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Research Article

Comprehensive Characterization of Soils with Analytical and Numerical Simulation for Bearing Capacity and Settlement Requirements of the Footing

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Characterization and analysis of foundation material are basic concerns of geotechnical activities to have safety for the structure and users as well. Particularly, it is quite important for the areas of lagging experiences with a lack of equipment and accessibility to investigate the subsurface conditions sufficiently. This study was designed for comprehensive soil investigations through analytical and Plaxis 2D simulation by considering square footing in Bule Hora town, Southern Ethiopia. Considering the investigation depth up to 5.0 m, fourteen soil samples at 1.5 m and 3.0 m depths (two samples from seven pits) were collected, and physical and engineering properties were investigated. Grain and consistency results indicated that soils lying between low to high plastic silt regions. Undrained shear strength (C_u) ranges from 49.5-–64.30 and 52.40–103.10 kN/m^2 at 1.5 m and 3.0 m depth, respectively. An average allowable bearing capacity of 145.35 kN/m^2 with a settlement of 40.77 mm at 1.5 m depth and 191.41 kN/m^2 with a settlement of 47.84 mm at a depth of 3.0 m using the analytical method whereas 122.72 kN/m^2 was obtained with the settlement of 30.57 mm at a depth of 1.5 m and 155.11 kN/m^2 with 29.08 mm at depth of 3.0 m using Plaxis 2D analysis. The results of bearing capacity and settlement analyzed by the numerical method are lower than the analytical method, which confirms that comparatively, Plaxis 2D analysis gives a better output in selected square footing of shallow foundations. In conclusion, Plaxis was a preferable analysis tool for a shallow foundation, square footing, using inputs of the exhaustively investigated actual condition of soils specifically in Bule Hora town.

1. Introduction

Foundation analysis having investigated beneath material is a usual activity for connected professions. It is highly impossible to analyze and design foundations without exhaustive soil and soil material investigation for the given construction project [1–3]. This is due to the complex nature of the soil that varies depending upon its environmental conditions from place to place horizontally and vertically within a short distance [4, 5].

The design of infrastructures primarily depends on foundation material behavior that provides safety and long life to the constructions. Unless a detailed investigation is made on the properties of this material under consideration, unexpected failure of the foundation as well as the whole structure is anticipated, which are indispensable and their remedial measures will be expensive and intermittently difficult [6, 7]. In fact, it is time-consuming and expensive to conduct appropriate soil investigations. But it is a necessary condition to explore soils for associated geotechnical properties and has massive significance in designing and providing safety for building structures for any construction work and the users as well [8–11].

Infrastructure expansions such as public, commercial, and residential buildings have been flourishing in recent years in Bule Hora town. But most of the town is covered with fine-grained soil materials. Such soils need special attention to investigate rigorously due to their susceptibility to environmental conditions than courser soil classes [12, 13]. Structural design of buildings and constructions on such soils require genuine foundation selection in order to minimize related issues. But most of the construction projects in the study area are constructed without inspecting the subsoil due to the lack of apparatuses, equipment, and experienced manpower. The methods and way of analysis of the foundations are technically not proper that are not nicely construed and associated with actual ground conditions existing. Thus, there were sudden failures of foundation soil resulting in structural failures that also occur in the post-construction period [14–16].

Thus, the current study aims to comprehensively investigate the physical and engineering properties to identify soils' behavior and to analyze the bearing capacity and settlement of the shallow foundation through analytical and finite element method (FEM) simulation, Plaxis 2D of Bule Hora town, Ethiopia study area. Hence, soil investigations, particularly, for engineering properties such as shear strength, consolidation, and permeability properties were conducted exhaustively under natural conditions preserved fashion by standard procedures [17]. And also, field density and in-situ moisture content tests were conducted in the field. Bearing capacity and settlement analysis and Plaxis 2D simulation were maintained by considering the foundation construction practices of the study town. Mohr-Coulomb shear failure criteria was adopted considering the square geometry of shallow footing for software simulation [18].

This research is quite significant for the lagging areas due to lack of accessibility, lack of soil investigation equipment with current technology, and shortage of experienced manpower in the field of study. No plenty of research has been studied through Plaxis simulation, rather policymakers and engineers involved in developing the construction work more often rely on conventional analytical methods or constructions without any cost of investigations. Hence, it can give direction to the practice of numerical formulations of foundations in the study town and Ethiopian community in order to have more promising results than traditional analysis and to come to a conclusion about the preferable and best approximation method that can be adopted in the study area.

2. Materials and Methodology

2.1. Description of Study Area. Bule Hora town is located at Addis Ababa, Moyale highway, in the West Guji Zone of the Oromia Regional state which is 465 km away from Addis Ababa towards Southern Ethiopia with an average latitude and longitude of 5.583°N and 38.250°E, respectively, (Figure 1).

2.2. Field and Laboratory Investigations

2.2.1. Sample Collection. Prior to sampling, reconnaissance surveys through visual site investigations and information from residents and construction firms were collected from the town. Seven sampling pit areas were selected according to the soil variation and profile observed in different locations of the town, which are supposed to represent all the types of soils found in the study area. The pit selection was confirmed through preliminary site investigation that the study was planned to address the current and future expansion of the town as well. For the selected test pits, the actual depth of investigation was made up to 5.0 m, which is important to define the soil boundary for FEM simulations as well. But, both disturbed and undisturbed samples were collected at the depth of 1.5 m and 3.0 m from each test pit and taken to the laboratory for testing.

2.2.2. Natural Moisture Content, In-Situ Unit Weight, and Density. These tests were partially conducted in the field and the laboratory in this study. Hence, moisture specimens were taken immediately after excavation got to the defined depth of investigation and weighed in the field whereas oven moisture dry was maintained in the laboratory. Similarly, undisturbed soil samples were collected in the field by a core cutter and weighed whereas moisture determination was conducted in the laboratory. Soil samples collected were carefully packed and transported in order to reduce the loss of moisture and the opportunity for sample disturbance. The mass of both moisture and density specimens with a core cutter was measured in the field just after sample collection from each pit. The soils from the core cutter were extruded carefully without any loss, weighted, and immediately taken to the oven. After 16 to 24 hours, the soil was dried at the temperature of 105°C and its weight was recorded [19]. Natural moisture content was determined by the conventional oven-drying method. Bulk unit weight and density were determined by recorded moist and dry weight with that of moisture content [20, 21].

2.2.3. Soil Classification Tests. In this research, soil grain and consistency tests were conducted to classify the soils of the study area. Sieve analysis for soil grain determination was conducted (ASTM D422-98) for soil sizes retaining at a maximum of 0.075 mm and the hydrometer method for finer than 0.07 were used. For the hydrometer test, soil samples were taken and soaked with water for 24 hrs to disperse particles. A slurry of soaked water was washed through a 0.075 mm sieve. Atterberg's Limit tests such as liquid and plastic limits were determined using the Casagrande method (ASTM D 4318-00). Lastly, soils were identified for defined depths interpreted to indicate the engineering characteristics of the Bule Hora town.

2.2.4. Unconfined Compression Test. A radially unconfined compression investigation was conducted on cylindrical specimen samples preserved in natural situations of each pit with a conventional dimension to identify the undrained shear strength of soils. In this research, due to the presence of the granular materials at the proposed soil sampling depth and its possibility of sample disturbance, remoulded samples were used for this test instead of undisturbed samples. Remoulded samples from oven-dried soil at 105°C

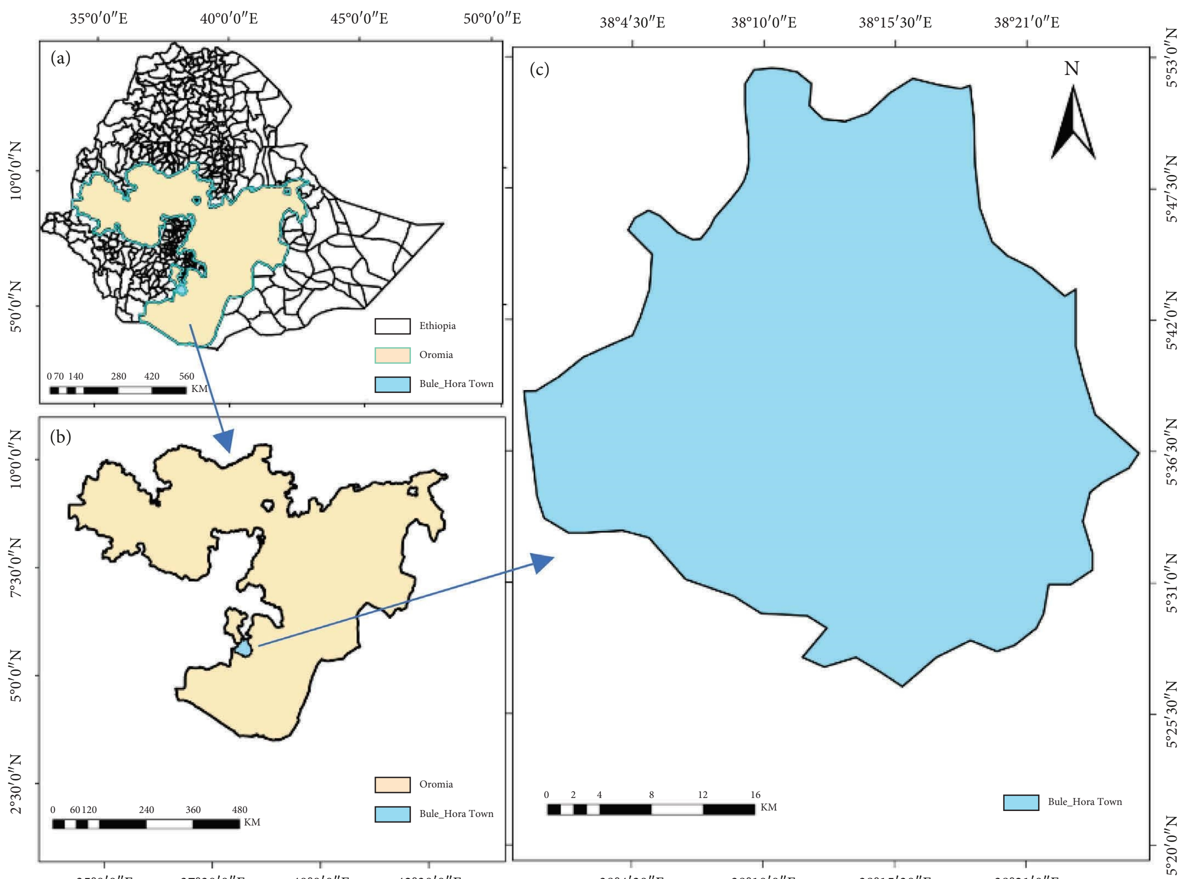


Figure 1: Study area location map of (a) Ethiopia, (b) Oromia region, and (c) Bule Hora town.

temperature and finer than 2.36mm have been prepared by keeping density and moisture content in order to maintain the natural condition of soils.. Soil specimen for every test pit was placed on the unconfined compressive machine and a 300 kN load was applied axially to produce axial strain at a rate of approximately 1%/min (0.76 mm/min) of the specimen height [22–25]. Deformation and axial load readings had been recorded till the soil sample failed from which axial pressure and strain had been calculated and plotted to decide the unconfined compressive strength and undrained cohesion. The results obtained from this test were used for analytical and finite element method formulations of the study.

2.2.5. One-Dimensional Consolidation. The soil specimens were taken from each pit by the consolidation ring that maintains the natural soil conditions. The consolidation cell was then mounted on a loading frame with a vertical deflection dial gauge appropriately in step and secured position to give a proper dial reading under the application of the load [26]. With an increased load, compression dial versus time readings were noted at the time interval until consolidation under the load increment is completed. On successive days, the intensity of the load was increased to 50, 100, 200, 400, 800, and 1600 kPa and for each load intensity compression dial versus time readings were noted in a routine consolidation test. Each load was allowed to stand until compression practically ceased (for 24 hours). The dial gauge readings were taken at elapsed times of 0, 0.13, 0.25, 0.5, 1, 2, 4, 8, 15, 30, 60, 120, 240, 480, 720, and 1440 minutes from the time the new increment of the load was placed on the sample. The unloading is carried out following the sequence of loading at the end of 24 hours. The void ratio of the soil sample was calculated from the initial and final reading of the dial gauge at the end of 24 hrs. Using the square root time fitting method, which gives good results for determining the coefficient of consolidation (C_v) and the coefficients of volume compressibility (m_v) from the plot of void ratio (e) against effective pressure [27]. This test was adopted to determine the elastic properties of soils by incorporated fashion with void ratio and effective stress [28, 29].

2.3. Analytical and Finite Element Analysis. The analysis of both analytical and finite element methods was conducted in order to have a comparative evaluation between these methods. In this research work, the actual soil properties found by laboratory tests were used in the analysis by considering the bearing capacity and settlement as measuring parameters to ascertain shallow foundation so-called square footing.

2.3.1. Analysis of Bearing Capacity and Settlement; Analytical Method. (1) Analysis of Bearing Capacity.

The calculations of the ultimate bearing capacity (q_{ult}) of the soil were accomplished using the equation proposed to calculate the bearing capacity of shallow foundation depending on the actual rigorously determined input soil parameters such as soil indices and shear strength [30]. Soils in the Bule Hora town are fine-grained soil classes on which an unconfined compressive test was conducted for the identification of undrained shear strength, in which third term is insignificant and left from the bearing capacity equation. Accordingly, the bearing capacity of square footing was analyzed using the following equation:

$$q_{ult} = 5.7 * C_u\left(1 + 0.3 * \frac{B}{L}\right) + \gamma_b D_f, \tag{1}$$

where C_u represents undrained shear strength of soil in kN/m^2, γ_b represents unit weight of soil, kN/m^3, B represents footing breadth (in m), and L represents length (in m) at depth D_f of 1.5 m and 3.0 m.

Equation (1) is established from the general bearing capacity formula of shallow foundations for the analytical formulation of bearing capacity by conducting a shear strength test of fine-grained soils in the study area [31, 32]. Analysis using this equation was achieved by considering shallow foundations such as strip, rectangular, square, and circular footings. But in this research, the focus was given to square footing for its most practical footing that the buildings were constructed in the study area and for comparative evaluation with finite element simulation. Hence, through intensive evaluation and building construction practices, this equation is the best analytical formula and is compatible with the soils found in the Bule Hora town.

Resulting in which the allowable bearing capacity (q_{all}) of the soil is determined as the ultimate bearing capacity (q_{ult}) to the factor of safety F_S (3 was being used).

(2) Settlement Analysis.

Total consolidation settlement (ρ_c) was calculated for foundation breadth (B), subjected to a net allowable bearing capacity. Based on the depth of the soil layer and soil affected by the foundation pressure under a square footing, a settlement was taken as the depth to the point where the induced vertical stress ($\Delta\sigma$) is equal to $0.55q_n$. The induced vertical stress ($\Delta\sigma$) at the center of the consolidating layer was used in calculating ρ_c (equation (2)) to calculate the consolidation settlement [33, 34].

$$\begin{aligned}\rho_c &= \mu_g * p_{oed},\\ &= m_v * 0.55q_n * 1.5B,\end{aligned} \tag{2}$$

where μ_g represents coefficient which depends on the type of clay, p_{oed} represents settlement calculated from oedometer test, m_v represents coefficient of volume compressibility, and q_n represents net foundation pressure.

2.3.2. Analysis of Bearing Capacity and Settlement Using Plaxis 2D Software; Finite Element Method. To carry out elastoplastic analysis, Plaxis 2D analysis of Mohr–coulomb's shear failure criteria was used for the simulation of the model [35]. During this research, square footing geometry was considered for the bearing capacity and settlement analysis using a nonlinear finite element Plaxis 2D modeling [36]. The boundary of numerical simulations was defined by considering stress influence on the proposed ground. A sufficient soil boundary, which was optimally far away from stress reflection, was adopted as presented in Figure 2. Hence, 8.0 m thickness and 10 m width soil model was provided to analyze the bearing capacity and settlement of the square footing under consideration [37, 38]. During Plaxis 2D analysis, automatically generated finer mesh was maintained using a 15-node element than a 6-node element having a larger mesh. Thus, the soil parameters used in this FEM model simulation are Young's modulus, Poisson's ratio, soil shear parameters, and dilatancy angle for the defined depth of study [39, 40].

3. Results and Discussion

Results of the investigation on the foundation material and analysis conducted for bearing capacity and settlement were exhaustively construed and presented through conserving the construction practice in the Bule Hora town. Accordingly, study area representing test pit locations were presented and tabulated with local coordinates and global positioning in Table 1, which is helpful for the community to estimate their nearby construction project design by aligning results obtained in these locations. Through comprehensive characterization of soils, an effort was provided to compare analytical and Finite element (Plaxis 2D) methods to evaluate square footing for bearing capacity and settlement.

3.1. Bulk Unit Weight, Density, and Moisture Content. The in-situ densities and moisture contents determined from the laboratory were presented in Table 2. Relatively, results ensured that the unit weight and density of the soil increase with depth, which indicates resting footings near to 1.5 m depth and below has the chance to obtain better ground for footing construction in the study area. But, pit 1 has some differences when compared to the other test pits due to the presence of ample sand within 3.0 m depth.

All fourteen soil samples possessed specific gravity values ranging from 2.65 to 2.94. This indicates that the soils are inorganic fine-grained as per reference of the standard specific gravity assortment.

3.2. Classification of the Soil. Soil classification is conducted by using the Unified Soil Classification System having grain size and Atterberg's limit results. Except for pit-1, the grain size distribution results obtained from the laboratory test illustrate less than 10% of sand content with less quantity of gravel materials. Pit-1 has sand content greater than 10% which consistently increases with depth below the ground level (Figures 3(a) and 3(b)).

The Atterberg limits of fine-grained soil vary due to the presence of water content in the soil and results of this study area were mobilized accordingly [41]. The liquid limit varies from 48.98 to 55.56%, which indicates medium to high

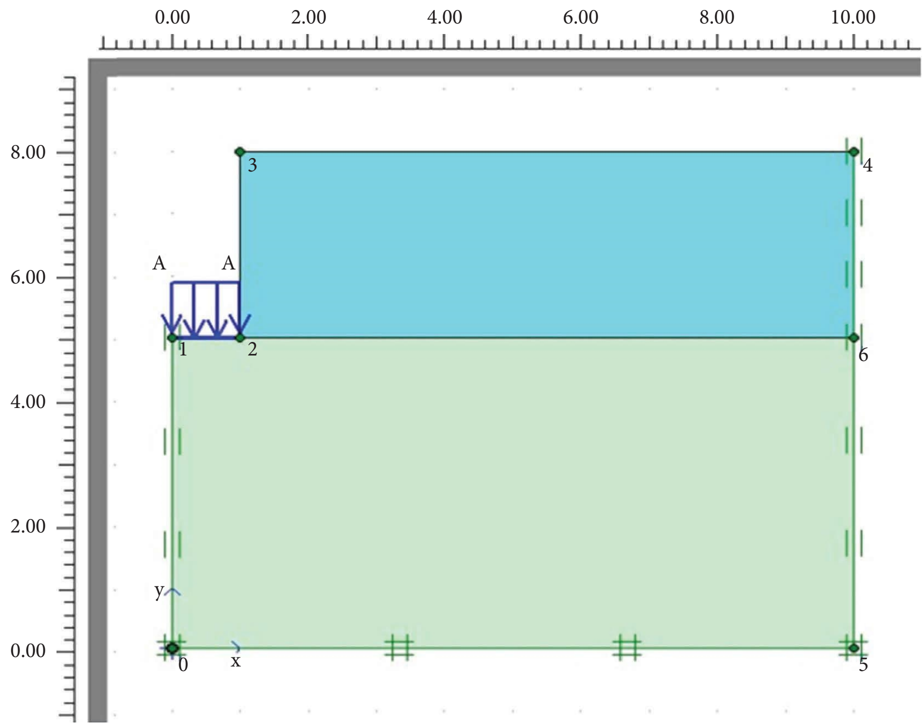


Figure 2: Material, model, boundary conditions, and loading for Plaxis 2D simulation.

Table 1: The location of the boreholes of Bule Hora town.

Pit no	Local coordinate	Northing (m)	Easting (m)
1	Around Sinaye school	621809	416461
2	Bule Hora preparatory school	624463	415972
3	Bule Hora University	622491	413556
4	Bule Hora hospital	621686	415752
5	Bule Hora teacher's college	620788	416085
6	Around electric power station	623179	416162
7	Abayi junior school	625042	416186

Table 2: Specific gravity, moisture content, unit weight, and density of soil.

Pit no	Depth (m)	Specific gravity	Wet mass (g)	Dry Mass (g)	Moisture content (w%)	Bulk density (kg/m^3)	Bulk unit weight (kN/m^3)	Dry density (kg/m^3)	Dry unit weight (kN/m^3)
1	1.5	2.66	1625	1290	25.97	1.66	16.25	1.31	12.9
	3.0	2.65	1882	1535	22.61	1.92	18.82	1.56	15.35
2	1.5	2.84	1562	1167	33.85	1.59	15.62	1.19	11.67
	3.0	2.83	1602	1186	35.08	1.63	16.02	1.21	11.86
3	1.5	2.87	1704	1269	34.28	1.74	17.04	1.29	12.69
	3.0	2.87	1738	1290	34.73	1.77	17.38	1.31	12.9
4	1.5	2.84	1508	1065	41.6	1.54	15.08	1.09	10.65
	3.0	2.84	1580	1101	43.51	1.61	15.8	1.12	11.01
5	1.5	2.82	1590	1120	41.96	1.62	15.9	1.14	11.2
	3.0	2.85	1753	1250	40.24	1.79	17.53	1.27	12.5
6	1.5	2.94	1560	1141	36.72	1.59	15.6	1.16	11.41
	3.0	2.93	1664	1184	40.54	1.7	16.64	1.21	11.84
7	1.5	2.84	1581	1152	37.24	1.61	15.81	1.17	11.52
	3.0	2.84	1628	1168	39.38	1.66	16.28	1.19	11.68

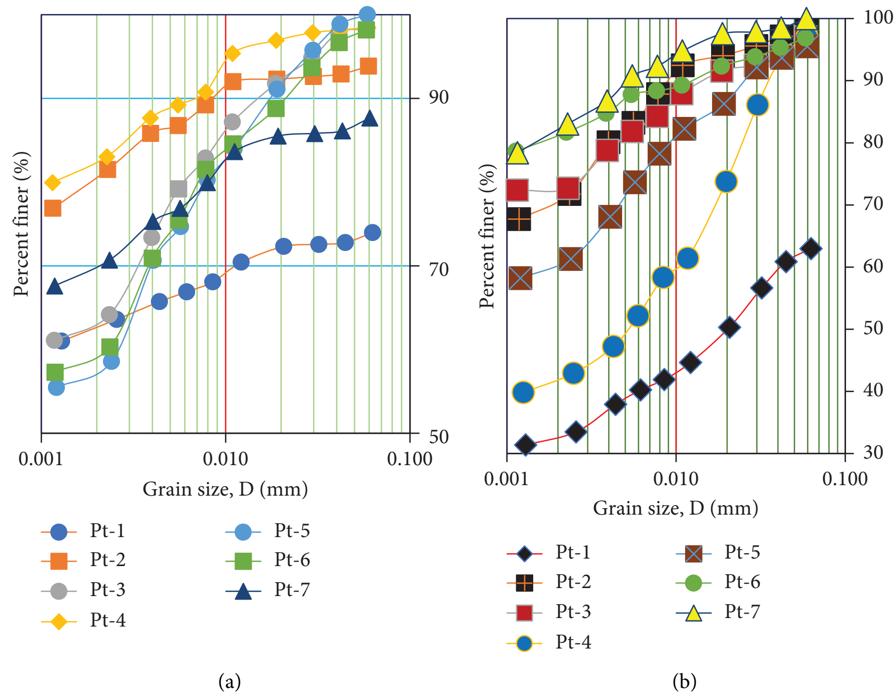


Figure 3: Grain size distribution (a) at 1.5 m and (b) at 3.0 m depth.

plasticity whereas the plasticity index value varies from 10.82 to 22.21% depicting medium to high plasticity as indicated in Table 3. A high value of the plasticity index is an indication of the presence of a high percentage of clay fraction in the soils.

Consistency limit test results revealed that the study area was almost covered with soils of high plastic inorganic silt (MH) in nature with plenty of clay fraction, except the soil sample of pit-5 at 1.5 m depth [42]. Figure 4 indicates the location of the soils on the plasticity chart.

3.3. Unconfined Compressive Strength. The unconfined compressive strength values (Figure 5) were obtained from the shear strength test on considered test pits of the study area. Accordingly, the results of unconfined compressive strength range from 99 to 206.20 kN/m^2, which indicates a firm-to-stiff consistency [43]. The top layer at a depth of 1.5 m of the sample soil has a moderate undrained cohesion (C_u) with 49.50–64.30 kN/m^2. Underneath this layer, there lies a stiff clay with C_u of 52.40–103.10 kN/m^2 at depth of 3.0 m. The study area indicated that the average result of 63.14 kN/m^2 depicts a stiff consistency.

3.4. One Dimensional Consolidation. The important parameters used to evaluate the settlement rate of soil compression index C_c, coefficient of volume compressibility m_v, and the coefficient of consolidation C_v at 1.5 m and 3.0 m depth (Table 4). The C_c result obtained from the test indicates the value ranging from 0.04 to 0.16 at a depth of 1.5 m and 0.06 to 0.25 at 3.0 m [44].

Results secured showed that cohesive soils with compression index (C_c) in the range of 0.15 to 0.3 are considered to have high compressibility and 0.075 to 0.15 and are considered to have medium compressibility. The results of C_v obtained from fourteen soil samples (seven test pits at a depth of 1.5 m and the remaining at 3.0 m) of this study area fall in the range of medium to a high degree of compressibility. The values obtained reveal that the compression index of the soil increases with applied pressure.

The m_v of the soils is defined as changes in volume per increase in the effective stress, with an increase in pressure (P) from P_0 to P_1, the void ratio decreases from e_0 to e_1. These values of the study area vary in average coefficient of volume compressibility (m_v) from 7.2×10^{-4} m^2/kN to 0.56×10^{-4} m^2/kN and from 5.6×10^{-4} m^2/kN to 0.67×10^{-4} m^2/kN at a depth of 1.5 m and 3.0 m, respectively, which reveals soils under study were significantly compressible.

3.5. Bearing Capacity by Analytical Method. As per the results attained from the field and laboratory, the bearing capacity of the shallow foundation was determined and presented in terms of the allowable bearing pressures [45]. Accordingly, square footing assorted and safety of factor of 3 was considered, and it was obtained that an allowable bearing capacity of 130.39 to 167.34 kN/m2 at a depth of 1.5 m and 151.70 to 272.03 kN/m2 at depth of 3.0 m. An average value of 168.38 kN/m^2 bearing capacity was achieved with a moderate increase at lower depths of the study area.

3.6. Settlement by Analytical Method. The result of the settlement was computed from the allowable bearing capacity and coefficient of volume compressibility (m_v) by interconnecting the shear strength and consolidation test at the specified allowable bearing pressure. The results of

Table 3: Test results of Atterberg limits.

Pit no	Liquid limit (%)	Plastic limit (%)	Plastic index (%)	Liquidity index (LI)	Liquidity index (CI)	Classification (unified)	Activity
1	53.91	40.06	13.85	−1.02	2.02	MH	0.22
	50.44	37.98	12.46	−1.23	2.23	MH	0.38
2	52.24	41.43	10.82	−0.70	1.70	MH	0.13
	51.08	39.61	11.47	−0.40	1.40	MH	0.16
3	50.35	33.56	16.79	0.04	0.96	MH	0.26
	51.90	36.93	14.97	0.05	0.95	MH	0.21
4	53.53	38.68	14.86	0.20	0.80	MH	0.18
	51.38	35.99	15.39	0.49	0.51	MH	0.36
5	48.98	36.93	12.05	0.42	0.58	ML	0.21
	50.75	37.10	13.65	0.23	0.77	MH	0.22
6	54.26	42.26	12.00	−0.06	1.06	MH	0.20
	52.15	34.52	17.63	0.34	0.66	MH	0.22
7	55.56	37.98	17.58	−0.04	1.04	MH	0.25
	52.81	30.60	22.21	0.40	0.60	MH	0.27

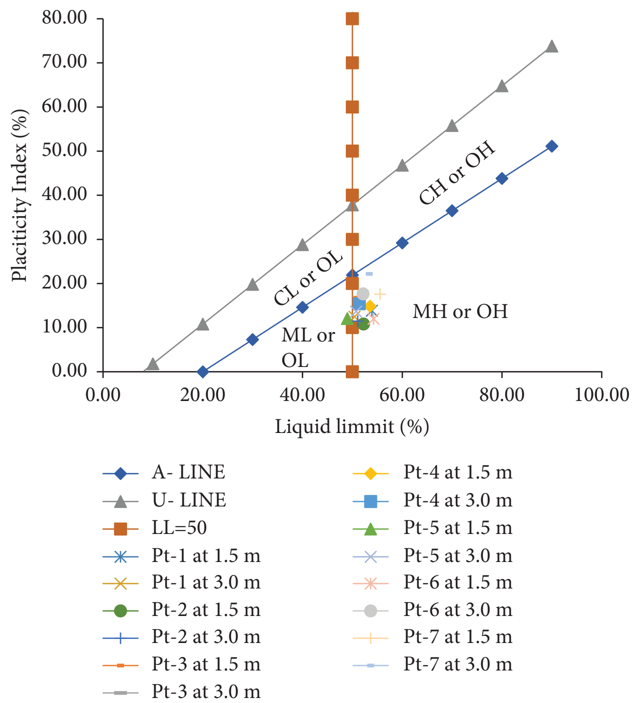


FIGURE 4: Plasticity chart for the soil samples.

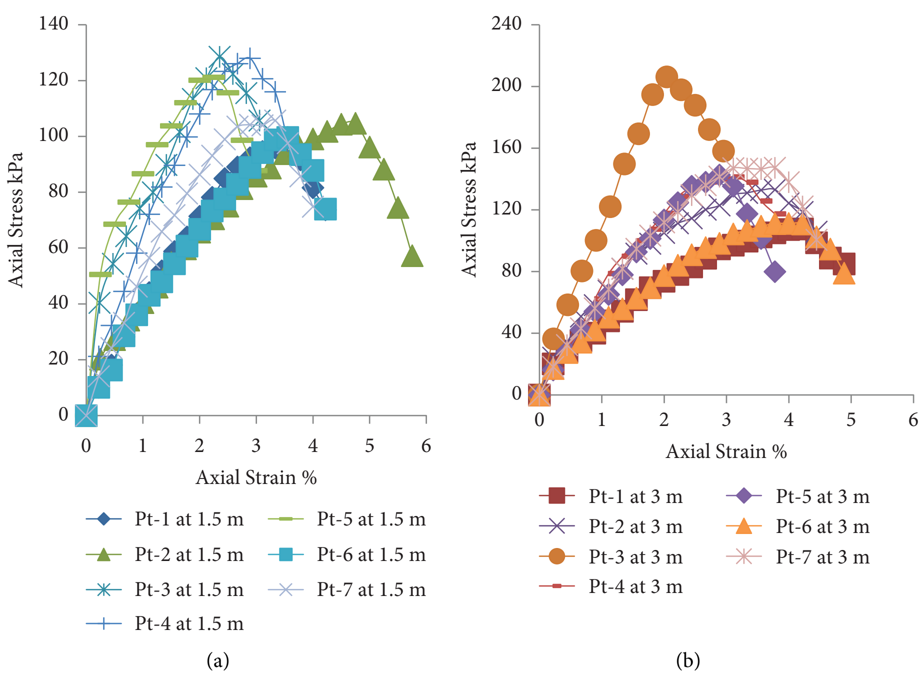


FIGURE 5: Axial stress-strain graph (a) at 1.5 m and (b) at 3.0 m depth.

consolidation settlement at considered depths of breadth to length ratio at the allowable bearing pressure are presented in Table 5.

The settlement result varies between 36.60 to 46.90 mm with an average of 39.27 mm at depth of 1.5 m whereas 40 to 53 mm with an average of 47.52 mm at depth of 3.0 m as indicated in Table 6. A slight increase in consolidation settlement at depth 3.0 m is associated with fine fraction and overburden pressure difference along with depth below the surface in the study area. The computed values as presented at both depths are significantly high, but less than the permissible settlements for isolated foundations on fine-

Table 4: Consolidation test results of compression index, coefficient of consolidation, coefficient of volume compressibility, and permeability.

Applied pressure (P) (kN/m^2)	Average compression index, C_c	Average coefficient of consolidation, C_v (10^{-7} m^2/sec)	Average coefficient of volume compressibility, m_v (10^{-4} m^2/kN)	Average permeability K (10^{-9} m/sec)
		At 1.5 m depth		
0–50	0.04	3.42	7.20	2.40
50–100	0.12	2.74	4.73	1.30
100–200	0.14	3.36	3.31	1.10
200–400	0.14	3.6	2.31	0.82
400–800	0.16	3.54	1.61	0.56
800–1600	0.16	3.24	0.56	0.19
		At 3.0 m depth		
0–50	0.06	3.76	5.60	2.20
50–100	0.16	4.00	5.40	2.10
100–200	0.18	3.24	3.20	1.00
200–400	0.21	3.32	2.10	0.70
400–800	0.22	2.57	1.10	0.30
800–1600	0.25	2.68	0.67	0.20

Table 5: Allowable bearing capacities and settlement for shallow foundations.

Pit no	Depth (m)	Unit weight (kN/m^3)	Angle of friction (φ°)	Undrained cohesion, c_u(kN/m^2)	Breadth/ length ratio	Ultimate bearing capacity, q_{ult}(kN/m^2)	Allowable bearing capacity, q_{all}, (kN/m^2)	Settlement (mm)
1	1.5	16.2	0	49.50	1	391.16	130.39	36.60
	3.0	18.8	0	53.80	1	455.10	151.70	40.00
2	1.5	15.6	0	52.40	1	411.71	137.24	38.50
	3.0	16.0	0	66.50	1	540.81	180.27	47.60
3	1.5	17.0	0	64.30	1	502.02	167.34	46.90
	3.0	17.4	0	103.10	1	816.10	272.03	53.00
4	1.5	15.1	0	60.00	1	467.21	155.74	43.70
	3.0	15.8	0	70.60	1	570.53	190.18	50.20
5	1.5	15.9	0	60.60	1	472.89	157.63	44.20
	3.0	17.5	0	71.30	1	580.91	193.64	51.10
6	1.5	15.6	0	49.80	1	392.41	130.80	36.70
	3.0	16.6	0	55.60	1	461.90	153.97	40.60
7	1.5	15.8	0	52.80	1	414.96	138.32	38.80
	3.0	16.3	0	73.60	1	594.20	198.07	52.30

Table 6: Average allowable bearing capacity and settlement result.

Depth (m)	B/L	q_{all}, (kN/m^2)	m_v (m^2/MN)	Settlement, ρ_v (mm)
1.5	1	140	0.33	39.27
3.0	1	180	0.32	47.52

grained soil of 65 mm. Hence, it was revealed the foundations can sustain the suggested allowable bearing pressure at a depth between 1.5 to 3.0 m.

3.7. Bearing Capacity and Settlement Result from Plaxis 2D. Results accomplished by FEM, Plaxis simulation for the considered square footing of concrete properties of weight 25 kN/m3 with normal stiffness (EA) of 5.8 ∗ 106 kN/m and flexural stiffness (EI) of 8500 kNm2/m. Stiffness values are momentous to automatically analyze an equivalent thickness by Plaxis 2D. In addition to the shear strength parameters of the foundation soil, elastic properties such as Young's modulus (E_u) and Poisson's ratio (ν_u) were applied. Soils in this study area performed almost similar elastic nature, and consequently, results of bearing capacity and settlement were also not considerably influenced within the suggested depth of investigation, and hence, average values of E_u and ν_u were adopted (Table 7). The loading stage and calculations for both bearing capacity and foundation settlement analysis were executed at depths of 1.5 m and 3.0 m. Results of settlement under applied incremental foundation pressure of 50 kN/m^2 up to the soil structure failure was achieved by performing staged construction by increasing load with each step increment until failure and extracting settlement contour at the founding level.

Bearing capacity and settlement of square footing analysis results obtained from Plaxis 2D were summarized in Table 8. The ultimate bearing capacity ranges between 326.03 to 414.00 kN/m^2 and 370.76 to 594.43 kN/m^2 at depths of 1.5 m and 3.0 m, respectively. The allowable bearing capacity varies from 108.68 to 138.00 kN/m^2 and 123.59 to 198.14 kN/m^2 at depths of 1.50 m and 3.0 m, respectively, (Figures 6 and 7).

An average allowable bearing capacity by the Finite Element Method (Plaxis 2D) varies with depth from 122.72 to 155.11 kN/m^2 and settlement from 30.57 to 29.08 mm at 1.5 m and 3.0 m depth respectively. The settlement estimated at the ultimate bearing capacity of soil varies between 26.94 to 40.41 mm from both depths. The maximum settlement of 40.41 mm was recorded at the maximum ultimate bearing capacity of 594.43 kN/m^2 from test pit-3 at 3.0 m. The computed maximum settlement at maximum ultimate bearing capacity by Plaxis is less than the permissible settlement suggested for isolated foundations on fine-grained soils, high plastic silt class of soils in the study area.

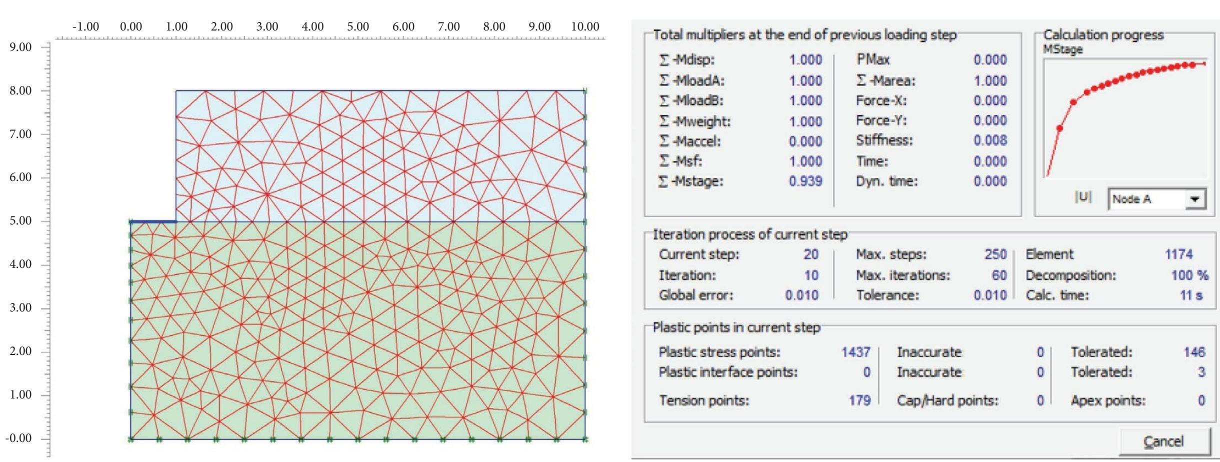
3.8. Comparison of Analytical and Plaxis 2D Results. From the results of analytical calculations and finite element simulations, the bearing capacity and settlement values determined by analytical are greater than that of finite element method results [46]. There is an average difference observed of about 16% and 19% variation in allowable bearing capacity results from Plaxis 2D at 1.5 m and 3.0 m depth, respectively. Both bearing capacity and settlement results are lower with best approximations and accuracy than that of analytical methods from all test pits at both depths (Figures 8–10). This is clear through the consideration of Plaxis Mohr-Coulomb's failure criteria and cluster-based finer mesh generation for detailed software analysis, rather than that of a more assumption of the analytical method. This indicates that the finite element method can be used to analyze in different loading conditions with their

Table 7: Parameters of soil used in Plaxis 2D modeling and analysis.

Pit no	Depth of sample (m)	Unit weight (γ_b) (kN/m^3)	Undrained cohesion (c_u) (kN/m^2)	Average young's modulus (E_u) (kN/m^2)	Average Poisson's ratio (ν_u)
1	1.5	16.2	49.5	15000	0.3
	3.0	18.8	53.8	15000	0.3
2	1.5	15.6	52.4	15000	0.3
	3.0	16.0	66.5	15000	0.3
3	1.5	17.0	64.3	15000	0.3
	3.0	17.4	103.1	15000	0.3
4	1.5	15.1	60.0	15000	0.3
	3.0	15.8	70.6	15000	0.3
5	1.5	15.9	60.6	15000	0.3
	3.0	17.5	71.3	15000	0.3
6	1.5	15.6	49.8	15000	0.3
	3.0	16.6	55.6	15000	0.3
7	1.5	15.8	52.8	15000	0.3
	3.0	16.3	73.6	15000	0.3

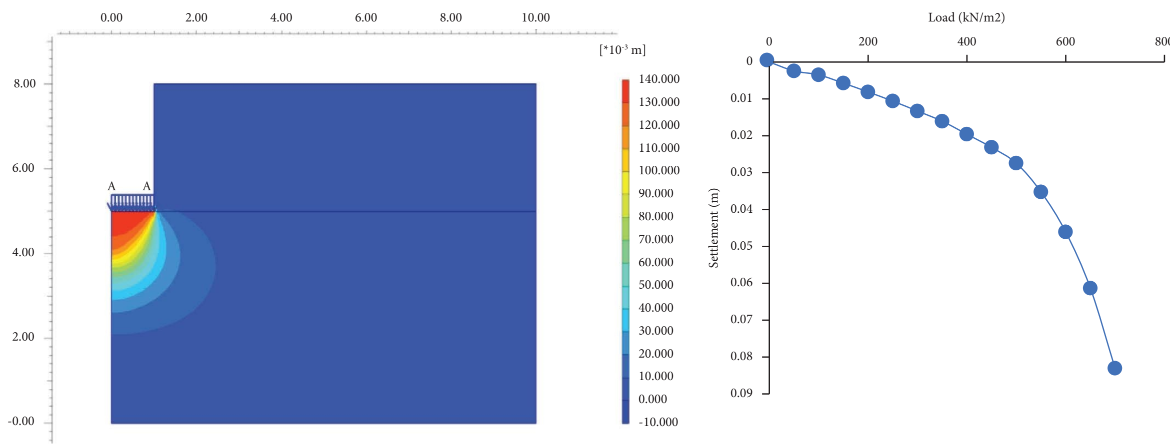
Table 8: Summary of bearing capacity and settlement result from Plaxis 2D.

Pit no	Ultimate bearing capacity, q_{ult} (kN/m^2)	Allowable bearing capacity, q_{all} (kN/m^2)	Settlement (mm)
	At 1.5 m depth		
1	388.13	129.38	31.25
2	326.03	108.68	27.55
3	414.00	138.00	36.15
4	372.60	124.20	31.95
5	414.00	138.00	32.00
6	331.20	110.40	27.55
7	331.20	110.40	27.55
	At 3.0 m depth		
1	463.45	154.48	26.94
2	408.04	136.01	28.29
3	594.43	198.14	40.41
4	503.75	167.92	29.63
5	453.38	151.13	24.25
6	370.76	123.59	21.69
7	463.45	154.48	32.33



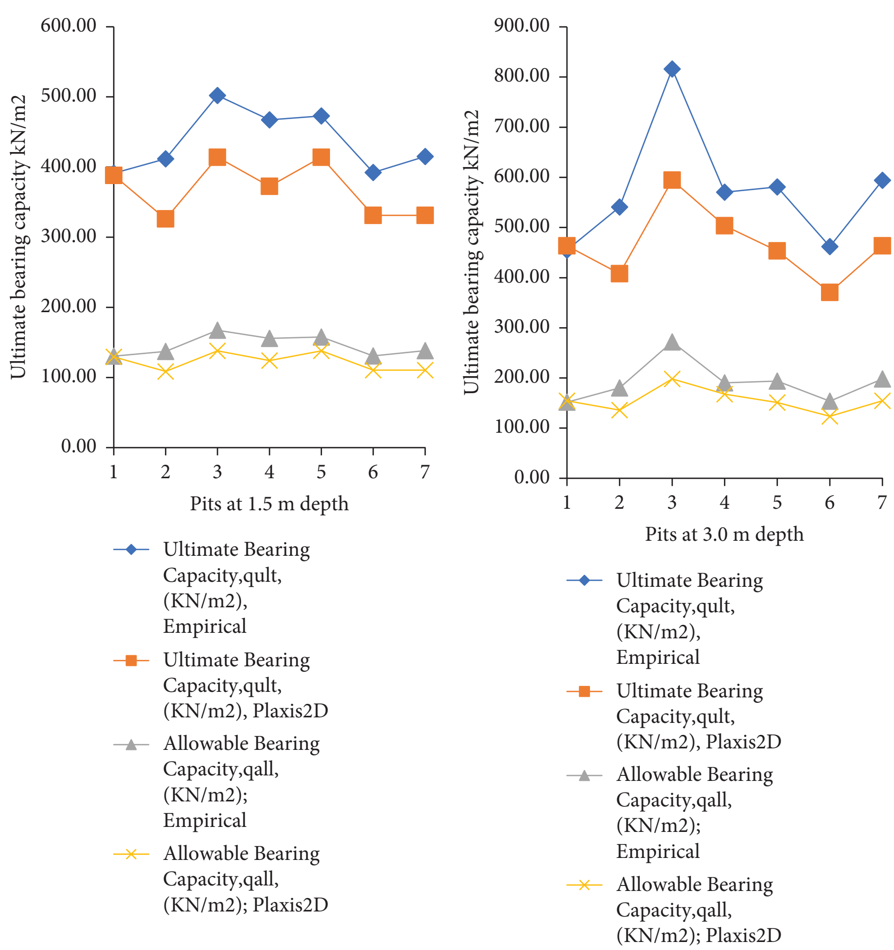
(a) (b)

Figure 6: Plaxis 2D analysis (a) mesh for simulation and (b) output calculations.



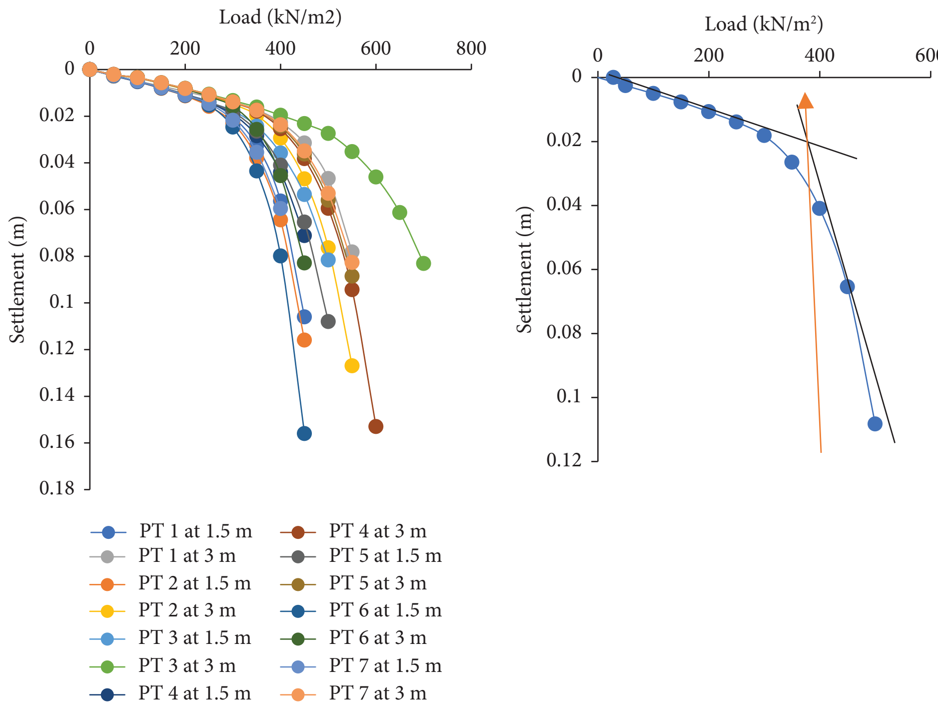
(a) (b)

Figure 7: Plaxis 2D (a) stress and vertical displacements and (b) pressure-settlement plot.



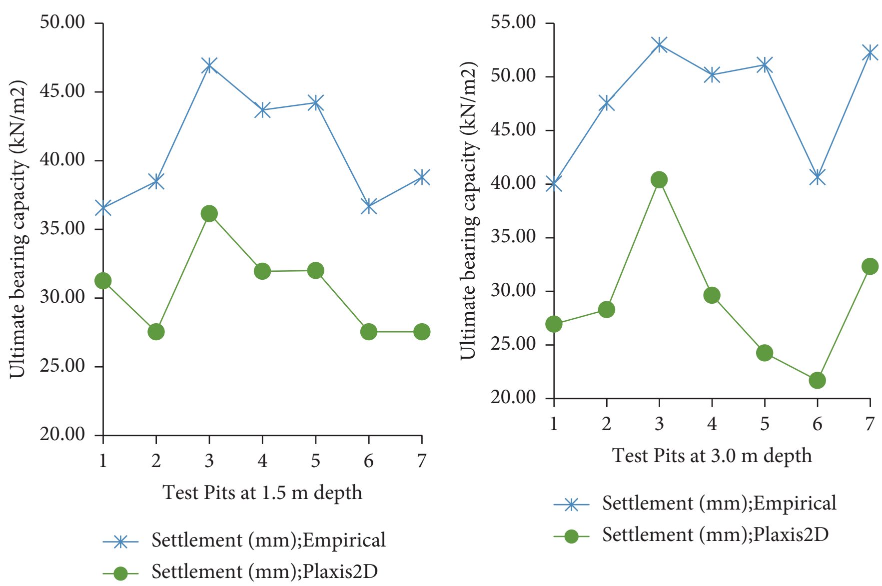
(a) (b)

Figure 8: Comparative graphs of empirical and Plaxis 2D results (a) at 1.5 m and (b) 3.0 m depth.



(a) (b)

Figure 9: (a) Pressure-settlement plot and (b) determination of pressure and settlement.



(a) (b)

Figure 10: Empirical and Plaxis 2D results (a) at 1.5 m and (b) at 3.0 m depth.

precedence, and stresses as well as deformation can be assessed in all directions.

4. Conclusions

Through rigorous and time-consuming soil sample collection and investigation of actual soil conditions of Bule Hora town, a comparative analysis between analytical and Plaxis 2D in ascertaining square footing was achieved. Most of the soil samples analyzed in the study town are silty in nature and predominantly highly plastic except the sample collected from pit-5 at 1.5 m depth which is having low plasticity. The top layer has moderate unconfined compressive strength with an undrained shear strength of 49.50 kN/m^2 to 64.30 kN/m^2 and 53.80 kN/m^2 to 103.10 kN/m^2 at a depth of 1.5 m and 3.0 m, respectively. The average allowable bearing capacity of 145.35 kN/m^2 and 191.41 kN/m^2 with a settlement of 40.77 mm and 47.84 mm at depth of 1.5 m and 3.0 m, respectively, was recorded using the analytical method; whereas, 122.72 kN/m^2 and 155.11 kN/m^2 with 30.57 mm and 29.08 mm at depth of 1.5 m and at 3.0 m, respectively, was recorded using finite element method (Plaxis 2D analysis). Samples collected at a maximum depth of 3 m are plenty to confirm the analysis and design parameters for a square footing for a shallow foundation. In both methods, the settlement analyzed is less than the recommended allowable settlement of 65 mm for the isolated shallow foundation in fine-grained soils in the study area. A comparison between analytical and numerical (Plaxis 2D) methods revealed that the Plaxis 2D simulation abides by the prevailing conditions of allowable bearing capacity and settlement of square footing. The results of bearing capacity and settlement analyzed by the numerical method are lower than the analytical method but relatively accurate with 15-node element small mesh automatically generated 2D simulation results. This is with an average variation observed of approximately 16% and 19% in allowable bearing capacity at 1.5 m and 3.0 m depth, respectively, in the Plaxis model analysis. It is hence advised to use the finite element method (Plaxis 2D) to analyze shallow foundation, square footing, instead of the conventional analytical method in order to get a better approximation in the study area.

Data Availability

All the data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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