



The Essential Role of Geotechnical Properties in Determining the Foundation for Buildings and Structures: A Case Study in South-central Region of Nigeria

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Abstract

This study examines the geotechnical characteristics that influence the selection of suitable foundations for buildings and structures within Airport Road G.R.A., a major urban area in Nigeria's south-central region. Soil samples were obtained from borehole depths of 1 m, 3 m, and 6 m, and subjected to geotechnical laboratory analyses, including moisture content, particle size distribution, atterberg limits, bulk density, and triaxial shear tests. Results reveal that the soil is clay-rich, containing more than 51% fines. The plasticity index ranges from 21.02% to 31.65%, the plastic limit from 25.16% to 31.75%, and the liquid limit from 46.18% to 58.37%. Specific gravity values range between 2.40 and 2.67, while cohesion values vary between 22.0 and 24.0 kN/m². Findings indicate that clay content increases with depth, implying that foundation type and depth must be adjusted according to soil strength and the structural load. The recommended foundation design in the study is Pad or pile for high rise buildings.

Keywords

Geotechnical, Foundation, Structure, Building, Bearing capacity

1. Introduction

Nigeria's growing population has led to an increasing demand for housing and infrastructural development. To sustain this growth, structures must be designed with stable and reliable foundations capable of safely transmitting applied loads to the underlying soil or rock. The foundation is a critical structural component that ensures stability by transferring superstructure loads to the ground. Its design must consider the building load, subsoil condition, and local geological setting (Andre-Obayanju and Otoakhia, 2023).

Foundations are generally categorized into shallow and deep types, depending on the depth of load transfer. Shallow foundations, such as pad or strip footings, are suitable for light structures and low-rise buildings, while deep foundations, such as piles or caissons, are used for high-rise or heavy structures where stronger bearing strata are located

deeper below the surface. The design of foundations in Nigeria commonly follows the British Standard Code of Practice for Foundations (BS 8004, 1986) and locally developed empirical guidelines based on field experience. Spread footings are typical for residential structures, as they distribute loads over a wide area to minimize settlement and ensure stability. For deep foundations, load is transmitted beyond weak surface layers into competent strata capable of supporting the structure's weight.

Before any construction, it is essential to assess the geotechnical characteristics of the soil, as this determines foundation type, depth, and design parameters. Poor understanding of soil behaviour can lead to structural failure, excessive settlement, or collapse.

Debasis (2013) emphasized that foundation design should



ensure that loads remain below the allowable bearing capacity under both static and seismic conditions. Dhiraj and Bharathi (2014) discussed the application of shallow foundations in hilly terrains and the methods—such as limit equilibrium and finite element analysis—for estimating bearing capacity near slopes.

Aladin et al. (2024) evaluated the engineering index properties of soil for suitable foundation design in Ajah. The particle size analysis test revealed the predominance of granular materials ranging from fine to coarse sands in the sample. The specific gravity of the soil shows a gradual increase with depth, from 2.41 (at 1m), 2.50 (at 3m) and 2.57 (at 5m).

The results from the Atterberg limit test showed that the three

samples have liquid limit of 20.44%, 23.27%, and 25.61% respectively. The samples are also non plastic in nature, having neither plastic limit nor plastic index. The samples are almost cohesionless, having cohesion of 0.17, 0.95 and 0.76; and having internal friction angle of about 13.73°, 11.62°, and 11.36°.

Further analysis of the soil samples revealed that the optimum moisture content for the samples is 12.4%, 14.2% and 13.2% respectively, from top to bottom, while the maximum dry density for the samples is 1.75 g/cm³, 1.68 g/cm³ and 1.76 g/cm³. The aforementioned property of the soil proves that the soil is suitable for foundation, having low retention water capacity and relatively high specific gravity and permeability, high percentage of coarser grained fraction and very low percentage of clay minerals.

Table 1. Location points of sampled areas

Locations/GPS points sample identification	Longitude	Latitude
BH1 GRA	N 06° 19' 11.988"	E 005° 36' 56.454"
BH2 GRA	N 06° 19' 10.931"	E 005° 36' 57.287"
BH3 GRA	N 06° 19' 10.697"	E 005° 36' 56.261"

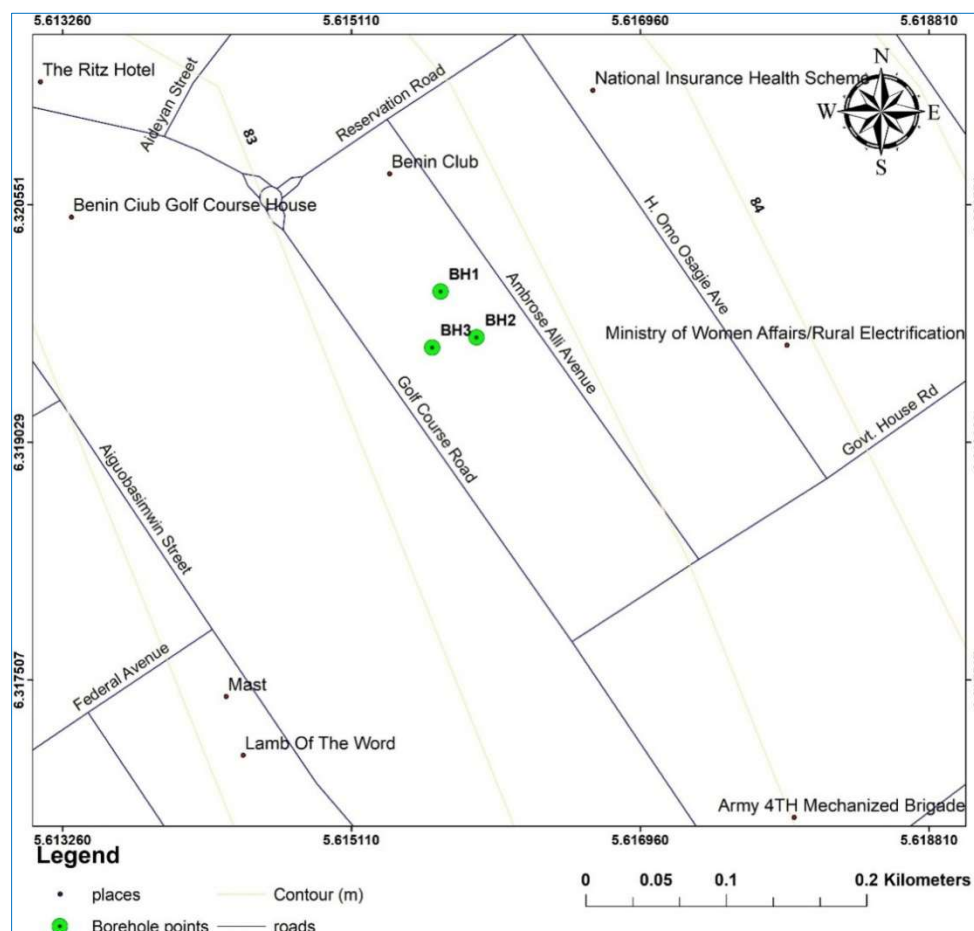


Fig. 1. Location points showing sample area

Srilakshmi and Rekha (2011) analyzed MAT foundations using the Finite Element Method, highlighting its advantages in handling complex boundaries and nonlinear materials. Kaneko et al. (2011) presented a systematic seismic

evaluation approach for building foundations, verified using case studies from Sendai, Japan. Ibeneme et al. (2014) stressed the need to consider foundation type, material, and bearing capacity in structural design. Similarly, Sharma et al.

(2014) compared raft and beam-slab raft foundations, concluding that beam-slab raft foundations are more economical and stable for bearing capacities between 180–250 kN/m².

2. Description of the Study Area

The study area is within the Oredo Local Government Area, Edo State, South-south Nigeria, which lies between longitudes N06°19'10.931" to N06°19'11.988" and latitude E005°36'57.287" to E005°36'56.454" as shown in Fig. 1. The area has a generally flat topography. There are two distinct climatic seasons in the area; the rainy season that lasts from

April to October and the dry season that lasts from November to March. The average annual rainfall in the area is 2,400 mm (Nigerian Meteorological Agency, 2007).

3. Geological Setting of the Study Area

The study area lies within the Benin Formation, characterized by Pleistocene sedimentary deposits of sandstone, shale, clay, and lignite (Aderemi and Iyamu, 2013). The terrain generally comprises lateritic soils, sandy clays, and alluvial deposits typical of the coastal plain. The region is underlain by red-yellow ferralsols with fine-grained lateritic clay and sandy alluvium (Akujeze and Irabor, 2014).

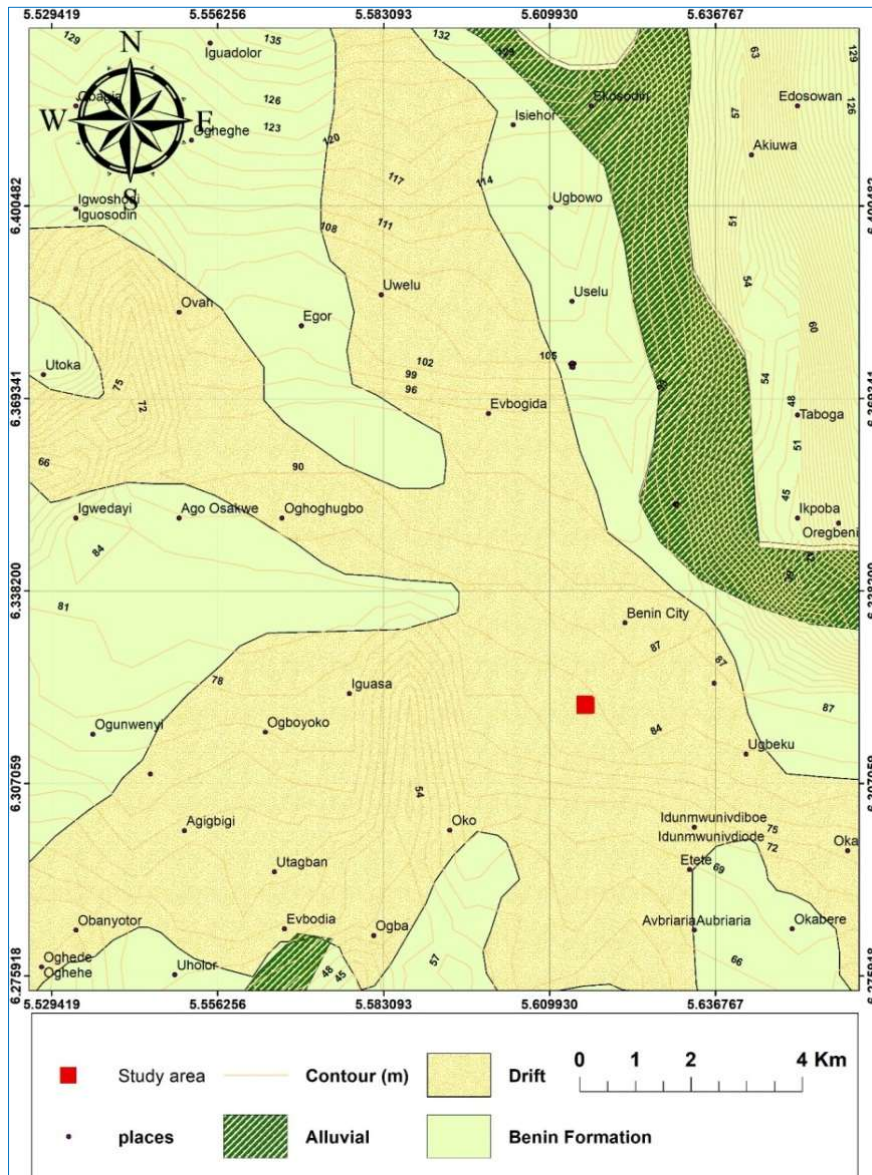


Fig. 2. Benin region geoloical formation (Akujeze, 2004)

The Benin Formation, a major component of the Niger Delta sedimentary sequence, consists mainly of unconsolidated sands and clays. It exhibits high permeability in sandy layers and low permeability in clayey horizons, both of which significantly influence foundation design as shown in Fig. 2.

Benin sand was first used by Parkinson (1907) to refer to the

Red Tropical Soils, Sands, Sandy Clays, and Ferruginous Sandstone that characterize the Paleo-Coastal Environment of the Paleocene-Pleistocene Age. The upper-level off-flaps of the Niger Delta are marked by these sediments, which are dispersed over the southern Anambra Basin. The creation of Red Tropical Soils, which are currently exposed in Calabar, Owerri, Onitsha, and the Benin Region with the date

Oligocene-Pleistocene, are marked by sands and clays that are underlain by coastal plain sands, according to Tattam (1943). To distinguish the reddish-brown-yellow, often white sands with clayey and pebbly layers with type-locality near Benin, Reyment (1965) restored the name Benin Formation. In Calabar and other regions of Southeastern Nigeria, this is also mentioned. The Etete 1 well, which was dug on-shore east of the River Niger by Shell Nigeria Petroleum Development Company (SPDC) and documented by Short and Stauble (1967), helped to further confirm the formation's existence. The formation is roughly 1830 m thick by the coast

but gets thinner as you move inland. The Benin Formation's sedimentary suites dip 2 to 8 south.

The aim of this research is to determine the engineering properties of soils that influence the choice of foundations for buildings and structures. The specific objectives are to determine the geotechnical characteristics and strength parameters of the soils, to assess whether the subsoil can support proposed loads without shear failure and recommend foundation types that ensure structural stability while minimizing construction costs.

Table 2. Specific gravity and Atterberg limit test parameters

Boreholes Points	Specific Gravity		Atterberg Limit Test		
	GS	Av. GS	LL	PL	PI
BH 1	2.74 2.60	2.67	46.18	25.16	21.02
BH 2	2.49 2.32	2.4	54.01	31.75	22.26
BH 3	2.64 2.64	2.64	58.37	26.72	31.65

Table 3. Unified Soil Classification System (USCS) and AASHTO Soil Classification

Borehole	LL (%)	PI (%)	USCS Group	Soil Description	LL (%)	PI (%)	AASHTO Group	Subgrade Rating
BH 1	46.18	21.02	CL	Inorganic clay of medium plasticity	46.18	21.02	A-7-6	Poor
BH 2	54.01	22.26	CH	Inorganic clay of high plasticity	54.01	22.26	A-7-6	Poor
BH 3	58.37	31.65	CH	Inorganic clay of high plasticity	58.37	31.65	A-7-6	Very Poor

Table 4. Plasticity (FMWH / BS 5930 / ASTM D4318) and Compaction (ASTM D698 – Standard Proctor)

Parameter	Observed Range	Acceptable for Subgrade	Assessment	Parameter	Range	Interpretation
LL (%)	46–58	< 35–40	Exceeds limit	MDD (Mg/m ³)	1.69–1.74	Low–moderate density
PI (%)	21–32	< 20	High plasticity	OMC (%)	16.3–18.8	High moisture demand

4. Materials and Methods

4.1. Materials

Soil samples were collected from borehole depths of 1 m, 3 m, and 6 m across three locations within the study area. The samples were air-dried, pulverized, and prepared for laboratory geotechnical testing.

4.2. Methods

A series of laboratory tests were conducted to determine the physical and mechanical properties of the soils. These included:

4.1.1. Moisture Content

Determined by oven-drying samples at 110°C for 24 hours and calculating the ratio of water weight to dry soil weight. The sample's weight was once more determined as a dried sample, and the formula below was used to determine its moisture content:

$$\text{Moisture content, } w = \frac{M_2 - M_1}{M_3 - M_1} \times 100\% \text{ (Mg/m}^3\text{)} \quad (1)$$

where, M_1 : mass of container, M_2 mass of wet soil + container and M_3 : mass of dry soil + container.

4.1.2. Particle Size Distribution (Sieve Analysis)

Dry samples were passed through standard sieves (14–200

µm). Percentage retained, cumulative retained, and percentages passing were computed to classify the soils.

4.1.3. Specific Gravity

Conducted using a density bottle method to determine the specific gravity (Gs) of soil particles.

4.1.4. Atterberg Limit

This also goes by the name of consistency limit. It is used to assess the impact of soil moisture levels on fine-grained soil, particularly soil that has passed through Sieve No. 40. It delineates the limits of different plastic soil consistency states. It is used to evaluate the soil's plasticity.

Liquid Limit: Determined using the Casagrande apparatus at 25 blows.

Plastic Limit: Measured by rolling soil into 3 mm threads until crumbling occurs.

Plastic Index: It is the distinction between the liquid limit (LL) and the plastic limit (PL). It displays the soil's plasticity over the entire moisture content range.

$$PI = LL - PL \quad (2)$$

Bulk Density: Determined by compacting moist soil into a

mould of known volume, oven-drying it, and computing dry density.

4.1.5. Compaction Test (Standard Proctor Method)

A 2.5 kg rammer was used to establish the relationship between moisture content and maximum dry density, with moisture contents varying between 4–20%. This test identifies optimum moisture content and maximum dry density.

Triaxial Compression Test: Conducted to determine shear strength parameters, including cohesion (c) and angle of internal friction (ϕ). The test also enabled control of drainage conditions and measurement of effective stress parameters.

Bearing Capacity Estimation: For soils with very low friction angles (ϕ < 5°), Terzaghi’s bearing capacity equation for shallow foundations was applied:

$$q_{ult} = 5.7c + \gamma D_f \tag{3}$$

Allowable bearing capacity was obtained using a factor of safety (FS) of 3

where; c: cohesion (kPa), γ: unit weight (kN/m³) and D_f: depth of foundation (assumed 1.0 m for shallow foundation) Using a Factor of Safety (FS) = 3

$$Q_{allow} = q_{ult}/3 \tag{4}$$

5. Results and Discussion

5.1. Index Properties of the Soils

5.1.1. Specific Gravity (GS)

The specific gravity values range from 2.49 to 2.67, which fall within the typical range for lateritic to clayey soils. The relatively high GS at BH 1 and BH 3 suggest the presence of iron-rich minerals and silicate mineral, indicating moderate to high soil strength and low porosity, common in tropical soils. Lower GS at BH 2 may indicate higher clay content or organic influence.

5.1.2. Atterberg Limits

The Liquid Limit (LL) values range from 46.18–58.37% while Plasticity Index (PI) values range from 21.02–31.65% as shown in Table 2. These values indicate that the soil is medium to high plasticity soils. According to the Unified Soil Classification System (USCS), the soils plot mainly as CL–CH (inorganic clays of medium to high plasticity).BH 3 (6m), with the highest PI (31.65%), exhibits the greatest swelling potential and compressibility, making it less suitable for direct foundation support without improvement as shown in Table 3.

BH 1 plots below the A-line with LL < 50 are CL while BH 2 and BH 3 have LL > 50 and PI above A-line is CH. These soils are predominantly cohesive, with increasing plasticity from BH 1 to BH 3.LL > 41 and PI > 11 classify all samples as A-7 soils while PI > (LL–30) confirms A-7-6. This indicates unsuitable natural subgrade without stabilization. Soils exceed recommended plasticity limits for pavement subgrade and shallow foundations. It indicates clayey soils

requiring strict moisture control during construction as shown in Table 3 and 4.

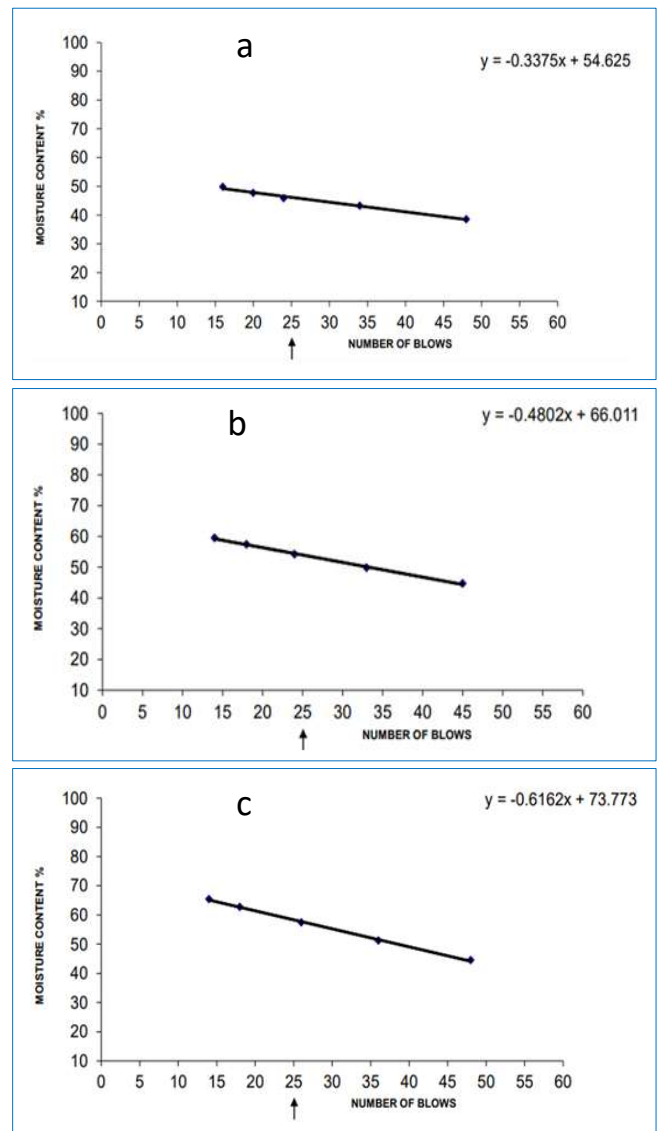


Fig. 3. Liquid limit chart: a) at depth 1.0 m, b) at depth 3.0 m and c) at depth 6.0 m

The Bearing Capacity has high PI and LL suggests low shear strength under saturated conditions. The soil is unsuitable for supporting structural loads without improvement. The Volume Change Behavior particularly at BH 3, high PI (31.65%) which implies that the Shrink–swell potential is high and there is risk of pavement cracking and foundation in distress. Pavement Suitability is classified as A-7-6; these soils are poor subgrade materials and require stabilization for road construction as shown in Table 3 and 4. Figs. 3a, 3b and 3c show the relationship between % of moisture content and numbers of blows.

5.2. Compaction Characteristics

The Maximum Dry Density (MDD) values range from 1.69–1.74 Mg/m³ while Optimum Moisture Content (OMC) values range from 16.3–18.8% as shown in Figs. 4a, 4b and 4c. The relatively low MDD values are typical of fine-

grained, plastic soils. The increase of OMC from BH 1 to BH 3 (depth) reflects increasing clay fraction, requiring more water to achieve maximum compaction. These soils would require careful moisture control during construction to achieve desired compaction levels.

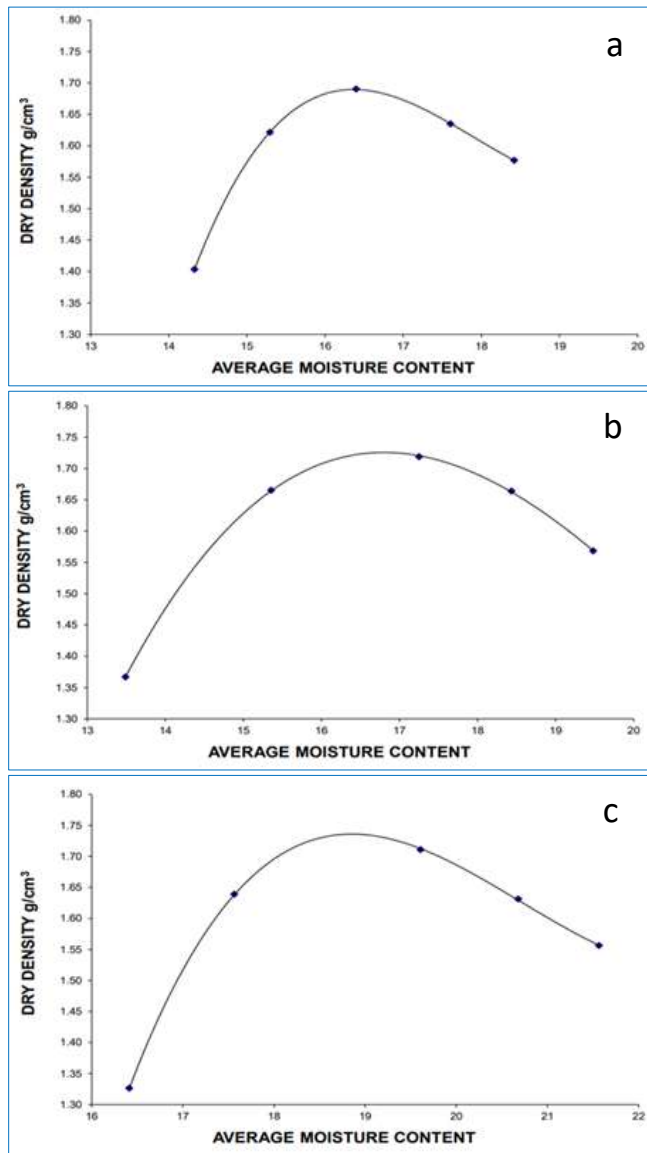


Fig. 4. Compaction chart; a) at depth 1.0 m, b) at depth 3.0 m and a) at depth 6.0 m

The soils exhibit moderate to poor load-bearing characteristics in their natural state. High plasticity implies susceptibility to shrink–swell behavior and potential settlement issues. Ground improvement should be carried out, such as lime/cement stabilization or soil replacement, which is highly recommended for foundation design or pavement works.

5.3. Grain Size Analysis Interpretation (Wet Sieving)

Particle Size Distribution (1.0 m): The % of Sand samples that passing the sieve size of 0.075 – 2.36 mm is 57.1%. The % of Fines (silt + clay,) that passing the sieve size of < 0.075 mm is 42.9%. According to Soil Classification (BS / USCS Basis) more than 35% passes the 0.075 mm sieve, the soil is fine-rich. The dominant coarse fraction is sand, but with very high fines content.

The grain size distribution is smooth but steep, indicating poorly graded soil, narrow range of particle sizes and lack of gravel-sized particles further confirms poor grading. The soil samples have high fines content indicating low to moderate permeability and water movement will be restricted. The presence of fines indicates moderate compressibility, and settlement may occur under load. The shear strength is low and strength strongly dependent on moisture content. The bearing capacity is low to moderate which is unsuitable for heavy foundations without improvement. The soil sample has poor drainage characteristics. There is risk of water retention and softening during wet seasons. The soil sample is probable description as Silty sand / Clayey sand (SM–SC) as shown in Table 5–6 and Fig. 5a.

Particle Size Distribution (3.0 m depth): Based on British Standard soil size limits, the % of Sand samples that passing the sieve size of 0.075 – 2.36 mm is 41.9%. The % of Fines (silt + clay,) that passing the sieve size of < 0.075 mm is 58.1%. The soil is dominated by fines, with sand as the secondary fraction. According to Soil Classification (BS / USCS Basis), more than 50% passes the 0.075 mm sieve, the soil is fine-grained. The presence of a significant sand fraction suggests sandy fine-grained soil. Which is probable classified as Sandy silt/Sandy clay (ML–CL). The grain size distribution indicates a poorly graded soil, with dominance of fine particles and limited range of coarse particles. The soil sample has very high fines content (58%) which indicates low permeability and the increase in fines indicates moderate to high compressibility and higher settlement potential.

The soil has lower shear strength, especially when wet and its strength is moisture-dependent. The bearing capacity is low and not suitable for shallow foundations without improvement. If clay fraction dominates, there is potential shrink–swell behavior and seasonal movement in the study area. Soil quality deteriorates with depth, becoming finer and weaker as shown in Table 5–6 and Fig. 5b.

Particle Size Distribution BH (Depth = 6.0 m): Based on British Standard, soil size limits the % of Sand samples that passing the sieve size of 0.075 – 2.36 mm is 50%. The % of Fines (silt + clay,) that passing the sieve size of < 0.075 mm is 50%. The soil contains equal proportions of sand and fines, indicating a transitional soil between coarse-grained and fine-grained behavior.

Table 5. Soil classification (USCS) and lithologic sequence

Depth	Soil Description	USCS Group	Lithology
1.0 m	Silty clayey sand	SC–SM	Silty clayey sand (topsoil influenced)
3.0 m	Clayey silt / sandy clay	CL–ML	Clayey silt / sandy clay (low permeability zone)
6.0 m	Silty sand with clay	SM–SC	Silty sand with clay lenses

Table 6. Soil sample suitability for engineering works, comparison with BH DEPTH (1.0 m and 3.0 m) and vertical trend within BH

Soil Sample Suitability for Engineering Works			Comparison with BH Depth (1.0 m, 3.0 m and 6.0 m)			Vertical Trend within BH		
Application	Suitability	Parameter	BH1 (1.0 m)	BH1 (3.0 m)	BH1 (6.0 m)	Depth (m)	Fines (%)	Soil Behavior
Shallow foundations	Fair to poor	Fines (%)	42.9	58.1	50	1.0	42.9	Sand-dominated
Road subgrade	Poor without stabilization	Sand (%)	57.1	41.9	50	3.0	58.1	Fine-dominated
Embankment fill	Only after treatment	Soil nature	Sand-dominated	Fine-dominated	Sand-fine mixture	6.0	50.0	Transitional
Drainage layers	Unsuitable	Engineering quality	Fair-poor	Poor	Fair	6.0	50.0	Transitional

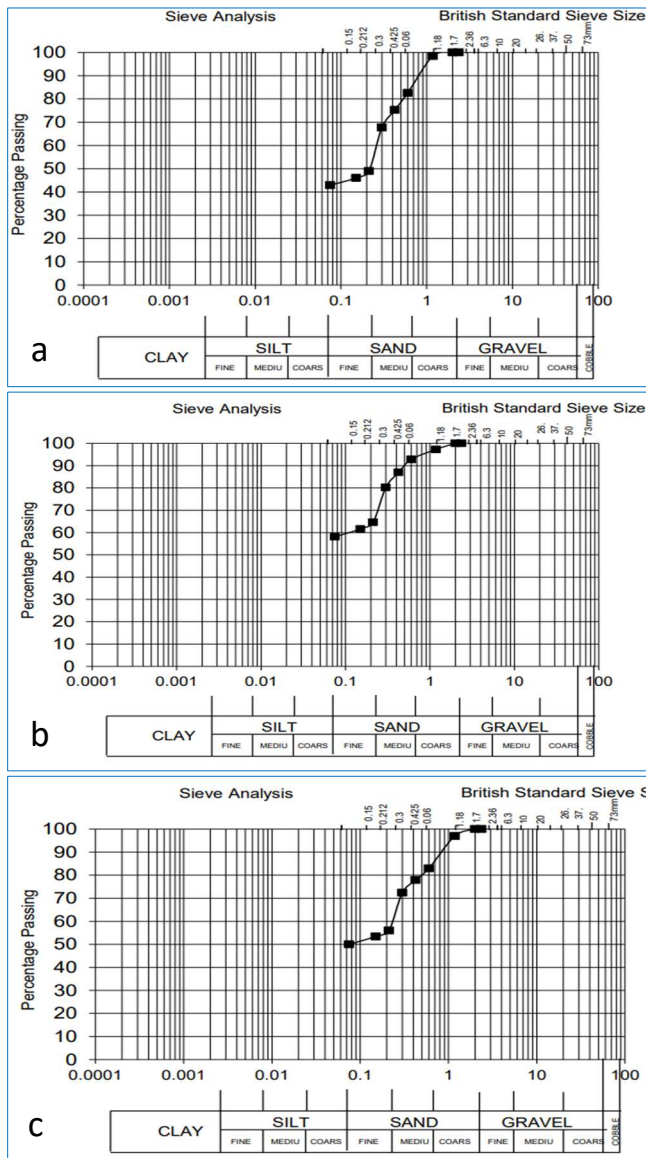


Fig. 5. Sieve analysis curve: a) at depth 1.0 m, b) at depth 3.0 m and c) at depth 6.0 m

Soil classification (BS/USCS basis), since exactly 50% passes the 0.075 mm sieve, the soil lies at the boundary between coarse- and fine-grained soils. With sand as the dominant coarse fraction and high fines content. The soil probable description as silty sand/clayey sand (SM-SC) or sandy silt (ML) (depending on plasticity). The grain size distribution shows absence of gravel, dominance of sand and fines and limited range of intermediate particle sizes. This indicates

poorly graded soil, typical of alluvial or weathered tropical deposits.

High fines content (50%) indicates low to moderate permeability and drainage will be restricted. The compressibility is moderate due to the presence of the fines content and settlement expected under sustained loading. The shear strength is low and the strength highly dependent on moisture content. The bearing capacity is low to moderate and not ideal for shallow foundations without improvement. The soil at BH (6.0 m depth) is a poorly graded sand-fine mixture, with approximately equal sand and fines content (50%) and no gravel. This indicates heterogeneous subsurface conditions, with alternating sand-fine dominance with depth.

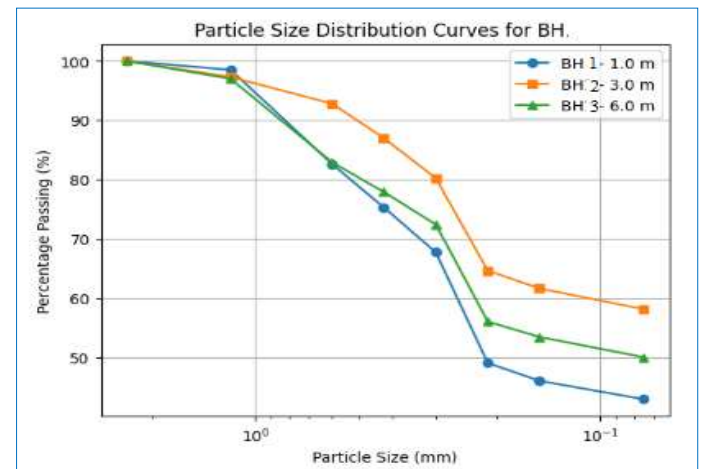


Fig. 6. The PSD curves for BH at 1.0 m, 3.0 m and 6.0 m (semi-log scale)

The soil exhibits low permeability, moderate compressibility, and reduced shear strength, making it marginal to unsuitable for engineering applications without stabilization. The variation in fines content with depth highlights the need for depth-specific foundation design considerations as shown in Tables 5–6 and Fig. 5c. Fig. 6 shows the relationship between the three boreholes.

5.4. Environmental and Geotechnical Significance

Fine-grained layers can trap contaminants, especially hydrocarbons and heavy metals. Clayey horizons may act as protective aquitards. However, once contaminated, natural attenuation is slow. This aligns well with your background in environmental geophysics and contamination studies, especially in coastal Niger Delta terrains.

5.5. Triaxial Compression Test

5.5.1. Unit Weight and Bulk Density

The unit weight values range from 16.26 to 16.91 kN/m³, it is typical of fine-grained, clayey soils and the bulk density values range from 1.66–1.72 Mg/m³, align closely with the

MDD results obtained from compaction tests, confirming the predominance of cohesive soils. BH 3 exhibits the highest unit weight and bulk density, suggesting slightly better packing or lower void ratio as shown in Table 7 and Figs. 7a, 7b and 7c.)

Table 7. Shear strength and density parameters of borehole soils

Borehole	Unit weight (kN/m ³)	Bulk density (Mg/m ³)	Friction angle (°)	Cohesion (kPa)
BH 1	16.64	1.70	3.20	22
BH 2	16.26	1.66	2.75	24
BH 3	16.91	1.72	3.43	23

Table 8. Ultimate bearing capacity and allowable bearing capacity

Borehole	c (kPa)	γ (kN/m ³)	q _{ult} (kPa)	Allowable bearing capacity (kPa)
BH 1	22	16.64	141.0	47.0
BH 2	24	16.26	153.1	51.0
BH 3	23	16.91	148.0	49.3

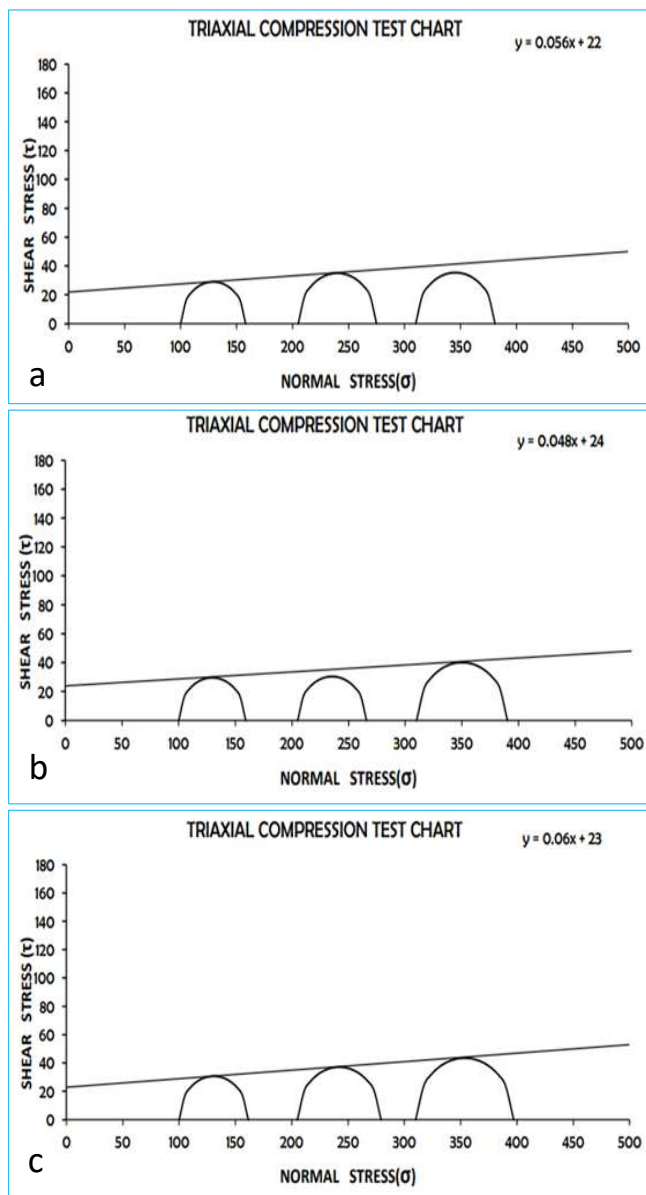


Fig. 7. Triaxial compression test chart: a) at depth 1.0 m, b) at depth 3.0 m and c) at depth 6.0 m

5.5.2. Shear Strength Parameters

Friction Angle (φ) : The friction angles values range from 2.75°–3.43°, which is very low, this indicate that shear resistance is largely cohesion-controlled. Such low φ values are characteristic of highly plastic clays, especially under saturated or remolded conditions.

This confirms the poor load-bearing capacity inferred from Atterberg limit results as shown in Table 8.

Cohesion (c): The cohesion values range from 22 to 24 kPa, which are moderate for soft to medium clays. BH 2 shows the highest cohesion (24 kPa), possibly due to higher clay content or bonding as shown in Table 8.

5.5.3. Engineering Implications

Foundation Performance: The low friction angles combined with moderate cohesion indicate low shear strength, particularly when soil become saturated. Shallow foundations placed on these soils may experience excessive settlement.

Slope and Excavation Stability: Cohesion provides short-term stability, but loss of cohesion due to moisture ingress may lead to instability.

Pavement Subgrade Suitability: These soils are unsuitable as natural subgrade materials due to low frictional resistance, high plasticity and moisture sensitivity.

For competent foundation soils, φ values are typically ≥ 25° for granular soils and ≥ 10° for stiff clays. The observed values (< 4°) fall well below acceptable limits, confirming the need for soil improvement.

5.5.4. Bearing Capacity

The allowable bearing capacities are < 60 kPa, which indicate weak foundation soils. These values are below typical minimum requirements for residential buildings (≥ 100 kPa). Foundations on these soils will be settlement-controlled rather than strength-controlled.

6. Conclusion

The investigation indicates that soil within the Airport Road G.R.A. area is predominantly clay, exhibiting medium to high plasticity, moderate specific gravity, and appreciable cohesion. These properties significantly control foundation performance, influencing bearing capacity, settlement behaviour, and overall structural stability. Soils encountered at shallow depths (1–3 m) are generally capable of supporting light to medium-weight structures using shallow foundation systems such as pad or strip footings. However, for heavier structural loads, deeper foundation solutions become necessary due to increasing clay content and a corresponding reduction in shear strength with depth.

Subsurface materials intercepted at the borehole locations consist mainly of inorganic clays of medium to high plasticity (CL–CH), characterized by low maximum dry densities and high optimum moisture contents. Based on the Unified Soil Classification System (USCS) and AASHTO classification, the soils fall within the CL and CH groups and are classified as A-7-6 subgrade materials, reflecting poor engineering quality. Their high plasticity and sensitivity to moisture render them unsuitable for direct application as foundation or pavement subgrade materials without prior improvement. Particle size distribution analyses reveal a dominance of fine-grained fractions across all investigated depths, with particularly high silt and clay contents at approximately 3.0 m depth. This textural composition suggests deposition under low-energy fluvio-deltaic environmental conditions. According to USCS classification, the soils vary from silty clayey sand (SC–SM) at shallow depths, to clayey silt (CL–ML) at intermediate depths, and silty sand with clay (SM–SC) at greater depths. These characteristics imply low permeability and moderate to high compressibility, conditions that are unfavorable for load-bearing structures and likely to induce excessive settlement. Consequently, the adoption of ground improvement measures or deep foundation systems is recommended.

At 1.0 m depth, the soil is predominantly sandy with a very high fines content (approximately 43%), classified as poorly graded silty/clayey sand. It exhibits low permeability and moderate compressibility, limiting its suitability for structural and pavement applications in its natural state. At 3.0 m depth, the soil becomes finer grained, with very high fines content (about 58%), minimal gravel, and a moderate sand fraction. This poorly graded material displays low permeability, low bearing capacity, and a high potential for settlement, rendering it unsuitable for engineering applications without stabilization. At 6.0 m depth, the soil consists of a poorly graded sand–fines mixture with nearly equal proportions of sand and fines and no gravel content. The material exhibits reduced shear strength, low permeability, and moderate compressibility, making it marginal to unsuitable for engineering use without treatment. The observed vertical variation in fines content emphasizes the need for depth-specific foundation design.

Shear strength evaluation indicates very low internal friction angles coupled with moderate cohesion, confirming the predominantly cohesive nature of the soils. Strength is therefore derived mainly from apparent cohesion rather than

particle interlocking. When combined with relatively low bulk densities and unit weights, this behaviour suggests poor performance under structural loading, particularly under saturated conditions.

7. Recommendations

1. Shallow foundation systems at depths of 1–3 m may be safely adopted for residential and other light structures where loading conditions are moderate.
2. Deep foundations (≥ 6 m), including pile systems, are recommended for heavy or multi-storey buildings to ensure adequate load transfer and long-term stability.
3. Comprehensive, site-specific geotechnical investigations should be conducted prior to construction to reduce the risk of differential settlement and structural failure.
4. Soil stabilization techniques, particularly lime treatment for high-plasticity clays and cement stabilization for strength enhancement and durability, should be applied where improved bearing capacity is required.
5. Untreated soils should not be used directly as foundation, base, or sub-base materials due to their poor engineering performance.
6. Atterberg limits tests should be performed to confirm soil plasticity characteristics and refine final soil classification for design purposes.
7. Adequate drainage systems should be incorporated into foundation and pavement designs to minimize moisture ingress and associated strength loss.
8. California Bearing Ratio (CBR) and consolidation tests should be carried out to provide reliable input parameters for pavement and foundation design.
9. Soil replacement may be considered at shallow depths where weak or highly compressible soils are encountered and stabilization is not feasible.
10. Continuous monitoring of foundation performance in similar clay-dominated environments is recommended to assess long-term behaviour and inform future developments.

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