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Research Article

Geotechnical Characterization and Foundation Design for a Multi-Story Factory in the Bengal Delta: Insights from Sub-Surface Investigation

Md.Mohibullah [1],

[1]*Department of Civil Engineering, BUBT, Dhaka, Bangladesh*

ABSTRACT:

This study provides a geotechnical study of a six-story factory building in the proposed Liberty Knitwear Ltd. in Kaliakair, Gazipur, Bangladesh. The characteristics of the subsoils were identified using four boreholes that were 60 ft deep and found a typical Bengal delta stratigraphy: a thin surface of reddish, plastic clays (0–22 ft, SPT N=4-24) covered densely with silty sands (SPT N=14-50). The level of groundwater was observed 14-17 ft in to ground. Engineering design was based on laboratory tests, including grain-size distribution (top fines to 88 per cent and bottom sands to 92 per cent), Atterberg limits, and direct shear tests (φ = 26-40 degrees, c = 0.11 -0.049 tsf). The calculated bearing capacities of shallow foundations reached 1.68tsf at 10 ft depth (factor of safety = 3). Furthermore, 24-inch-diameter piles with pile capacities of more than 120 tons at a depth of 60 ft support the feasibility of deep foundations in terms of heavier loads. The location of the site in Seismic Zone-2 (z = 0.20, BNBC 2020) requires a dynamic analysis and supports the suggestions for shallow foundations. These results provide a strong basis for cost-effective and secure foundation construction in the problematic deltaic soils of Bangladesh.

Keywords: *SPT, bearing capacity, grain size distribution, Terzaghi equation, seismic Zone-2, pile design*

1. INTRODUCTION

The delta area of Bengal, which includes much of Bangladesh, has some special geotechnical problems in the construction of multiple stories which can be explained by the fact that the soils are usually of young age and compressible, groundwater levels are high, and the area is prone to earthquakes. As the garment industry continues to grow and the rate of industrialization is ever-increasing, the need to have viable and affordable foundation solutions is at the top in the list. This study has explored the geotechnical report of Water Treatment Plant Building of Liberty Knitwear Ltd., located at Pallibidyut, Chandra, Kaliakair, Gazipur, a typical industrial location in the deltaic region in 2013. The study utilized both the consideration of the site as part of the BNBC Seismic Zone 2 and both the use of static and dynamic factors through the implementation of four boreholes that were strategically positioned to a depth of 60 ft to characterize the conditions of the subsoil, as well as to make foundation recommendations regarding a six-story factory footprint (around 119.8 x 158.5 ft). The paper negatively synthesizes the field observations, lab findings, and calculation of bearing-capacity, based on available theories and current developments in geo-technical engineering to practice. The relevant insights in this context include structural integrity of deltaic soils which are often viewed as having high fine-grained content and prone to liquefaction and settling [1]. In this regard, the paper will provide a geotechnical analysis that is intended to reduce these threats as well as assist in developing resilient infrastructure in the area [2].

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2. LITERATURE REVIEW

2.1. Classical Approaches to Bearing Capacity and Soil Characterization

The bearing capacity of soils for shallow foundations is most commonly estimated using Terzaghi's general bearing capacity equation [3]:

$$q_u = cN_cS_c + D_fN_qS_q + 0.5B\gamma N_\gamma S_\gamma$$

where q_u is the ultimate bearing capacity, c is cohesion, N_c, N_q, and N_γ are bearing capacity factors dependent on the soil's angle of internal friction (ϕ), γ is the unit weight of soil, D_f is the depth of foundation, B is the foundation width, and S_c, S_q, and S_γ are shape factors [3]. For clays ($\phi \approx 0\circ$), typical values are N_c=5.7, N_q=1, and N_γ=0, reflecting the predominance of cohesion in bearing resistance. Standard Penetration Test N-values, derived from ASTM D1586 tests, are widely used as proxies for strength and stiffness. These values are empirically correlated to unconfined compressive strength (q_u=0.25–4tsf for N=2–30) and allowable bearing capacities [3].

2.2.Geotechnical Modelling and AI Applications.

Recent studies have embraced the use of machine learning such as artificial neural networks to make predictions of bearing capacity using limited or noisy data. The efficacy of deep neural networks to estimate bearing capacity using only six high-quality samples was demonstrated by Bagińska and Srokosz [4], which is better than what conventional regression and shallow ANN models can do. These data-oriented techniques do not replace, but instead go hand in hand with classical computations, particularly when a far-reaching laboratory-field test is feasible.

Recent research has also investigated ensemble learning algorithms including the random forests and gradient boosting to predict the California Bearing Ratio (CBR) which is a key subgrade strength indicator. Kökçam et al. [5] demonstrated that random forest regressors demonstrated a high level of accuracy (R^2 = 0.83) in nonlinear and complex relationship between soil index properties and the CBR, which, according to them, justified their implementation in geotechnical processes.

2.3. Workflows and Foundation Design Automation.

With the emergence of large language models and multi-agent systems, studies of foundation design calculation automation have risen. Youwai et al. [6] came up with router based multi-agent architectures to classify the types of foundations and automate calculations to achieve over 90-percent performance accuracy in both shallow and pile foundation design. Even though these systems are not yet capable of making the human engineering oversight unnecessary, they make a huge step in providing computational support in geotechnical analysis.

2.4. Mechanical Deterioration and Load-Bearing Behavior on a Micro-Scale.

On the microscale, materials science has elucidated the ability of electrokinetics and compositional changes such as lithium intercalation in electrode materials as a method to have a significant impact on load bearing capacity. Mukherjee et al. showed that the electrokinetic coupling in the compliant channels can increase load-bearing capacity in symmetry-breaking phenomena, Xu et al. [7] even warned that mechanical deterioration by intercalation needs to be included in high-reliability designs. Though these remarks are primarily with respect to microfluidic and battery situations, they highlight the importance of considering compositional and environmental effects - corresponding to the impact of groundwater and soil chemistry in geotechnical systems.

3. METHODOLOGY

3.1. Field Investigation

The Liberty Knitwear Ltd. site investigation involved four strategically located boreholes (BH-1 to BH-4) to bring spatial variability throughout the approximate 119.8 -158.5 ft. building area (Figure 1).

All boreholes were wash bored up to a depth of 60 ft and Standard Penetration Tests (SPT) conducted at 5-ft increments as per ASTM D1586. Laboratory analyses of undisturbed Shelby tube samples were obtained later on. Groundwater table (GWT) measurements were also made during the boring activities and recorded at the depths of 14-17 ft below the current ground level (EGL; TBM 100.00 RL).

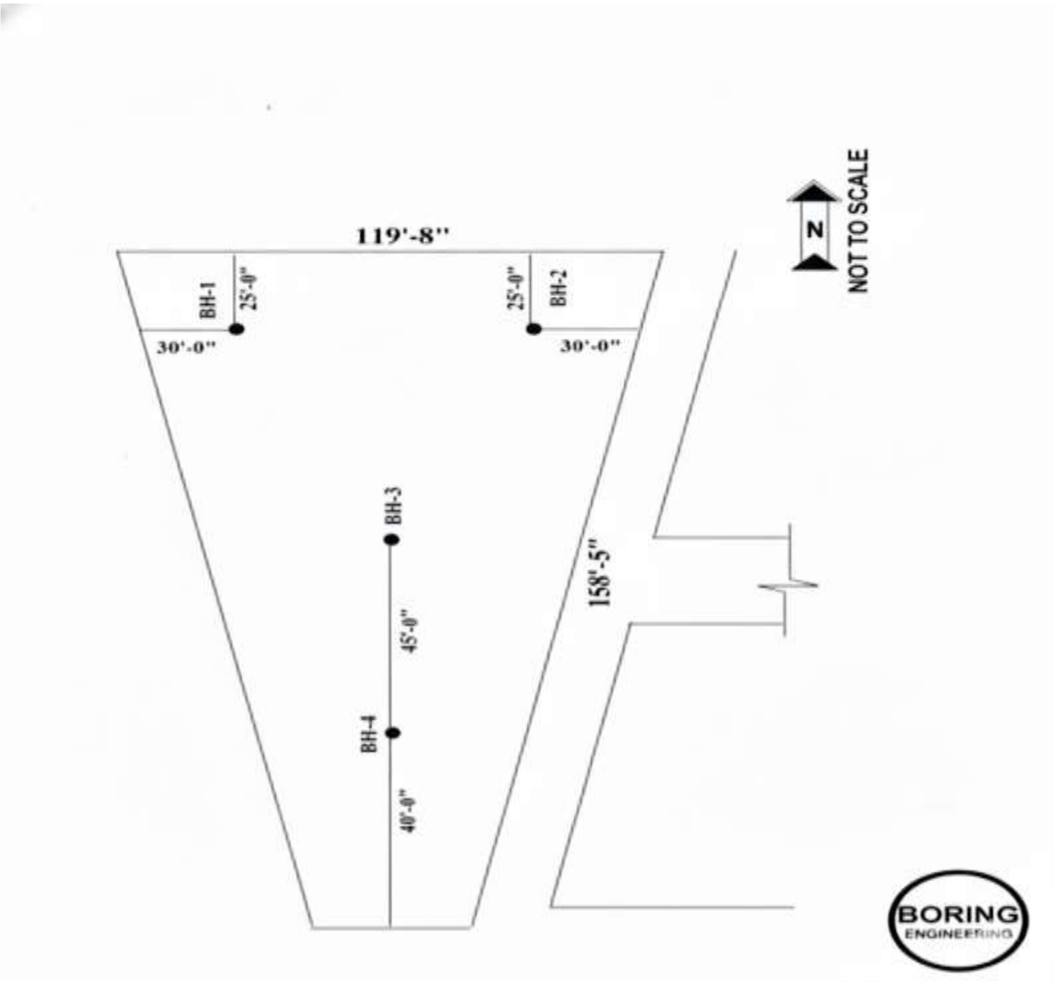

Figure 1: Construction of Proposed 06 (Six) Storied Factory Building Site Plan - Borehole Location Plan (BH-1: 25′-0″, BH-2: 25′-0″, BH-3: 45′-0″, BH-4: 30′-0″; not to scale).

3.2. Laboratory Testing

- Laboratory tests were performed according to ASTM:
- Grain Size Distribution: ASTM D422, including mechanical sieving and hydrometer.
- Atterberg limits: ASTM D4318, which involves determination of liquid limit, plastic limit and plasticity index.
- Direct Shear: ASTM D3080, in the evaluation of shear strength parameters (coefficient of cohesion (c) and angle of internal friction (φ).
- Specific Gravity: Pycnometer procedure.
- Moisture Contents: drying in the oven.

To fully describe the upper clayey as well as lower sandy strata, the laboratory suite was especially designed.

4. RESULTS

4.1. Stratigraphy and In-Situ Properties

The deep-subsurface exploration that was carried out by four boreholes showed a uniform stratigraphy of the Bengal delta region [8], [9]. An overlying layer of reddish, medium to stiff clay stretches downward at the ground surface the depth of the layer is about 22 ft and then a layer of medium dense to dense sand is encountered. Ground water table was also revealed at depths of 14-17 ft, a typical lithologic condition of the region and its existence mandates that it is to be taken into careful consideration in the foundation design since it affects the bearing capacity and may pose construction problems [10], [11], [12].

Detailed borehole logs of each borehole are as summarised below:

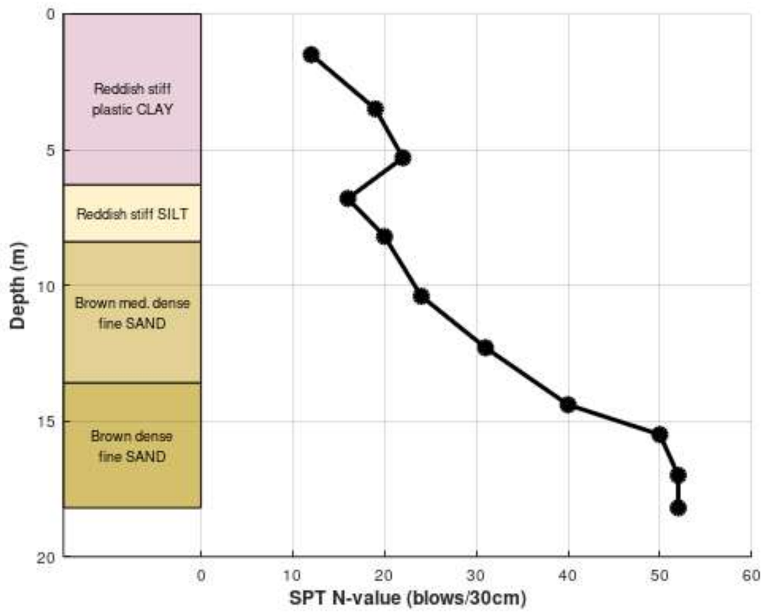

Figure 2: Borehole No.01

- 0–22 ft: Reddish clay (SPT N-values: 6–20)
- 22–60 ft: Sand (SPT N-values: 14–50)
- Groundwater Level: –15 ft

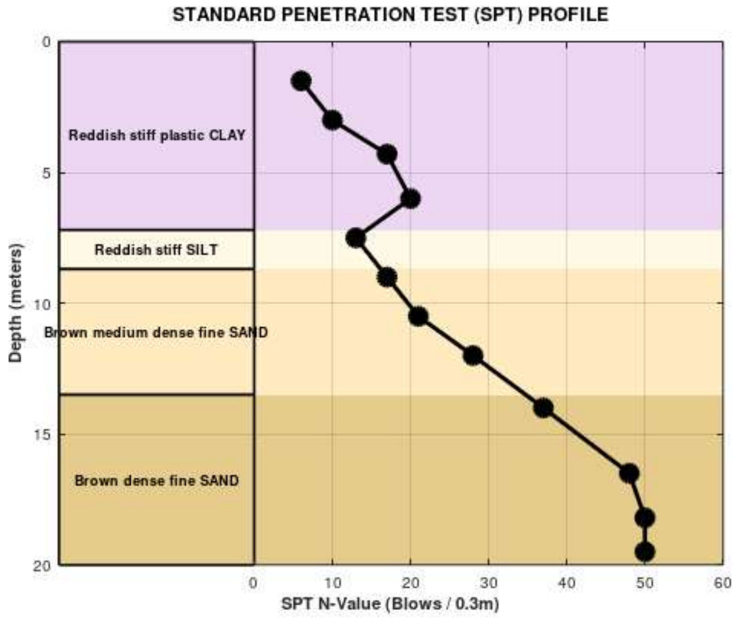

Figure 3: Borehole No.02

- Similar profile: Clay (SPT N-values: 5–18) transitioning to sand (SPT N-values: 16–50)
- Groundwater Level: –14 ft

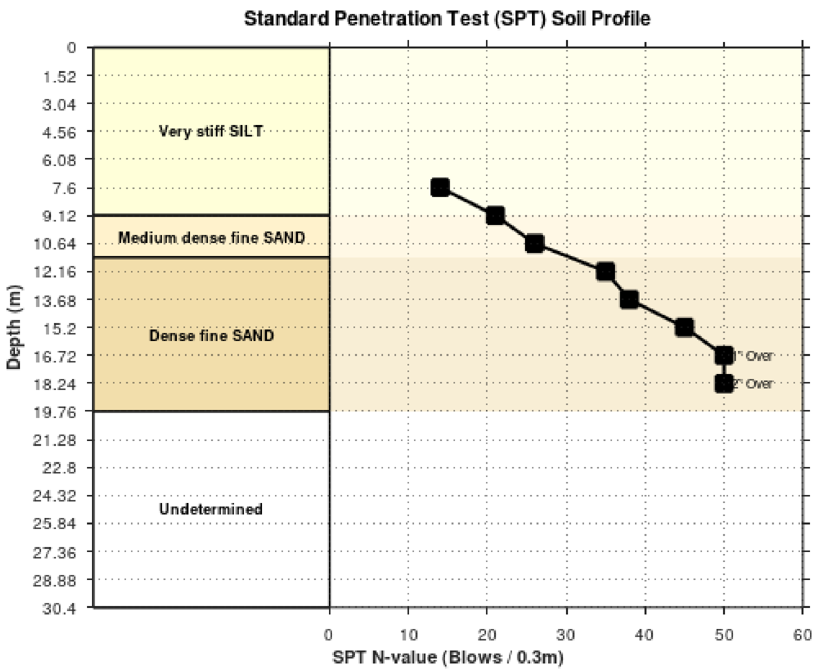

Figure 4: Borehole No.03

- Clay (SPT N-values: 6–24) transitioning to sand (SPT N-values: 16–50)
- Groundwater Level: –17 ft

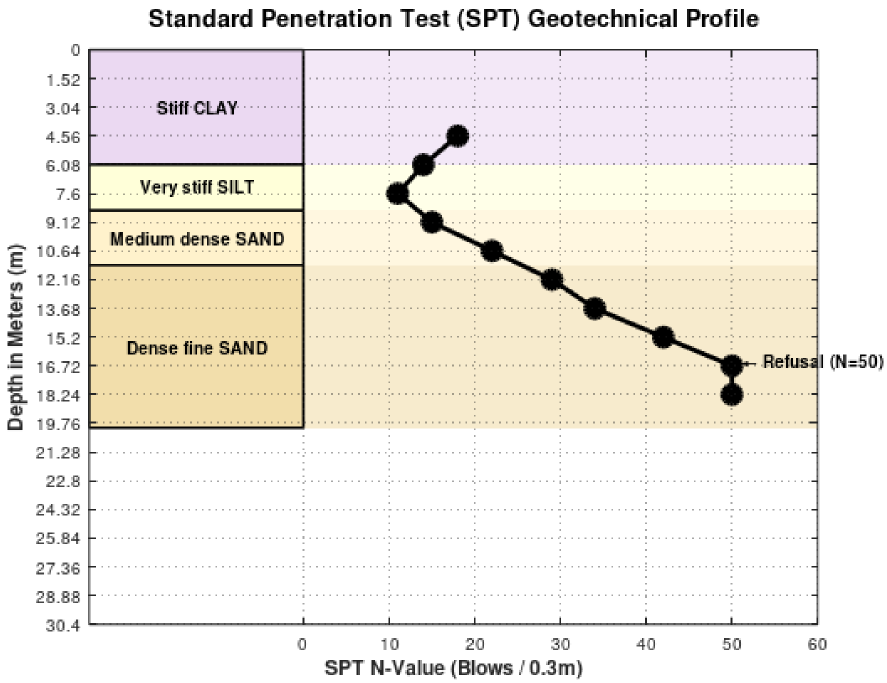

Figure 5: Borehole No.04

- Soft clay top (SPT N-values: 4–22) transitioning to sand (SPT N-values: 17–50)
- Groundwater Level: –17 ft

The values (N-values) of Standard Penetration Test values of all boreholes show that there is a traceable pattern of the growing density and strength of soil with depth which is very important in the geotechnical design [13], [14], [15]. Namely, at the top 0-5 ft of the site, the value of N traditionally borders on 4-6, which is typical of very soft clay, and in the 5-20 ft section, the N-values become 10-20, typical of hard clay, and later N-values become 14-50+ typical of dense sand [

4.2. Seismic Zoning

Figure 6: Seismic Zoning Map of Bangladesh (Source: BNBC 2020)

As Figure 6 shows, the project location is definitely located in Seismic Zone-2. This classification is associated with a moderate and serious seismic hazard with a design zone coefficient (Z) of 0.20 [17], [18]. This designation therefore requires full integration in dynamic analysis in the foundation design activities of the shallow foundation system and the deep foundation system [1], [2]. It, therefore, follows that the seismic requirements in the Bangladesh National Building Code must be strictly followed to ensure the structural integrity and long-term stability of the proposed factory building in case of some seismic events [19].

4.3. Classification of Soils and Results in Laboratory.

Systematic laboratory tests including grain size distribution, Atterberg limits were conducted on representative sample of soils to obtain the most accurate characterization of the underlying strata and determine their most important engineering properties. The findings have always shown a strong change in the fine-grained cohesive soils in the top layer to coarser granular soils as the depth is increased.

The tabular findings, as represented in Figures 7 to 10 can be summarized as follows:

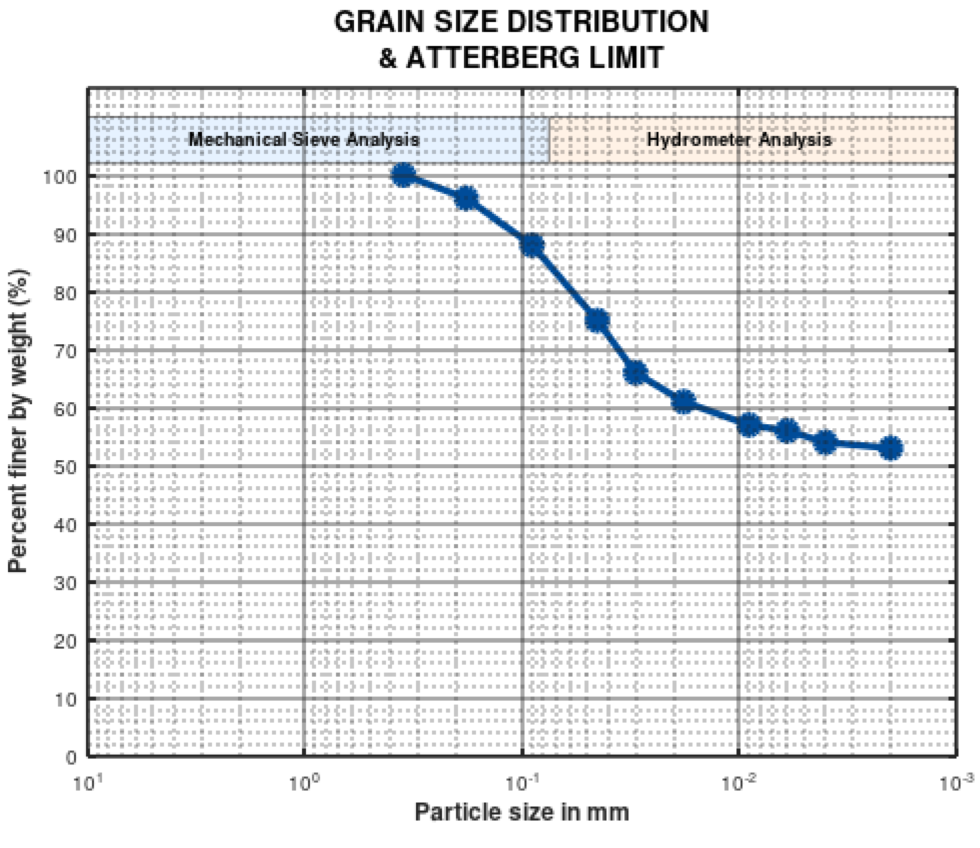

Figure 7: Grain Size Distribution & Atterberg Limit - BH-1 D-2 Depth=10 ft

- Composition: Sand: 11.62%, Silt: 34.84%, Clay: 53.54% (Total Fines: 88.38%)
- Specific Gravity: 2.671
- Interpretation: This sample was prepared out of the upper stratum; it has a high content of fines and has a high content of clay hence depicting the nature of a surficial cohesive layer.

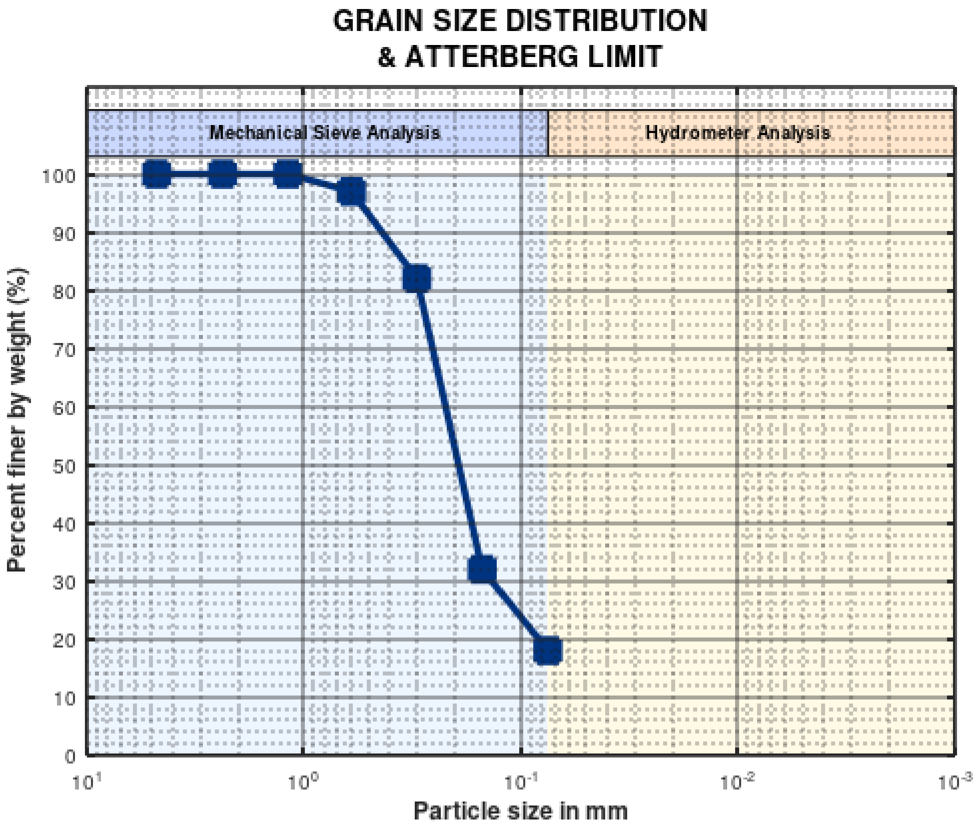

Figure 8: Grain Size Distribution & Atterberg Limit - BH-2 D-8 Depth=40 ft

- Composition: Sand: 81.31%, Fines: 18.69%
- Specific Gravity: 2.681
- Interpretation: This significant percentage increase in sand material and equivalent percentage decrease in fines supports the fact that a predominately sandy make-up exists at this lower altitude.

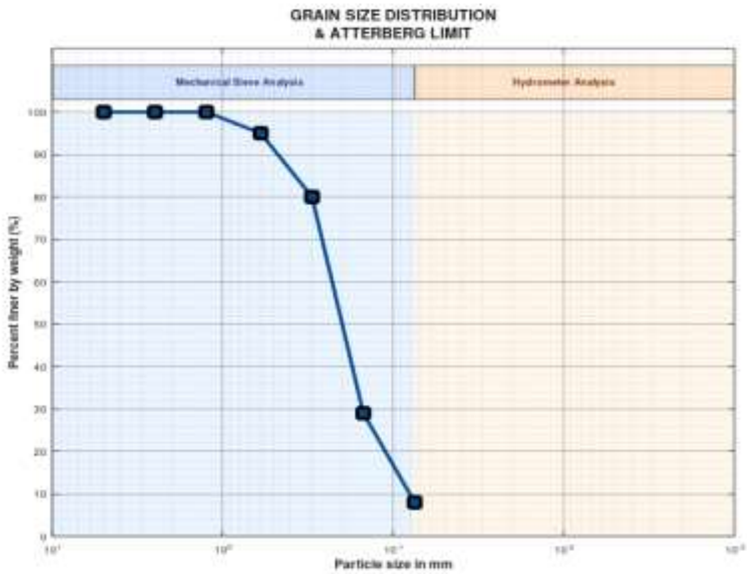

Figure 9: Grain Size Distribution & Atterberg Limit - BH-3 D-10 Depth=50 ft

- Composition: Sand: 91.99%, Fines: 8.01%
- Specific Gravity: 2.688
- Interpretation: This sample also shows the gradual increment in the sand content and consequent reduction in fines, thus strengthening the change to the granular soils.

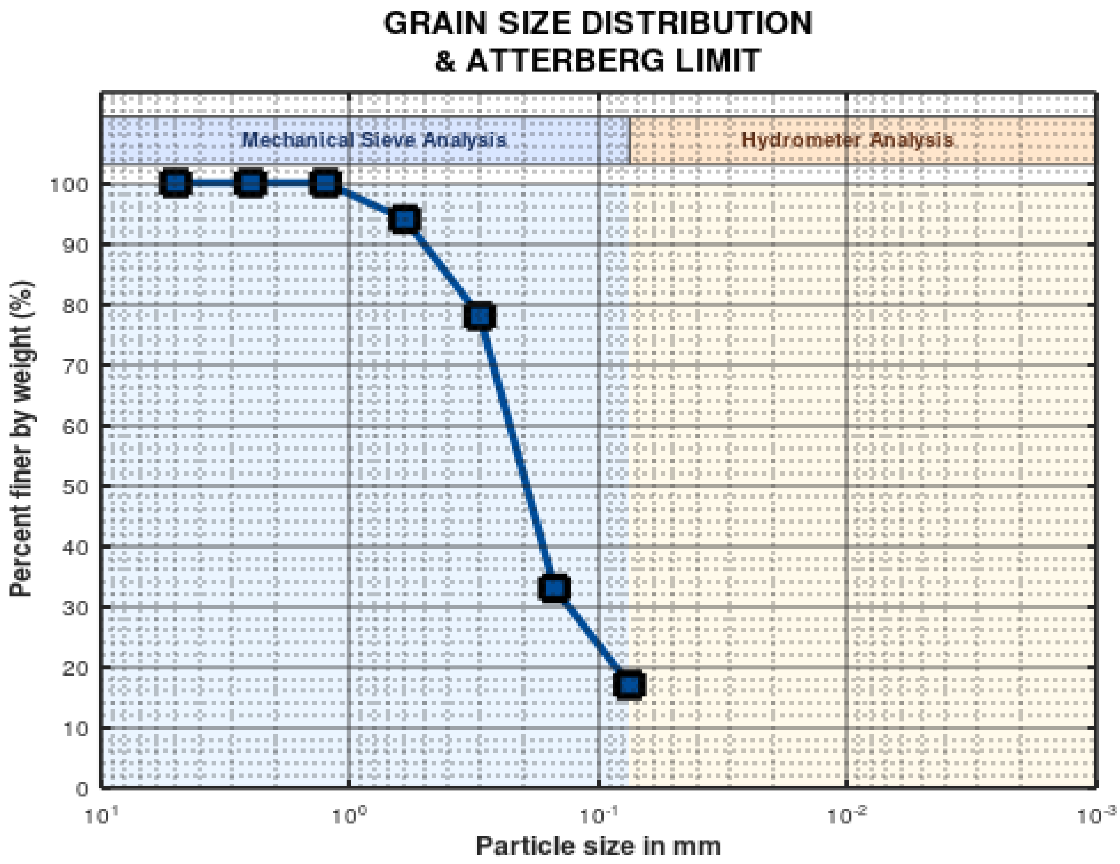

Figure 10: Grain Size Distribution & Atterberg Limit - BH-4 (40–50 ft sample)

- Interpretation: This analysis shows that the site has a high rate of sand content, which unanimously proves gradual but clear transition of clayey (top) and sandy (bottom) strata throughout the site.

On the basis of these extensive laboratory data, the surficial cohesive soils are either CL (low plasticity clay) or CH (high plasticity clay) with reference to the Unified Soil Classification System [20]. On the other hand, the more profound ones are classified into SM (silty sand) or SP (poorly graded sand) though the same system. This stable categorisation is in line with the stratigraphy observed and offers a strong fundamental ground on the interpretation of the geotechnical behaviour and further foundation design consideration of the site [21], [22], [23].

4.4. Shear Strength Parameters

The designed direct shear tests carried out on soil samples, which are representative of the site under analysis were aimed at measuring the parameters of shear strength in the form of angle of internal friction (φ) and cohesion (c) parameters that are considered important in designing foundations. The data as in Figures 11 through 14 show an overall upward trend in shear resistance with depth which is directly related to the stratigraphic changes as observed.

The obtained parameters can be summed up as the following:

The measured parameters are summarized as follows:

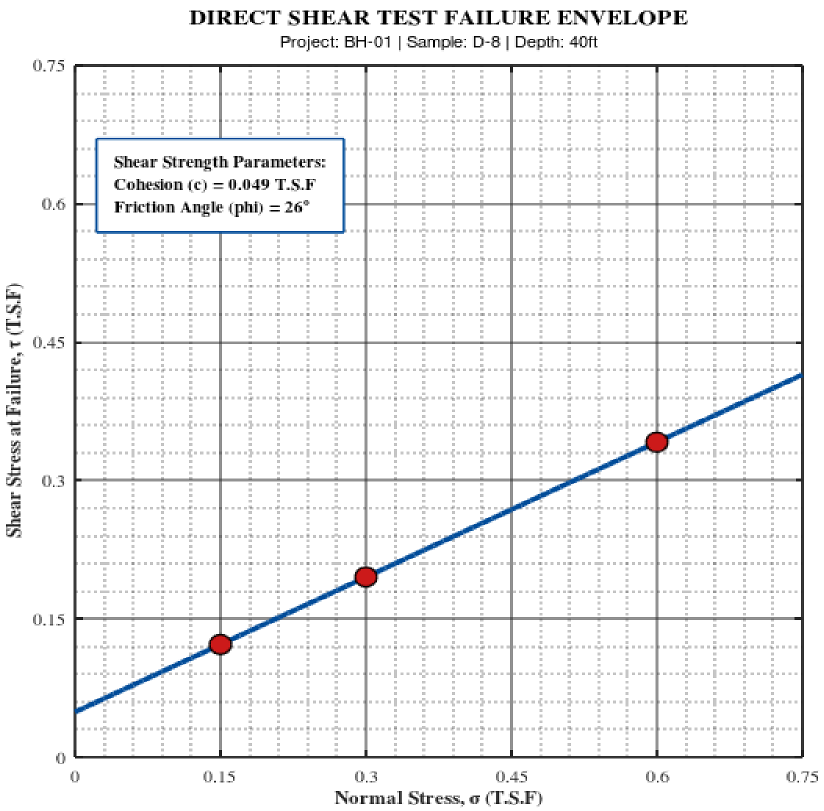

Figure 11: Direct Shear Test - BH-1 Sample D-8 Depth=40 ft

- Angle of Internal Friction (ϕ): 26°
- Cohesion (c): 0.049 tsf

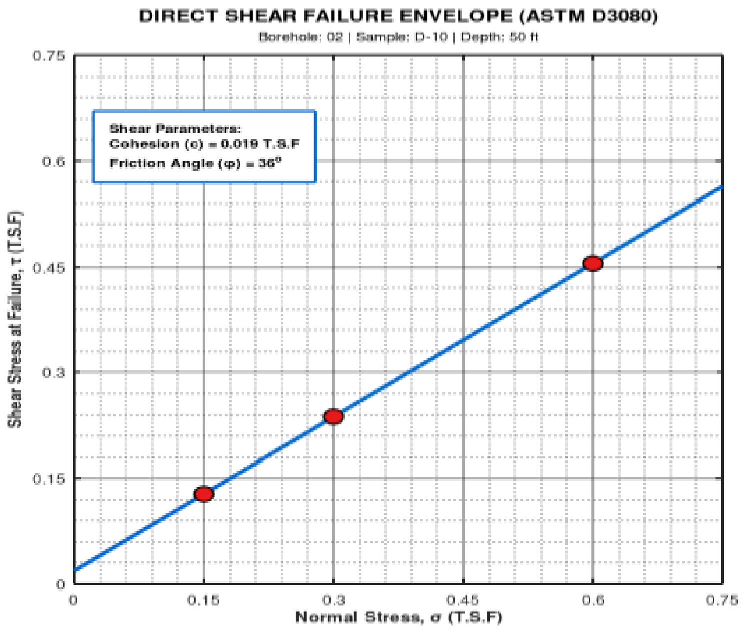

Figure 12: Direct Shear Test - BH-2 Sample D-10 Depth=50 ft

- Angle of Internal Friction (ϕ): 36°
- Cohesion (c): 0.019 tsf

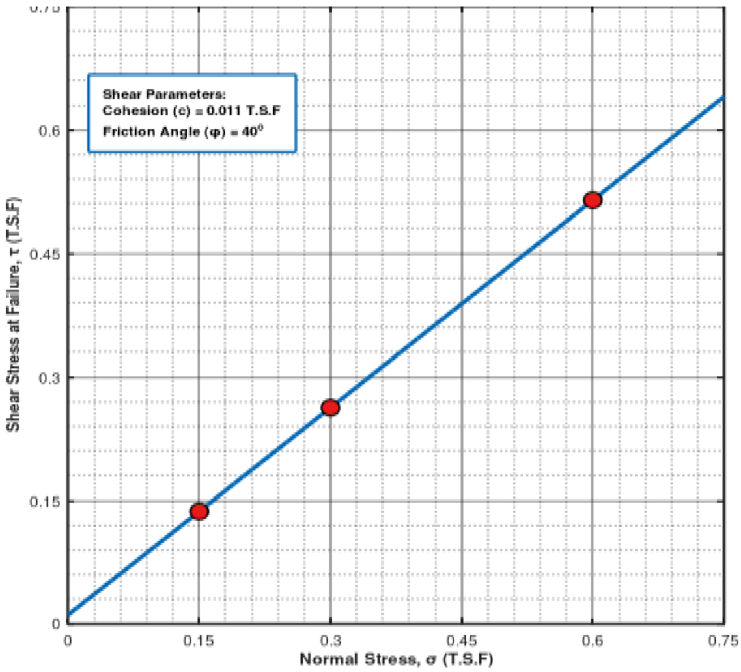

Figure 13: Direct Shear Test - BH-3 Sample D-12 Depth=60 ft

- Angle of Internal Friction (ϕ): 40°
- Cohesion (c): 0.011 tsf

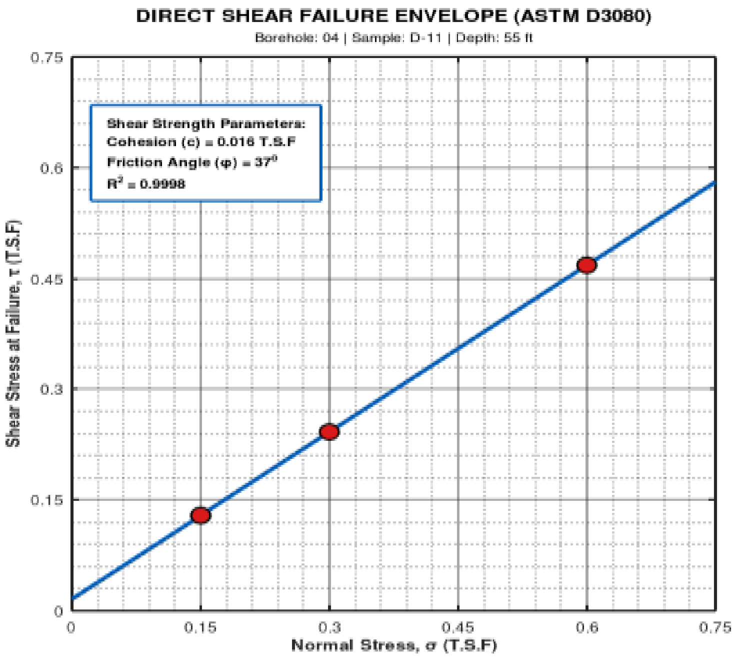

Figure 14: Direct Shear Test - BH-4 Sample D-11 Depth=55 ft

- Angle of Internal Friction (ϕ): 37°
- Cohesion (c): 0.016 tsf

The trend of shear resistance increasing with depth has been observed to be due to two main reasons, firstly, improvement of consolidation of overburden in deeper strata and secondly, the change in the nature of the soils, which are initially cohesive clay soils and then change into granular sandy soils which generally offer greater angles of internal friction. This effect of the shear strength enhances the bearing capacity and stability of deeper foundation systems considerably.

According to the Standard Penetration Test N-values, direct shear parameters and the general bearing capacity equation of Terzaghi [3], the safe bearing capacities of isolated foundations of different depth were calculated carefully with a factor of safety of 3. Some of the computed values that are important in designing foundations are summarized in Table 1 and they show that bearing capacity varies as depth and foundation geometry increases.

4.5. Calculations in Bearing Capacity.

Table 1: Bearing Capacities (tsf, F.S.=3)

Depth (ft)	BH-1 N	BH-2 N	BH-3 N	BH-4 N	Sq./Circ. Avg	Strip Avg
5	6	5	6	4	0.88	0.70
10	10	10	12	11	1.80	1.43
15	17	17	16	14	2.57	2.05
20	20	18	21	20	3.33	2.65

Particularly, the safe bearing capacity of isolated (square/circular) footings at 10ft of depth is between 1.68 and 1.80tsf and in strip footing between 1.34 and 1.43tsf. Such capabilities reflect the appropriateness of the site in a situation where shallow foundation systems are used in normal conditions of industrial loading.

4.6. Design and Capacity of Piles.

Figures 15 through 18 represent a pile design chart of each borehole developed carefully with respect to 16-to-24-inch diameter cast-in-situ piles. The calculations mainly used Meyerhof approach and direct correlations between SPT and end bearing to predict both the shaft and end bearing resistances [24], [25], [26], [27]. Although SPT-based techniques provide a convenient way of establishing the pile capacity particularly in coarse-grained soils, their application has to be cautiously considered taking into account its inherent uncertainties and may not be reliable as compared to CPT-based techniques with some soil types [28], [29]. However, the SPT still is a popular and viable in-situ test that can be used in predicting pile capacity [30], [31], [32].

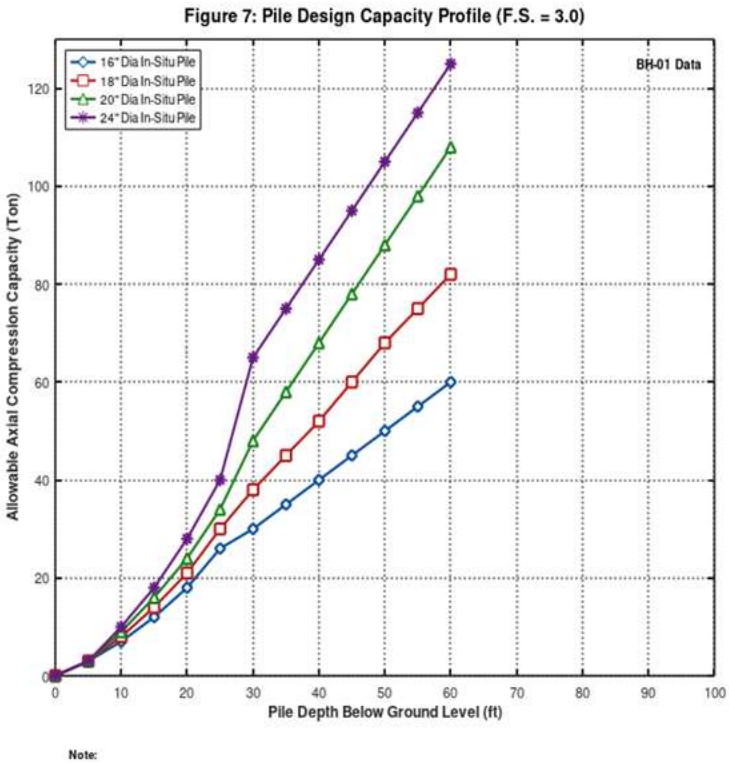

Figure 15: Pile Load Capacity Chart for Borehole 1 showing 16-24 inch diameter cast-in-situ piles supporting up to 120 tons at 60 ft depth.

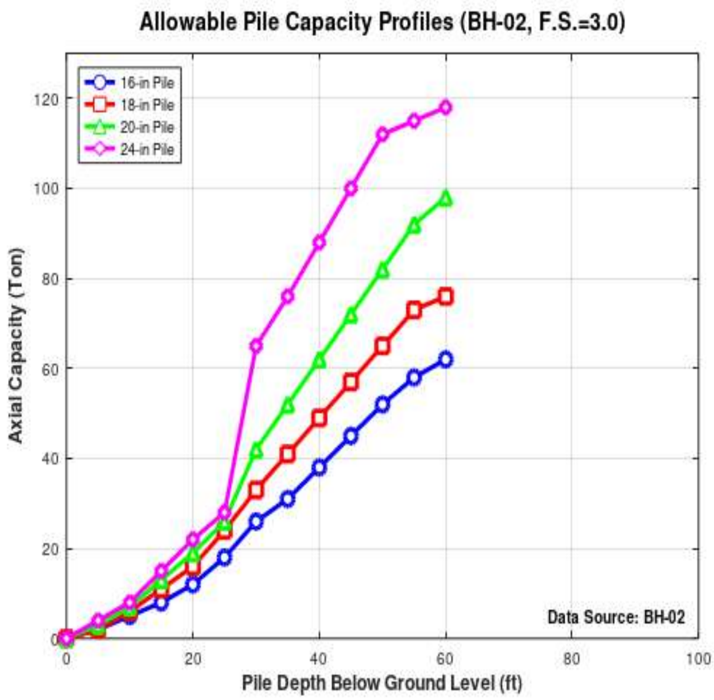

Figure 16: Pile Load Capacity Chart for Borehole 2 illustrating capacities extending to a depth of 100 ft.

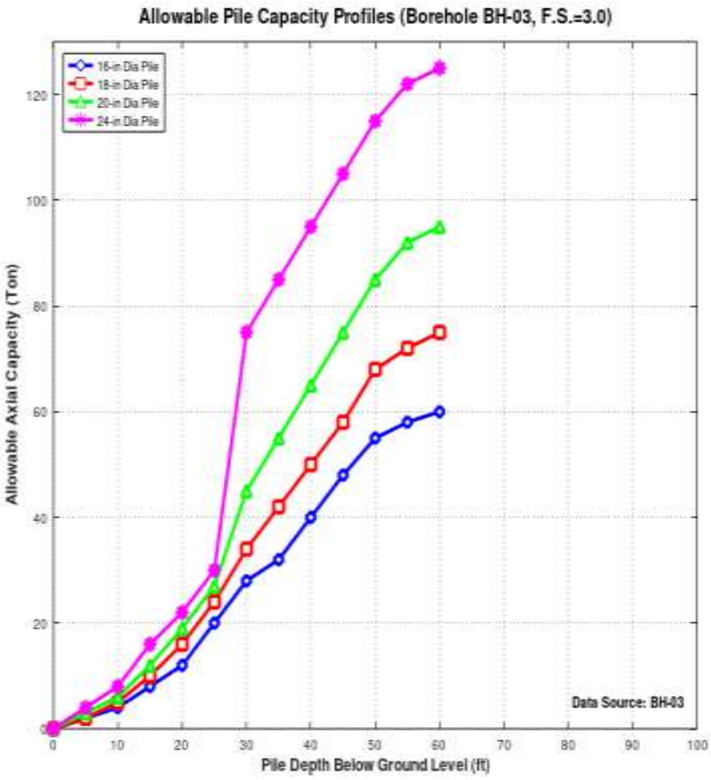

Figure 17: Pile Load Capacity Chart for Borehole 3 indicating 24 Inch diameter piles supporting ultimate loads up to 130 tons.

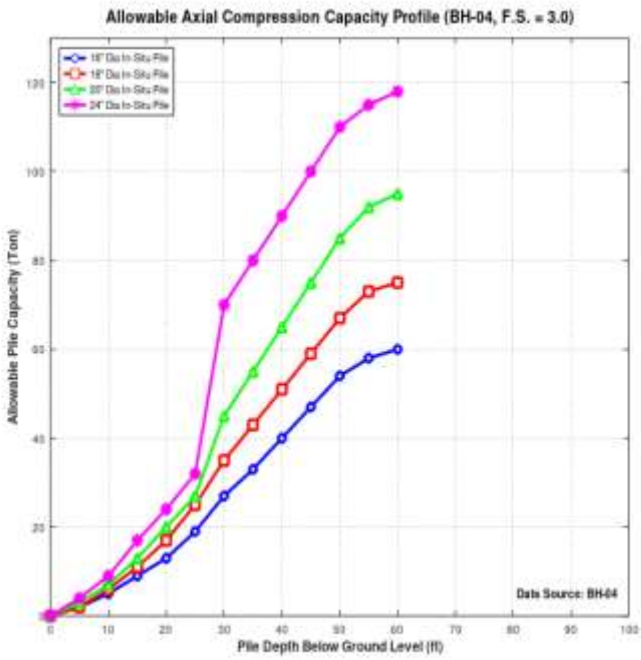

Figure 18: Pile Load Capacity Chart for Borehole 4 demonstrating similar capacities extending to a depth of 100 ft.

These findings definitively determine that in cases where the column loads are heavy, or the settlement control is critical, deep foundation solutions, i.e. cast-in-situ piles, are a highly feasible and strong means of structure support, and is also capable of taking advantage of the dense sand stratum that is present at the deeper elevations.

5. DISCUSSION

5.1. Interpretation of Stratigraphy and Soil Behavior

The uniformity of all the borehole logs (Figures 2-5 in the main report) means that there was little lateral difference in the underground conditions, an essential factor when it comes to achieving regular results in the foundation behaviour. The top clayey layer with a Standard penetration test N-values between 4 to 24 is common to Ganges-Brahmaputra delta area. Such stratum is highly plastic, low permeable, medium to low shear strength, which is in line with deltaic environment. It is also changing at a depth of around 22 ft with a change to the medium-dense dense sand stratum level with N-values generally falling between 14 and above 50. The sandy layer is an excellent foundation stratum both as regards to shallow and deep foundations. The lower area of the surficial clay layer is penetrated at the depth of between 14-17 ft which is the groundwater table. This depth is not out of the norm of the region, but one that must be carefully taken into consideration when designing foundations, especially as far as buoyancy correction of in-ground foundations is concerned, as well as the adoption of construction dewatering measures.

5.2. Bearing Capacity and Foundation Recommendations

The calculated safe bearing capacity of 1.68 tsf at 10 ft (Table 1 in the main report) justify the use of isolated footings in the majority of column loads on a typical six-storied factory building. The direct shear parameters also support this recommendation, with an angle of internal friction (ϕ) of 26- 40^0 and cohesion (c) of 0.011- 0.049tsf. The low plasticity index (PI< 20 %) of the upper clay also means that it has moderate compressibility and can only swell and shrink to a certain extent, which again validates the appropriateness of shallow foundations when subjected to normal loads.

In cases where column loads are more than 100 tons or a high level of settlement tolerance is necessary, a pile foundation is appropriate. Figure 15 of the main report concurs the pile design charts (Figures 15-18) that 24 inch diameter cast-in-situ piles driven to a depth of 60ft are capable of safely taking charge of 120-130 tons at an assumed factor of safety of 3. Such abilities are through effective utilization of the dense sand stratum in end bearing resistance as well as shaft friction.

5.3. Seismic Considerations

The location of the site in the BNBC Seismic Zone-2, which has a zone coefficient (Z) of 0.20 (Figure 6 in the main report), requires that both the shallow and deep foundation designs must be based on the dynamic loads. Although the stratigraphy of firm clay above dense sand shown is inherently less prone to liquefaction than loose alluvial sand lenses or unconsolidated fills, the closeness of the groundwater table is an issue to be considered. As a result, stringent adherence to BNBC 2020 seismic requirements and full-scale dynamic settlement assessment is highly encouraged to be structurally sound to withstand seismic loading.

5.4. Boosting of Advanced Modelling and Artificial Intelligence.

Although the present research was based on classical approaches to analytical design of geotechnical, the new stream of computational approaches gives great promise of an efficiency improvement in the future project. Among other things, automated agentic systems may be used to help with all sorts of activities, including classifying types of foundation (e.g., distinguishing between shallow and pile foundation requirements), performing code compliance checks, and simplifying the documentation, as discussed by Youwai et al. [6]. It is important to underscore however, that these sophisticated tools are only supposed to supplement, and not to substitute good sound engineering judgment, particularly in cases of safety critical design.

On the same note, machine-learned models have been found to be quite accurate with predicting parameters such as the bearing capacity and the California Bearing Ratio when fed on high quality data, including the Deep Neural Networks [4] and random forest regressors [5]. They may be of great use especially in situations where there is a paucity of field data, or where quick, preliminary geotechnical analyses are required.

5.5. Expansive Implications to Deltaic Construction.

The results given below are widely applicable to the general deltaic subsoil conditions found in the country in central Bangladesh. The uniform clay-sand stratigraphy, average SPT -values, and shallow groundwater table are common geotechnical patterns in the area. Hence, the sound structure developed in the given study based on the SPT-based calculations of the bearing capacity that is confirmed by laboratory testing of shear strength and soil classification can be safely projected and applied to analogous industrial and commercial development projects in the Bengal delta. This ground improvement technique of searching the most efficient foundation solutions to the conventional foundation systems also eases the industrial growth in high seismic areas, where the costs are minimized [33].

6. CONCLUSIONS

This is a complete geotechnical study that proves that the site where Liberty Knitwear Ltd. factory is located at Gazipur has a good profile of subsoil both in terms of shallow and deep foundation system. The main conclusions are the following:

1. **Stratigraphy**: A reddish clay, surficial in nature 022ft thick, subsequently overlying medium-dense to dense sand (N=14-50), and having GWT of 14-17ft.
2. **Soil Classification**: Above soils are high-fines clays (PI< 20 %) and the soils change to the low-fines and well-graded sands below 22 ft.
3. **Shear Strength**: Direct shear tests provide $\phi = 26\text{-}40^0$ and c = 0.011-0.049 tsf, which gets deep-rooted.
4. **Bearing Capacity**: Shallow footings of 10 ft may be safely made with 1.68 tsf (FS = 3), which allows 6-story industrial loads.
5. **Pile Capacity**: Smaller piles can withstand greater loads or more demanding settlement requirements 16–24-inch diameter piles with 60 ft support below 120 -130 tons.
6. **Seismic Vigilant**: Seismic Zone- 2 of the site needs to be dynamically analyzed and with the right safety factors.
7. **Design Recommendations**: Piles are only used on heavy columns, where isolated shallow footings at 10ft are the most economical and safe.
8. **Wider Generality**: The analytical framework that is developed here can be applied to the other relevant sites in the Bengal delta.

In summary, combinations of rigorous field study, laboratory tests and classical theory of bearing capacity offers a valid foundation to designing foundations in the problematic deltaic environment in Bangladesh. It is possible to investigate the combination of sophisticated computational and AI-based approaches in the future, and continuous observation of the conditions in the subsoil to take into consideration the temporal variation.

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