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Bearing capacity estimation of driven piles based on CPT and validated by static load tests

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Abstract

There exists a multitude of CPT techniques that can be utilized to determine the ultimate load bearing capacity of square-shaped driven precast concrete piles. This study analyzes the suitability of Eslami and Fellenius (Unicone), Philipponnat, and LCPC methods for determining pile capacity (Qp). The present study involves the analysis of soil behaviour type using CPT methods to establish the soil profiling of various regions within Dhaka city. Five data sets were gathered from multiple locations within the Dhaka Metropolitan Development Plan (DMDP) area. These piles exhibit variations in both their size and length. The pile capacities (Qm) obtained from the Static Load Test were gathered from prior research studies. Two criteria were used to analyze the performance of these three CPT methods by making a comparison with the results found from the Static Load Tests: (1) the best-fit line for Qp versus Qm, (2) the arithmetic mean and standard deviation for the ratio Qp/Qm. The analysis results have shown that the performance of Eslami and Fellenius (Unicone) and LCPC are satisfactory and LCPC ranked the first position among them. Philipponnat ranked the last position but it has also shown acceptable performance. There has been no significant deviation observed in the capacities of the piles obtained from the CPT-based methods from those of the Static Load Test.

Keywords: Cone penetration test (CPT), static load test, driven piles, CPT soil classification.

1. Introduction

The establishment of a building's foundation is a crucial component of the overall construction procedure. Various categories of foundations exist, such as shallow and deep foundations. Deep foundations are employed in the field of construction for various purposes and are marked by a challenge in Geotechnical Engineering accompanied by different sources of uncertainty (Heidarie, G. S., 2020). Pile foundations are commonly constructed using materials such as concrete and steel, and are comprised of elongated, slender, column-like components. Pile foundations are utilized to transmit the compressive load through either tip bearing or end bearing. Besides, Pile foundations are employed in scenarios where the soil at shallow depths is inadequate to withstand excessive uplift or settlement, particularly for large structures. They are advantageous in scenarios where the soil is deemed unsuitable for construction, as is the case with inappropriate soil. The usage of driven pile as deep foundation is widespread in the building industry in Bangladesh. Driven piles offer several benefits such as their adaptability, wide range of sizes, prefabricated nature, ability to support deep foundations, resistance to groundwater, cost efficiency, expedited construction, assurance of quality, and noise mitigation. It is general practice to determine the bearing capacity of pile through Static Load Test. But this method is time-consuming and costly. Recently in situ capacity testing is becoming popular and it is using improved mechanics and sensing technologies which are cheaper compared to full-scale Static Load Test of pile (Song, C. R., et al., 2022).

Cone penetration test (CPT) is the quickest and simplest method to determine the ultimate capacity of driven pile (Obeta, I. N., et al., 2018). Since the mechanism of cone penetration is similar to driven pile, CPT-based methods are used to determine the driven pile capacity. For this estimation shaft friction and end bearing resistance are used. There are two Primary approaches for the accomplishment of the analysis of pile capacity (Kumala, S. P., and Kusuma, W. M., 2021). They are (1) Rational or Indirect Method and (2) Direct Method. In the indirect method, soil properties like friction angle, undrained shear strength, etc. are calculated using CPT data through different correlations. Then pile capacity is calculated from the static analysis method. Error can occur in both the correlations and the static analysis method resulting the indirect method as an impractical method.

On the contrary, in the direct CPT methods, the measured penetrometer reading is used to estimate pile capacity (Abu-Farsakh, M., et al., 2020). Semi-empirical and Empirical formulas are found in this method. Direct CPT method will be discussed in this study. The axial capacity is defined as Qt which is calculated from the summation of the shaft capacity (defined as Qs) and base capacity (defined as Qb):

$$Q_t = Q_b + Q_s = \Sigma f_{pi} A_{si} + q_b A_b \quad (1)$$

where f_{pi} = unit shaft resistance of the i^{th} soil layer through which the pile shaft is embedded; A_{si} = shaft area providing frictional resistance with the adjacent soil in the i^{th} layer against axial displacement; q_b is the unit end bearing resistance; A_b is the pile base area (Niazi, F., and Mayne, P., 2013).

There are different CPT-based methods developed over the years. Some of these methods need Soil Behavior Type (SBT) analysis to understand the zone type. These zones are used to characterize soil in layers (Lunne T., et al., 1997). Previous studies have established statistical ranking criteria for assessing the performance of CPT-based pile bearing capacity estimation methods. These ranking criteria and Static Load Test data are used in this study. Three CPT-based methods are selected for this study. They are Eslami and Fellenius (1997), LCPC (1982), and Philipponnat (1980). Their capacity prediction behaviour and ranking are done in this study.

2. CPT methods for the axial pile capacity prediction

A lot of study has been carried out on evaluating the accuracy of different CPT-based methods for different pile characteristics and soil behavior. Table 1 presents the past CPT-based pile capacity estimation methods. A recent study based on pile load test of 80 driven precast piles was done in Louisiana (Amirmojahedi, M., and Abu-Farsakh, M., 2019). They evaluated 18 CPT methods using the test database. The required information such as length and diameter of pile, static load tests, and CPT tests are obtained from Louisiana Department of Transportation and Development (LA DOTD). The ranges of pile length and diameter are 11 to 61 m (35-200 ft.) and 356 mm to 915 mm (14-35 inches) respectively. Best fit line, cumulative probability, arithmetic mean and standard deviation, and log-normal distributions and histogram are four different criteria used to analyze the overall performance of the CPT-based methods. Probabilistic, Philipponnat methods, and UF (University of Florida) showed the best performance. They have an identical approach for assessing the capacity of piles. LCPC, De Ruiter, UWA, and CPT 2000 had shown acceptable performance.

A study was made by Abu-Farsakh et al., 2020 in which soil categories are taken as the main focus while ranking CPT-based methods. CPT-based pile capacity estimation methods may overpredict or underpredict pile capacity in both sand and clay. To develop a combined method, log-normal distribution was developed for piles according to different soil categories. A database of 80 driven precast piles was collected from 35 test sites in Louisiana. Soil is classified into clay and sand. The classification criteria are sand percentage smaller than 50% for clays and sand percentage greater than 50% for sands. Besides, sample piles are divided into 4 groups according to their contribution to capacity for specific soils. Piles that have less than 25% contribution are in group 1. Group 2, 3, and 4 consists of piles with 25-50%, 50-75% and > 75% of their capacity developed in sandy layers respectively. The multidimensional unfolding (MDU) technique has been used in this study which is a machine learning that uses two-dimensional space (Abu-Farsakh et al., 2020). From MDU, for group 1 piles performance of UF and LCPC are best, for group 2 Schmertmann, UF, and UWA for group 3 UF and probabilistic and for group 4 De Ruiter, probabilistic, and ERTC3 methods are found to be acceptable. Also, a log-normal distribution is plotted for the combined CPT method where Q_p is the estimated capacity from CPT data and Q_m the is measured capacity using Davisson failure criterion. The results of this distribution for developed combined pile CPT methods have shown reasonable accuracy in estimating pile capacity.

Another study is done about bearing capacity (axial) of driven piles in sand using CPT methods by Moshfeghi and Eslami, 2019. A database of 76 driven piles in sand and 9 CPT methods are used in this study. Among these CPT methods, four of them are before the year 2000 and five others have been developed recently. Geometric mean, standard deviation, and log-normal distributions are done in this research work. All the CPT-based methods are consistent with the load at the displacement of 10%B criteria and Brinch Hansen 80%. Brinch Hansen 80% is a static load testing method (Fellenius, B. H., 2001). From statistical parameters, it is found that, for compression piles NGI-05, Fugro-05, Meyerhof, Unicone, German, and ICP-05 (Moshfeghi and Eslami, 2019) over predict the pile bearing capacity, and the other three methods under predict. For tension piles, German and Unicone methods (Moshfeghi and Eslami, 2019), except the Meyerhof, all other six methods underpredict the tension capacity of the piles. Different safety factors are provided to eliminate the overprediction or underprediction effects of the methods. Wasted capacity index (WCI) proposed by Long et al., 1999, is a measure to identify the inefficiency of a method in predicting pile capacity. The precise CPT-based method has a low WCI value. The German method showed the lowest WCI which is satisfactory. The next more effective and efficient methods were Meyerhof, LCPC, and Unicone respectively (Moshfeghi and Eslami, 2019).

For pile used in tension, Zwara and Bałachowski, 2022 did research on 3 tension screw piles. The pile shaft capacity was estimated following the AFNOR standard, Doan and Lehane 2018 centrifuge tests-based method (Delft University of Technology approach), the Modified Unicone method, KTRI (Kajima Technical Research Institute), and LCPC (Laboratoire Central des Ponts et Chaussées) method. The best match was found between static load test results and the estimated pile capacity from the AFNOR method.

Lehane et al., 2013 did a study on the shaft capacity of displacement piles. 75 different sample piles at 26 different clay sites were used for this study. The paper is based on 5 CPT methods (API (2000), ICP2005, CPT2000, Almeida et al., 1996, LCPC) and their usability. The paper depicts that the capacity estimation reliability of displacement piles found by these methods is analogous despite the dissimilarities between their respective formulations. However, a new empirical formula is derived in this paper to accurately evaluate the capacity of piles.

Another study on 6 CPT methods was done by Moshfeghi and Eslami, 2018 on 65 records of static load tests on displacement piles. The 6 methods are Method A (NeSmith 2002b; Brettmann and NeSmith 2005), Method B (Bustamante and Gianeselli 1993, 1998), UWA (Lehane, Schneider, and Xu 2005), Unicone (Eslami and Fellenius 1997), Togliani (2008), and German method (Kempfert and Becker 2010). Mean, (b) standard deviation (SD) are used for evaluation purposes. Eslami and Fellenius (1997) and Togliani (2008) have shown good performances.

Before this research, Moshfeghi and Eslami, 2016 had done a study on 43 piles that were driven in sand deposits. The database has been obtained from 23 countries (47 sources) where a majority of the cases are located in the USA. The results of these samples are used to evaluate the effects of ultimate capacity interpretation criteria found from load-displacement diagrams and they are evaluated by the results of these samples. 10 plie CPT methods were taken in this study. They are Meyerhof (1976), Schmertmann (1978), German method (2010). Dutch (1979), LCPC (1982), Fugro-05 (2005), NGI-05 (2005), Unicone (1997), ICP-05 (2005), and UWA-05 (2005). Mean, standard deviation as well as coefficient of variation are used for ranking purposes. Overall, ICP-05. Fugro-05, and German method showed the best accuracy, but scatter in their predictions was relatively notable. The Unicone method overpredict the capacity of pile by about 12%, and the Schmertmann (1978) and the Dutch methods underpredict the capacity of pile by about 14 and 31%, respectively (Moshfeghi and Eslami, 2016). But the Schmertmann, the Dutch, and the Unicone methods were more precise. They showed a small scatter and were more exact compared with the other scrutinized methods.

In Florida and Louisiana, 21 examples (tested load data with neighboring CPT data) had been used to examine the LRFD resistance factor for 14 pile capacity prediction algorithms utilizing CPT records (Hu, Z., et al., 2012). Philipponnat approach, which was modified and proposed as the UF method, was one of the methods chosen. The LRFD modified FOSM methodology was used to analyze this method and the resistance factor was determined as well. The expression (Φ/λ_R) refers to the percentage of measured Davisson capacity used for design. The better the approach, the higher the (Φ/λ_R) value. For Florida soils, the proposed UF technique has the greatest (Φ/λ_R), whereas Louisiana soils have the second highest. The Philipponnat and LCPC approaches performed well**.**

Puppala and Moalim, 2002 had done basic research on two CPT methods (European and LCPC). They had used 14 driven piles and compared the predicted capacity with the measured capacity found from Davisson's method. Best fit line method was used for the analysis and LCPC is found to be the best method. Another study was done by Abu-Farsakh and Titi, 2004 where 35 driven piles were used and failed during static load test. They measured load capacity using Butler - Hoy method and compared it with the capacity found from 8 direct CPT method. Four criteria for statistical analysis were selected and LCPC was found to be the best performing method. In Louisiana, using the data of 35 piles the performance of eight CPT methods was evaluated Abu-Farsakh and Titi, 2010. In this case, LCPC, De Ruiter and Beringen were best in their performance.

A study was conducted on the causeway embankment at Urmiyeh Lake, Iran (Eslami, A., et al., 2011). Ten piles were used for analysis and sensitive clay soil was predominant in that area. After analysis Eslami and Fellenius was found as the best CPT method. Another study was done to evaluate the ultimate capacity of piles in cohesive soils only (Vukicevic, M., et al., 2018). Eight Franki piles and seventeen jacked-in MEGA piles of different lengths are considered. LCPC was found as the best CPT method.

The database of 83 full-scale pile load tests and CPT records were used for analysis by Eslami et al., 2020. Best fit line and log-normal distributions were used for statistical analysis. A recent study was made by Heidari and Ghazavi considering USA soils and taking 61 piles as samples (Heidari, P., and Ghazavi, M., 2021). Best-fit line, mean, standard deviation and log normal distribution were used for statistical analysis. In both cases, Eslami and Fellenius had shown more precise calculation.

Cai et al., did thorough research on CPT in Jiangsu Province of eastern China (Cai, G., et al., 2009). Thirty-two piles were used for analysis and the predominant soil type was sand, silty clay, and silty sand. Best-fit line, arithmetic mean and standard deviation were used for comparison of the methods. Eslami and Fellenius, Philipponnat, and Schmertmann had shown acceptable performance in this study. They further did another research at the same place (Cai, G., et al., 2012). This time they had taken twenty-six piles and the soil type is clay. Log-normal and histogram distributions were used for ranking of the CPT methods. Eslami and Fellenius was found to be more accurate this time.

Schneider et al., 2008, 2010 did two research taking two different sample sets of piles. In one set there are 77 piles and in the other set, there are 49 piles. In both cases, the soil type is sand. Mean and standard deviation were used for analysis purposes. UWA method had performed accurately in all cases. Another study was done by Hung et al., 2016 at West of Busan City in South Korea. 82 CPTu and 190 PDA test piles were taken for consideration. The soil type was sand. After using four statistical ranking criteria Aoki and De Alencar, LCPC, Philipponnat, ICP-05, Schmertmann, Eslami and Fellenius, UWA- 05, and Meyerhof were found to show acceptable performance.

3. Test sites

Figure 1 shows the locations of CPT and static pile load tests. The red boundary means Dhaka Metropolitan Area (DMA) boundary and the green boundary means Dhaka Metropolitan Development Plan. The collocations of CPT and SPT-boreholes are shown by triangle and circle respectively.

The Dhaka Metropolitan Development Plan (DMDP) is a comprehensive development plan that encompasses various sectors and pertains to the Dhaka Metropolitan Area located within the administrative jurisdiction of the RAJUK. The Dhaka Metropolitan Area's long-term development strategy spanning two decades, from 1995 to 2015, was established in 1995. The plan encompasses an area of 590 square miles (1,528 square kilometers).

The DMDP encompasses a comprehensive strategy for urban development that encompasses various sectors, such as housing, water supply, transportation, sanitation, and environmental management. The tests conducted for the projects were conducted within the DMDP area and primarily financed by Public Works Department (PWD), RAJUK, Roads and Highways Department, and Dhaka Mass Transit Company (MRT). The Department of Civil Engineering at BUET provided direct supervision for nearly 90% of the static load test. Icon Engineering Services is responsible for conducting the remaining load tests on the piles.

Table 1
Past CPT-based pile capacity estimation methods

Study Area	Soil Type	Analyzed Sample No.	Ranking Method Used	CPT Methods	References
San Francisco, California	Clay and sand	14 piles	Best fit line	LCPC	Puppala and Moalim (2002)
Louisiana	Clay	35 piles	Best fit line, Arithmetic mean and Standard deviation, Cumulative probability, and log-normal distributions	LCPC	Abu-Farsakh and Titi (2004)
Different countries worldwide	Sand	77 piles	Mean and Standard deviation	UWA	Schneider et al., (2008)
Jiangsu Province of eastern China.	Clay, silty clay, silty sand	32 piles	Best-fit line, Arithmetic mean, Standard deviation.	Eslami and Fellenius, Philipponnat, Schmertmann	Cai et al., (2009)
Different countries worldwide	Sand	49 piles	Mean and Standard deviation	UWA	Schneider et al., (2010)
Louisiana	All soils	35 piles	Best fit line, Arithmetic mean and Standard deviation, Cumulative probability, and log-normal distributions	LCPC, De Ruiter and Beringen	Titi et al., (2010)
Urmiyeh Lake, Iran	Soft clay	10 piles	Best fit line, Arithmetic mean and Standard deviation, Cumulative probability, and log-normal distributions	Eslami and Fellenius	Eslami et al., (2011)
Jiangsu Province, China	Clay soil	26 piles	log-normal and histogram distributions	Eslami and Fellenius	Cai et al., (2012)
Florida, Louisiana	Sand and clay	21 cases from Florida and 28 from Louisiana	LRFD resistance factor and LRFD modified FOSM Method	University of Florida (UF) method, Philipponnat, Bustamante and Gianeselli (LCPC)	Hu et al., (2012)
26 different clay sites	Clay	75 piles	Five Empirical Methods	New Empirical Method	Lehane et al., (2013)
West of Busan City in South Korea	Sand	82 CPTu and 190 PDA test piles	RI index (Best fit line, Arithmetic mean and Standard deviation, Cumulative probability, and log-normal and histogram distributions)	Aoki and De Alencar, LCPC, Philipponnat, ICP-05, Schmertmann, Eslami and Fellenius, UWA- 05, and Meyerhof.	Hung et al., (2016)
USA	Sand	43 piles	The mean, standard deviation, and coefficient of variation	Fugro-05 and ICP-05, German Method	Moshfeghi and Eslami, (2016)
Western Europe, USA, and Brazil.	All soils	65 piles	Mean, Upper and lower confidence limits and standard deviation.	Togliani (2008) and Eslami and Fellenius (1997)	Moshfeghi and Eslami, (2018)
South-east and south-south regions of Nigeria.	All soils	40 piles	post-hoc tests (Least square difference and Bonferroni methods)	LCPC and Philipponnat	Obeta et al., (2018)

Table 1 (cont.)
Past CPT-based pile capacity estimation methods

Study Area	Soil Type	Analyzed Sample No.	Ranking Method Used	CPT Methods	References
Belgrade, Zemun, Novi Sad, Zagajica	All soils	17 Jacked-in MEGA piles and 8 Franki piles	Best-fit line, Coefficient of variation (CV), and histogram and log-normal Distribution.	LCPC	Vukicevic et al., (2018)
Western Europe, USA, and Brazil.	Sand	76 piles	Mean, Standard deviation and Log normal distribution	German Method, LCPC, Meyerhof and Unicone	Moshfeghi and Eslami, (2019)
35 different sites in Louisiana	All soils	80 driven precast piles	Best fit line, Arithmetic mean and Standard deviation, and Cumulative probability of Qp/Qm	Probabilistic, UF, Philipponnat, Bustamante and Gianeselli (LCPC), De Ruiter and Beringen, and Schmertmann, CPT2000, UWA	Amirmojahedi and Abu-Farsakh, (2019)
35 different sites in Louisiana	All soils	80 driven precast piles	The multidimensional unfolding (MDU) technique and the lognormal distribution	LCPC, ERTC3, Probabilistic, UF, De Ruiter and Beringen, UWA, and Schmertmann	Abu-Farsakh et al., (2020)
Different countries worldwide	Clay, sand, mixed soil	83 piles	Best fit line, log-normal distributions	Eslami and Fellenius	Eslami et al., (2020)
Different countries worldwide	All soils	60 driven piles	FOSM, FORM, MCS, and modified FOSM	Direct CPT methods	Heidarie Golafzani et al., (2020)
Surabaya Area	Clay soil, sandy soil	20 CPT data (10 for clay, 10 for sand)	Mean, Standard deviation and Log normal distribution	Scmertmann, Tumay and Fakhroo, Philipponnat, de Ruiter and Beringen.	Kumala Sari and Kusuma Wardani, (2021)
USA	Sand, clay, and mixed soil	61 piles	Best-fit line, Mean, Standard deviation and Log normal distribution	Eslami and Fellenius (1997)	Heidari and Ghazavi (2021)
Eastern Nebraska and Louisiana areas.	Clay soil	22 piles	Best-fit line, Coefficient of variation (CV), and histogram and log-normal Distribution.	De Ruiter and Beringen (1979), Eslami and Fellenius (1997), and Bustamante and Gianeselli (LCPC)	Song et al., (2022)
Poland	Clay soil	3 tension piles	Chin's method	AFNOR methodology, LCPC	Zwara and Bałachowski, (2022)

4. Soil classification

Robertson, 2010 has suggested methods for analyzing SBT values. Figure 2 presents updated non-normalized SBT chart based on dimensionless cone resistance, (qc/ pa) and friction ratio, Rf, showing contours of I_{SBT} (after Robertson 2010) which provides soil type for SBT value. This is the non-normalized SBT chart which is updated by Robertson, 2010. Although the normalized SBT chart is more reliable than the non-normalized I_{SBT}, in case of the in-situ vertical effective stress which is between 50 kPa to 150 kPa, there is often little difference in the results of non-normalized and normalized SBT. Non-normalized SBT uses basic CPT parameters which make the whole process easier. The related equations are provided in the following.

$$I_{SBT} = ((3.47 - \log(q_c/p_a))^2 + (\log R_f + 1.22)^2)^{0.5} \quad (1)$$

Where,

q_c = Cone tip resistance (or corrected cone resistance, q_t)

R_f = Friction ratio = $(f_s/q_c)100\%$

F_s = Sleeve friction

p_a = atmospheric pressure (p_a = 1 bar = 100 kPa = 0.1 MPa)

Soil behavior type is classified and is designated according to different SBT zones. Table 2 presents the soil behaviour type index, Ic, zones, after Robertson and Wride (1998). Besides, SBT zones have a relation with the Soil behavior type index (Ic). Using these formulas, the soil profile can be plotted, and the variety of layers can be classified in the plot. Figures 3 to 7 have presented CPT profiles and soil properties at Uttara, Agargaon, Mirpur, Savar and Motijheel area, respectively.

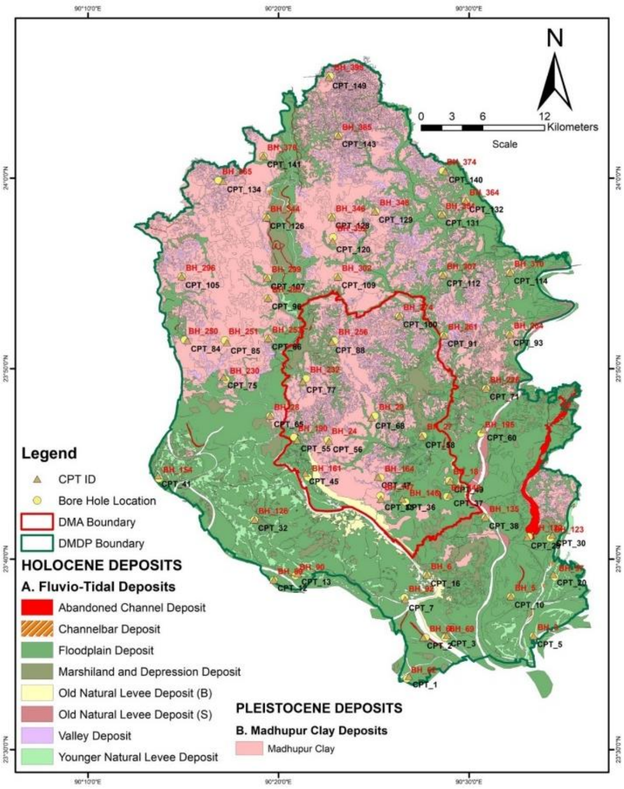


Fig. 1. Locations of CPT and pile load tests.

Table 2
Soil behaviour type index, I_c, zones, after Robertson and Wride (1998)

Soil behavior type index, I_c	SBT zone	Soil behavior type
I_c<1.31	7	Gravelly sand
1.31 < I_c < 2.05	6	Sands: clean sand to silty sand
2.05 < I_c < 2.60	5	Sand mixtures: silty sand to sandy silt
2.60 < I_c < 2.95	4	Silt mixtures: clayey silt to silty clay
2.95 < I_c < 3.60	3	Clays: silty clay to clay
I_c > 3.60	2	Organics Soils: Peats

5. Characteristics of the investigated piles

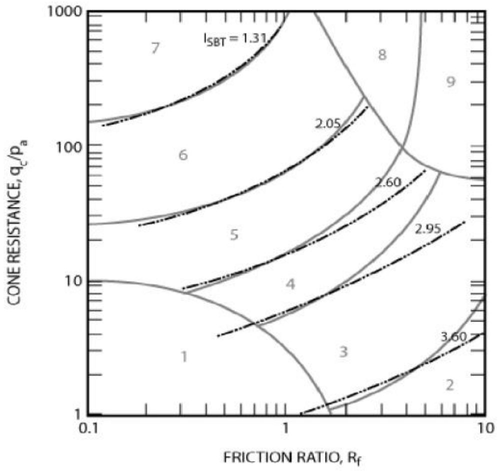
Data of five driven piles are used for this study. The corresponding location, CPT number and pile information are provided in Table 3.

Table 3
CPT numbers according to locations and pile information

Locations	CPT No.	Pile information	
		Length (m)	Size (mm x mm)
HBRI, Dar-Us-Salam Road, Mirpur	SCPT-160	12.2	350 x 350
Islamic Foundation, Agargaon	SCPT- 159	9.15	300 x 300
Residential Tower Building, Motijheel	CPT-47	12.2	300 x 300
International Training Complex, BPATC, Savar	CPT-85	12	300 x 300
Sector 11, Uttara	SCPT-226	30.5	400 x 400

5.1 Static pile load test

The static pile load test is widely used in Bangladesh. The static pile load test provides a highly precise estimation of the pile's capacity. The process is executed through a reaction-based approach. The testing methodology entails the application of an axial load to the uppermost part of the test pile utilizing one or multiple hydraulic jacks. The utilization of strain gauges is employed for the purpose of quantifying the displacement of piles caused by axial loading. Continuous data recording is performed followed by analysis to determine the pile capacity. Despite its precision in determining capacity, the aforementioned approach is both time-consuming and expensive. The application of a static load test has the potential to cause harm to the pile. Five methods of Static Load Test are used in this paper and their results are found from previous research works (Khan, 2002, Dey, 2020, Halder, 2016). They are Davisson Offset Method, Indian Standard, BNBC Code, Butler and Hoy, and British Standard.



Zone	Soil Behaviour Type (SBT)
1	*Sensitive fine-grained*
2	*Clay - organic soil*
3	*Clays: clay to silty clay*
4	*Silt mixtures: clayey silt & silty clay*
5	*Sand mixtures: silty sand to sandy silt*
6	*Sands: clean sands to silty sands*
7	*Dense sand to gravelly sand*
8	*Stiff sand to clayey sand**
9	*Stiff fine-grained**

** Overconsolidated or cemented*

Fig. 2. Updated non-normalized SBT chart based on dimensionless cone resistance (qc/ pa) and friction ratio, Rf, showing contours of ISBT (after Robertson 2010)

5.2 Cone penetration test

Cone penetration test is an expedient and modern approach in which a penetrometer is pushed into the ground (Schmertmann, J. H., 1978). It is also known as Dutch Cone Penetration test. In this test, a 60° cone (base area 10 cm^2) is inserted into the ground and the rate is 20 mm/sec. For determining the capacity, the resistance to penetration is measured. Mechanical and electrical are two types of cone penetrometers found in the market. The values tip resistance (q_c), porewater pressure (u_2), and sleeve friction (f_s) are measured continuously with depth by an electric cone. The advantages of CPT are many. In determining soil profile CPT plays a key role. It detects thin layers and retrieves data at a very close interval. Because of being a machine-operated process, it is less prone to error. Table 4 presents the summary of the three CPT-based pile capacity estimation methods used in this study.

Table 4
Summary of direct CPT-based pile design methods

Method / Reference	Design Equations	
	Pile unit side resistance (f_s)	Pile unit end bearing (q_b)
Eslami and Fellenius (Unicone)	fs = Cse q_E q_E = qt – u2 qt = qc + u2 (1 – a) where a= ratio between shoulder area (cone base) unaffected by pore water pressure to total shoulder area = 0.8 Cse = 0.004 (sand), 0.01 (silty sandy mix), 0.025 (stiff clay and silt), 0.05 (soft clay and silt), 0.08 (soft sensitive clay)	q_b = Cte qEg qEg = (q_{E1} × q_{E2} × q_{E3} × ……. × q_{En})1/n Cte = 1 for d ≤ 0.4m =1/3d for d > 0.4m Averaging Zone: 8B or 2B above, 4B below pile base.
Philipponnat	fs = q_{ca}(side) αs / Fs ≤ fp (max) αs = 1.25 (driven PCC piles and drilled shaft with casing); 0.85 (drilled shaft (d < 1.5 m)); 0.75 (drilled shaft (d > 1.5 m)); 1.10 (H-piles (circumscribed perimeter)); 0.6 (driven/jacked steel pipe piles); 0.3 (OE steel pipe pile) Fs = 50 (clay and calcareous clay); 60 (silt, sandy clay and clayey sand); 100 (loose sand); 150 (medium dense sand); 200 (dense sand and gravel) f_p(max) = 120 (driven PCC piles, H-piles (circumscribed perimeter) and drilled shaft with casing); 100 (drilled shaft (d < 1.5 m); 80 (drilled shaft (d > 1.5 m)); 50 (driven/jacked steel pipe piles); 25 (OE steel pipe pile)	q_b = kb qca(tip) kb = depends on soil type = 0.35 for gravel; 0.4 for sand; 0.45 for silt; and 0.5 for clay. q_{ca} (tip) = (q_{ca} (A) + q_{ca} (B))/2 q_{ca} = Average of qc in the specified zone Averaging Zone: 3B above and 3B below the pile toe.
LCPC	fs = q_{side}/ks ks = 30-150 depending on soil type, pile type, and installation procedure.	q_b = kb $q_{eq(tip)}$ kb for non-displacement pile: 0.375 (clay and/or silt), 0.15 (sand and/or gravel), 0.2 (chalk) kb for displacement pile: 0.6 (clay and/or silt), 0.375 (sand and/or gravel), 0.4 (chalk) Averaging Zone: 1.5B above and 1.5B below the pile toe.

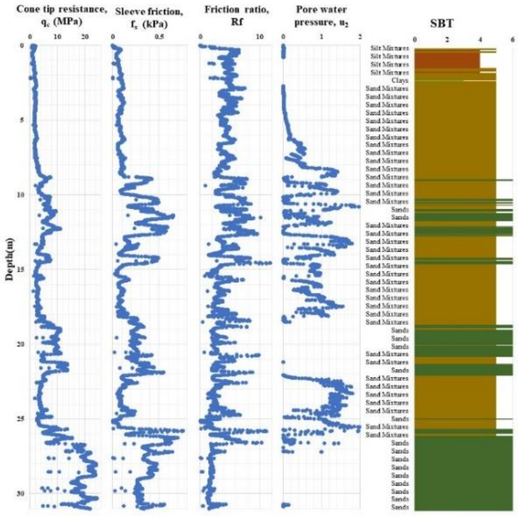


Fig. 3. Typical CPT profiles and soil properties at Uttara sector 11 area.

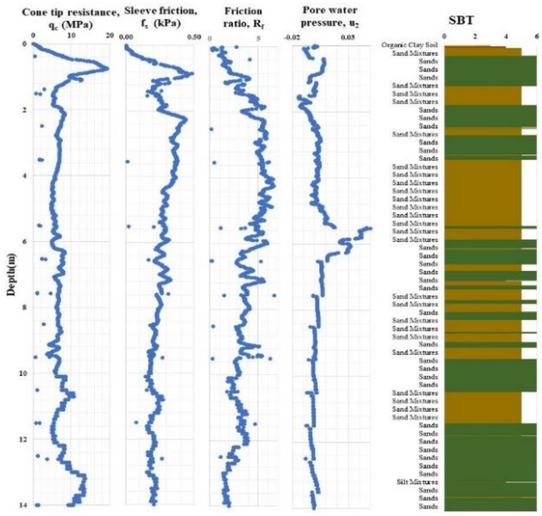


Fig. 4. Typical CPT profiles and soil properties at Agargaon area.

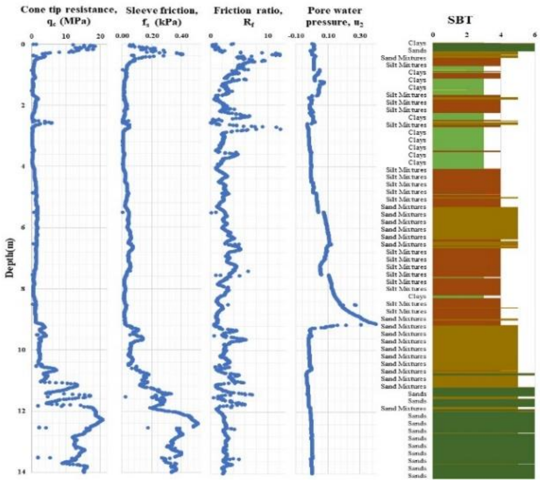


Fig. 5. Typical CPT profiles and soil properties at Dar-Us-Salam Road, Mirpur area.

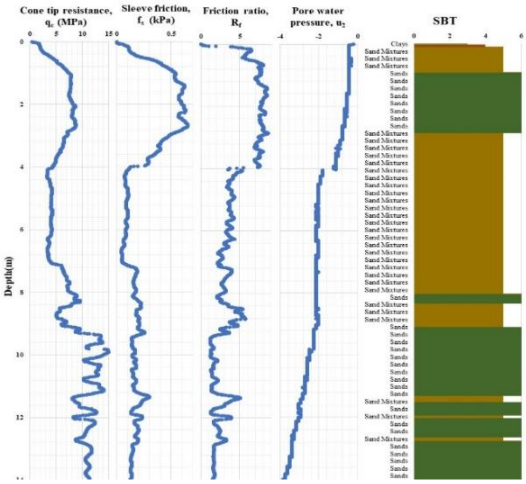


Fig. 6. Typical CPT profiles and soil properties at BPATC, Savar area.

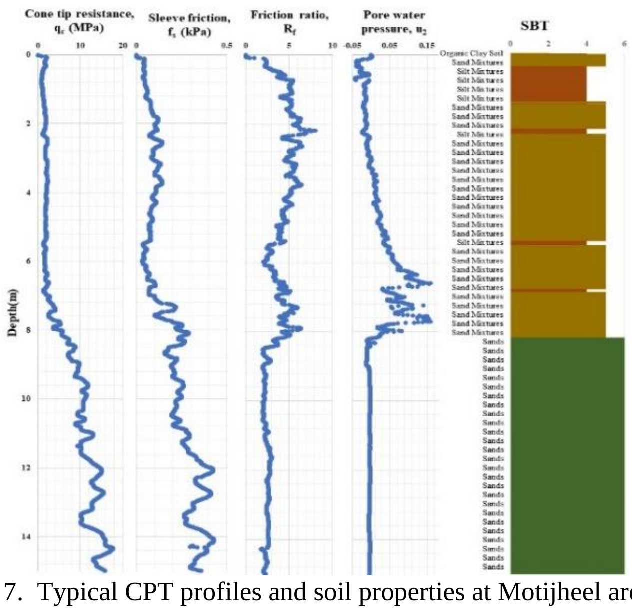


Fig. 7. Typical CPT profiles and soil properties at Motijheel area.

6. Statistical analysis and definition of rank criteria

Abu-Farsakh and Titi, 2004 has proposed a ranking index to determine the applicability of the CPT-based methods in predicting pile capacity mentioned in this study. Ranking index (RI) comprised of two ranking criteria R1 and R2. The lower the ranking index, the better the CPT method. Q_p vs Q_m graph is plotted for determining R1. The slope of the best fit line Q_{fit} / Q_m and corresponding coefficient of correlation r^2 are calculated. The sub-ranks A and B indicate the Q_{fit} / Q_m slope and r^2. The sub-ranks are obtained low when the Q_{fit} / Q_m slope and r^2 values approach unity. The average of sub-rank A and B finally provide R1 criterion. The arithmetic mean (μ) and standard deviation (σ) for Q_p / Q_m ratios is used for R2 criterion. The sub-ranks C and D are used for arithmetic mean (μ) and standard deviation (σ) respectively. The sub-rank C is obtained low when the arithmetic mean (μ) approaches unity and the sub-rank D is obtained low when the standard deviation (σ) approaches zero. The average of sub-rank C and D finally provide R2 criterion. Then R1 and R2 is added to get RI (RI=R1+R2). The method having low RI value holds the first position. Finally with the increasing value of RI the positions of the methods are defined.

Table 5
Evaluation of performance of different CPT-based methods

CPT method	Best-fit line of Q_p vs Q_m					Arithmetic calculation of Q_p/Q_m					Overall rank	
	Q_{fit}/Q_m	r^2	A	B	R1	μ	σ	C	D	R2	RI	Final rank
Eslami and Fellenius	1.1625	0.9937	2	3	2.5	0.9945	0.1110	1	2	1.5	4	2
Philipponnat	1.2500	0.9962	3	2	2.5	0.9461	0.1175	3	3	3	5.5	3
LCPC	0.9104	0.9995	1	1	1	0.9805	0.0294	2	1	1.5	2.5	1

Note: Rank index RI=R1+R2, R1 = (A + B)/2, R2 = (C + D)/2, r2 = Coefficient of correlations between Qp and Qm, μ = Arithmetic mean, σ = Standard deviation

8. Analysis results

The estimated pile capacity from CPT methods and Static Load Test are denoted as Q_p and Q_m respectively. Figure 8 shows the best-fit line found from regression analysis of Q_p / Q_m. The corresponding coefficient of correlations are calculated and shown in these figures. The arithmetic mean and standard deviation are determined for ranking purpose. Table 5 shows the evaluation of performance of different CPT-based methods. LCPC method has the best fit equation Q_{fit} = 0.9104 Q_m with r^2 = 0.9995. It ranks first position at final ranking. This method under predicts the pile capacity by 9%. The arithmetic mean (μ) and standard deviation (σ) for this method are 0.9805 and 0.0294 respectively. Eslami and Fellenius hold the second position. It has the best-fit equation Q_{fit} = 1.1625 Q_m with r^2 = 0.9937. The arithmetic mean (μ) and standard deviation (σ) for this method are 0.9945 and 0.1110 respectively. This method overestimates the pile capacity by 16.25%. Philipponnat has shown larger overestimation which is 25%. The best-fit equation for this method is Q_{fit} = 1.25 Q_m and r^2 = 0.9937. The arithmetic mean (μ) and standard deviation (σ) for this method are 0.9461 and 0.1175 respectively. This method is found at the third position at the final ranking.

9. Discussion

After a thorough investigation on previous research works, three CPT-based methods are considered for this study. Dhaka city soil is mostly composed of clay, silt mixture, sand mixture and sand. In some areas like Uttara, Savar, and Agargaon have little amount of clay and silt mixture soil. Sand mixture and sand are prevalent in these areas. All soil conditions of Dhaka Metropolitan Area are taken into consideration in this study. Pile capacities are calculated both from the Static Load Test and CPT-based pile capacity estimation methods. Statistical analysis is done to make a comparison and finally choose the best CPT-based method.

Among these methods, LCPC and Philipponnat are established almost at the same time before the Unicone. Since Eslami and Fellenius (Unicone) is relatively newer with respect to the other two CPT-based methods, it has considered all the basic CPT parameters. Tip resistance is corrected in this method. This is the reason why Unicone can better predict pile capacity, which is close to the capacity obtained from the Static Load Tests. Out of the five study locations, only at Agargaon Unicone has underpredicted the pile capacity which is also negligible. For other piles Unicone method has performed well. LCPC method is the oldest among these three methods. It has also shown the best results, but it includes some assumptions based on pile type, installation procedure etc. In LCPC approach, the pile capacity is predicated upon utilizing only q_c measurements to assess f_p.

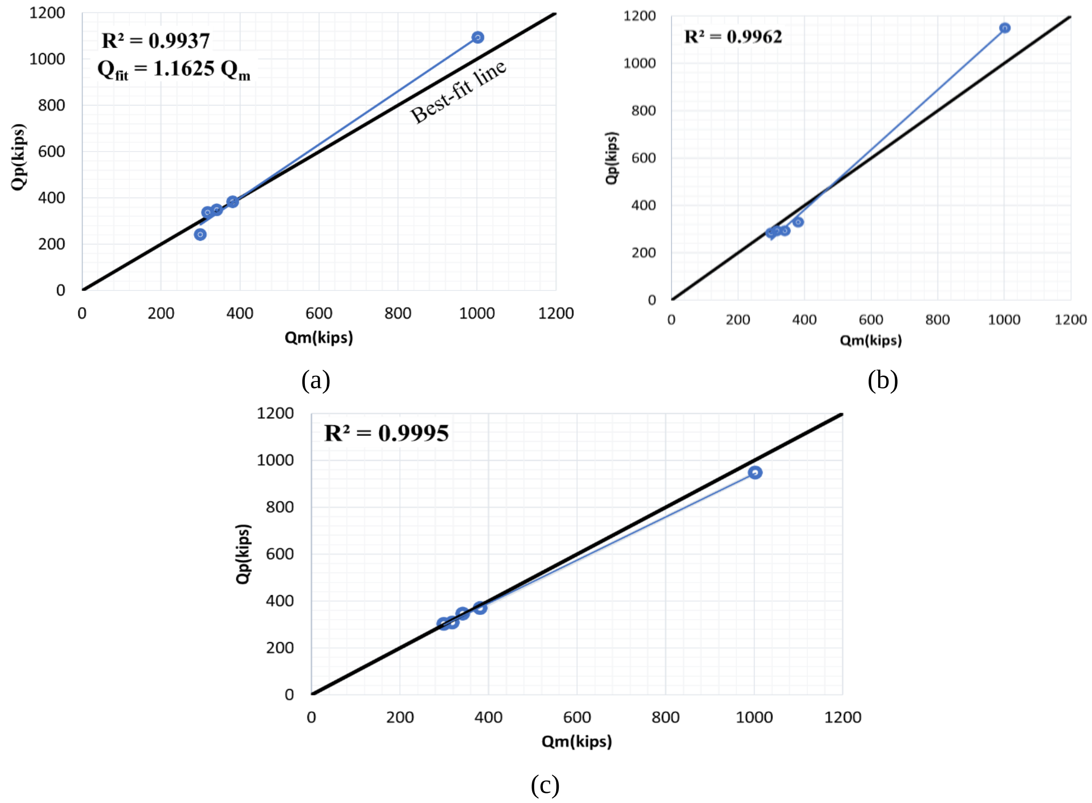


Fig. 8. Best-fit line of Qp versus Qm for different CPT-based methods (a) Eslami and Fellenius (b) Philipponnat (c) LCPC.

Philipponnat has shown satisfactory performance for one location. This method has underpredicted pile capacity for three locations and overpredicted pile capacity for another location. It is evident that Philipponnat method has shown moderate performance. Based on the aforementioned results, a ranking of the method has been carried out. LCPC holds the first position in the list. Unicone and Philipponnat methods hold the second and third positions respectively. In summary, LCPC method and Eslami and Fellenius (Unicone) method has shown quite similar performance in this study. Though LCPC is first but it has some limitations too. Results of CPT-based methods largely depend on soil condition. The results found in this area may not be suitable for other areas if the soil condition is not the same.

10. Conclusion

This study evaluates the performance of the CPT-based methods for determining the ultimate capacity of driven piles. The pile capacities from the CPT-based methods are compared to the capacities obtained from the Static Load Test methods. Five pile data were used for this purpose within the DMDP area. The soil profile for each of the areas is plotted to understand the soil behaviour layer by layer and it is also necessary for using the CPT methods. Statistical ranking criteria like arithmetic mean and standard deviation, best-fit line of Q_p / Q_m are used for ranking purposes. The results shows that LCPC has taken the first position, and Eslami and Fellenius (Unicone) and Philipponnat have taken the second and third positions respectively.

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