand the increasing effective overburden stress. PT1 consistently shows lower N-values compared to the remaining pits, which reflects its higher values of plasticity index (PI)of approximately 22 %, thereby suggesting a higher content of clay. In contrast, PT2-PT5 exhibit similar values of penetration resistance, suggesting the lower values of'PI' of approximately 7-10 %; that is, soils of similar composition.

Table 4: SPT N-values with depth

Depth (m)	PT1	PT2	PT3	PT4	PT5
1.0	3	4	4	5	4
1.5	5	6	6	6	6
2.0	7	8	8	9	8
2.5	9	10	10	11	10
3.0	11	12	12	13	12

Table 5: Standard SPT-based consistency correlations for fine-grained soils (Skemton, 1986)

N-value	Soil consistency
0-2	Very soft
2-4	Soft
4-8	Medium stiff
8-15	Stiff

Comparison with the Atterberg limit and particle size distribution results demonstrates good consistency between the datasets. The soils are classified as low-plasticity clay to silty clay (CL–ML) according to the Atterberg limits, and higher PI values correlated with lower penetration resistance, which is consistentwith established geotechnical literature (Budhu, 2015; Mohammed *et al*., 2019; Skemton, 1986). PT1, classified as CL due to its position above the A-line on the Casagrande plasticity chart, reveals lower SPT N-values relative to the other pits. On the other hand, PT2-PT5 exhibit greater N-values and plot near or below the A-line, indicating silty clay or clayey silt behaviour. The similaritybetween theSPT results and the Atterberg limits demonstrates that soil plasticity is a major factor in determining the strength and penetration resistance of the investigated soils. The PSD curves indicate that the soils are predominantly fine-grained with poor gradation, as evidenced by coefficients of uniformity ($C_u \approx$ 2.7-2.9) and curvature (Cc ≈ 0.8-0.9). Such uniformly graded fine soils lack the interlocking particle structure characteristic of well-graded sands and therefore derive strength primarily from cohesive forces rather than frictional resistance (Faiz *et al*., 2019). This explains the moderate SPT N-values and their smooth increase with depth, confirming a relatively homogeneous subsurface profile dominated by silty clay and clayey silt. Similar observations have been reported in previous studies linking PSD characteristics to penetration resistance and soil stiffness (Das & Sobhan, 2018; Faiz *et al*., 2019; Mohammed *et al*., 2020).

CONCLUSION

The integrated analysis of Atterberg limits, PSD, and SPT for subsurface site characterization reveals that the soils are predominantly fine-grained and poorly graded,which are classified mainly as silty clay to clayey silt (CL–ML). The soils indicate low to medium plasticity, moderate compressibility, and low permeability, with strength governed largely by cohesive behavior. PT1 shows relatively weaker characteristics due to its higher plasticity index. The gradual increase in SPT N-values with depth is consistent with natural consolidation and increasing overburden stress, demonstrating strong agreement between index properties and penetration resistance. Overall, the study area subsoils are suitable for supporting lightly loaded structures (such as small single-story buildings, low-rise residential houses) on shallow foundations with appropriate drainage and settlement control. However, if high-rise buildings or settlement-sensitive structures are desired, the foundations can be supported by transferringthe load to deeper, competent strata via piles or drilled shafts.

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