VOL. 12 NO. 4,
MAY, 2026
E-ISSN 3026-9210
P-ISSN 3026-815X

African Scholar Publications & Research International
www.africanscholarpub.com

Journal of Built Env. & Geological Research (JBEGR)

Geotechnical Subsurface Characterization and Foundation Design Recommendations for a Proposed Six-Story Structure in Port Harcourt, Nigeria

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DOI: https://doi.org/10.70382/ajbegr.v12i4.070

Abstract

The influence of groundwater on foundation performance, poor soil characteristics, and insufficient subsurface foundation depth, which can lead to structural settlement, are some of the factors responsible for foundation failure. This work presents a geotechnical investigation carried out in part of Port Harcourt, Nigeria, to assess subsurface conditions for the establishment of a multi-story structure. In situ field and laboratory investigations, including geotechnical and geochemical analyses, were carried out on soil and water samples collected from the proposed construction site. Geotechnical laboratory analysis included natural moisture content, Atterberg consistency limits, and particle size distribution to classify the soils. Seven boreholes were advanced to a depth of 30 m employing the rotary boring method, with groundwater conditions examined. During and after the drilling exercise. Standard Penetration Tests (SPTs) were executed at uniform spacing to measure soil resistance through N-values documented on borehole logs. Results showed grey sandy clay of intermediate plasticity overlying medium- to coarse-grained dense sand. The soil pH values ranged between 5.1 and 7, suggesting neutral to slightly acidic soil conditions that may influence long-term structural integrity. At a shallow subsurface depth of 1.5 m, estimated settlement of 36.4 mm indicates potential instability. Subject to heavy structural loads. Resultantly, a piled foundation extending to Dense sand layers below 30 m is advised, substantiated by pile load testing for design validation.

Keywords: Geotechnical, Soil, Foundation, Settlement, Borehole, Structure, SPT.

Introduction

A structural foundation serves as the singular entity responsible for transferring and distributing loads from a structure to the subsurface soil or rock while maintaining stresses that are within the allowable bearing capacities and minimizing excessive settlement or structural failure (Omolaiye *et al*., 2024; Venkatramaiah, 2006). Adequate knowledge of subsurface conditions for any engineering or construction is a necessity, as the safety, durability, and performance of the structures is strongly influenced by the engineering characteristics of subsurface lithologies (Udom & John, 2023). The determination of subsurface water conditions, lithological characteristics, and geotechnical properties play a vital role in the design and construction of safe foundations (Kennedy, 2024). Soils on which structural foundations are laid are a product of the physical and chemical weathering of rocks (Amadi *et al*., 2010). Particle size distribution, natural moisture content, shear strength, permeability, compressibility, and mineral constituents are the engineering behaviors that define the soil (Ayogu *et al*., 2024).

Soil is a natural material that exists in a three-phase system consisting of solid particles, water, and air; the variation in this soil phase composition and structure has relevance to foundation performance (Cartel & Bentley, 2016). The physical, chemical, and mineralogical properties of soil, such as its origin, grain-size distribution, plasticity, ability to drain water, compressibility, shear strength, load-bearing capacity, pH, and sulfate concentration, should be properly studied before the establishment of any structure on the soil (Muhammed et al., 2024; Carter and Bentley, 2016). Elevated sulfate content can degrade concrete and cause an overall loss of concrete strength, leading to a loss of concrete strength (Teme & Nwankwoala, 2023). As a result, a higher concrete exposure class is required in the areas of soil deficiency to improve the durability of concrete. There is a range of potential geotechnical challenges that can affect constructed structures (Morrison & Esonanjor, 2024; ASTM 2024; Braja, 2010). In coastal terrains such as Port Harcourt, southern Nigeria, subsurface Exploration is primarily indispensable because of the prevalence of unconsolidated sediments, compressible clayey deposits, shallow groundwater tables, and saline properties that may adversely affect foundation integrity (LongJohn & Jaja, 2026). Coastal lithologies are often linked with differential settlement, low soil bearing capacity, corrosive geochemical conditions, and flooding susceptibility, consequently increasing the risk of structural failure when deficient foundation systems are implemented (Morrison & Esonanjor, 2024; Udom & John, 2023). According to reports from the Building Collapse Prevention Guild, there have been no fewer than 531 fatalities out of 271 collapses recorded in the past 10 years. These failures have culminated in considerable economic losses and casualties, highlighting the significance of comprehensive subsurface evaluation before any engineering construction (Ekponyoh *et al.,* 2025). Several Studies have investigated the geotechnical characteristics of the Niger Delta. Subsurface assessing bearing capacities of subsurface soil and examined the influence of groundwater on foundation

performance. Although previous subsurface assessments have significantly improved the knowledge of coastal soil underlying the Niger Delta region, the bulk of the studies have concentrated primarily on generalized regional geotechnical characterization of the area, without the integration of detailed subsurface characterization (Akuboh & Aimola, 2025; Orikpete & Ewim, 2023). Relatively few investigations have integrated detailed borehole stratigraphy, in-situ testing, comprehensive laboratory analyses, settlement evaluation, bearing capacity assessment, and practical foundation recommendations for a specific proposed multi-story structure (Ogwo & Ehibor, 2026). Furthermore, many published studies stop at describing subsurface conditions without translating the findings into engineering design decisions that directly support foundation selection. Moreover, several empirical studies stop at describing subsurface conditions without converting them into practical engineering design decisions that clearly validate foundation choices.

This study explores the knowledge gap by executing a site-specific integrated geotechnical investigation of a proposed high-rise six-story building in Port Harcourt using borehole drilling, Standard Penetration Testing (SPT), laboratory assessment, soil bearing capacity, and settlement analyses to delineate the subsurface conditions and recommend the most appropriate foundation system. The study presents a site-specific configuration that translates geotechnical data into practical engineering design recommendations, consequently contributing valuable guidance for the safe and economical design of multi-story structures within the challenging geological environment of the Niger Delta.

STUDY LOCATION AND GEOLOGY

Based on the site concept plan drawing, the development will consist of a six-story building in the landed area within the Port Harcourt metropolis, Rivers State. The site is generally flat-lying and is currently a vacant parcel of land. covered by adjacent buildings within its vicinity. The area of investigation lies within the Niger Delta sedimentary basin. This comprises an upper sandy Benin formation, an intervening unit of alternating Sandstone and shale named the Agbada formation, and a lower, shaly Akata. formation (Nwajide, 2013; Michele *et al*., 1999). These three units extend across the whole delta, and each ranges in age from early Tertiary to Recent. They are related to the present outcrops and environments of deposition. (Reijers *et al*., 1997). A separate member of the Benin formation is recognized in the Port Harcourt area. This is the Afam clay member, which is interpreted to be an ancient valley fill formed in Miocene sediments (Obaje, 2009). Subsurface structures are described as resulting from movement under the influence of gravity, and their distribution is related to growth stages of the delta.

Recent comparative geotechnical studies of adjacent coastal sites in Rivers State and its environs have reiterated the existence of these coastal near-subsurface lithologies of clay, sand, and shale (Ogwo & Ehibor, 2026; Avery *et al*., 2025; Morrison & Esonanjor, 2022). Locally, the soil conditions at the site are characterized by medium to firm, brown sandy clayey formations overlying alternating layers of sandy formations of variable thickness and grain sizes with appreciable densities.

METHODOLOGY

The subsurface exploration comprised fieldwork, laboratory analysis, geotechnical assessment, and foundation design evaluation to characterize near-subsurface conditions and determine the suitability of the site for the proposed six-story building in Port Harcourt, Nigeria.

Field Investigation

The field investigations entailed the exploitation of seven boreholes (BHs) to an average depth of 30 m below ground level, employing the rotary drilling method. The borehole locations were recorded using a handheld Global Positioning System (GPS) receiver device. Borehole logging was carried out continuously during the drilling process to ascertain the lithostratigraphic sequence and subsurface soil characteristics in accordance with BS EN ISO 14688-1:2018 and BS 5930:2020, documenting groundwater occurrence, soil colour, consistency, density and stratigraphic succession.

Standard Penetration Tests (SPTs) were executed at consistent depth intervals employing a standard split-spoon sampler to measure soil resistance and relative density in accordance with ASTM D1586/D1586M-24 and BS EN ISO 22476-3:2022 at 1.5 m intervals and whenever a considerable change in lithology was encountered. The SPT N-value was ascertained from the sum of hammer blows necessary for the second and third 150 mm penetrations after an initial seating drive, complying with standard procedures.

Representative disturbed and soil samples were obtained at varied sampling depths from borehole cuttings for classification tests, while undisturbed soil samples were collected from cohesive soil strata using thin-walled Shelby tubes in line with ASTM D1587/D1587M-24 standards for strength and compressibility testing. All samples were properly sealed in airtight containers, labelled, and placed in insulated sample boxes. The samples were stored under controlled conditions and immediately transported to the laboratory to preserve their natural moisture content and structural integrity prior to laboratory testing.

Laboratory Testing

Laboratory testing was carried out in accordance with internationally recognized standards in an accredited geotechnical laboratory. Natural moisture content was determined in line with ASTM D2216-19, while particle-size distribution analysis was carried out employing sieve analysis (ASTM D6913/D6913M-17) and hydrometer analysis (ASTM D7928-21). Soil consistency characteristics, including the Atterberg consistency liquid limit, plastic limit, and plasticity index, were determined using ASTM D4318-17e1. Coefficient of uniformity (Cu) and coefficient of curvature (Cc) were derived from particle-size distribution curves to determine grading characteristics. Soil classification was undertaken using the Unified Soil Classification System (USCS) in line with ASTM D2487-17e1 standard.

The undrained shear strength parameters were ascertained employing the unconsolidated-undrained triaxial compression tests carried out in line with ASTM D2850-23 procedure. Bulk

density, dry density, and unit weight were computed following appropriate ASTM procedures for soil engineering analysis.

The chemical analysis of soil and subsurface water, including pH, sulphate and chloride concentrations, total dissolved solids (TDS) and electrical conductivity, were determined following appropriate ASTM, BS EN, and APHA Standard Analytical Methods. Quality assurance in compliance with the requirements of the Institute of Public Analysts of Nigeria (IPAN) Act, CAP I16 LFN 2004 was strictly adhered to during the course of the chemical analysis.

Bearing Capacity and Settlement Analysis

The allowable bearing capacity of the analysed soil samples was appraised using the determined engineering properties obtained from field and laboratory investigations. Ultimate bearing capacity was determined employing the classical Terzaghi (1943) bearing capacity equation for shallow foundations, with corrections applied where necessary for foundation geometry and groundwater conditions. The allowable bearing capacity was obtained by applying a factor of safety. The classical Terzaghi (1943) bearing capacity equation for a shallow foundation is expressed as:

$$q_u = cN_c + qN_q + 0.5\gamma BN_\gamma$$

Where $q_u$is the ultimate bearing capacity (kPa), $c$is the soil cohesion (kPa), $\gamma$is the unit weight of the soil (kN/m³), $D_f$is the depth of foundation (m), $B$is the footing width (m), and N_c, N_q, and $N_\gamma$are bearing capacity factors corresponding to the soil friction angle (ϕ).

The allowable bearing capacity (q_a) was obtained by dividing the ultimate bearing capacity by a factor of safety (*FOS*) of 3.0:

$$q_a = \frac{q_u}{FOS}$$

The determined allowable bearing capacity was thereafter compared with the anticipated structural loads to scrutinize the suitability of shallow foundations for the proposed six-story building.

Quality Assurance and Quality Control

Quality assurance procedures were followed throughout the field and laboratory investigation to ascertain data reliability and reproducibility. Drilling equipment and testing apparatus were calibrated before field operations. Standard operating procedures specified by ASTM and BS standards were strictly followed during the investigations.

All field records and laboratory measurements were independently verified before data interpretation. Samples were properly assigned unique labels as identification codes corresponding to borehole number and sampling depth to eliminate transcription errors. Engineering permutations, including bearing capacity and settlement analyses, were independently verified before interpretation.

Results from borehole logging, SPT measurements, laboratory testing, and engineering analyses were integrated and subsequently synthesized to characterize near-subsurface conditions and used to develop appropriate foundation design recommendations for the proposed six-story building.

RESULTS AND DISCUSSION

The shallow subsurface water conditions were recorded in the open boreholes during and immediately following the drilling operations. Representative borehole logs are presented in Figure 1. A summary of some engineering properties of the soil is shown in Table 1. Table 3 shows the engineering soil gradation. A summary of the bearing pressures for shallow foundations are given in Table 4. Table 5 shows the bearing capacities of piles at 20.0m depth, while Table 6 and Table 7 indicate the chemical analysis results of soil samples and water samples, respectively. Undrained triaxial test results are displayed in Table 8, while Table 9 indicates the estimated total settlements (SP) based on the allowable bearing capacities of the soil.

Subsurface Investigation and Analysis

Boring and In-Situ Tests

The area is underlain in the near-surface by medium to firmly-consolidated sandy/silty clayey formation, which in turn overlies layers of fine to medium to coarse-grained sands and gravels. The summary of the litho-stratigraphy of the area is presented below.

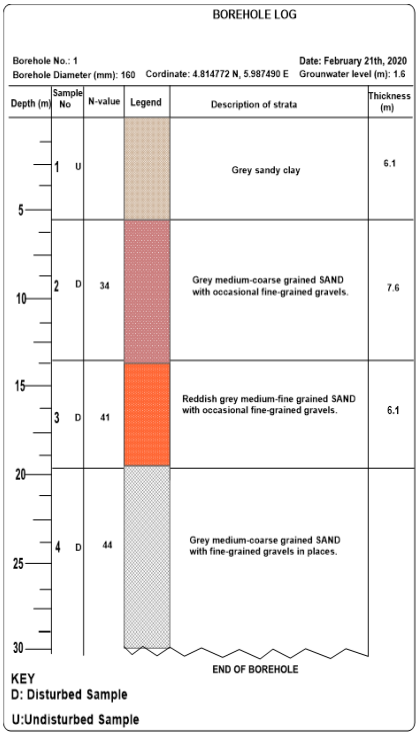
Subsurface Investigation

Borehole 01 (BH-01): BH-01 is composed of a 6.0 m thick layer of grey medium-fine grained sand with occasional fine gravels (6.0–13.7 m; N = 34) underlying a medium to firm grey sandy-clay. The topmost lithologic layer is underlain by a medium-coarse grained greyish-red sand with infrequent gravels (13.7–17.8 m; N = 41), accompanied by medium-coarse grained dense grey sand with fine gravels (N = 43), demonstrating efficient foundation material (Figure 1).

Borehole 02 (BH-02): BH-02 shows a near-identical profile to BH-1, composed of 6.1 m of sandy clay underlain by grey medium-fine grained sand accompanied by intermittent gravels (N = 34), greyish to red medium to coarse grained sand (N = 41), and a core compact grey medium to coarse grained sand with fine gravels (N = 43).

Borehole 03 (BH-03): The near subsurface at BH-03 is composed of 6.0 m of medium to firm grey sandy clay, underlain by grey medium to fine grained sandy soil with infrequent gravels (N = 34) and greyish-red medium to coarse grained sand (N = 41). The borehole discontinued at 30 m depth within a dense grey medium to coarse-grained sandy soil with fine gravels (N = 43), revealing a compactable soil bearing layer for footing.

Borehole 04 (BH-04): BH-04 observed 6.1 m of sandy clay lying above grey medium to fine-grained sand with infrequent gravels (N = 34), accompanied by greyish-red medium to coarse-grained sand (N = 41). The borehole terminated in a dense grey medium to coarse-grained sand associated with fine gravels (N = 43), spanning 30 m depth.



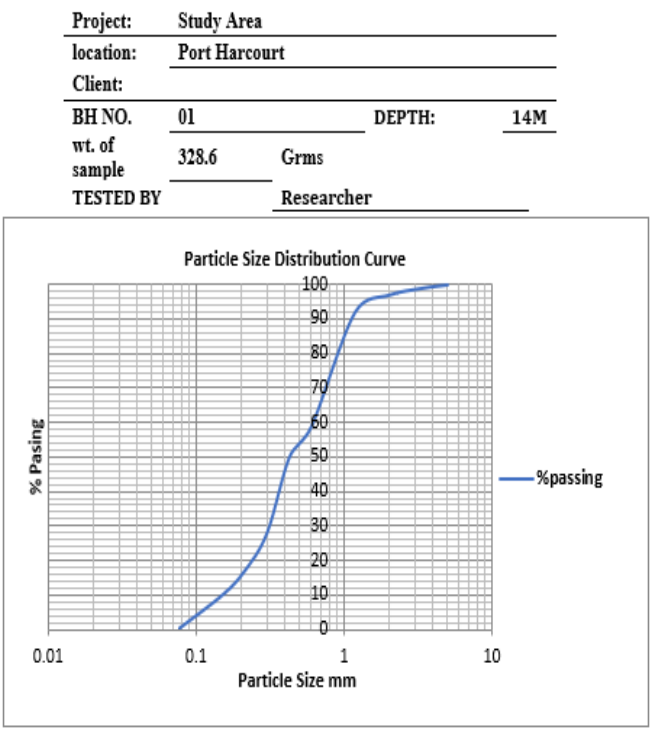


Figure 1a. Borehole Log for Borehole No. 1.| Figure 1b. Particle size distribution curve, sample 1

Borehole 05 (BH-05): Borehole 05 profile is composed of 6.1 m of sandy clay with dense grey fine- to coarse-grained sand underlying it with infrequent gravels (N = 34), reddish to grey dense coarse-grained sand (N = 41), and dense grey coarse-grained sand with fine gravels in the interval of 17.0 m and 30.0 m depth (N = 43).

Borehole 06 (BH-06): BH-6 is composed of sandy clay stretching to 6.1 m depth, lying above a dense grey fine- to coarse-grained sandy soil with infrequent gravels (N = 34) and greyish-red medium to coarse-grained sand (N = 41). The borehole was completed in dense grey medium to coarse-grained sand accompanied by fine gravels (N = 43) at a depth of 30 m.

Borehole 07 (BH-07): Borehole 07 is composed of a 6.1 m medium to firm sandy clay which covers a dense grey fine to coarse-grained sand with infrequent gravels (N = 34). The upper layer is underlain by greyish to red dense coarse-grained sand extending to the depth of 19.8 m (N = 38–41), accompanied by dense grey coarse-grained sand with fine gravels (N = 42–44), suggesting a proficient foundation layer**.**

In summary, the seven advanced boreholes indicated a generally uniform subsurface lithologic sequence comprising of a near-surface sandy clay layer (6.0–6.1 m thick), lying above increasingly denser sand units with infrequent fine gravels. SPT N-values advance from about 34 in the upper sand layer to 42–44 further down in the strata, suggesting increasing density and strength with relation to depth. The thick coarse-grained sand observed below the region of 17–20 m depths establish an effective bearing layer suitable for sustaining engineering foundations.

Soil Classification

The soil exhibited natural moisture content values spanning from 18.9% to 19.8%. The liquid limit spanned between 46.0% and 46.2%, whereas the plastic limit was roughly 16.0%, cumulating in a mean plasticity index of 30.1%. The mean undrained shear strength and friction angle were 40.5 kN/m² and 6°, respectively**.** According to the classification tests, the near-surface profile consists mainly of grey to brownish clay of intermediate plasticity, overlying a dense medium-grained sandy soil stretching to the maximum depth explored. The Atterberg consistency limits and associated index properties are shown in Table 1.

Table 1: Summary of Index properties and Engineering Parameters

Test Parameters	Maximum	Minimum	Average
Moisture Content (%)	19.8	18.9	19.35
Liquid Limit (%)	46.0	46.2	46.1
Plastic Limit (%)	16.0	16.0	16.0
Plasticity Index (%)	30.2	30.0	30.1
Bulk Unit weight (kN/m^3)	19.6	18.26	18.93
Dry Unit Weight (kN/m^3)	14.84	14.20	14.52
Undrained Shear Strenght	42	39	40.5
Friction Angle (^{0})	7	5	6

Soil Gradation

The grading parameters, as developed by the engineering standard is shown on Table 2.

Table 2: Standard Grading Parameters Categories

Well-graded sand	Well-graded gravel	Poorly or uniformly graded soil	Gap soil
Cu > 6	Cu > 4	Cu < 4	1 < Cc or Cc > 3
Cc 1 – 3	Cc 1 – 3		

Grain Size Distribution and Permeability

The effective grain size (D_{10}) spanned from 0.12 mm to 0.37 mm, whereas D_{30} and D_{60} span between 0.39 mm and 0.49 mm and 0.76 mm to 0.91 mm, respectively. The coefficient of uniformity (Cu) falls within the range of 1.92 to 4.81, while the coefficient of curvature (Cc) spans from 1.61 to 2.13. The soils manifest an average coefficient of permeability of 6.8 × 10^{-3} m/s. Based on the particle-size distribution parameters; the soils are principally classified as well-graded to uniformly graded sandy soils (Table 3).

Table 3: Engineering Soil Gradation

Test Parameter	Maximum	Minimum	Average
D_{10}Effective Diameter (mm)	0.37	0.12	0.24
D_{30}	0.49	0.19	0.34
D_{60}	0.76	0.39	0.57
Coefficient of Uniformity (C_u)	4.81	1.92	3.37

Test Parameter	Maximum	Minimum	Average
Coefficient of Curvature (C_c)	2.13	1.61	1.87
Coefficient of Permeability (K) m/sec	$7.2*10^{-3}$	$6.5*10^{-3}$	$6.8*10^{-2}$

Bearing Pressures for Shallow Foundations

The soil bearing strength of the proposed shallow foundations of raft or strip footing was estimated employing Terzaghi's bearing capacity theory for general shear failure conditions. The assessment took into consideration the inputs of soil cohesion, surcharge pressure, and soil self-weight, with suitable shape factors utilized for foundation geometry. Based on the computed bearing capacities at the explored depths, a mean ultimate bearing capacity of 98 kN/m² and an allowable bearing capacity of 39 kN/m² were acquired for a raft foundation at the subsurface depth of 1.5 m. For shallow strip footings founded at approximately the same depth, the average ultimate and allowable bearing capacities were 73 kN/m² and 29 kN/m², respectively. These values suggest that shallow foundations can be utilized provided that the imposed structural loads do not surpass the suggested allowable bearing pressures.

Table 4: Summary of the Bearing Pressures for Shallow Foundations

S/No.	Depth (mm)	Bearing Pressure (Footings) (kN/m^2)		Bearing Pressure (Raft) (kN/m^2)	
		Ultimate	**Allowable**	**Ultimate**	**Allowable**
1	0.6	33	13	43	17
2	0.8	40	16	55	22
3	1.0	50	20	65	26
4	1.2	65	26	88	35
5	1.5	73	29	98	39

Bearing Pressures for Pile Foundations

The axial load-carrying capacities were assessed employing the combined end-bearing and skin-friction approach. 600 mm and 800 mm diameter cased piles founded in the dense sand stratum at a depth of 20.0 m were estimated. The pile capacities were computed from the sum of the base resistance and shaft resistance contributions. The assessment result indicates that the allowable axial load capacity spans from 2,820 kN to 2,995 kN for the 600 mm diameter piles and equally extends from 1,805 kN to 1,902 kN for the 800 mm diameter piles (Table 5). To validate the design assumptions and establish that settlements remain within the allowable limit of 22.5 mm, static compression load tests are suggested on selected piles before construction commences.

Table 5: The bearing capacities of the piles at -20.0m

BH No.	Depth (m)	Ø600mm (KN)		Ø800mm (KN)		Maximum Settlement (cm)
		Ultimate Load	Permissible Load	Ultimate Load	Permissible Load	
BH-1	20.0	2,940	1,176	4,582.1	1,833	2.25
BH-2	20.0	2,925	1,170	4,512.5	1,805	2.25
BH-3	20.0	2,815	1,126	4,545	1,818	2.25
BH-4	20.0	2,972.5	1,189	4,545	1,818	2.25
BH-5	20.0	2,887.5	1,155	4,755	1,902	2.25
BH-6	20.0	2,820	1,128	4,572.5	1,829	2.25
BH-7	20.0	2,995	1,198	4,657.5	1,863	2.25

Soil Chemical Analysis

In accordance with the standards of the Institute of Public Analysts of Nigeria (IPAN), soil chemical analysis was carried out on soil recovered from the site. Results show a variation of salinity with depth across the boreholes. The soil pH spans from 6.7 to 7.0, suggesting generally neutral to slightly acidic soil conditions, except at BH1 (5 m depth) where a pH of 5.1 was observed. The concentration of sulphate varies from 4.85 mg/kg to 499.21 mg/kg, with increased levels potentially posing a risk of sulphate attack on buried concrete structures and foundation materials. The concentration of chloride spans from 39.12 mg/kg to 59.82 mg/kg, which is within acceptable limits and unlikely to negatively affect the soil or foundation materials. The percentage of the Total Organic Content (TOC) varies from 0.34% to 4.29%, which is within allowable limits. Generally, the soils are chemically stable for foundation design, with the potential of localized acidic conditions and an increase in sulphate concentrations being continually checked during foundation design and material selection to ensure long-term durability.

Table 6: Chemical Analysis Results of Soil Samples

Sample	Depth(m)	pH	SO_4 (mg/kg)	Cl^- (mg/kg)	TOC (%)
BH1	5	5.1	499.21	51.32	4.29
BH1	11	6.9	9.85	58.3	0.71
BH1	17	7.0	14.65	40.22	0.61
BH1	25	7.0	4.85	39.60	0.34
BH2	4	6.8	481.68	56.69	4.25
BH2	12	6.7	9.80	59.82	0.68
BH2	17	7.0	14.71	40.22	0.51
BH2	28	7.0	4.95	39.60	0.34
BH3	3	6.7	482.68	57.54	4.25
BH3	10	6.8	9.80	59.82	0.68
BH3	18	7.0	14.71	39.12	0.51
BH3	26	7.0	4.95	39.50	0.34
BH4	4	6.9	479.61	57.69	4.25

Sample	Depth(m)	pH	SO_4 (mg/kg)	Cl^- (mg/kg)	TOC (%)
BH4	8	7.0	9.80	58.82	0.68
BH4	17	7.0	14.71	39.22	0.51
BH4	24	7.0	4.95	39.60	0.34
BH5	1	6.8	483.68	57.69	4.25
BH5	9	6.9	9.82	58.82	0.68
BH5	6	7.0	14.71	39.23	0.51
BH5	29	7.0	4.94	39.61	0.34
BH6	5	6.9	482.68	57.69	4.25
BH6	11	6.9	9.82	58.79	0.68
BH6	17	7.0	14.71	39.22	0.51
BH6	22	7.0	4.94	39.61	0.34
BH7	3	6.7	482.68	57.69	4.25
BH7	10	6.9	9.80	58.82	0.68
BH7	16	7.0	14.71	39.22	0.51
BH7	28	7.0	4.95	39.60	0.34

Water Chemical Analysis

The chemical analysis of groundwater reveals that sulphate concentration (SO_4^{2-}) varies between 6.9 mg/L and 7.1 mg/L, which is within acceptable limits and is not expected to negatively affect concrete during construction and post-construction. However, the pH values span between 4.1 and 5.3, suggesting acidic water conditions. Such acidity may adversely affect the durability of concrete and reinforcement integrity if sufficient protective measures are not implemented. Therefore, the right concrete mix design and sulphate-resistant or chemically resistant building materials should be used in the construction to mitigate the potential adverse effects of acidic groundwater on foundation performance.

Table 7: Chemical Analysis Results of Water Samples

Sample	PH	SO_4(mg/l)
BH1	4.1	7.1
BH2	5.1	7.0
BH3	5.2	7.0
BH4	5.3	7.0
BH5	5.3	7.0
BH6	5.1	6.9
BH7	5.3	7.0

Triaxial Compression Test

The angle of internal friction and cohesion as shear strength characteristics were determined through the triaxial compression test. The results show that the angle of internal friction varies between 5° and 7°, whereas cohesion values range from 39 kN/m² to 42 kN/m² (Table 8). These shear strength parameters are a function of soft to medium stiff cohesive soils (clays). Additionally, the soil indicates an average Poisson's ratio of 0.46, indicating dominantly

saturated, fine-grained soil behavior. Generally, the results affirm that the subsurface lithologic materials indicate moderate shear strength with characteristics typical of saturated clayey deposits.

Table 8: Undrained Triaxial Compression Test

Borehole No	Depth (m)	Unit Weight		Shear Strength		Poisson's Ratio μ	Sub-merged Δ kN/m-^{3}	Normal Stress δ kN/m-^{3}
		Bulk Unit Weight γ_b kN/m^3	Dry Unit Weight γ_b kN/m^3	Undrained Cohesion C $_{kN/m}{}^{u}2$	Angle of Friction Deg.			
BH-1	3	18.26	14.43	42	6	0.472	8.94	40
BH-2	1	18.75	14.20	40	5	0.482	8.93	42
BH-3	4	18.76	14.21	40	6	0.468	8.95	38
BH-4	6	18.81	14.63	41	7	0.468	8.94	41
BH-5	2	18.91	14.84	42	5	0.477	8.93	39
BH-6	3	18.22	14.51	39	7	0.463	8.81	42
BH-7	2	18.78	14.41	40	6	0.453	8.54	43

Soil Settlement

Settlement analysis shows that the shallow subsurface clayey soils will experience immediate (elastic) settlement when load is placed on them, accompanied by consolidation settlement because of the expulsion of pore water, and thereafter secondary settlement over the long-term period. The estimation of immediate settlement was based on the soil modulus of elasticity, gotten from the relationship between modulus of elasticity and undrained cohesion. For a foundation placed at 5 m depth and 1.5 m depth, the analysis results showed estimated settlements of approximately 26.6 mm and 36.4 mm, respectively. The increase in settlement with foundation depth shows the compressible nature of the underlying clayey soils. A brief of the estimated settlement values at variant foundation depths is shown in Table 9, and the summary of the key engineering parameters analysed is displayed in Table 10.

Table 9: Estimated total Settlements (SP) based on the Allowable Bearing Capacities

Depth of Footing (m)	Estimated Settlement Value of Soil (mm)
0.5	26.6
0.8	30.1
1.0	32.1
1.2	33.2
1.5	36.4

Table 10: Summary of Key Engineering Parameters for Foundation Design

Parameter	Value/Range	Average/Representative Value	Engineering Significance
Number of Boreholes	7	7	Adequate site coverage
Maximum Borehole Depth	30 m	30 m	Competent bearing stratum identified
Overall Representative SPT N-value	34–44	**39**	Dense to very dense foundation material
Average Natural Moisture Content	18.9–19.8%	19.35%	Moderately moist soil
Average Plasticity Index	30.0–30.2%	30.1%	Medium plastic clay
Average Bulk Unit Weight	18.26–19.60 kN/m³	18.93 kN/m³	Saturated cohesive soil
Average Undrained Cohesion	39–42 kN/m²	40.5 kN/m²	Moderate shear strength
Average Friction Angle	5–7°	6°	Clay-dominated behavior
Average Coefficient of Permeability	6.5×10^{-3}–7.2×10^{-3} m/s	6.8×10^{-3} m/s	Moderate permeability
Allowable Bearing Capacity (Strip Footing)	13–29 kN/m²	29 kN/m² (1.5 m depth)	Suitable for light structures only
Allowable Bearing Capacity (Raft Foundation)	17–39 kN/m²	39 kN/m² (1.5 m depth)	Marginal for a six-story building
Recommended Pile Founding Depth	20 m	20 m	Dense sand layer
Allowable Load (600 mm Pile)	1126–1198 kN	1163 kN	Suitable for heavy structural loading
Allowable Load (800 mm Pile)	1805–1902 kN	1838 kN	High-capacity foundation option
Estimated Shallow Foundation Settlement	26.6–36.4 mm	31.7 mm	Exceeds desirable limits for multi-story structures
Estimated Pile Settlement	22.5 mm	22.5 mm	Within acceptable design limits

CONCLUSION AND RECOMMENDATIONS

The subsurface profile comprises a 6.0 to 6.1 m thick layer of medium to firm sandy clay underlain by dense medium to coarse-grained sands with intermittent fine gravels. Soil classification tests reveal intermediate-plasticity clay with moderate shear strength, while particle size analyses classify the sands as generally well-graded to uniformly graded and moderately permeable. SPT N-values elevate with depth, confirming improved soil strength and density in the deeper strata.

Chemical analyses indicate that the soils are predominantly suitable for construction, notwithstanding those localized acidic conditions and an increase in sulphate concentrations may affect concrete durability. Sulphate concentration in groundwater samples is within acceptable limits, though the acidic pH advocates the need for protective measures for buried concrete structures.

The assessment of the soil bearing capacity demonstrates an allowable bearing pressure of approximately 39 kN/m² for raft foundations and 29 kN/m² for strip footings at 1.5 m depth. The range of values from 26.6 mm to 36.4 mm defines the estimated settlements. For high-

rise structures that could transfer heavy loads to the foundation, pile foundations established in the dense subsurface sand stratum at about 20 m depth can safely sustain loads ranging from 1,805 kN to 2,995 kN**.** Comprehensively, the site is suitable for structural development, provided that appropriate foundation design and durability measures take into cognizance the relatively compressible shallow subsurface clayey overburden and the mildly aggressive chemical environment.

It is recommended that raft foundations be utilized for lightly to moderately loaded structures and for heavily loaded structures where structural settlement control is critical; pile foundations should be employed. The recommended allowable bearing capacities in the structural foundation design should be implemented. Static pile load tests should be conducted to satisfy pile performance and settlement characteristics. Sulphate-resistant and durable concrete should be utilized to mitigate the effects of acidic soil and subsurface water conditions. Sufficient site drainage should be made available to mitigate moisture-related soil movements and long-term settlement. Geotechnical supervision during the engineering work is necessary to affirm that field conditions are conforming to the investigation outcomes.

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