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Engineering Geological and Geotechnical Investigations for Design of Oxygen Plant

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Abstract

The most important aspect of every civil engineering project is acquiring reliable information on the ground on which the project will be constructed. This research includes a site investigation, which is seen as a primary stage in gathering geological, geotechnical, and other essential engineering data for structures' safe and cost-effective design. Five boreholes at well-spaced spots were drilled for subsurface investigation at a maximum depth of 15 m to 30 m. The standard penetration tests (SPT) were performed at different depths, soil samples were taken at various intervals, and lithological changes were observed. The friction angle was between 19.6˚ and 33.03˚, whereas the cohesion ranges between 0.25 kg/cm^2 and 0.42 kg/cm^2, indicating a strong resistance to shearing and a high capacity to sustain the load. Furthermore, the soil samples' maximum dry density ranges from 1.63 g/cm^3 to 1.80 g/cm^3. In addition, water table depths were recorded from 6.0 m to 7.0 m. The net bearing capacity for isolated/pad foundation at a depth of 1.5 m to 2.5 m below the ground level has been calculated as 95.0 to 120.0 kPa and 120.0 to 180.0 kPa for raft foundation. The net allowable pressure settlement limits for isolated/pad and raft foundations are 25 mm (1-inch) and 50 mm (2-inches), respectively. The investigation has found no severe geological flaws on the proposed construction site, and therefore it is appropriate for the construction of an Air Separation Unit (ASU) Oxygen Plant.

Keywords

Geotechnical Properties, Subsurface Profile, Water Conditions, SPT, Bearing Capacity, Foundation

1. Introduction

The civil engineering structures such as buildings, bridges, highways, tunnels, dams, towers, etc., are built either below or on the surface of the ground. Proper foundation soil is necessary to ensure its structural integrity. It is essential to evaluate soil properties to determine whether or not it is suitable for use as a foundation or as building materials [1]. Different researchers assert that to examine subsoil's geotechnical properties on the project site, it is essential to provide appropriate input data for the design and construction of foundations for the proposed buildings [2]. According to several researchers, effective design and construction of civil engineering constructions prevent negative environmental impact, structural collapse, or post-construction difficulties [3].

Before designing and building an oxygen plant, it is necessary to characterize the ground along the plant's route and anticipate geological, hydrogeological, and geotechnical characteristics [4]. Recent studies have shown that the ground is often a key source of technical and financial risk in civil engineering projects [5]. Inadequate geotechnical investigations are frequently the cause of foundation problems [3]. Only adequate qualifications and accurate primary data will allow an engineer to do the task. A structural engineer considers geotechnical conditions below a building to be just as important as the specification of proper foundation loads when designing a structure [5]. Information regarding surface and subsurface properties is critical for planning structural design and construction [6]. When buildings impose extreme loads, and the zone of impact is extremely deep, it is preferable to invest some money in the subsurface investigation rather than overdesigning the building and increasing its cost. Detail investigation is critical for complicated projects requiring massive structures, such as bridges, dams, and multi-story buildings [7].

The settlement will occur when the foundations of any building are constructed on compressible soil. Knowing the rate at which the soil compresses is critical for design consideration. Soil qualities such as plasticity, compressibility, and strength always impact structure design [8]. Construction mistakes will occur due to a lack of understanding of the subsoil's geotechnical properties. The appropriateness of soil for a particular purpose should be evaluated by its technical qualities rather than by visual inspection or apparent resemblance to other soils [9]. The kind of soil determines the loading capacity of the soil. On average, coarse-grained soils can sustain heavyweight than fine-grained soils [10]. A thorough analysis of the ground state would be necessary to adequately identify the obstacles, including all information on regularly recurring difficulties such as obstructions or difficult local subsurface conditions and the overall subsoil data [11].

The research begins with evaluating the geological and geotechnical parameters of the project area in the literature. A preliminary site survey was carried out to analyze and determine the best sites for boreholes. The lab performed laboratory testing on the materials collected on site, including determining index characteristics by grain size distribution (GSD), natural moisture content (NMC), Atterberg limits, bulk and dry density, specific gravity, and a direct shear test. Total dissolved solid, sulfate content, chloride content, and pH were used to examine the chemical properties of soil and groundwater samples. The purpose of this research is to determine subsurface lithologies and investigate the geotechnical engineering properties of the area's sub-soils, including their bearing capacities for shallow and deep foundations to ensure the structural integrity of the proposed ASU oxygen plant and new civil engineering structure projects in the vicinity.

2. Location and Physiography

An Air Separation Unit (ASU) oxygen plant (**Figure 1**) is scheduled to be built in Port Qasim, about 22 km from Jinnah International Airport and 15 km from the National highway. Port Qasim is located in the southern portion of Malir district, Karachi division, Sindh, near Bin Qasim town. It is 35 kilometers east of Karachi's city center and is located in a historical indus river channel.

There are no significant depressions or raised places in the terrain, mostly plain or flatland sloping towards the shore. The land elevation in this system is only a few meters above mean sea level. The area has been developed, and the ground level has been increased by transferring earth from a sand bar to the region where the sea creek meets the land. Variations in sea level and, to a lesser extent, tidal activity have affected the Ghaggar Nallah delta [12].

Chowdhry Creek connects Ghaggar Nala to Ziarat Hassan Shah Island. The causeway that joins Ziarat Hassan Shah Island to the mainland has decreased the tidal prism of the creek. During low tides, mainly the extreme lows of spring tides, Chowdry Creek contains virtually little water. The canal is well-defined all

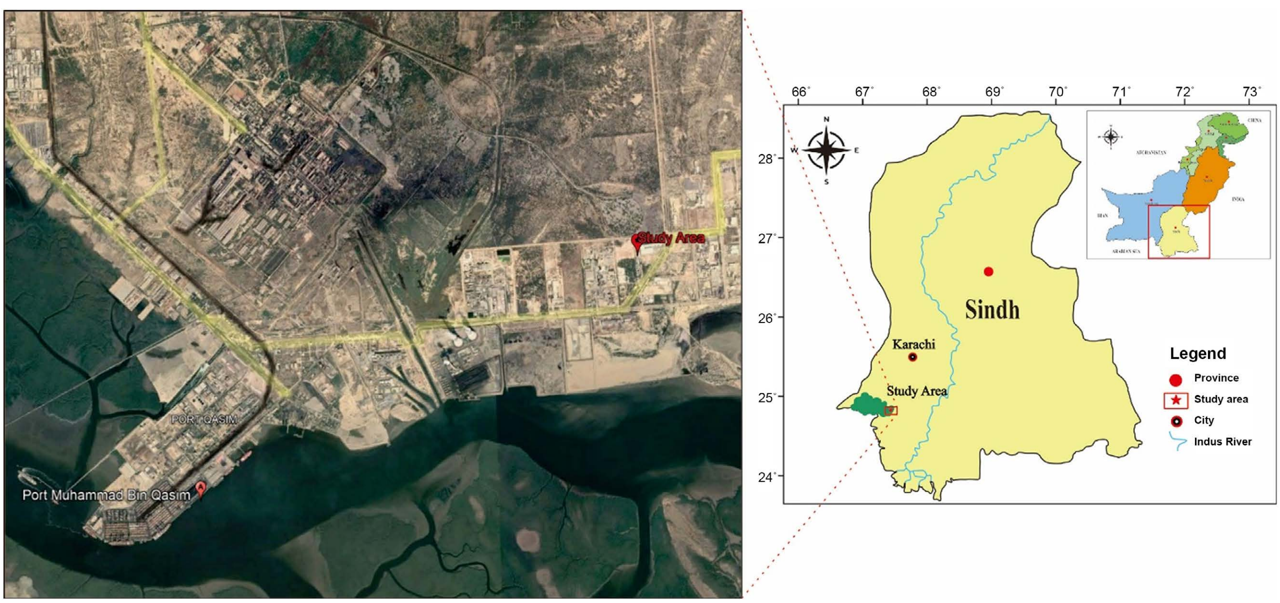

Figure 1. Location map of the study area.

the way from the causeway to the south-eastern point of Ziarat Hassan Shah Island, where it falls back into Gharo Creek [12].

3. Geological and Stratigraphical Setting of the Study Area

According to the geological survey (**Figure 2**), the Bin Qasim region only has Middle and Upper Tertiary rock layers that include fresh and slightly weathered recent and sub-recent coastal deposits. The Gaj Manchhar formations, which range in age from the Lower Miocene to the Middle Miocene and the Upper Miocene to the Pliocene, provide these deposits. Similar deposits may be found all along Karachi's coastline strip and in other locations [13].

The seabed is primarily composed of sand and silt, but the delta sediment is fine-grained and resembles soil from the continental shelf near the mouth of the Indus delta. The Gaj formation is mainly limestone, with subordinate shales and sandstone. The Gaj formation primarily comprises limestone with minor amounts of shales and sandstone. The limestone is extremely hard, sand-like, and fossiliferous. This formation is superimposed over the Nari formation, composed of denser limestone layers and shales [13]. The Manchhar formation is found to be conformably overlying the Gaj formation. Similar Manchhar formations can be found across Karachi's coastal zones, with the best exposure at Clifton, Ibrahim Hydri, Gizri, Korangi, and Landhi. This formation comprises sandstone, clay layers, cemented sand, and gravel (pseudo-conglomerate). Sandstone has conglomerate patterns and is thick, porous, and brittle. The clay comes in various

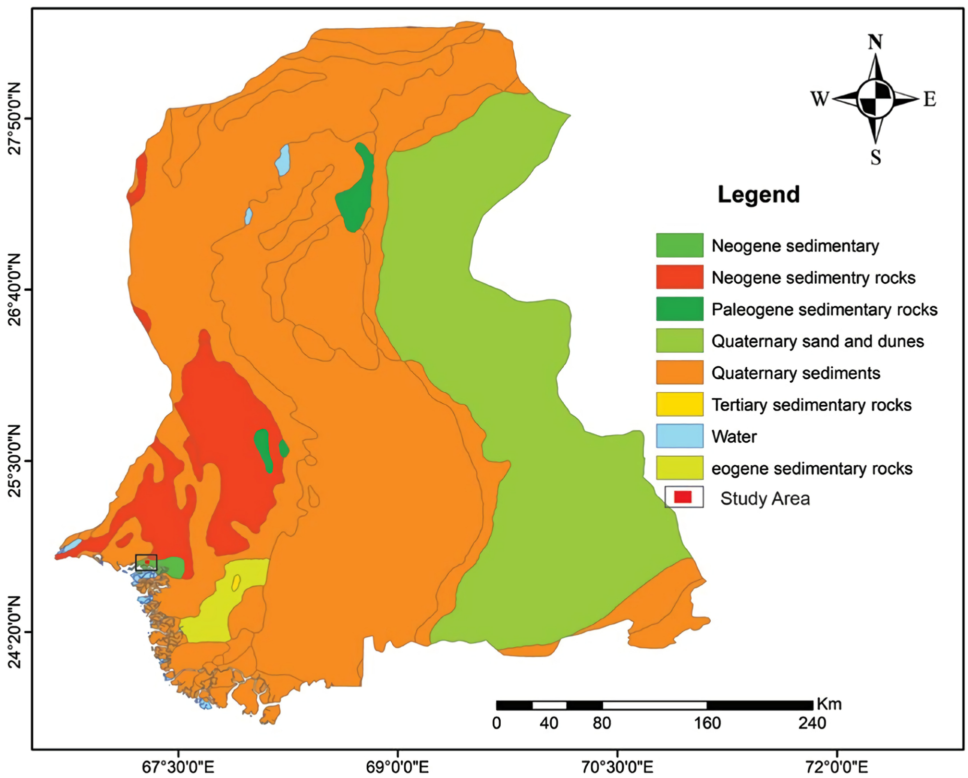

Figure 2. Geological map of the Port Qasim, Karachi, Pakistan.

colors, including grey, brown, chocolate, and orange, although light brown and dark grey is most common. Additionally, sandy strata are interbedded with clay and gravel [14].

4. Methodology

4.1. Fieldwork

As shown in (**Figure 3**), the field testing program consisted of drilling works, rock coring, and *in-situ* testing, including the SPT, collection of soil samples, disturbed rock samples, and groundwater samples.

Five boreholes, designated BH-1 to BH-5, were bored using a straight rotary wash boring technique to examine subsurface conditions. Soil samples were collected at intervals of 1.0 m to 1.5 m for visual assessment, laboratory testing, and classification at locations with notable changes in soil lithology. The penetration resistance values of cohesionless soils at specific depths within boreholes were determined using the Standard Penetration Test (SPT). It's an excellent way to figure out *in-situ* density and relative density. At the time of the examination in July 2021, the water level at the site was usually 6.0 m to 7.0 m below the ground level. Seasonal variations will influence this. This system's land elevation is merely a few meters above mean sea level. The consequence is that water penetrating the confined permeable layers from the creek during high tides may promote groundwater recharge.

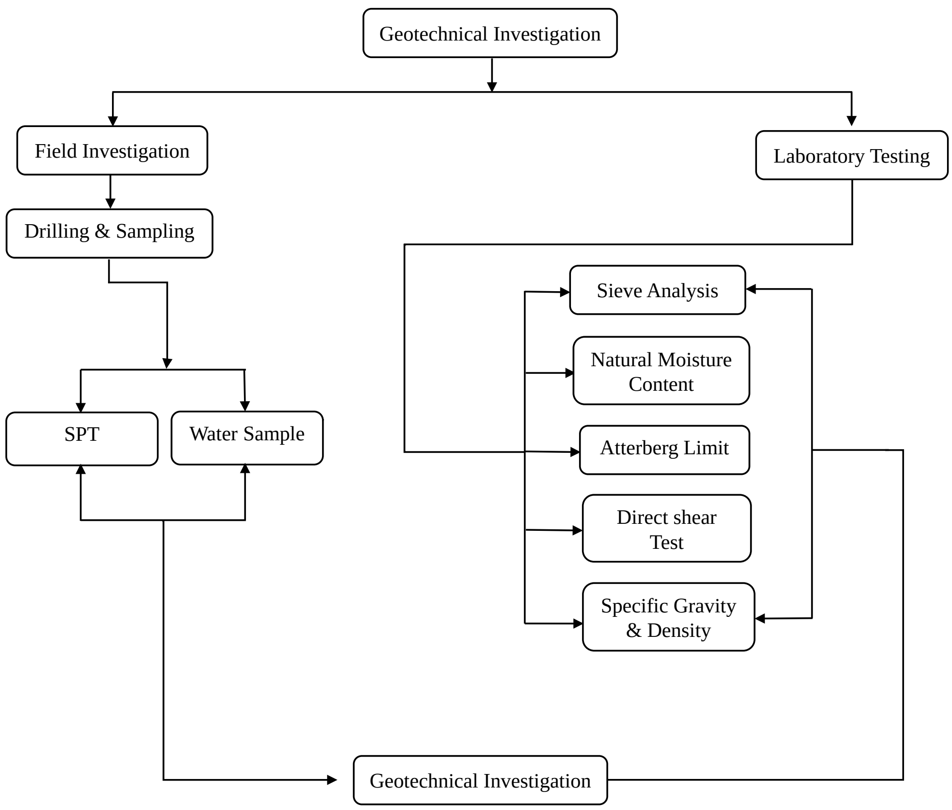

Figure 3. Flow chart of the soil investigation of ASU Plant.

4.1.1. Standard Penetration Test (SPT)

The SPT is an *in-situ* test that considers the impacts of stress and strain history, soil fabric, effective horizontal stress, and the combined effect of relative density and vertical stress [15]. Because of the high strain rate, the SPT is primarily a shear strength test performed under practically undrained circumstances [16].

A conventional 50 mm outer diameter split spoon sampler is used to perform the test in boreholes. It is advantageous for estimating the estimated *in-situ* density of cohesionless soils. The sampler is driven to penetration of 450 mm by repeated blows of a 63.5 kg hammer falling through a height of 760 mm. The SPT was carried out at 0.1 m to 1.5 m depth intervals, and the boreholes were terminated, one to a depth of 30 m and four boreholes to a depth of 15 m. The penetration resistance was determined as the number of blows (N-value) required to drive the sampler across a total distance of 300 mm after an initial penetration of 150 mm.

The split spoon sampler was used to collect SPT samples, then put in sealed bags as disturbed samples. Sampling procedures were determined mainly by the kind and thickness of subsurface material encountered. The SPT was carried out per the process [17].

4.1.2. Water Sample

A water sample was taken from one of the SPT boreholes at a certain depth. The borehole water was used to rinse the container thoroughly. The pH was measured on the spot using a pH meter, and the water sample in the airtight container was sent to the lab to be tested for sulfate (SO_4) content. These two parameters were principally investigated to ascertain the existence of leachate infiltration and its effect on portland cement.

4.2. Laboratory Testing of the Soil

The soil samples collected from the research region were subjected to various tests, including grain size distribution, natural moisture content, consistency limits, direct shear strength, specific gravity, density, and chemical analyses.

The word gradation refers to the distribution and size of grains in soil. For soil gradation, the coefficient of uniformity (C_u) and the coefficient of curvature (C_c) were utilized. A material must fulfill one or more of the following criteria to be regarded as well graded. For gravels, C_c must be between 1.0 and 3.0, while C_u must be greater than 4.0 and greater than 6.0 for sands. Grain size analysis of twenty-four (24) soil samples was carried out per [18] standards.

NMC test was performed to determine the soil's water content. It is expressed as a percentage of the soil's dry weight to the weight of water. The natural moisture content of twelve (12) selected soil samples was determined following the [19] standard.

Consistency limits are used to observe how moisture content affects fine-grained soil, particularly soil that has passed through Sieve No. 40. It determined the limits of different states of plastic soil consistency. The Atterberg limit test determines factors such as liquid limit, plastic limit, and plasticity index. These parameters aid in determining a soil sample's plasticity and clay content. Liquid and plastic limits of nine (09) samples extracted from boreholes were carried out following the [20] standard procedure.

The Soil shear strength parameters can be obtained through a direct shear test. The maximal resistance of the soil to shearing loads is its shear strength. The cohesiveness and angle of soil's internal friction can be determined using the direct shear test, which is essential in engineering projects such as foundations and retaining walls. A series of direct shear tests were performed per [21] standard to obtain strength parameters for the selected soil samples. The test was carried out under drained conditions (consolidated drained).

The specific gravity of a material is defined as the ratio between its density and the density of water at 4˚C [22]. Specific gravity has no dimensions. Water has a specific gravity of 1. It indicates the soil's appropriateness as a building material, and a greater specific gravity value offers better strength for roads and foundations [23]. The specific gravity of soil ranges from 2.65 to 2.85; sand has a specific gravity of 2.65 to 2.67; silty sand has a specific gravity of 2.67 to 2.70; inorganic clay has a specific gravity of 2.70 to 2.80; and organic clay has a specific gravity of 1.00 to 2.60 [24]. The specific gravity of twenty-four (24) samples was determined following the procedure described in ASTM designation [25].

Particle (dry) density is the weight of a unit volume of soil's solid component divided by the soil's solid portion volume. In addition, bulk (wet) density refers to the oven-dry weight of a unit soil volume, including pore spaces. The particle density of soil is always greater than the bulk density. Increased soil dry density is often associated with increased strength, reduced permeability, and improved volume stability. The laboratory compaction tests of twenty-four (24) samples were determined by the procedure described in [26].

4.3. Chemical Analysis

pH content

pH was measured using a pH meter. Set the pH meter on pH mood and set the temperature to 25˚C. The pH meter was calibrated using buffer solutions of 7.0 and 4.0 or pH 7.0 and pH 9.12, depending on the acidic and basic nature of the water/soil to be tested. A known sample of soil/water was taken in a beaker, and distilled water was added in case of soil. The electrode was inserted into the beaker after rinsing it with distilled water and noted the value shown on the pH meter screen. Repeat the experiment 2 or 3 times to get a constant value.

Chlorine content

The sample was poured into a conical flask. 2 g of potassium iodide (KI) solution and 3 mL of glacial acetic acids were added to maintain the pH of 3 to 4. Flask was covered, and the solution was shaken well. The mixture was titrated with sodium thiosulfate ($Na_2S_2O_3$) to become yellow. 2 mL of starch solution was added, and blue color appeared. The mixture was continued to be titrated with $Na_2S_2O_3$ for blue color disappearance. The experiment was repeated 2 to 3 times to get a constant value.

Sulfur content

The sample was filtered at room temperature to remove turbidity and was added to a flask. After that, 10 ml of sodium chloride (NaCl)-hydrochloric acid (HCl), 10 ml of glycerol ethanol solution, and 0.15 g of barium chloride ($BaCl_2$). Stir the sample with the help of a magnetic stirrer for about an hour. Absorbance was measured, and distilled water was added. Standard solutions of different strengths were measured similarly, and absorbance was recorded. Repeat the experiment 2 to 3 times to get a constant value.

Sulfate in groundwater or soil may corrode concrete that has been buried or exposed to the elements. Complex compounds are crystallized due to reactions between the cement's aluminate molecules and the sulfate. The expansion due to crystallization creates stresses in the concrete, causing it to disintegrate mechanically. When exposed to wet environments, such as saltwater, the chloride ion Cl^- presence poses considerable risk of reinforcement corrosion. Because sulphates and chlorides have a negative impact on the quality of concrete, it is essential to undertake chemical testing on soil and groundwater. Chemical tests were carried out following [27] [28].

5. Results and Discussion

5.1. Subsurface Stratigraphy

The five borehole logs interpreted (**Figure 4**) revealed the subsurface sequence of BH-3 drilled to 30 m, and BH-1, BH2, BH-4, and BH5 were drilled to a depth of 15 m. The sequence consists of fine to medium-grained, sandy, silty clay to a depth of approximately 6.5 m, underlain by fine to coarse-grained sand to a depth of 15 m and 26 m in BH-3. Deposits of distinctly weathered and poorly compacted mudstone underlay the sand in Bh-3 to a depth of 30 m.

5.2. Soil Types and SPT Blow Count

Borehole No. 1 was drilled up to 15 m in depth, and the water table was observed at 7.0 m. Silty clay with some fine-grained sand generally met at 4.0 m. Clay with some silt, fine-grained sand, and few gravels was encountered at a depth of 6.5 m. This sequence was followed by fine to coarse-grained sand, including traces of silt and gravel to a depth of 15 m. The SPT test indicated that the "N" values were very high above 38 and reached 50 at 6.5 m of depth.

Borehole No. 2 was drilled to a depth of 15 m too, and the water table was observed at 6.5 m. The strata consist of a large amount of fines clay with some silt, sand, and a few traces of gravel to a depth of 4.5 m. This sequence was followed by sandy, silty clay to a depth of 6.5 m. Deposits of fine to coarse-grained sand, including little silt, were encountered at a 15 m. The SPT' N' values were high and reached 50.

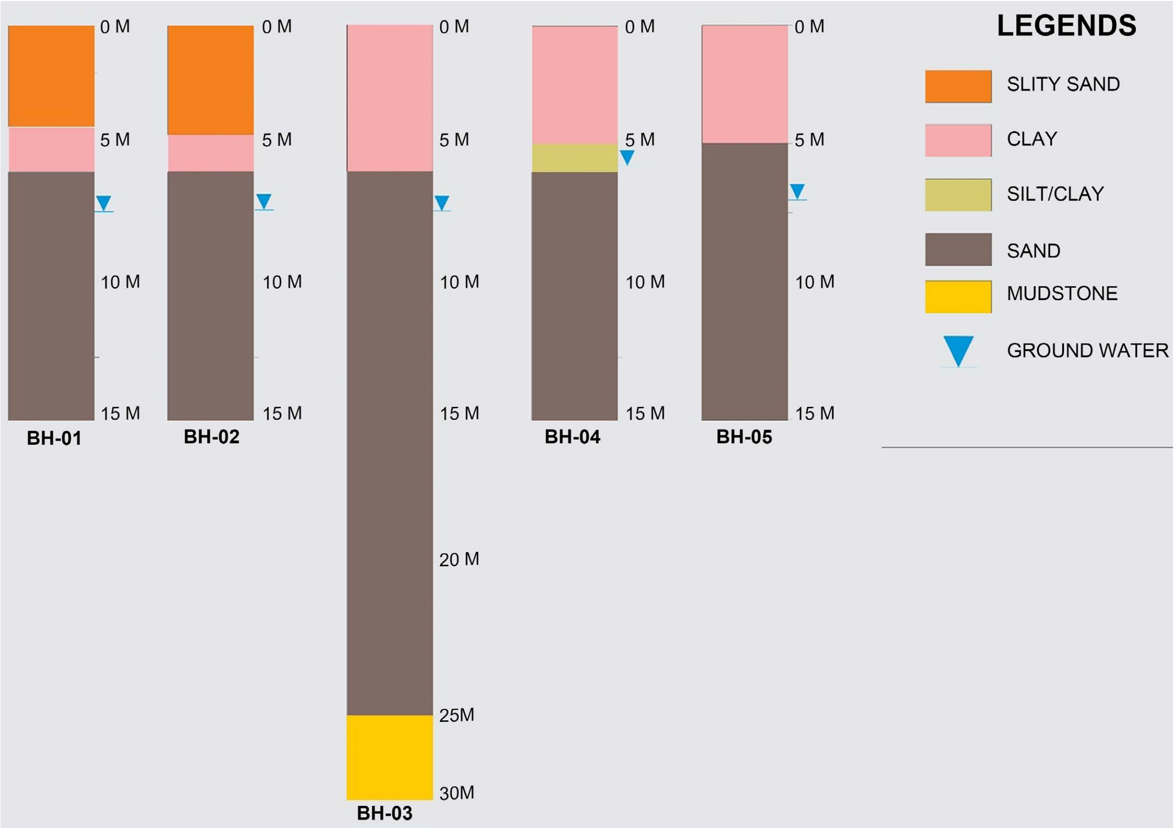

Figure 4. Subsurface soil profile, Port Qasim, Karachi, Pakistan.

Borehole No. 3 was drilled to a depth of 30 m, where a water table was observed at 7.0 m. Deposits of fine to medium-grained sandy clay were observed, including some silt at a depth of 6.5 m. This sequence was followed by fine to coarse-grained sand to a maximum depth of 26 m. Deposits of distinctly weathered and poorly compacted mudstone were observed to a depth of 30 m, where the borehole was terminated. The SPT' N' values were very high and reached 50.

Borehole No. 4 was drilled to 15 m, and the water table was present at 6.0 m. Deposits of clay, including some silt and sand, were observed to a depth of 5 m. Sandy clay was encountered to a depth of 6.5 m. This sequence was followed by fine to coarse-grained sand, including traces of gravel and silt. SPT' N' values recoded were 50.

Borehole N. 5 was drilled to 15 m of depth, too, and a water table was encountered at 6.5 m. Deposits of clay, silt, sand, and some traces of gravel were observed at a depth of 5.0 m. This sequence was followed by fine to coarse-grained sand to a depth of 15 m, where the borehole was terminated. The SPT' N' values recorded were very high and reached 50.

5.3. Laboratory Tests

5.3.1. Grain Size Distribution (GSD) Analysis

According to the sieve analysis results, Cc ranges between 0.021 and 10.034, while Cu varies between 3.829 and 189, which are values compatible with well graded soil [29]. When paired with the Atterberg limit data, the sieve analysis findings classified the soils as low plasticity clay with sand [30].

5.3.2. Natural Moisture Content (NMC)

The moisture content of typical soil samples from BH-1 to BH-5 varies from 12.8% to a maximum of 37.4%. These results suggested that the soil has a high ability to hold water during the wet season, which, when lost during the dry season, could cause severe shrinkage. The in situ moisture content of the soil is influenced by weather, amount of clay, organic matter in the soil, and drainage parameters of soil. [31]. The soil's water content value is closer to the plastic limit than the liquid limit suggests pre-consolidation. [24].

5.3.3. Consistency Limits

The consistency of soil in the area was investigated by calculating the liquid and plastic limits and the plasticity indices. Atterberg limits results show that liquid limit (LL) ranged from 22.6% to 34.7%, plastic limit ranges from 18.1% to 26.3%, and plasticity index ranges from range from 4.2% to 8.4%. Soil samples in this study area have low plasticity and will not pose a problem when used in any engineering construction, as stated by [32]. These results indicated that the soil could be classified as low plasticity clay with sand. The results showed that the soil could not be remolded, indicating low plasticity [33].

5.3.4. Direct Shear Test

The testing aims to determine the cohesion (C) and internal friction angle (ϕ), which are two shear strength parameters (ϕ). The friction angle (ϕ) in the direct shear test is between 19.6˚ and 33.03˚, while the cohesion (ϕ) is between 0.25 kg/cm^2 and 0.42 kg/cm^2, indicating strong shear resistance and a higher ability to resist the load [34]. The soil's high internal friction angle and resulting shear strength indicated that it could sustain the stress imposed by a massive, heavy structure on top of it. The combination of high shear strength, low plasticity index, and no swelling characteristics provides an ideal foundation for a building. [35].

5.3.5. Specific Gravity

The specific gravity of 24 soil samples obtained from the study ranges from 2.60 to 2.70. Soil with a specific gravity greater than 2.55 is appropriate for massive construction works [23]. These values are within the range and prove their appropriateness in construction projects [22].

5.3.6. Density

The soil sample's bulk density values range from 1.86 g/cm^3 to 2.28 g/cm^3, while the maximum dry density of 24 soil samples obtained from the study area ranges from 1.63 g/cm^3 to 1.80 g/cm^3. The values obtained from the results give us an indication of durable construction [36].

5.3.7. Chemical Analysis

Chemical analysis of the water and soil samples in the study area shows that groundwater has a pH of 7.10 and soil samples pH ranges from 6.85 to 7.25, sulfate concentration ranges from 0.01% to 0.02%, and chloride concentration ranges from 0.24% to 0.29%. These results are within WHO guidelines and may not indicate pollutant or leachate intrusion. Based on these values, it seems unlikely that groundwater at depth would corrode Portland cement used in buried concrete. [37].

6. Bearing Capacity for Isolated and Raft Foundations

The maximum bearing pressure that may be applied to isolated/pad and raft foundations that are built on natural soils at the location will be restricted, based on the foundation width and depth of impact, either by the settling tolerance of particular buildings or by the strength of the soil [38]. Generally, for shallow foundations, the bearing pressure should be restricted to ensure that the overall settling of the foundation does not surpass 25 mm, with differential settlements equal to around 50% of the total settlement. For raft foundations on sand, the difference between entire settlements is approximately half that of an isolated footing [39]. Consequently, raft footings can sustain double the load of settling that isolated footings can handle, typically 50 mm. However, the structural engineer should define the exact settlement tolerance of various structures. The allowed bearing pressure for proposed shallow foundations was determined to be the lesser of two values derived using settling and shearing criteria. The allowable bearing pressures for shallow foundations at 1.5 m to 2.5 m from the existing ground level are given in (**Table 1**). The settlement of isolated/pad and raft foundation due to net allowable pressure has been estimated to be within the permissible limit of 25 mm (1-inch) and 50 mm (2-inches), respectively.

6.1. Modulus of Subgrade Reaction

The modulus of subgrade reaction (**Table 2**) may be necessary when designing

Table 1. Net allowable bearing pressure values for the shallow foundation.

Minimum Embedment Below Existing Ground Level (m)	Isolated/Pad Foundation (kPa/tsf)	Raft Foundation (kPa/tsf)
1.5	95.0/0.95	120.0/1.20
2.0	105.0/1.05	140.0 /1.40
2.5	120.0/1.20	180.0/1.80

Table 2. Modulus of subgrade reaction values based on allowable bearing pressure.

Minimum Embedment below EGL (m)	Modulus of subgrade reaction (MN/m^3/tcf)
1.5	7.2/21.6
2.0	8.4/25.2
2.5	10.8/32.4

raft foundations. The modulus is primarily determined by the soil's rigidity, raft foundation's rigidity, and foundation's size [40] and is computed using the following equation.

$$k_s = \frac{1}{A}(SF)q_a \tag{1}$$

k_s = Modulus of subgrade reaction, SF = Safety factor, q_a = Allowable bearing pressure, A = Allowable settlement.

The preceding equation predicts that the rafts will trend towards flexible instead of stiff behavior. The modulus values derived from the last equation must be doubled for fully rigid rafts.

The behavior of mat foundations will be:

Perfectly rigid if h/B > 1/5

Perfectly flexible if h/B < 1/55

h = Foundation thickness; and B = Faft foundation width.

6.2. Deep Foundations-Allowable Pile Capacities

The maximum load capacity of a drilled concrete pile penetration is determined by adding the friction factor on the pile walls and the final bearing on the pile tip:

$$Q = Q_s + Q_p = \sum fA_s + qA_p \tag{2}$$

where A_s and A_p denote the immersed surface and pile end area, respectively, whereas f and q denote the unit skin friction and unit end bearing, respectively.

The ultimate bearing capacity term in the preceding equation is omitted when determining maximum tensile strength. Therefore, the maximum tensile capacity value is the same as the ultimate compression capacity due to skin friction [41].

The design parameters for calculating pile capacities have been derived from shear strength determination through *in-situ* field tests and laboratory tests of collected soil samples.

Table 3. Allowable pile capacities for a deep foundation.

Diameter (mm)	Length (m) below EGL	Tension (kN)	Compression (kN)
600	15	806	1450
	20	950	1595
	25	1094	1739
760	15	1029	2200
	20	1241	2438
	25	1452	2650
900	15	1219	2860
	20	1493	3402
	25	1778	3668

The analysis results for 600 mm, 760 mm, and 900 mm diameter drilled concrete piles are presented below (**Table 3**). The settlement criteria of net settlement not to exceed 1% of the pile diameter at working load and total penetration of the base not to exceed 10% of the pile diameter at test load shall be fulfilled.

7. Conclusion

The study site soil stratigraphy was determined using data from deep soil borings and laboratory studies. The different boreholes drilled at the site have almost uniform soil strata, which can be found in three main layers. The soil profile generally consists of a 5 m to 6 m hard sandy silty clay of low plasticity underlain by very dense fine to coarse-grained sand to a depth of 26 m and distinctly weathered, poorly compacted mudstone up to the investigated depth of 30 m. C_c ranges between 0.021 and 10.034, while C_u varies between 3.829 and 189, which are values compatible with well graded soil. The natural moisture content ranges from 12.8% to 37.4% higher than the liquid limit. The plasticity index ranges from 4.2% to 8.4%. The direct shear test result shows that the friction angle is between 19.6˚ to 33.03˚ while the cohesion, C, is between 0.25 kg/cm^2 to 0.42 kg/cm^2, indicating strong shear resistance and a higher ability to resist the load. The bulk density values range from 1.86 g/cm^3 to 2.28 g/cm^3, while the maximum dry density is 1.63 g/cm^3 to 1.80 g/cm^3. The exposure of underground concrete to aggressive chemicals is negligible for sulfates and chlorides in soil and water samples that have influenced the cement selection for underground concreting. All underground concrete work is recommended to be performed with Ordinary Portland Cement (OPC). Allowable net bearing pressure values have been established for shallow foundations as 95.0 kPa to 120.0 kPa for 1.5 m to 2.5 m below the existing ground level for the isolated foundation and 120.0 kPa to 180.0 kPa for the raft, depending on the depth of the foundation. The raft foundation's subgrade reaction values are also given at different depths. Different diameters and lengths of piles have been specified, and their respective pile capacities.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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