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Geotechnical Investigation of Subsoils for Foundation Design in Port Harcourt, Nigeria

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Abstract: Geotechnical investigation was carried out at a proposed construction site in Port Harcourt, to establish the soil profile and determine the engineering geological properties of subsoils in the area. Boring activities were conducted in 4 locations at the site by means of a manual percussion rig to a depth of 30m. Visual observation and laboratory analysis of the recovered samples reveal that the subsurface materials in the area consist of soft clays from the existing ground surface to an average depth of 5.0m. Beneath the clay formation are different sand facies which occur to the final depth of the boreholes. Shallow foundation analysis conducted on the soil samples gave allowable bearing capacity values ranging from 35 - 78kN/m^2 for square footings founded at depths of 0.5 - 2.0m. Total settlement from the anticipated imposed load of the proposed structure was determined to range between 70 and 52mm at foundation depths of 0.5 and 2.0m for square footing of 1.0m, while settlement for 5.0m footing, was evaluated to be 130 and 80mm at foundation depths of 0.5 and 2.0m respectively. Pile foundation analysis was also carried out for the soil profile encountered at the site. Straight shaft, closed pipe piles of diameters 305, 406, 508 and 610mm were designed. The pile compressive resistance of the 305mm diameter pile was between 20 and 740kN when founded between 5.0 and 30.0m depths respectively, while that of the 610mm diameter pile gave a compressive resistance between 50kN and 1690kN when founded between the same depths. It is therefore recommended that while shallow foundation could be used for supporting structures within the study area, pile foundation should be considered for multi-storey buildings.

Introduction

Civil engineering structures such as buildings, bridges, highways, tunnels and dams are founded below or on the surface of the earth. For stability of these structures, soil suitable for foundation is required. This is because foundations of structures constructed on compressible soil, often leads to excessive settlement (Roy and Bhalla, 2017).

Incessant incidences of building collapse in Nigeria have continued unabated in recent times (Amadi et al, 2012). Several probable causes, including substandard materials used for building, old age of buildings, and poor foundation design have been highlighted by the engineering community. However, the subsurface earth conditions that seriously affect foundation performance are either trivialized or rarely given the needed consideration by foundation designers and structural engineers prior to construction (Abija et al, 2018).

Geotechnical site investigation is carried out to determine properties of rock and soil, and for underground stratigraphic analysis of geotechnical systems (Mayne et al., 2002). Soil, in the geotechnical engineering perspective, is the soft unconsolidated material, which overlies the rocks in the outer part of the earth's crust (Clayton et al., 1995). The suitability of soil for a particular purpose should be determined by its geotechnical properties and not merely by visual examination or its apparent similarity with other soil types, because soil properties are subject to strong spatial and temporal variations (Teme, 2002).

The primary objective of this study is to determine specific geotechnical parameters to guide engineering design of both shallow and deep foundations for proposed building projects and make recommendation of suitable foundation type in the study area.

Geology and Description of Study Area

The study area is part of the Niger Delta Sedimentary Basin which approximately covers a land area in excess of 105,000 km^2 and a larger offshore part. The Niger Delta constitutes an advance of terrestrial deposits into a high energy marine environment. The geology of the Niger Delta has been well described by various authors including, Allen, (1965), Short and Stauble, (1967), Onyeagocha, (1980) and Asseez, (1989). Specifically, the site under investigation is located at GRA Phase III, Port Harcourt, Rivers State and lies approximately between latitudes 4^{o}48'30"N and 4^0 49'0"N and longitude 6^{0}59'30"E and 7^{0}0'0"E (figure 1).

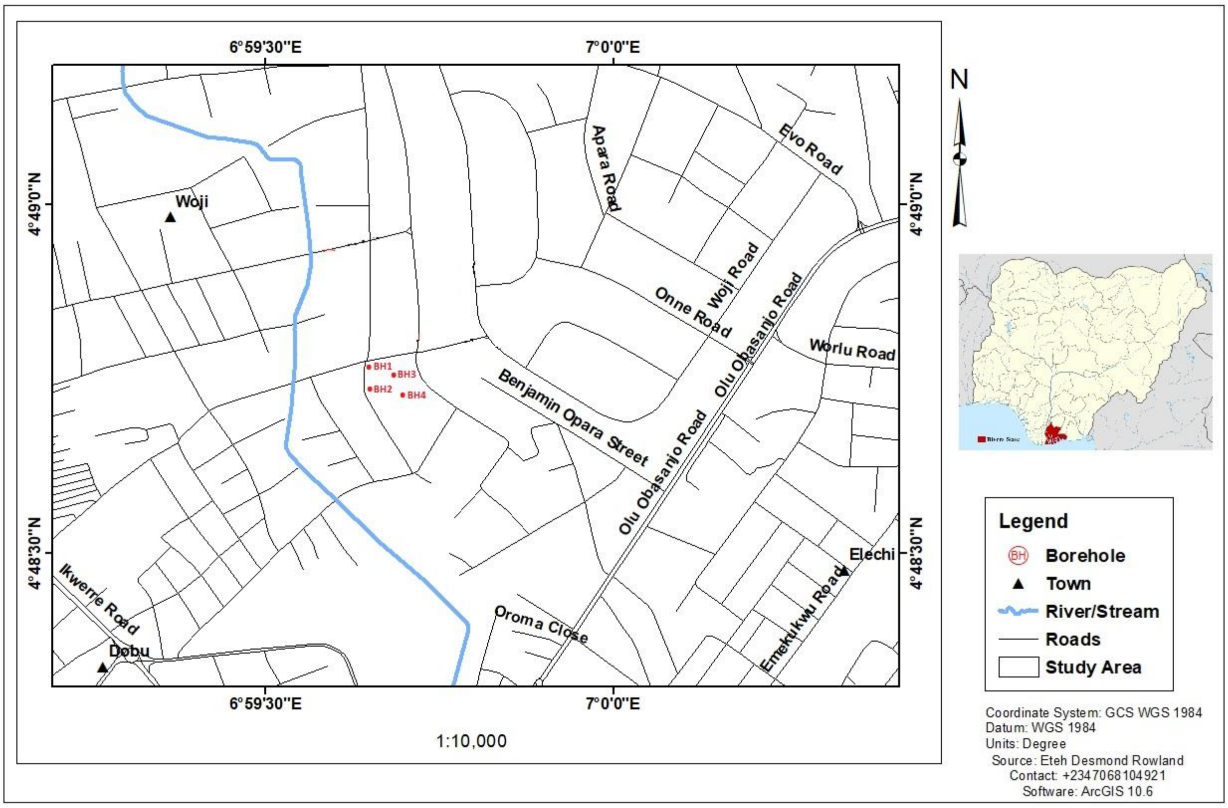

Figure 1: Map of study area showing borehole locations

Port Harcourt City displays climatic characteristics that could be classified as humid, semi-hot equatorial type (Gobo, 1990). The area experiences heavy rainfall from March to October and even the dry months of November to February are not free from occasional rainfall. The mean annual rainfall is about 2,500mm (Akintola, 1986). With the extensive rainfall and the consequent reduction in the infiltration capacity of the soil due to its low permeability, flooding is commonly experienced in some homes during the rainy season.

The city has a flat topography with inadequate drainage facility. Its elevation varies between 3m to over 15m above mean sea level. The low relief of the area is gently inclined towards the sea. Discharges are into the major natural drainage through the Bonny River. The streams are south flowing streams. They tend to be turbid during the wet season due to the discharge of clay and silt into the drainage channels. In the dry season however, the discharge and turbidity are highly reduced (Abam, 1996).

Materials and Method

Field and laboratory Studies

Four geotechnical boreholes were explored to a depth of 30m below the existing ground level. Boring operation was by means of a manual percussion rig. Representative samples were taken at every 1m from the boreholes. The samples recovered to the soil laboratory were used for a detailed and systematic description of the soil in each location. The laboratory tests conducted on the samples include moisture content, unit weight, particle size distribution, Atterberg's limit tests, shear box test, and undrained shear strength test.

Bearing Capacity Analysis for Shallow Foundation

The ultimate bearing capacity, Q_u, for shallow square footing on cohesive soils using Terzaghi's equation (Terzaghi, 1943) and modified for shape factor is given below as:

$$Q_u = 0.867 * c * N_c + \gamma * D_f * N_q * + 0.4 * \gamma * B * N_\gamma \quad (1)$$

Where;

c – Undrained shear strength of the soil at depth d

γ – Unit weight of soil at depth d

D_f – Depth of foundation, (0.5m, 1.0m, 1.5m & 2.0m)

B – Foundation width

N_c, N_q, N_γ – Bearing capacity factors

Settlement Analysis

Settlement from the anticipated imposed load from the proposed structure was obtained from the sum of both the immediate settlement (ρi) and the consolidation settlement (ρ_{con}) given by

$$\rho i = q * B * (1 - v^2) * \frac{I}{E_d} \quad (2)$$

Where;

q = uniform intensity of pressure,

B = width of the shallow footing, m

I = Influence factor = 0.82

ν = Poisson's ratio of soil (= 0.5) for undrained condition

E_d= modulus of deformation of the soil beneath the foundation

$$\rho_{con} = H * \left[\frac{c_c}{1+e_o}\right] * \log_{10}\left[\frac{(P_o+\Delta P)}{P_o}\right] \quad (3)$$

Where;

H = thickness of consolidating layer = 1.5B (m)

Cc = compression index of the clay = 0.009(LL-10)

e_o = initial void ratio of the clay layer
P_o = overburden pressure on the consolidating layer
ΔP = imposed pressure from applied load

Bearing Capacity Analysis for Deep Foundation

The pile bearing capacity, Q_u, of driven piles is determined by the equations below derived from Eurocode 7, BS EN 1997 - 1: 2004. Q_u, of a pile is conventionally taken as consisting of two parts. One part is due to friction, called skin friction or shaft friction, Q_f, and the other is due to end bearing at the base or tip of the pile or pile toe, Q_b.

$$Q_u = Q_f + Q_b \quad (4)$$

The Pile Design Resistance, Rcd, of driven pile is determined by the equation;
$R_{cd} = R_{bd} + R_{sd}$
Where;
R_{bd} = End bearing resistance of the pile = $q_b * A_b$
R_{sd} = Skin frictional resistance of the pile = $f_s * A_s$
Therefore,

$$R_{cd} = (q_b * A_b) + f_s * A_s \quad (5)$$

Where;
q_b = unit end bearing capacity
F_s = unit skin friction
A_b = gross base area of pile tip
A_s = side surface area of pile

End Bearing Resistance of the Pile

The end bearing resistance, R_{bd}, of the pile is determined in one of two ways
(i) In cohesive soil, $R_{bd} = 9 * Cu_{kb} * A_b$ (6)
(ii) In non-cohesive soil, $R_{bd} = N_q * \sigma_v * A_b$ (7)
Where,
Cu_{kb} = Characteristics undrained shear strength of the clay at the pile toe
N_q = bearing capacity factor
σ_v = Vertical effective stress at the pile toe

Shaft Resistance of the Pile

The shaft resistance, Rsd, of the pile is determined from
(i) Cohesive soil, $R_{sd} = \alpha * Cu_{ks} * A_b$ (8)
(ii) Non-cohesive soil, $R_{sd} = k_s * \sigma_{vs} * \tan\delta * A_s$ (9)
Where,
Cu_{ks}= characteristics undrained shear strength of clay along the pile shaft
α = adhesion coefficient of the clay along the pile shaft
Ks = lateral load factor
σ_{vs} = average effective stress on the pile shaft
tan δ = mobilised friction at the pile-soil interface
δ = friction angle between the soil and pile wall
= 0.75 x φ (angle of frictional resistance)

Results and Discussion

Ground Water Condition

During boring operation, ground water was encountered at all the boring points. The average height of the water table on site was about 0.5m below the existing ground level.

Soil Stratigraphy

Description of the subsurface materials underlying study site as obtained from the boreholes is presented in Table 1. Generally, the shallow subsurface profile reveals soft sandy clay from the ground level to an average depth of 5.0m. Directly below the clay unit are silty sands followed by fine-coarse sands, occasionally gravelly towards the bottom of the boreholes.

Table 1: Description of soil profile

Borehole No.	Depth (m)	Description
1	0-4.5 4.5-9.0 9.0-21.0 21.0-30.0	CLAY, sandy SAND, fine to coarse SAND, fine to coarse SAND, fine – coarse, gravelly
2	0-5.0 5.0-18.0 18.0-30.0	CLAY, sandy SAND, fine - coarse SAND, fine – coarse, gravelly
3	0-4.0 4.0 -9.0 9.0-30.0	CLAY, sandy SAND, fine to coarse SAND, fine to coarse
4	0-5.0 5.0-30	CLAY, sandy SAND, fine - coarse

Geotechnical Properties of the Soil

Laboratory analytical results show that the clay encountered in this investigation had natural moisture content that varied between 18.4 – 24.1%, liquid limit was 20.0 – 31.0% (Figure 2), plastic limit 4.0 - 9.0% and plasticity index of 12.0 – 23.0%. Most of the clay samples classify as low plasticity inorganic clays (CL) based on the unified soil classification scheme with low to moderate compressibility. Average values of specific gravity, bulk unit weight, dry unit weight and submerged unit weight of this lithologic unit were determined to be 2.63, 19.73KN/m^3, 16.15KN/m^3 and 9.92KN/m^3 respectively. The undrained shear strength of the layer varied from 10 – 21.0KN/m^2, while the elastic modulus of deformation ranged between 211 – 759MN/m^3 (Figure 3). The clays were acidic having pH values ranging from 4.91 to 6.43. The geotechnical properties of the soil in the study area are shown in Table 2.

Underlying the clay unit are sand layers which extend from 5 to 30m where boring terminated. Visual inspection and grain size analysis (Figure 2) showed the sands were fairly compacted, fine to coarse grained, non-plastic and tending to be gravelly towards the bottom of the boreholes. Moisture content of the sands ranged from 11.3 – 23.0%, while average values of specific gravity, bulk unit weight, dry unit weight and submerged unit weight were 2.65, 20.10KN/m^3, 17.50KN/m^3 and 10.59KN/m^3 respectively. Average pH of this layer was determined to be 5.71 which indicate moderate corrosivity towards buried metallic construction materials like iron and steel rods. The angle of frictional resistance ranged between 28^0-32^0.

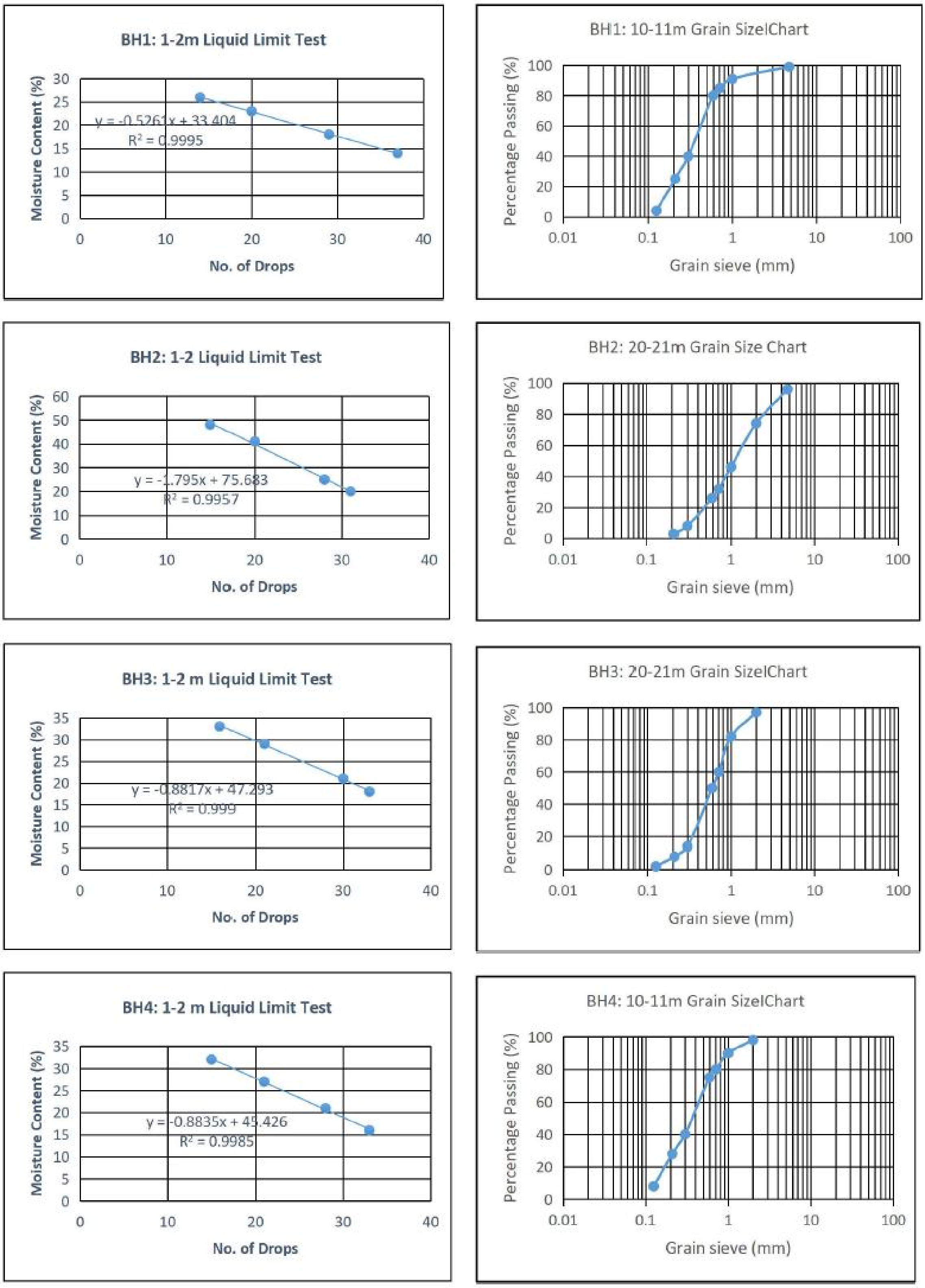

Figure 2: Liquid limit test and particle size distribution of representative samples

Table 2: Geotechnical properties of the clay and sand layers

	Clay layer			Sand layer		
Parameters	Min	Max	Mean	Min	Max	Mean
Moisture content (%)	18.4	24.1	22.2	11.3	23.0	17.7
Bulk unit weight (KN/m^3)	19.72	20.39	19.73	16.86	22.96	20.10
Dry unit (KN/m^3)	16.06	17.02	16.15	15.15	20.61	17.50
Submerged unit weight	9.91	10.58	9.92	7.05	13.15	10.59
Specific gravity	2.59	2.66	2.63	2.56	2.70	2.65
pH	4.91	6.43	5.34	4.13	6.89	5.71
Angle of frictional resistance (ϕ)^0	-	-	-	28	32	30
Undrained shear strength (KN/m^2)	10	21	16	-	-	-
Elastic modulus of deformation MN/m^2)	211	759	414	-	-	-
Liquid limit	20	31	25	-	-	-
Plastic limit	4	9	7	-	-	-
Plasticity index	12	23	18	-	-	-

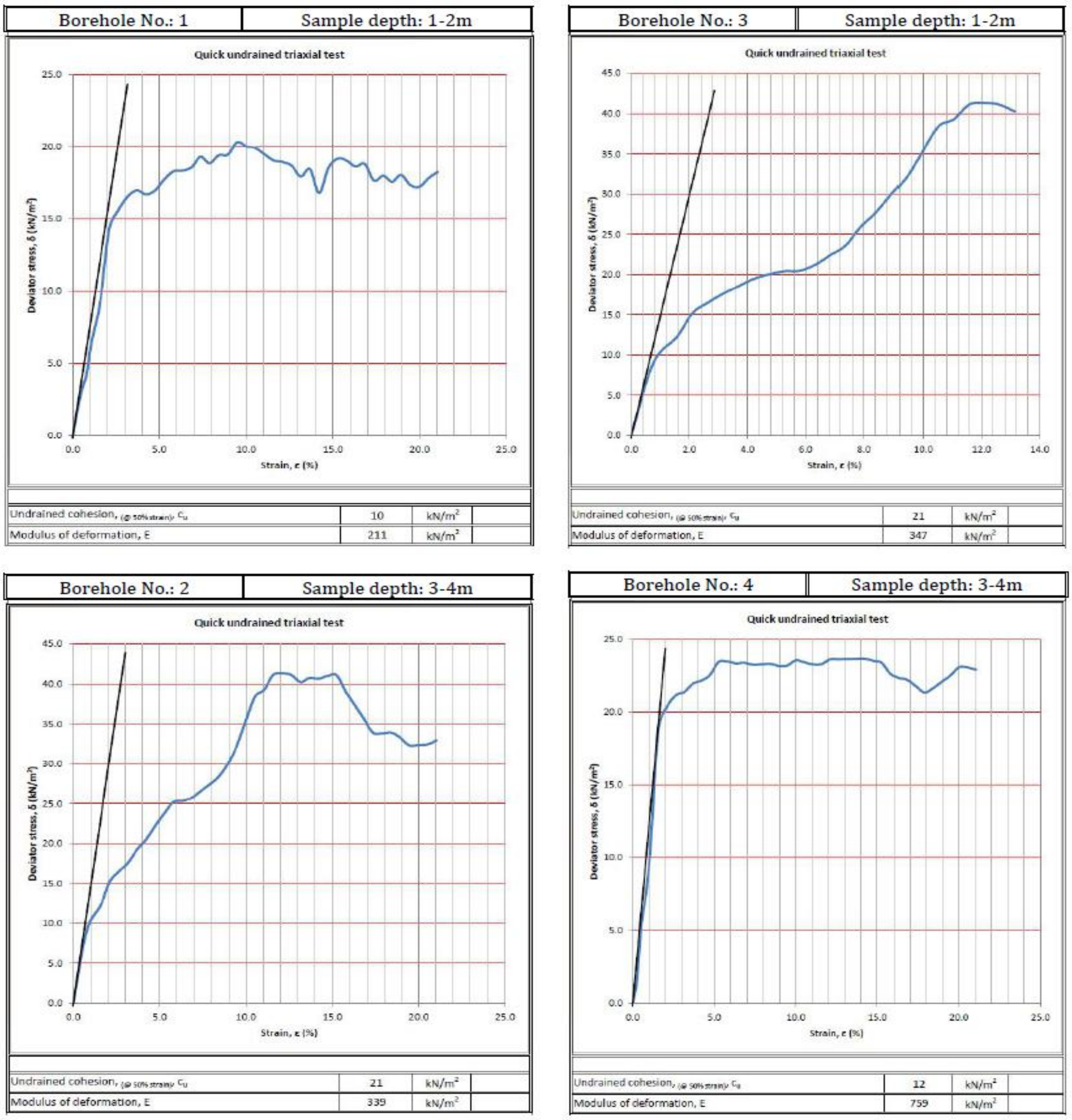

Figure 3: Unconsolidated undrained triaxial test results of selected samples

Bearing Capacity Results for Shallow Foundation

Table 3 and Figure 4 show both the ultimate and allowable bearing capacities for 1m square footing foundation placed at depths between 0.5 and 2.0m below the existing ground surface. The allowable bearing capacity was derived by dividing the ultimate bearing capacity by a factor of safety of 2.0.

Table 3: Ultimate and allowable bearing capacity results

Foundation depth (m)	Bearing capacity Qa (kN/m^2)	
	Ultimate	Allowable
0.50	70	35
1.00	100	50
1.50	132	66
2.00	156	78

$$\text{Allowable bearing capacity} = \frac{\text{Ultimate bearing capacity}}{\text{Factor of safety}}$$

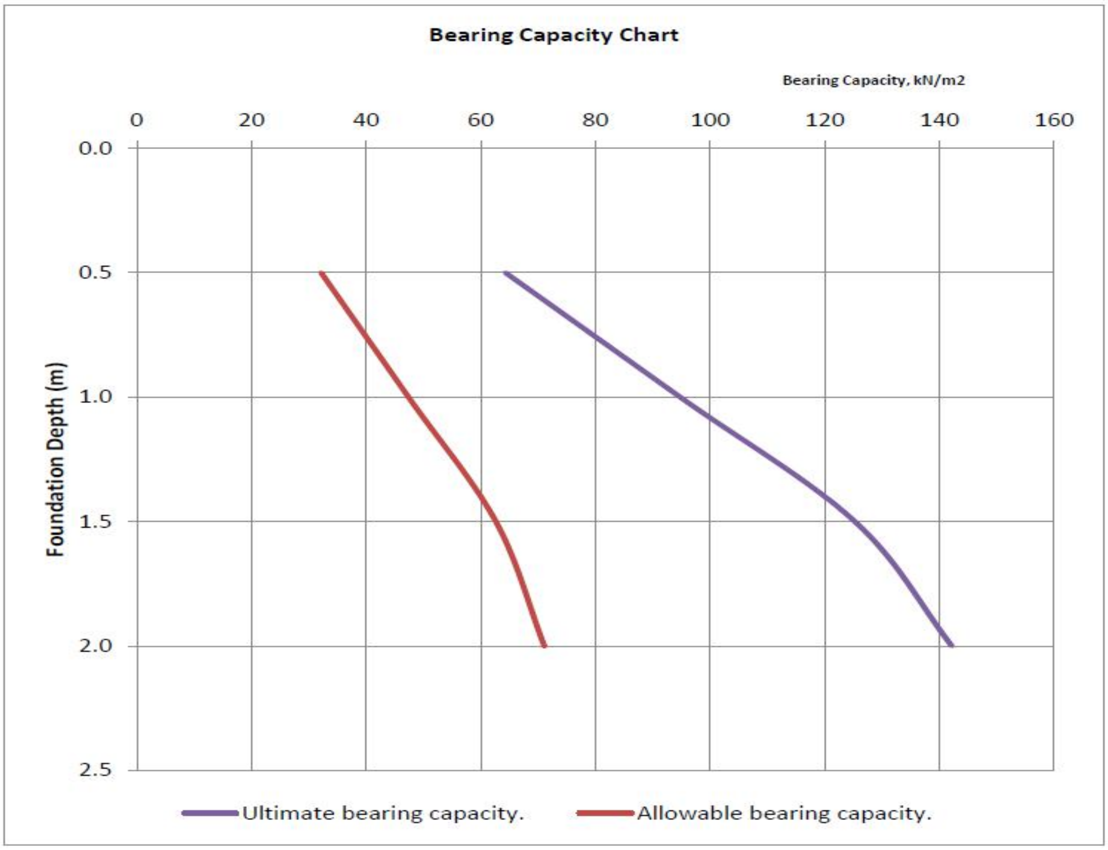

Figure 4: Shallow foundation depth against bearing capacity

From the shallow foundation analysis, square footing of 1.0m width is observed to have an allowable bearing capacity of 35kN/m^2 at a depth of 0.5m below the existing ground level. At a founding depth of 1.0m, the shallow square footing of the same width is seen to have an allowable bearing capacity 50kN/m^2. At a depth of 1.50m, the footing is seen to have an allowable bearing capacity value of 66kN/m^2, While at a founding depth of 2.0m it is observed to have an allowable bearing capacity of 78kN/m^2.

Settlement Analysis

Settlement analysis results of the investigation are presented in table 4 and graphically represented in figure 6. Total settlement from the anticipated imposed load from the proposed structure was obtained from the sum of both the immediate settlement and consolidation settlement. Quantitative values of total settlement was determined to range between 70 and 52mm at foundation depth of 0.5 and 2.0m respectively for the square footing of 1.0m, while for the 2.0m footing, it was evaluated to be 95 and 64mm respectively when founded between the same depth. Total settlement for footings of 3.0 and 5.0m widths were also analysed. Settlement of 108 and 71mm was recorded for the 3.0m square footing at foundation depths of 0.5 and 2.0m, whereas for the 5.0m footing, it was 130 and 80mm respectively when founded between the same depth.

Table 4: Results of total settlement

Foundation depth (m)	Total settlement (mm)			
	B = 1.0 m	B = 2.0m	B =3.0m	B = 5m
0.50	70	95	108	130
1.00	69	91	105	123
1.50	68	90	103	119
2.00	52	64	71	80

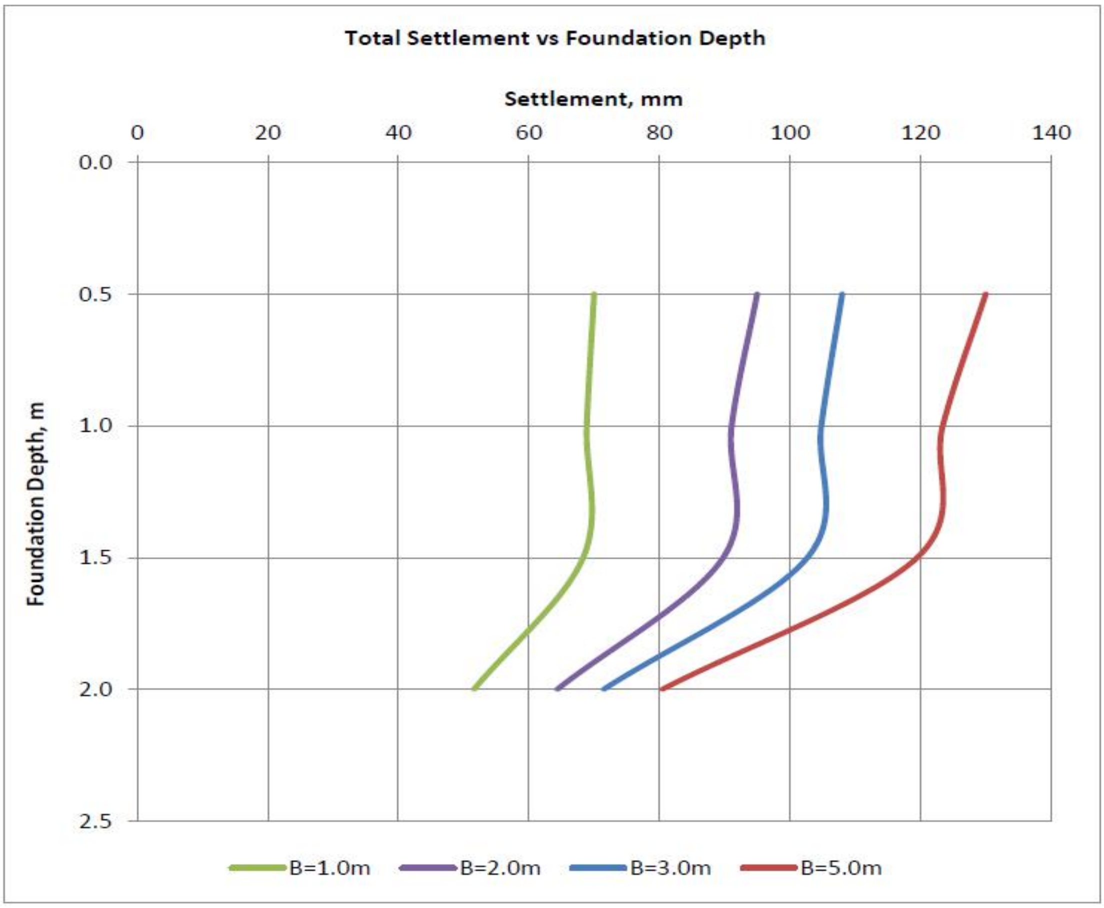

Figure 5: Foundation depth against total settlement

Bearing Capacity Results for Deep Foundation

Partial resistance factors were applied in calculating the limiting state of the pile for the deep foundations. The pile design for single pile is presented in tables 5 and 6.

Table 5: Partial resistance factors for soil parameters

S/No.	Soil parameters	Symbol	Partial factors
1	Angle of shearing resistance	γ_{φ}	1.25
2	Undrained shear strength	γ_{cu}	1.40

Table 6: Partial resistance factors for piles

S/No.	Resistance	Symbol	Driven piles	Partial factors
1	Base	γ_b	1.3	1.4
2	Shaft	γ_s	1.3	1.4

Pile Compressive Resistance

The summary for the pile compressive resistance for straight shaft concrete piles with diameters of 0.305m, 0.406m, 0.508m and 0.610m using the design parameters for the soil profile is presented in table 7

Table 7: Pile compressive resistance for soil profile

Foundation depth (m)	Diameter (m)			
	0.305	0.406	0.508	0.610
	Pille compressive Resistance (kN)			
5.0	20	30	40	50
10.0	170	230	300	380
15.0	310	430	560	700
20.0	450	630	820	1030
25.0	600	830	1080	1350
30.0	740	1030	1350	1690

Pile foundation analysis carried out for the soil profile encountered at the study area shows that pile compressive resistance of the 305mm diameter pile was between 20 and 740kN when founded between 5.0 and 30.0m depth, while that of the 406mm diameter pile gave a compressive resistance between 30kN and 1030kN when founded between the same depth. The 508mm diameter pile was observed to have a compressive resistance between 40kN and 1350kN while that of the 610mm diameter pile gave between 50kN and 1690kN when founded between 5 and 30.0m depth.

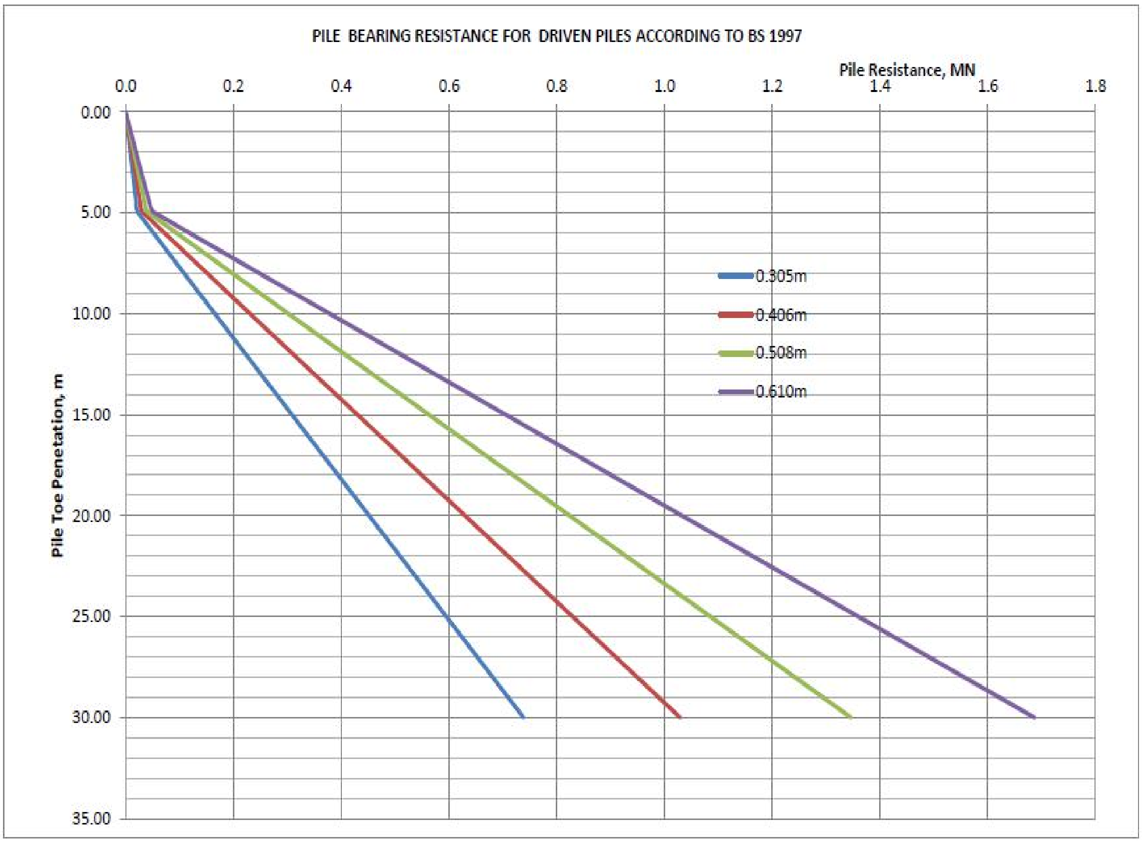

Figure 6: Pile toe penetration against pile bearing resistance against depth

Conclusion

The investigation was carried out with the aim of obtaining geotechnical parameters that will guide the choice of foundation type appropriate for the construction of multi-storey buildings in the study area. Field investigations and laboratory tests revealed that the site is underlain by two soil types. The soil formations were dominantly sandy clays from the existing ground level to an average depth of 5.0m and sands of variable texture from 5.0m to the final investigation depth of 30m.

Both shallow square footing and deep pile foundation analysis have been carried out in this investigation. It is recommended that while shallow foundation could be used for supporting structures within the study area, deep pile foundation should be considered for multi-storey buildings. Pile load tests should be carried out on installed piles to confirm pile working loads and stresses.

Groundwater was encountered during boring at an average depth of 0.5m below the existing ground level and thus should be expected to be a challenge during foundation works.

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