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ORIGINAL PAPER

Statistical Evaluation of CPT and CPTu Based Methods for Prediction of Axial Bearing Capacity of Piles

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Abstract Piles are structural members made of steel, concrete, or wood installed into the ground to transfer superstructure loads to the soil. Nowadays, many structures are built on poor lands, and therefore piles have crucial roles in such structures. Performing in-situ tests such as cone penetration (CPT) and piezocone penetration tests (CPTu) have always been of great importance in designing piles. These tests have a brilliant consistency with reality, and as a result, the outcome data can be used in order to achieve reliable pile designing models and reduce uncertainty in this regard. In this paper, the capability of various CPT and CPTu based methods developed from 1961 to 2016 has been investigated using four statistical methods. Such CPT and CPTu based methods are adopted for direct prediction of axial bearing capacity of piles using CPT and CPTu field data. For this purpose, 61 sets of field data prepared from CPT and CPTu have been collected. The data sets were utilized in order to calculate the axial bearing capacity of piles (Q_E) through 25 different methods. In addition, the measured axial pile capacities (Q_M) have been collected, recorded and prepared from field static load tests, respectively. Then, four different statistical approaches have been applied to assess the accuracy of these methods. Finally, the most reliable and accurate methods are presented.

Keywords Cone penetration tests (CPT) · Piezocone penetration tests (CPTu) · Axial bearing capacity of piles · Static load tests · Statistical methods

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1 Introduction

Determination of accurate ultimate bearing capacity of piles has always been a challenge for geotechnical engineers in order to have a safe design. In this regard, estimating the axial bearing capacity of piles can be achieved via static analysis, in-situ testing methods, full-scale loading tests, and presumed values recommended by codes and handbooks (Obeta et al. 2018). The in situ tests which have been used for the estimation of the axial bearing capacity of piles are mostly CPT (and CPTu), SPT, and more recently DMT (Vukićević et al. 2018). The cone penetration test (CPT) is considered one of the most practical in-situ tests for the prediction of the ultimate bearing capacity of piles for the similarity between pile and cone (Amirmojahedi and Abu-Farsakh 2019). Furthermore, CPT is a powerful, fundamental, quick, dependable, and inexpensive test, and can provide continuous soundings of the subsurface soil (Eslami and Fellenius 1997). Site variability assessment, soil stratigraphy and liquefaction assessment are the other applications of CPT. The CPT measurements are comprised of the cone tip resistance (q_c) and sleeve friction (f_s). Soil identification, classification, and evaluation of soil properties such as strength and deformation characteristics can be carried out effectively by these measurements (Lunne et al. 2002). Piezocone penetration test (CPTu) is a more advanced CPT test for its additional capability of measuring pore water pressure. One of the most efficient applications of CPT data is the determination of pile capacity, due to the similarity between the cone and the pile. One of the major advantages of using CPT or CPTu data for pile designing is the attainment of undisturbed sampling and less need for subsequent standard laboratory testing (Eslami and Fellenius 1997). In the literature, there are some empirical and semi-empirical approaches for estimating the ultimate bearing capacity of piles directly based on CPT and CPTu data. These approaches have been developed to overcome the uncertainties in geotechnical engineering predictions. Empirical and semi-empirical methods are based on simplifying assumptions including soil stratigraphy, soil-pile interaction, and distribution of soil resistance along the pile. Therefore, they cannot be reliable in order to be directly useful for the foundation design (Eslami et al. 2014). In this research, 25 available CPT and CPTu-based direct methods are considered to determine the estimated axial pile capacity (Q_E). In Appendix, Table 5 presents these methods in details.

The pile capacities predicted from CPT or CPTu data by 25 methods have been compared with measured values through static load tests. To compare Q_E values with Q_M, four statistical criteria have been employed. These are the best-fitted line for Q_E versus Q_M, the geometric average and standard deviation of the ratio Q_E/Q_M, the cumulative probability for the ratio of Q_E/Q_M, and the accuracy of 20 percent of the histogram and the lognormal distribution curve (Eslami et al. 2011). These comparisons will be presented below.

2 Collected Database from CPTu and Static Load Tests

A series of data has been collected, containing the results of 61 static loading tests of piles and CPT, and CPTu soundings performed close to the pile locations. For measuring the axial bearing capacity of piles, the static compression pile load tests have been performed which have acceptable accuracies. The main application of CPT and CPTu is to determine the soil classifications (Begemann 1963, 1965, 1969; Douglas 1981; Robertson et al. 1986; Robertson 1990; Jefferies and Davies 1991; Olsen 1995; Eslami and Fellenius 1997; Zhang and Tumay 1999; Hegazy and Mayne 2002). In these series of data, soils consist of clay, sand, and mixture of soils called mixed soil. For instance, a typical piezocone profile is shown in Fig. 1 and the soil profile is determined using the approach of Eslami and Fellenius (1997) by calculating corrected cone resistance (q_E) and sleeve friction.

Most piles have been installed by driving. These tests are collected from 26 various sites in 16 countries, the majority of which have been performed in the U.S.A. For most databases, the pore water pressure measurements are available. The piles are made of concrete or steel with circular, rectangular or H-shape cross sections, the majority of them is square concrete. Embedment lengths of the piles range from 8.2 m to 67 m, and 61% of embedment lengths are in the range of 10 m < L < 20 m. The pile diameters range from 235 to 1372 mm, and about 79% of the pile diameters are less than 450 mm. The axial ultimate bearing capacities of piles that have been determined from pile load tests are 290–7500 kN. Eighty percent of total capacities are calculated on the basis of Hansen (1970) criteria. In cases where the load obtained from this criterion exceeds the applied load in pile load test, the maximum load in the test was used. Figure 2 shows different percentages of pile shape and material, pile diameter, embedment length, soil type, and site location in 61 databases.

Table 1 summarizes the main case recorded data, including pile specifications, pile loading test results, and soil profiles. These 61 databases are divided into three categories based on soil type as sand, clay and mixed soil.

3 Statistical Analysis

Briaud (1988), Eslami and Fellenius (1997), Long and Wysockey (1999), Abu-Farsakh and Titi (2004), Schneider et al. (2008), and Eslami et al. (2011) evaluated the accuracy of some of the CPT and CPTu-

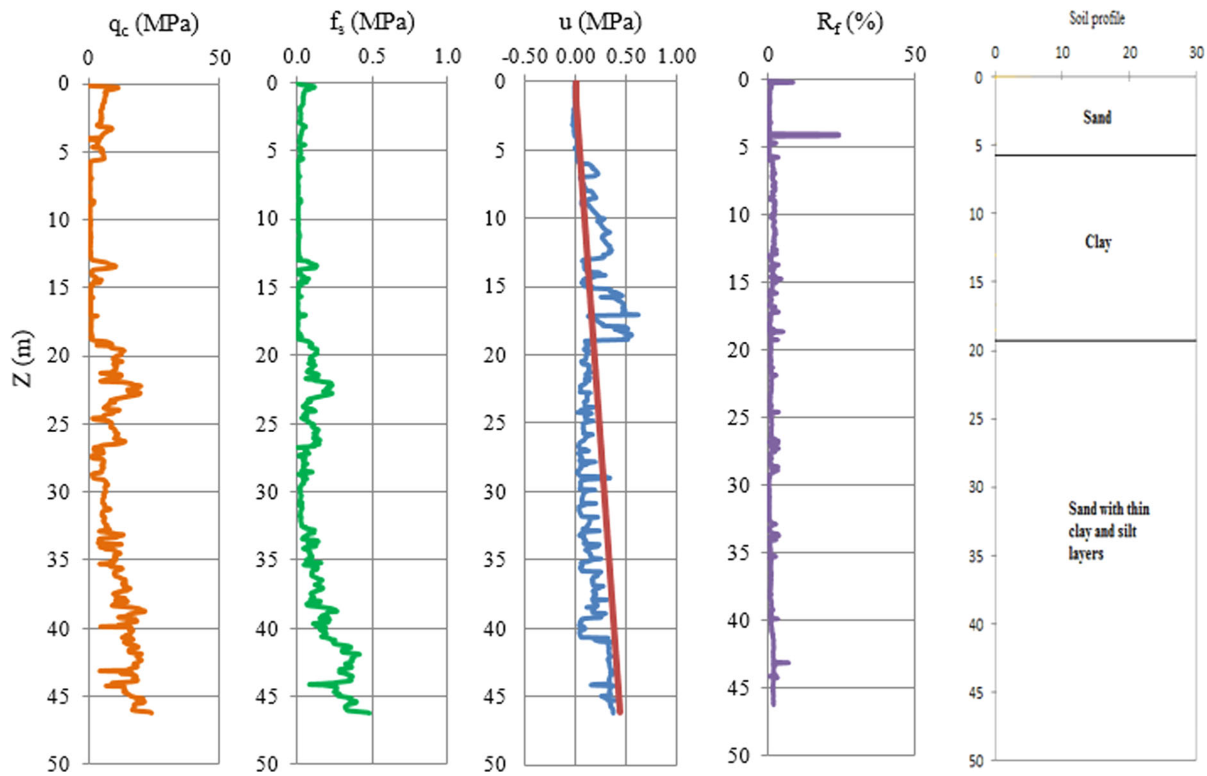


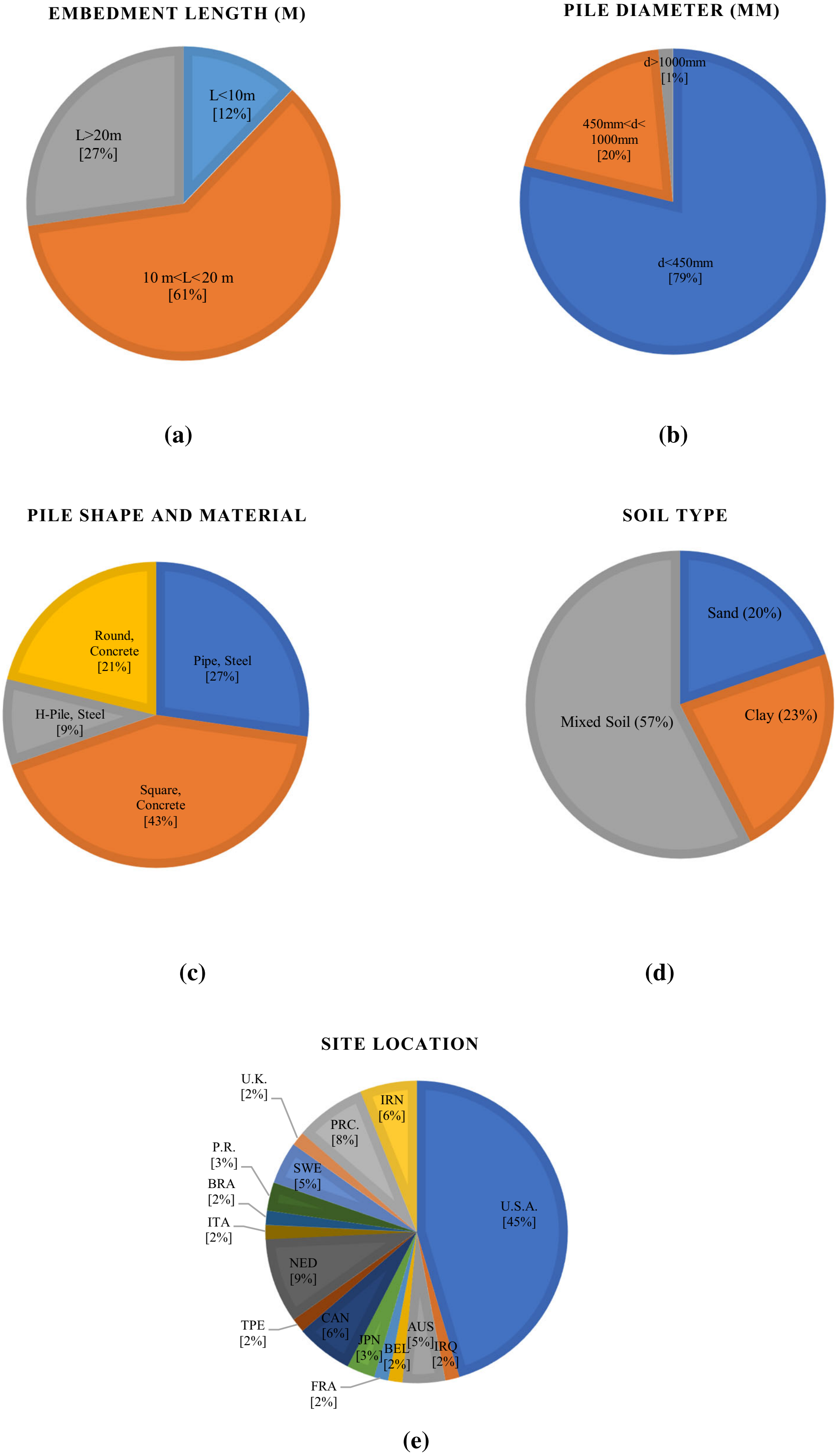
Fig. 1 A typical piezocone profile with soil classification from the chart given by Eslami and Fellenius (1997) and Yen et al. (1989)

based methods in estimating the pile axial bearing capacity when both measured data on piles from real field tests and predicted data from empirical and semi-empirical methods were accessible. However, it is felt that it is necessary to perform a comprehensive investigation to rank different approaches according to their prediction accuracy and resulting in much more economic design. In this paper, an extensive range of CPT and CPTu-based methods from 1961 to 2016 have been investigated by four statistical methods. The aim is to carry out statistical analyses to rank CPT and CPTu-based methods comprehensively.

3.1 Equations of the Best-Fitted Line for Q_E versus Q_M

The values of Q_E from the CPT and CPTu-based methods are plotted against the Q_M from pile loading test results in different soil types. The soil profiles reported are divided into sand, clay, and mixed soil. In order to compare the estimated and measured pile capacities for all piles in three soil types, three terms of "most," "medium," and "least" resembling "the most accurate," "medium accurate," and "the least accurate" are used, and the results are shown in Figs. 3, 4, and 5. The line with the angle of 45° which is named diagonal line, in each diagram, indicates a perfect consistency between estimated and measured pile capacities. For each CPT and CPTu-based methods, a regression analysis is conducted on 61 databases to obtain the best fitting line for Q_E/Q_M. The relationship between Q_E and Q_M, and corresponding coefficient (R^2) are determined for each CPT and CPTu data in 25 CPT and CPTu-based methods. As can be seen in Figs. 3, 4, and 5, the method of the Niazi and Mayne (2016) method in sand, the SEU method (Cai et al. 2011, 2012) in clay and the Niazi and Mayne (2016) method in mixed soil have the best-fitted equation. Therefore, the method of Niazi and Mayne (2016) and the SEU method (Cai et al. 2011, 2012) in the sand, mixed soil and in clay are ranked first according to this criterion with R_1 = 1, while R_1 is the ranking based on this criterion.

Figures 3, 4, and 5 represent the most accurate methods for sand, clay, and mixed soil, respectively. As shown in Figs. 6, 7, and 8, the UniCone (Eslami


EMBEDMENT LENGTH (M)
L<10m [12%]
L>20m [27%]
10 m<L<20 m [61%]
(a)
PILE DIAMETER (MM)
d>1000mm [1%]
450mm<d< 1000mm [20%]
d<450mm [79%]
(b)
PILE SHAPE AND MATERIAL
Round, Concrete [21%]
Pipe, Steel [27%]
H-Pile, Steel [9%]
Square, Concrete [43%]
(c)
SOIL TYPE
Sand (20%)
Clay (23%)
Mixed Soil (57%)
(d)
SITE LOCATION
U.K. [2%]
IRN [6%]
PRC. [8%]
P.R. [3%]
SWE [5%]
BRA [2%]
ITA [2%]
U.S.A. [45%]
NED [9%]
TPE [2%]
CAN [6%]
JPN [3%]
BEL [2%]
AUS [5%]
IRQ [2%]
FRA [2%]
(e)

◀**Fig. 2** Percentages of: (a). embedment length; (b) pile diameter; (c) pile shape and material, (d) soil type; (e) site location in 61 databases

and Fellenius 1997; Fellenius 2002), Cambridge (White and Bolton 2005), Lee and Salgado (1999), Tumay and Fakhroo (1981), Bogdanovic (1961), Eslami and Fellenius (1997) in the sand, Eslami and

Table 1 Case recorded data

No	Case	Reference	Site location	Pile shape and material*	Pile diameter (mm)	Embedment length (m)	Total capacity (kN)	Dominant soil type
1	FHWA	O'Neil (1988)	Calif., USA	P, S	273	9.1	490	Sand
2	BGHD1	Altaee et al. (1992a, b)	Iraq	Sq, C	285	11	1000	Sand
3	L and D 314	Briaud et al. (1989)	Ill., USA	HP, S	360	12	1170	Sand
4	L & D 35	Briaud et al. (1989)	Ill., USA	P, S	350	12.2	630	Sand
5	A & N2	Haustorfer and Plesiotis (1988)	Australia	Sq, C	450	13.7	4250	Sand
6	SEATW	Horvitz et al. (1981)	Wash. , USA	Rd, C	350	15.8	900	Sand
7	UFL 22	Avasarala et al. (1994)	Fla., USA	Sq, C	350	16	1350	Sand
8	KP1	Weber (1987)	Belgium	HP, S	400	14	3500	Sand
9	A & N 1	Haustorfer and Plesiotis (1988)	Australia	Sq, C	450	14	3850	Sand
10	GIT 1	Mayne (1993)	Ga. , USA	Rd, C	750	16.8	4500	Sand
11	MP1	Weber (1987)	France	HP, S	400	14	2125	Clay
12	JPNOT 2	Matsumoto et al. (1995)	Japan	P,S	800	8.2	3190	Clay
13	UHUC 1	O'Neill et al. (1981)	Tex., USA	P, S	273	13.2	780	Clay
14	LSUR 30	Tumay and Fakhroo (1981)	Calif. , USA	Sq, C	750	19.8	2610	Clay
15	UBC 3	Campanella et al. (1989)	B.C., Canada	P, S	324	16.8	630	Mixed Soil
16	UBC 5	Campanella et al. (1989)	B.C., Canada	P, S	324	31.1	1100	Mixed Soil
17	NWUP	Finno (1989)	Ill. , USA	P, S	450	15.2	1020	Mixed Soil
18	TWNTP 4	Yen et al. (1989)	Taiwan	P,S	609	34.3	4330	Mixed Soil
19	UBC 2	Campanella et al. (1989)	B.C., Canada	P,S	324	13.8	290	Mixed Soil
20	UBCA	Campanella et al. (1989)	B.C., Canada	P,S	915	67	7500	Mixed Soil
21	NWUH	Finno (1989)	Pa. , USA	HP, S	450	15.2	1010	Mixed Soil
22	JPNOT 1	Matsumoto et al. (1995)	Japan	P, S	800	8.2	4700	Mixed Soil
23	LSUA 1	Tumay and Fakhroo (1981)	Calif. , USA	Sq, C	350	9.5	900	Mixed Soil
24	LSUN 11	Tumay and Fakhroo (1981)	Calif. , USA	Sq, C	350	9.5	900	Mixed Soil
25	LSUN 15	Tumay and Fakhroo (1981)	Calif. , USA	P, S	400	37.5	2800	Mixed Soil
26	LSUN 215	Tumay and Fakhroo (1981)	Calif. , USA	P, S	350	31.1	1710	Mixed Soil
27	LTN 742	Reese et al. (1988)	Tex. , USA	Rd, C	810	24.1	5850	Mixed Soil
28	NETH 2	Viergever (1982)	The Netherlands	Sq, C	256	9.3	700	Mixed Soil
29	MILANO	Gambini (1985)	Italy	P,S	330	10	625	Mixed Soil
30	OKLACO	Nevels and Snethen (1994)	Okla. , USA	Rd, C	660	18.2	3600	Mixed Soil
31	A & N 3	Haustorfer and Plesiotis (1988)	Australia	Sq, C	355	10.2	1300	Mixed Soil
32	USPB 1	Albiero et al. (1995)	Brazil	Rd, C	350	9.4	645	Mixed Soil
33	PRS	Urkkada (1996)	Puerto Rico	P, S	300	28.4	1240	Mixed Soil

Table 1 continued

No	Case	Reference	Site location	Pile shape and material*	Pile diameter (mm)	Embedment length (m)	Total capacity (kN)	Dominant soil type
34	PRL	Urkkada (1996)	Puerto Rico	P, S	300	31.4	1890	Mixed Soil
35	UFL 53	Avasarala et al. (1994)	Fla., USA	Sq, C	350	20.4	1260	Sand
36	LSUN 216	Tumay and Fakhroo (1981)	Calif. , USA	P, S	400	41.8	1890	Clay
37	OKLAST	Nevels and Snethen (1994)	Okla. , USA	P,S	610	18.2	3850	Mixed Soil
38	A & M 20	Briaud et al. (1989)	Mass. , USA	Sq, C	400	21	1330	Clay
39	A & M 24	Briaud et al. (1989)	Mass. , USA	Sq, C	400	13.4	1170	Sand
41	A & M 39	Briaud et al. (1989)	Mass. , USA	HP, S	299*306	19	1370	Sand
45	LAHW 1-T233	Rauser (2008)	Louisiana, USA	Sq, C	406	33.5	1899	Clay
46	LAHW 1-T242	Rauser (2008)	Louisiana, USA	Rd, C	1372	41.8	5760	Clay
47	LAHW 1-T544	Rauser (2008)	La. , USA	Sq, C	610	44.2	3287	Clay
48	LAHW 1-T552	Rauser (2008)	La. , USA	Sq, C	610	51.8	3380	Clay
49	FITTJAA	Axelsson (1998)	Sweden	Sq, C	235	19	560	Sand
50	FITTJAB	Axelsson (1998)	Sweden	Sq, C	235	19	529	Sand
51	FITTJAC	Axelsson (1998)	Sweden	Sq, C	235	19	736	Sand
52	ASCOT	Wilkinson et al. (2006a, b)	U.K	Rd, C	600	8.9	3750	Sand
53	XIAN 1	Huichang (1991)	China	Sq, C	350	16.5	1655	Clay
54	XIAN 3	Huichang (Huichang 1991)	China	Sq, C	350	15.5	1322	Clay
55	XIAN 4	Huichang (1991)	China	Sq, C	350	16	2618	Clay
56	XIAN 5	Huichang (1991)	China	Sq, C	350	21	2445	Clay
57	XIAN 7	Huichang (1991)	China	Sq, C	350	13.1	855	Clay
58		AZADEGAN TP14	Attar and Fakharian (2013)	Iran	Sq, C	400	16.4	2150
	Clay							
59		AZADEGAN TP22	Attar and Fakharian (2013)	Iran	Sq, C	400	12.7	1050
	Clay							
60		AZADEGAN TP24	Attar and Fakharian (2013)	Iran	Sq, C	400	15.9	1850
	Clay							
61		AZADEGAN TP28	Attar and Fakharian (2013)	Iran	Sq, C	400	14.5	1550
	Clay							

(* P = pipe; Sq = square; HP = H-section; Rd = round; C = concrete; S = steel)

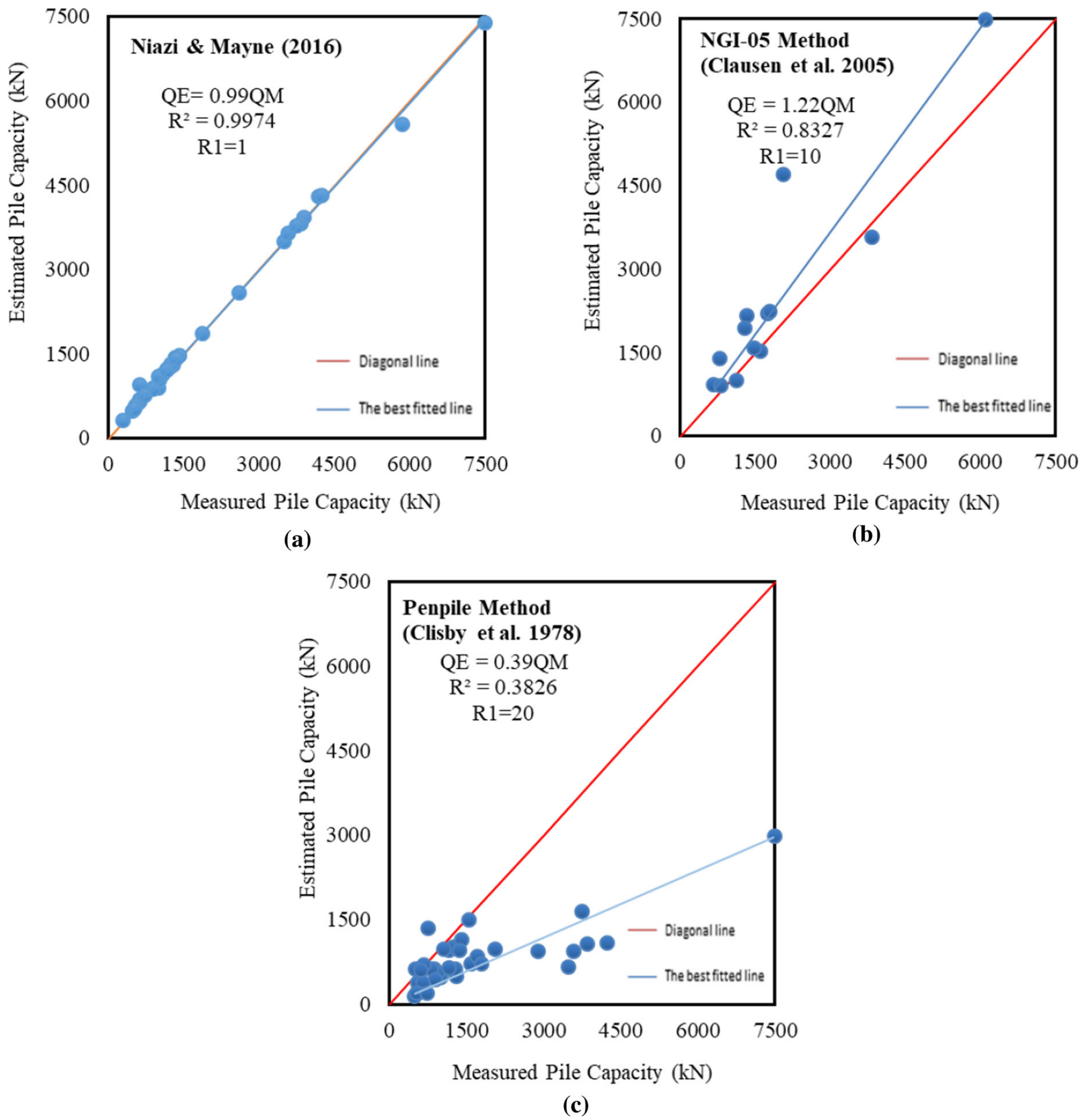


Fig. 3 Values of Q_E versus Q_M for piles in sand

Fellenius (1997) in clay and UniCone (Eslami and Fellenius 1997; Fellenius 2002), Eslami and Fellenius (1997) in mixed soil with $R^2 \geq 0.9$ have good agreement with the results of a real situation.

3.2 Geometric Mean (μ) and Standard Deviation (σ) for Q_E/Q_M

The geometric mean (μ) and standard deviation (σ) of Q_E/Q_M for each method are calculated and used as a

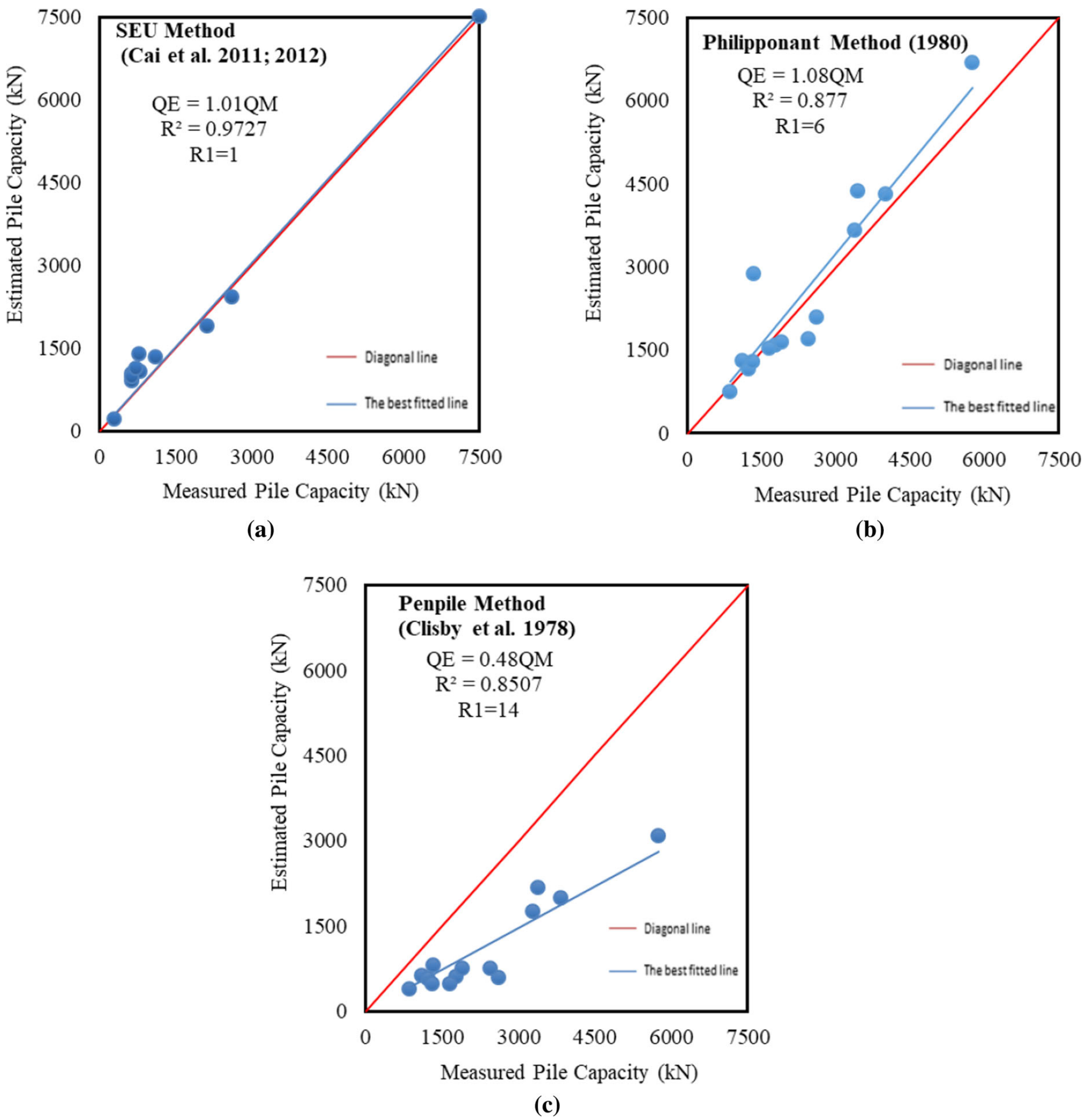


Fig. 4 Values of Q_E versus Q_M for piles in clay

second evaluation criterion. According to μ and σ values, various approaches have been ranked as summarized in column 7 of Tables 2, 3, and 4. The smaller the standard deviation, the better agreement can be determined between Q_E and Q_M. Consequently, the Eslami and Fellenius Method (Eslami and Fellenius 1997) ranks number one in sand, clay, and mixed soil. In this criterion, R_2 is the rank number based on the geometric mean (μ) and standard deviation (σ) of Q_E/Q_M values.

3.3 Cumulative Probability for $\mathbf{Q_E/Q_M}$

Alsamman (1995) and Long and Wysockey (1999) suggest that the cumulative probability is a statistical criterion for evaluating the CPT and CPTu-based

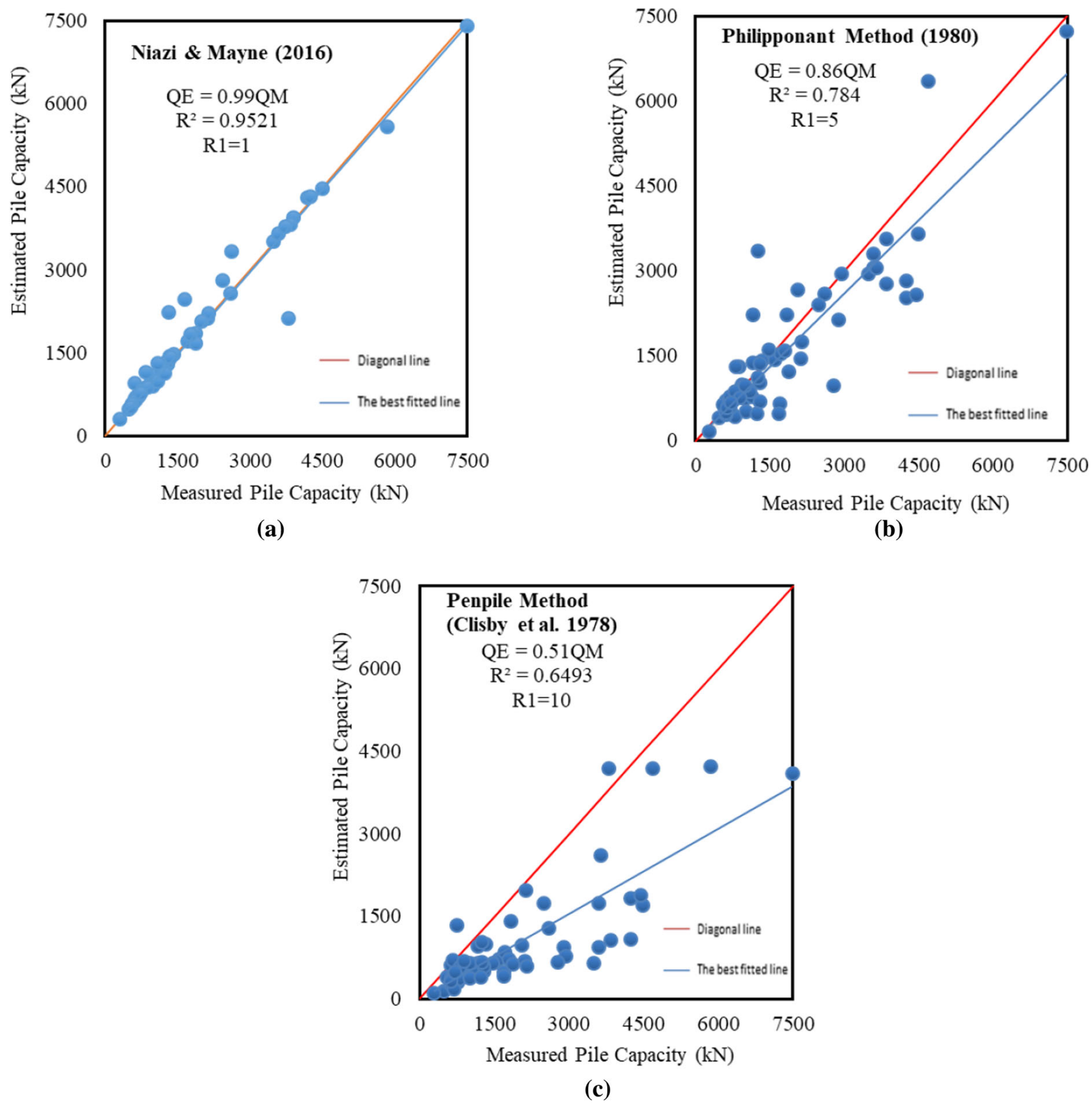


Fig. 5 Values of Q_E versus Q_M for piles in mixed soil

methods for estimating the ultimate bearing capacity of piles. For obtaining the cumulative probability, the following procedure should be taken into account:

1. Arrangement of Q_E/Q_M values for each method in ascending order (1, 2, 3,…, i,…,n).
2. Estimation of cumulative probability (P) from Eq. 1. (Long and Wysockey 1999):

$$p = i/(n+1) \tag{1}$$

where i denotes the order number given for the considered ratio and n is the pile number.

Fifty and ninety percent cumulative probabilities (P_{50} and P_{90}) should be calculated and utilized to quantify the accuracy of various approaches estimating the ultimate pile capacity. For example, the P_{50} value is used as a measure of the tendency of the

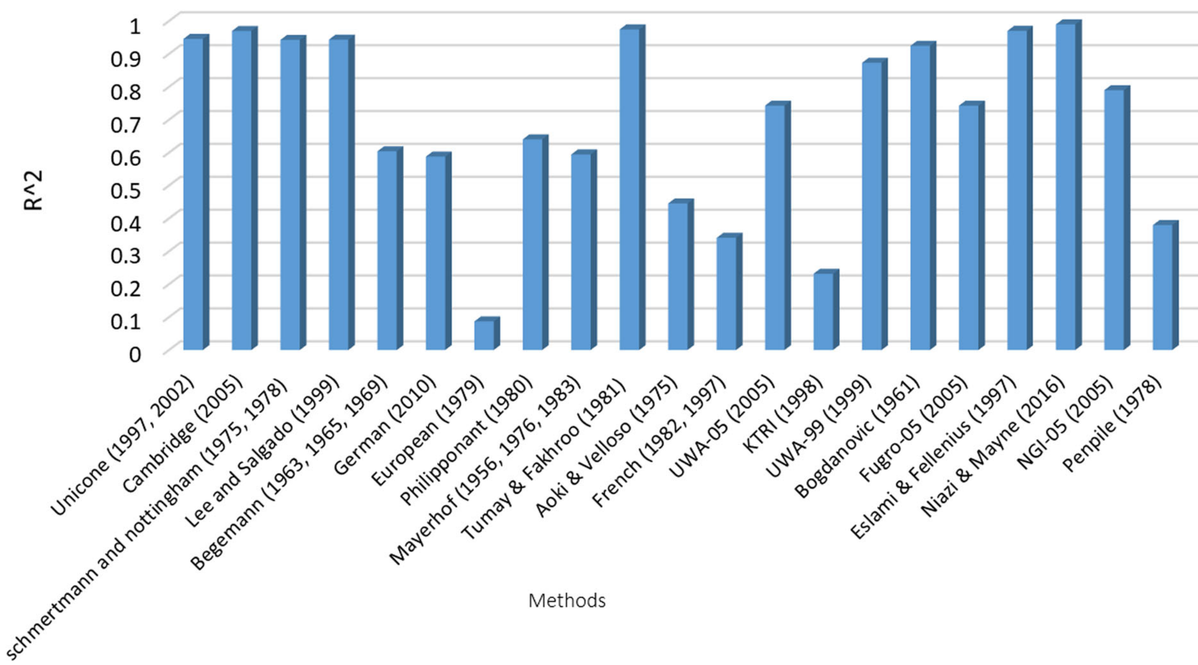


Fig. 6 Comparison of methods based on the best-fitted line criteria in sand

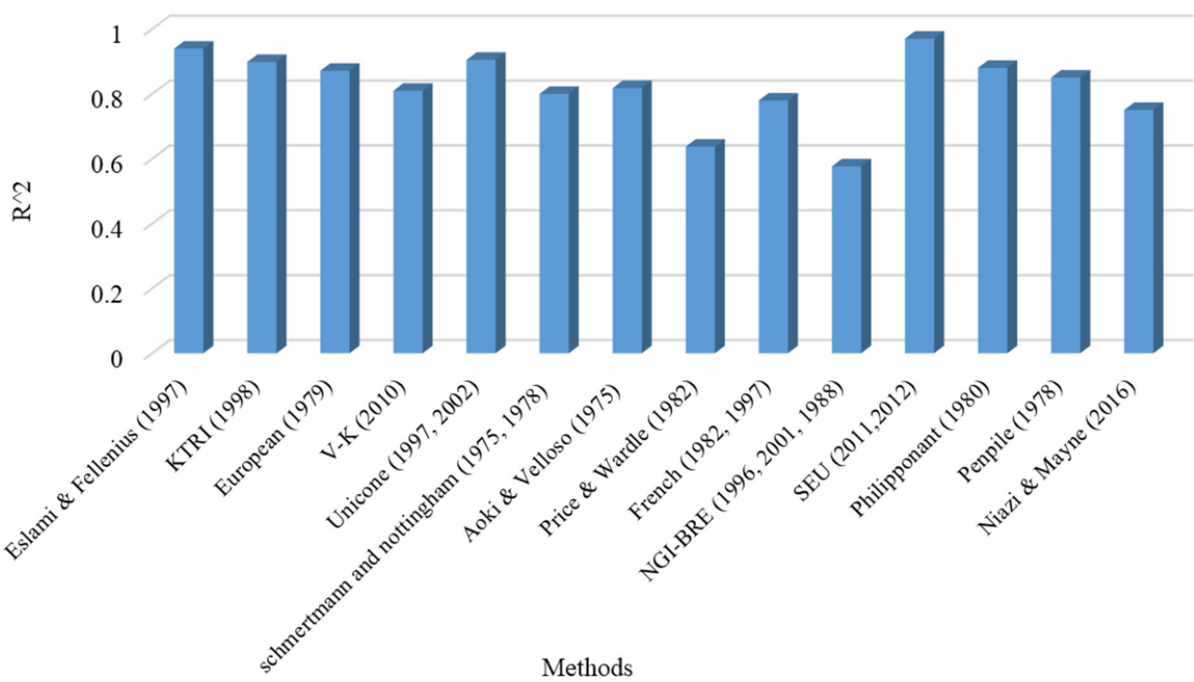


Fig. 7 Comparison of methods based on the best-fitted line criteria in clay

method to over-predict or under-predict the measured pile capacity. The determination of over-prediction and under-prediction depends on the intended type of distribution. If the Q_E/Q_M values are close to 1, the estimated ultimate bearing capacity is almost equal to the measured value and the method has a precise

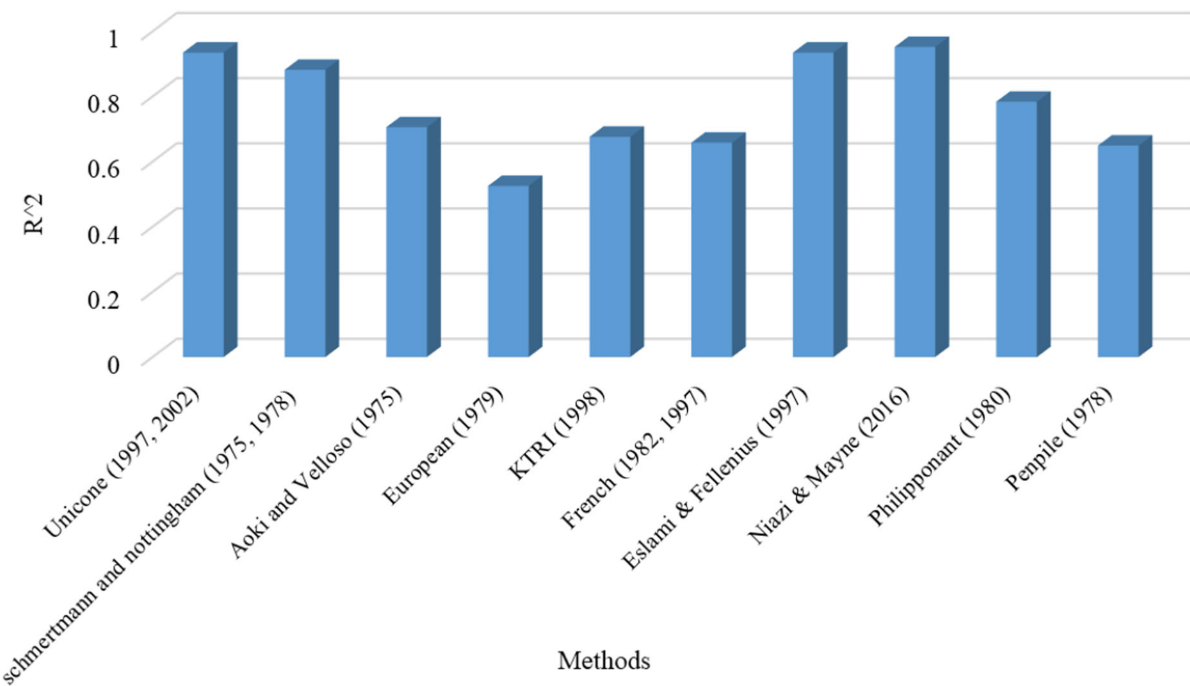


Fig. 8 Comparison of methods based on the best-fitted line criteria in mixed soils

prediction. The cumulative probability for Q_E/Q_M values is shown in Fig. 9 for sand, clay, and mixed soil, respectively.

As shown in Fig. 9, according to the cumulative probability criterion, the method of Niazi and Mayne (2016) with P_{50}=1.007, 1.012 and P_{90}=1.080, 1.196 ranks number one in sand and mixed soil, respectively, and the Eslami and Fellenius Method (Eslami and Fellenius 1997) with P_{50}=1.009 and P_{90}=1.45 ranks number one in clay.

3.4 Twenty Percent accuracy from the Histogram and Lognormal Distribution for $\boldsymbol{Q_E/Q_M}$

The range of Q_E/Q_M value is from 0 to an unlimited upper value with an optimum value of unity. These result in a non-symmetric distribution of Q_E/Q_M values around the average value, not giving a uniform weight of under-prediction and over-prediction (Briaud 1988). In this respect, Briaud and Tucker (Briaud 1988) state that in order to assess the performance of the methods predicting the ultimate bearing capacity of piles, a log-normal distribution of Q_E/Q_M should be used. With this criterion, it is possible to determine the under-prediction and over-prediction of CPT and CPTu-based methods. The CPT and CPTu-based method under-predicts the measured capacity when $Q_E/Q_M < 1$ and over-predicts the measured capacity when $Q_E/Q_M > 1$. The lognormal distribution is defined as the distribution with the following density:

$$f(x) = \frac{1}{\sqrt{2\pi}\,\sigma_{\ln} x} \exp\left[-1\Big/2\left(\frac{\ln(x)-\mu_{\ln}}{\sigma_{\ln}}\right)^2\right] \quad (2)$$

where $x = Q_E/Q_M$, μ_{ln} = mean of $\ln(Q_E/Q_M)$, and σ_{ln} = standard deviation of $\ln(Q_E/Q_M)$.

In statistical analysis, the mean value (μ) and standard deviation value (σ) of Q_E/Q_M are essential indicators of the accuracy and precision of the predicting method.

Due to the lack of information and accucy of tests, upper and lower limits are considered for Q_E/Q_M values. The upper and lower limits mean that when more accumulation of data exists between upper and lower limits, lower distribution of the results obtained from the method exists, and thus, this method is better (Long and Wysockey 1999). For this purpose, the accuracy rate in this study is chosen 20%. Then, histograms and standard probability distribution graphs are drawn for Q_E/Q_M values. When the area of two graphs is calculated as $0.8 \leq Q_E/Q_M \leq 1.2$,

Table 2 Summary results of the evaluation of bearing capacity of piles in sand

Sand														
Method of calculating bearing capacity of piles based on CPT	Best-fitted line for Q_E-Q_M			Geometric mean (μ) and standard deviation (σ) for Q_E/Q_M			Cumulative probability of Q_E/Q_M			20% accuracy from the histogram and lognormal distribution for Q_E/Q_M			Final prioritize	
	QE/QM	R^2	R1	σ	μ	R2	P50	P90	R3	Lognormal	Histogram	R4	RI	Final rank
Niazi and Mayne (2016)	0.99	0.99	1	0.09	1.01	1	1.007	1.08	1	67.02	97.06	2	5	1
Eslami and Fellenius (1997)	0.99	0.97	2	0.11	1.05	2	1.08	1.18	2	84.96	93.33	1	7	2
Cambridge-05 Method (2005)	1.05	0.97	3	0.19	1.05	2	1.05	1.28	2	32.35	84.21	9	16	3
UniCone (1997, 2002)	1.04	0.96	2	0.16	1.10	8	1.10	1.33	3	56.70	63.89	3	16	3
Nottingham (1975), Schmertmann (1978)	1.11	0.94	4	0.28	1.09	5	1.08	1.54	5	41.29	66.67	4	18	4
Lee and Salgado (1999)	0.84	0.94	5	0.14	0.88	9	0.93	1.07	4	61.39	71.78	2	20	5
Philipponant (1980)	0.95	0.64	8	0.39	1.05	4	1.03	1.74	6	30.22	54.05	6	24	6
French Method (1982, 1997)	0.78	0.34	14	0.54	1.01	3	0.97	1.81	7	25.01	51.43	7	31	7
Aoki and Velloso (1975)	0.81	0.45	13	0.46	0.92	6	0.93	1.78	8	34.29	27.03	8	35	8
Begemann (1963, 1965, 1969)	0.99	0.49	6	0.68	1.26	13	1.15	2.26	10	20.55	51.61	10	39	9
European Method (1979)	0.97	0.09	9	0.69	1.19	11	1.15	2.24	9	18.99	34.29	13	42	10
German Method (2010)	0.97	0.50	7	0.63	1.29	14	1.28	2.22	11	21.50	41.94	13	45	11
Meyerhof (1956, 1976, 1993)	0.75	0.63	11	0.47	0.82	10	0.84	1.78	13	28.51	36.96	12	46	12
Tumay and Fakhroo (1981)	1.24	0.77	12	0.59	1.36	16	1.25	2.22	15	41.04	64.71	5	48	13
UWA-05 Method (2005)	0.68	0.39	15	0.59	0.92	7	0.85	1.85	12	17.81	30.43	15	49	14
NGI-05 Method (2005)	1.21	0.79	10	0.51	1.22	12	1.22	2.13	14	21.58	23.81	16	52	15
Fugro-05 Method (2005)	0.48	0.34	19	0.26	0.59	17	0.58	1.07	18	49.28	19.35	11	65	15
Bogdanovic (1961)	0.53	0.69	18	0.29	0.64	15	0.62	1.11	16	2.45	7.69	19	68	16
Penpile Method (1978)	0.40	0.38	20	0.32	0.54	18	0.54	0.99	19	17.39	34.21	14	71	17
UWA-99 Method (1999)	0.55	0.88	17	0.29	0.50	19	0.52	0.83	17	7.02	11.11	18	71	17
KTRI (1998)	1.31	0.23	16	0.82	1.59	20	1.45	3.21	20	9.92	25	17	73	18

with approximation of data under the graph to 100%, the method will be more accurate. Figures 10, 11, and 12 show these criteria in sand, clay, and mixed soils for methods with the most, medium, and minimum accuracy. For other methods, such analyses are illustrated by bar charts in three types of soils in Figs. 13, 14, and 15.

The amounts of Log-Normal and Histogram for different methods have been illustrated in columns 11 and 12 of Tables 2, 3, and 4 in the sand, clay, and mixed soil, respectively. In the sand, clay, and mixed soil the Eslami and Fellenius Method (Eslami and Fellenius 1997), the UniCone method (Eslami and Fellenius 1997; Fellenius 2002), and the Niazi and Mayne (2016) method are the most accurate methods based on this criterion, respectively.

Figures 13, 14 and 15 show that the method presented by Niazi and Mayne (2016) in the sand and clay and the UniCone method (Eslami and Fellenius 1997; Fellenius 2002) in mixed soil also have a good agreement with measured capacity in a real situation.

4 Results of Statistical Analysis for Various Experimental Methods

In this study, four evaluation criteria based on statistical approaches have been taken into account

Table 3 Summary results of the evaluation of the bearing capacity of piles in clay

Clay														
Method of calculating bearing capacity of piles based on CPT	Best-fitted line for Q_E-Q_M			Geometric mean (μ) and standard deviation (σ) for Q_E/Q_M			Cumulative probability of Q_E/Q_M			20% accuracy from the histogram and lognormal distribution for Q_E/Q_M			Final prioritize	
	QE/ QM	R^2	R1	σ	μ	R2	P50	P90	R3	Lognormal	Histogram	R4	RI	FINAL rank
Eslami and Fellenius (1997)	0.95	0.94	2	0.21	1.02	1	1.01	1.37	1	34.84	66.67	2	6	1
UniCone Method (1997, 2002)	0.89	0.90	7	0.19	0.97	2	0.98	1.28	2	53.59	76.92	1	12	2
KTRI (1998)	1.03	0.89	3	0.21	0.89	7	0.94	1.23	5	40.16	53.85	5	20	3
Philipponant (1980)	1.08	0.88	6	0.35	1.02	4	0.96	1.71	4	32.31	64.29	7	21	4
European Method (1979)	1.02	0.87	4	0.32	0.97	5	0.89	1.64	7	30.95	69.23	6	22	5
SEU—Method (2011, 2012)	0.99	0.97	1	0.32	1.06	6	0.98	1.60	3	8.07	1.03	13	23	6
Niazi and Mayne (2016)	0.90	0.75	8	0.32	1.02	3	0.07	0.35	14	90.66	46.15	4	29	7
Nottingham (1975), Schmertmann (1978)	0.85	0.79	9	0.19	0.78	10	0.79	1.02	8	35.42	75	3	30	8
Aoki and Velloso Method (1975)	1.24	0.82	10	0.31	1.11	8	1.16	1.64	6	34.49	38.46	8	32	9
V-K Method (2011)	0.99	0.84	5	0.32	0.85	9	0.86	1.34	9	21.95	47.06	9	32	9
Price and Wardle (1982)	0.67	0.75	11	0.25	0.54	12	0.58	0.89	11	17.36	5.88	11	45	10
NGI-BRE Method (1988, 1996, 2001)	1.34	0.69	13	0.80	1.37	13	1.27	2.54	10	1.96	31.25	10	46	11
French (1982, 1997)	0.65	0.78	12	0.31	0.63	11	0.57	1.32	13	19.12	7.69	12	48	12
Penpile Method (1978)	0.49	0.85	14	0.13	0.43	14	0.45	0.62	12	0	0	14	54	13

for ranking the performance of a wide variety of CPT and CPTu-based methods for predicting the ultimate bearing capacity of piles. The overall performance of CPT and CPTu-based methods are then evaluated using the four different criteria via RI. For example, RI for the Eslami and Fellenius Method in the sand is determined from RI $= R_1 + R_2 + R_3 + R_4 = 1 + 1 + 1 + 1 = 4$ in which R_1, R_2, R_3, and R_4 are rank numbers for the regression, geometric average and standard deviation, cumulative probability, accuracy of 20 percent of the histogram and the lognormal distribution, respectively. The RI values for all methods in sand, clay, and mixed soil are presented in column 14 of Tables 2, 3, and 4, respectively. The final overall rank for each CPT or CPTu method obtained based on RI values in sand, clay, and mixed soil has been presented in column 15 of Tables 2, 3, and 4.

According to the results of the current research, the Niazi and Mayne method (Niazi and Mayne 2016) in sand and mixed soil, and the Eslami and Fellenius Method (Eslami and Fellenius 1997) in clay rank first. These CPTu-based methods (Niazi and Mayne and Eslami and Fellenius Method) show the best efficiency according to the four evaluation criteria. The KTRI method (Takesue et al. 1998) in sand and mixed soil and the Penpile method (Clisby et al. 1978) in clay show the lowest performance amongst all methods. Therefore, the rank of the KTRI (Takesue et al. 1998) method is number 18 and 10 corresponding to sand and mixed soil. The rank of the Penpile method (Clisby et al. 1978) is 13 in clay. Generally, the CPT-based methods exhibit more dispersion than CPTu-based methods. The results of this investigation help to consider methods in terms of their accuracy for designing purposes. In addition, the results help to quantify the most accurate methods to have much better agreement with the real situation.

Table 4 Summary results of the evaluation of the bearing capacity of piles in mixed soil

Mixed soil															
The method of calculating bearing capacity of piles based on CPT	The best-fitted line for QE-QM			The geometric mean (μ) and standard deviation (σ) for QE/QM			The cumulative probability of the ratio QE/QM			20% accuracy from the histogram and lognormal distribution for the ratio QE/QM			Final prioritize	
	QE/QM	R^2	R1	σ	μ	R2	P50	P90	R3	Lognormal	Histogram	R4	RI	Final rank
Niazi and Mayne (2016)	0.99	0.95	1	0.16	1.02	1	1.01	1.19	1	99.26	85.19	1	4	1
Eslami and Fellenius (1997)	0.97	0.96	2	0.17	1.02	1	1.03	1.21	2	65.81	76.56	2	7	2
UniCone Method (1997, 2002)	0.96	0.95	3	0.19	1.03	2	1.03	1.22	3	63.43	77.94	3	11	3
Nottingham (1975; Schmertmann 1978)	0.94	0.89	4	0.28	0.92	3	0.96	1.37	5	46.74	57.14	4	16	4
Aoki and Velloso (1975)	1.05	0.76	6	0.42	0.96	4	1	1.62	4	36.39	46.15	5	19	5
Philipponant (1980)	0.96	0.79	5	0.48	0.95	5	0.92	1.87	7	38.77	41.27	6	23	6
European Method (1979)	0.97	0.68	7	0.75	1.10	6	1.01	2.38	9	20.73	47.62	7	29	7
French Method (1982, 1997)	0.72	0.69	9	0.42	0.77	8	0.74	1.55	8	30.13	59.42	5	30	8
PenPile Method (1978)	0.51	0.70	10	0.26	0.50	9	0.49	0.91	6	13.21	28.13	9	34	9
KTRI Method (1998)	1.14	0.66	8	0.72	1.19	7	1.10	2.40	10	21.01	11.11	10	35	10

5 Summary and Conclusions

In spite of doing comprehensive research by numerous researchers, for example Abu-Farsakh (1999, 2004), Eslami et al. (2011), the topic is still very interesting and needs further research. Much research has been conducted in this area. For example, Abu-Farsakh et al. (1999) evaluated 8 CPT-based methods with 35 databases in all types of soils and square precast prestressed concrete piles (PPC) using four statistical evaluation criteria and the prediction of pile capacity was performed on 60 piles. Abu-Farsakh and Titi (2004) evaluated 8 CPT-based methods with 35 databases in all types of soil and square precast prestressed concrete piles (PPC) utilizing 4 statistical methods. In addition, Eslami et al. (2011) evaluated 5 CPT-based methods with 13 databases and with 5 statistical approaches.

To the best of our knowledge, no research has been carried out to cover 25 empirical correlations predicting axial pile capacity at the same time in three different soil types. Each of these criteria reveals the accuracy of these methods by comparing their results with the real results obtained from in-situ tests.

This paper evaluates the accuracy of CPT and CPTu- based methods predicting the ultimate capacity of driven piles in sand, clay, and mixed soil. Each CPT or CPTu test is performed near the location of piles tested in the same field. The measured and estimated ultimate axial capacities of piles are obtained from static load test and CPT and CPTu data, respectively. Four statistical analyses have been operated to rank CPT and CPTu-based methods in terms of their accuracy for estimating the axial bearing capacity of piles. Four methods are the best-fitted line for Q_E versus Q_m, the geometric average and standard deviation for Q_E/Q_m ratio, the cumulative probability for Q_E/Q_m ratio and the accuracy of 20 percent of the histogram and the lognormal distribution curve for Q_E/Q_m ratio. Each of these criteria reveals the accuracy of these methods by comparing their results with the real results obtained from in-situ tests.

For each CPT and CPTu-based method, finally, the final rank of each criterion (RI) has been calculated. The main concluding remarks can be cited as:

- Statistical methods show that CPT and CPTu based methods have their drawbacks in predicting the axial pile capacity.

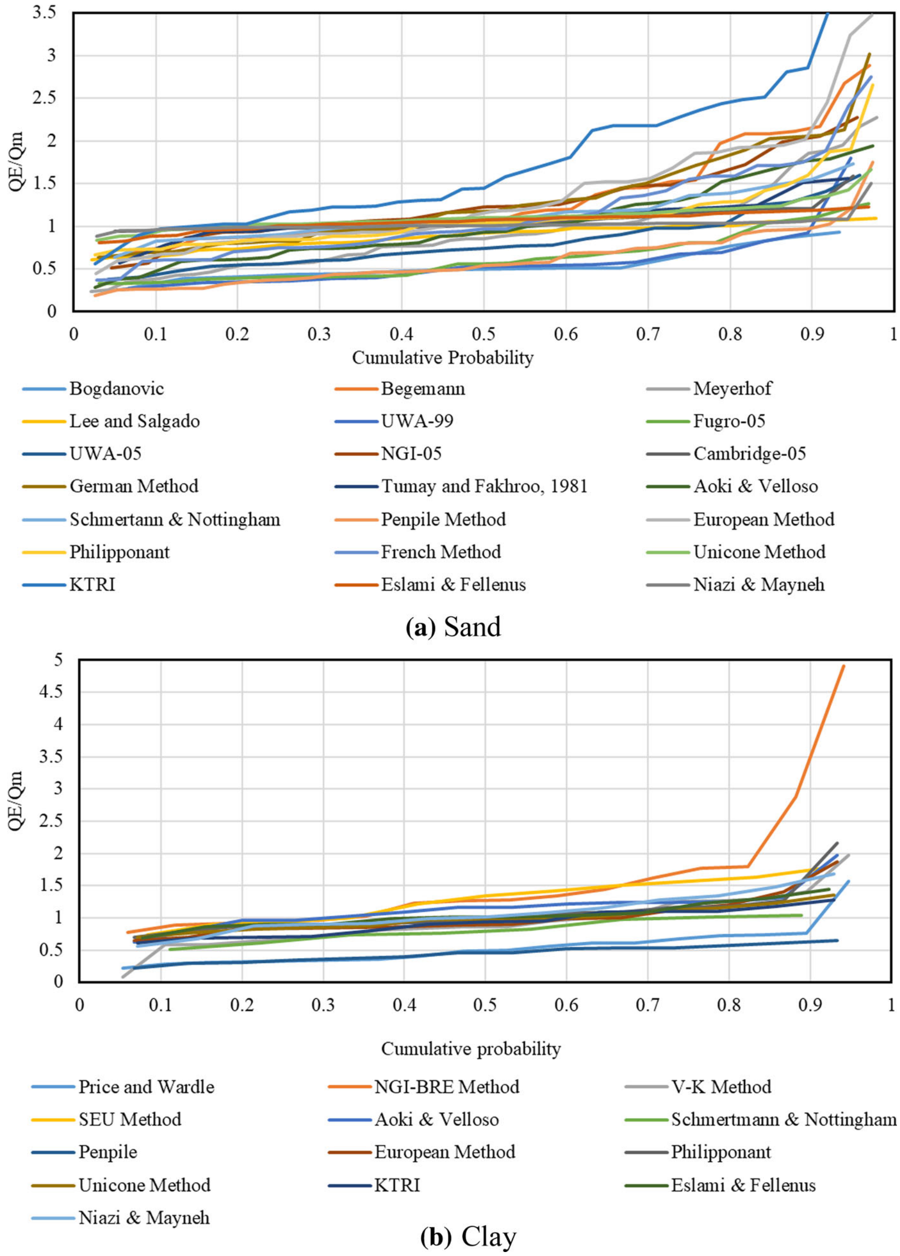
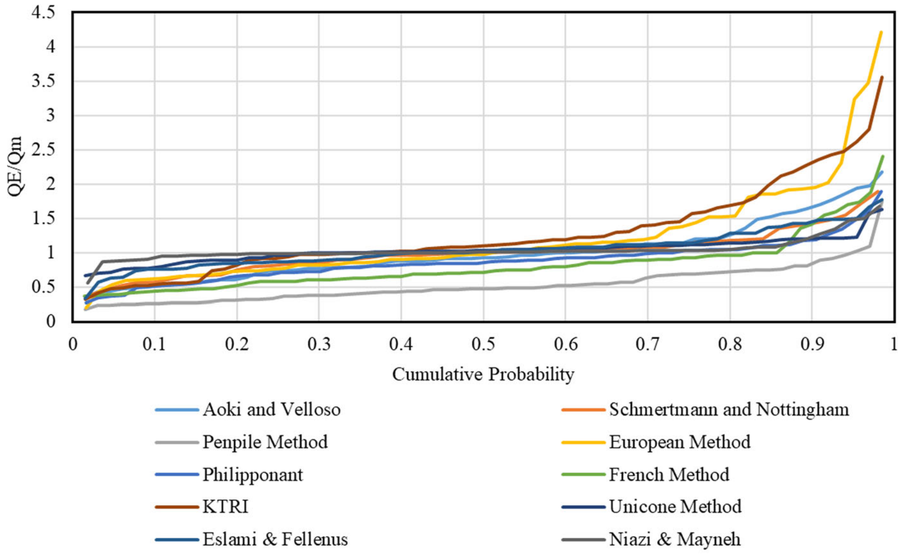


Fig. 9 Cumulative probability for Q_E/Q_M computed from various methods

- Based on the assessment of 25 CPT and CPTu based methods with 61 databases, amongst 25 methods, the one proposed by Eslami and Fellenius (1997) is the most accurate in estimating the ultimate bearing capacity of piles driven into clay and Niazi and Mayne method (Niazi and Mayne 2016) has the most accurate prediction in sand and mixed soil.
- Three relative reliability values amongst the 25 presented methods belong respectively to Niazi and Mayne (2016), Eslami and Fellenius (1997), and Cambridge-05 method (White and Bolton 2005) with ranks 1, 2 and 3 in the sand.
- In clay, Eslami and Fellenius method (Eslami and Fellenius 1997) with rank number 1 has the most relative reliability. The UniCone (Eslami and Fellenius 1997; Fellenius 2002) and KTRI

Fig. 9 continued



(c) Mixed Soil

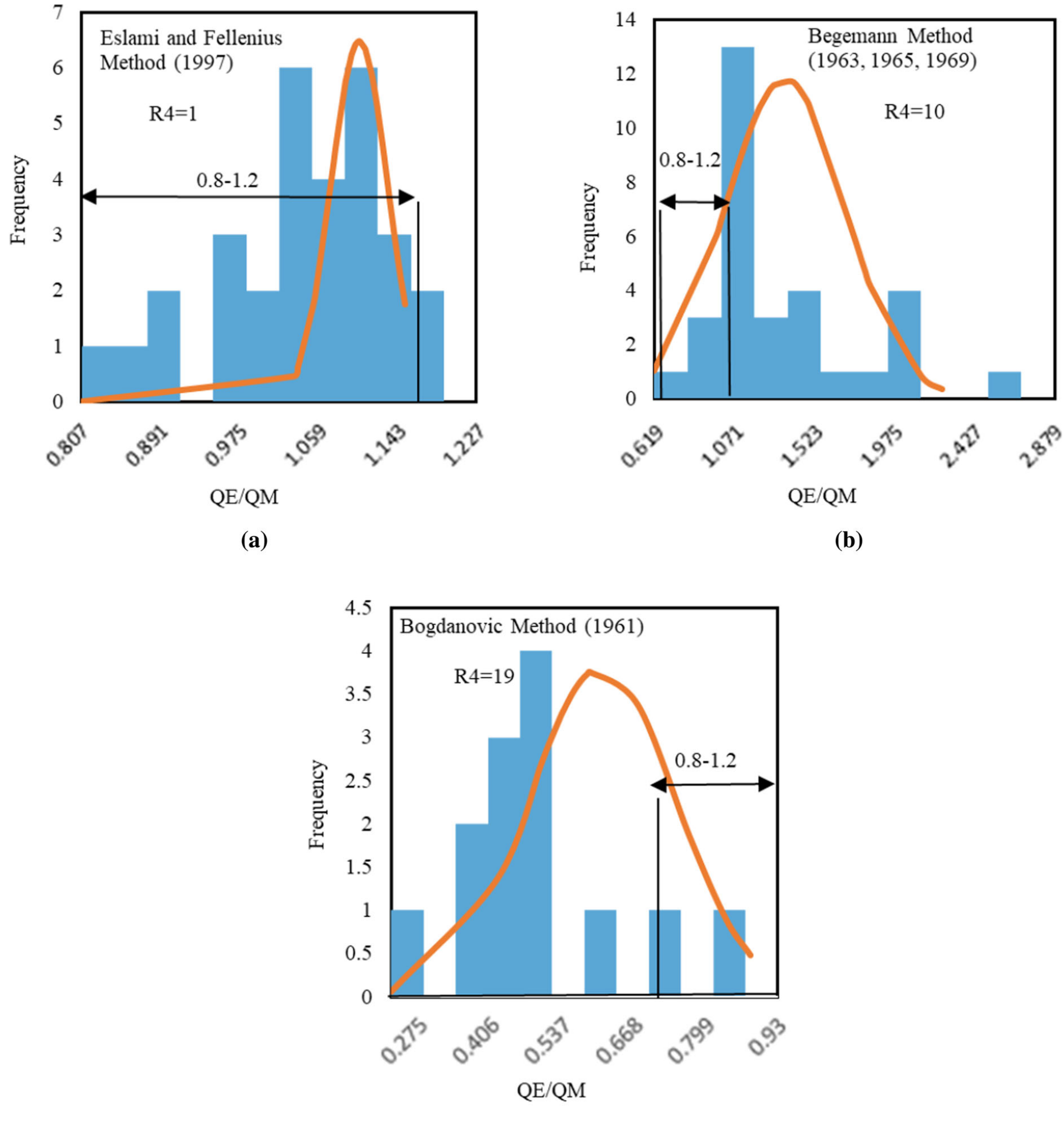
(Takesue et al. 1998) methods have the second and third relative reliability values, respectively.

- In mixed soil, Niazi and Mayne (Niazi and Mayne 2016) presented a method ranking one. Eslami and Fellenius method (Eslami and Fellenius 1997) and the UniCone method (Eslami and Fellenius 1997; Fellenius 2002) with rank number 2 and 3 have higher accuracy.

There are a number of reasons why some methods perform well in prediction of pile capacities while others do not. A chief reason is that some researchers have introduced methods ignoring the soil type, pile installation methods or pile material types in which approximation becomes a brilliant factor in such methods. If they had classified their methods in more details for pile installation, soil type and pile material, there would have been much more accurate methods. Unfortunately, some of the methods did not do these classifications. For instance, they presented their methods in all soil types or in all pile types and it is obvious that they did not consider some facts. For example, for pile-soil friction along the pile shaft, the soil type, pile material, and interaction features are of great importance, or steel and concrete piles have different α values in conventional α-method. These are because of the fact that these researchers seek simplicity in order not to confuse practicing engineers. However, nowadays for economical consideration in the pile design, it may be preferable to consider all contributing parameters in methods predicting the axial capacity of piles.

Moreover, these CPT-based methods are empirical fitting; sometimes their databases might not have any variations resulting in the accuracy reduction of the methods. The variations of databases have significant effect on all the empirical methods. In conclusion, the performance of CPT-based methods depends on classifying soil and pile types and the ranges of databases.

It is recommended that the results of this investigation be considered in practice which can assist geotechnical engineers to have more precise designs through the best methods in each soil type. Moreover, it is necessary to develop more CPT and CPTu based methods and qualify existing methods for better prediction of pile capacity. Both are beyond the scope of this paper and need further investigation.



(a)

(b)

(c)

Fig. 10 Twenty percent accuracy from the histogram and lognormal distribution for Q_E/Q_M in sand

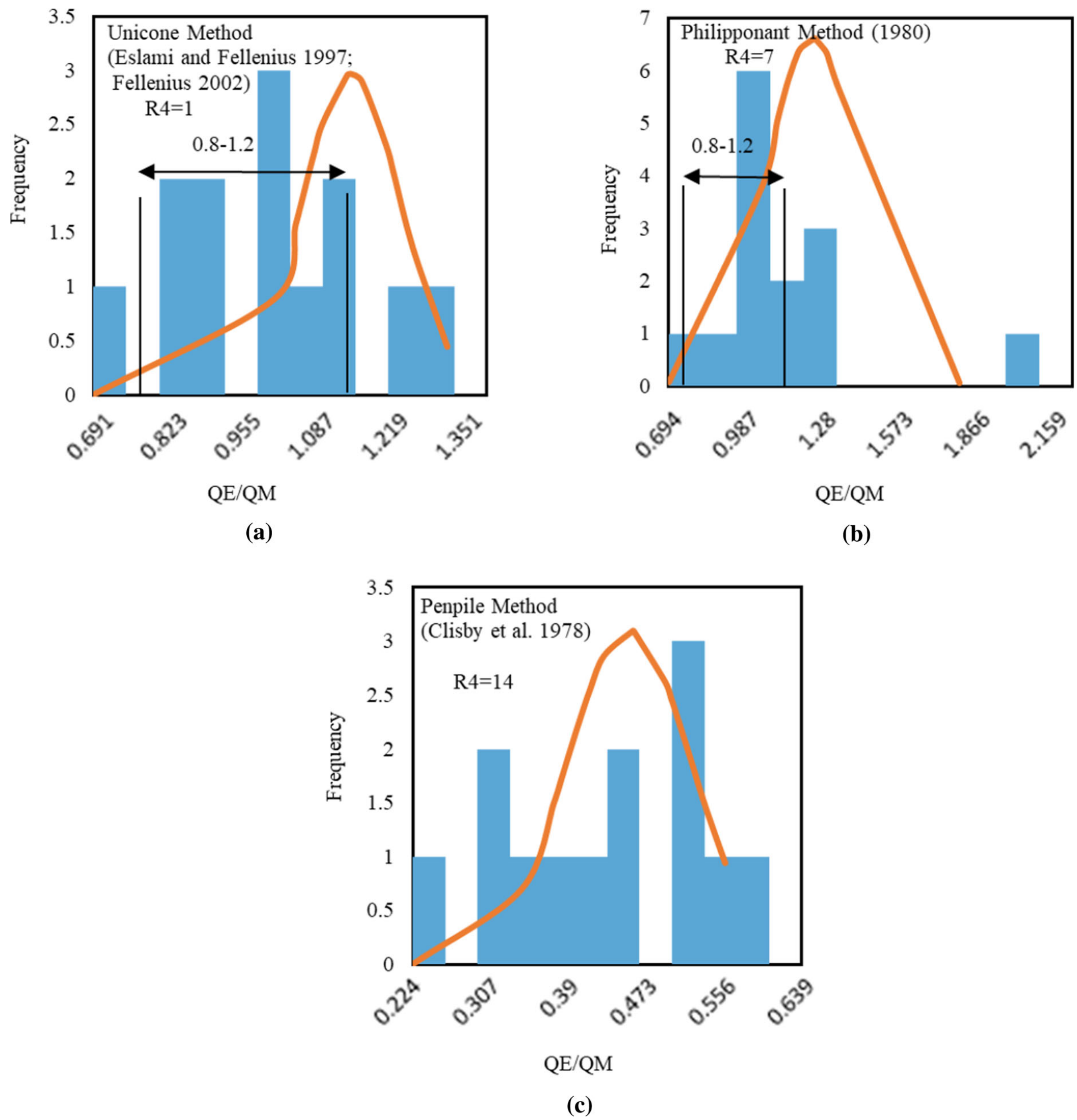


Fig. 11 Twenty percent accuracy from the histogram and lognormal distribution for Q_E/Q_M in clay

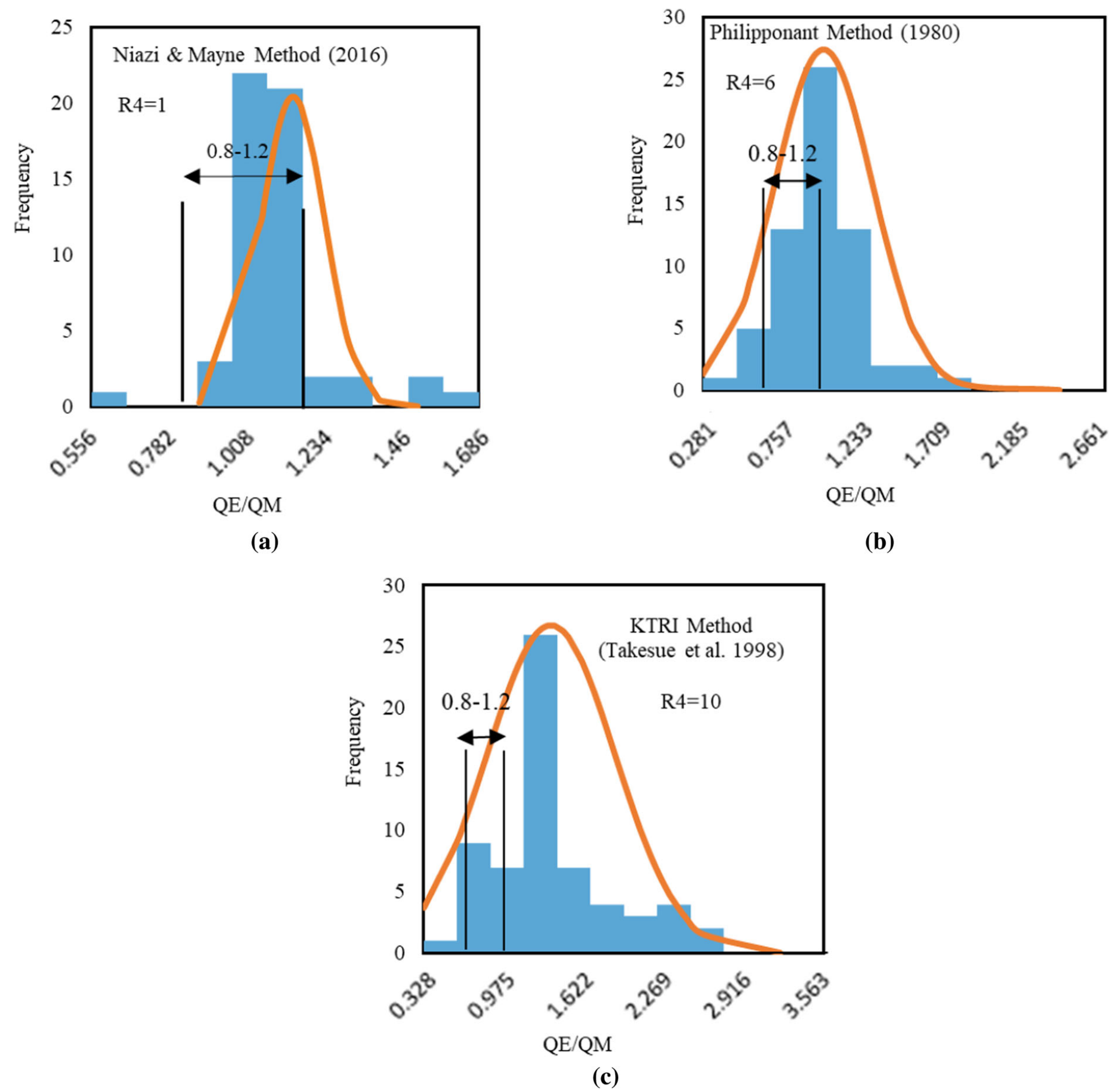


Fig. 12 Twenty percent accuracy from the histogram and lognormal distribution for Q_E/Q_M in mixed soil

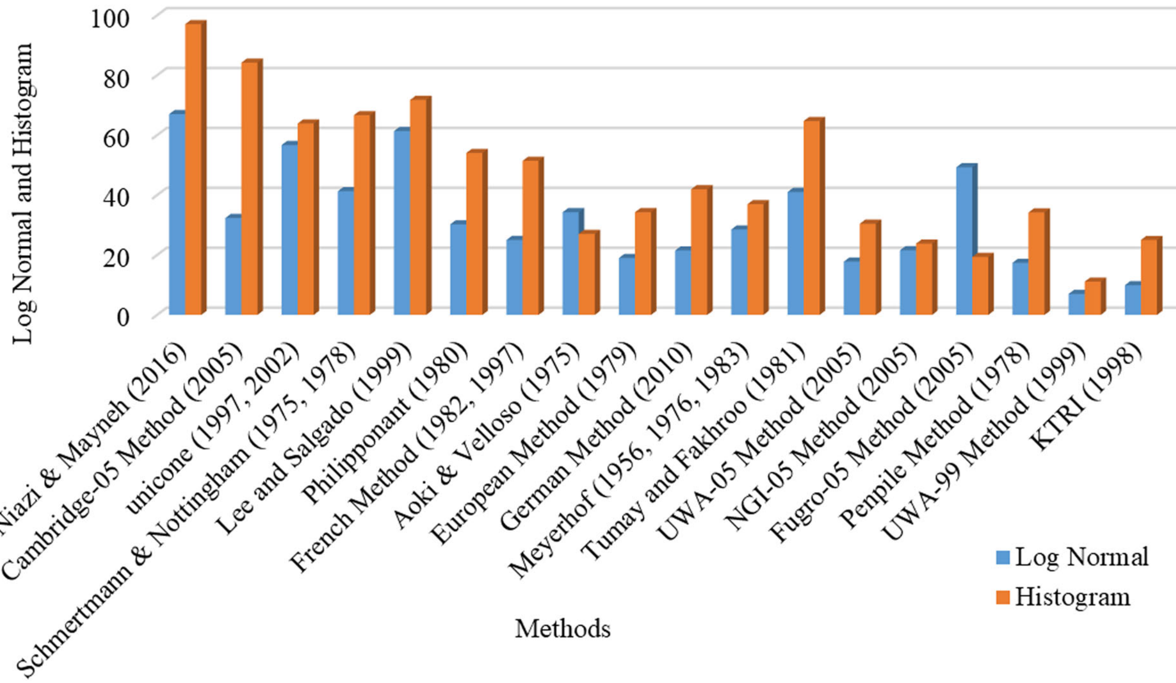


Fig. 13 Comparison of methods based on the accuracy of 20 percent of the histogram and the lognormal distribution curve for the ratio of Q_E/Q_M in sand

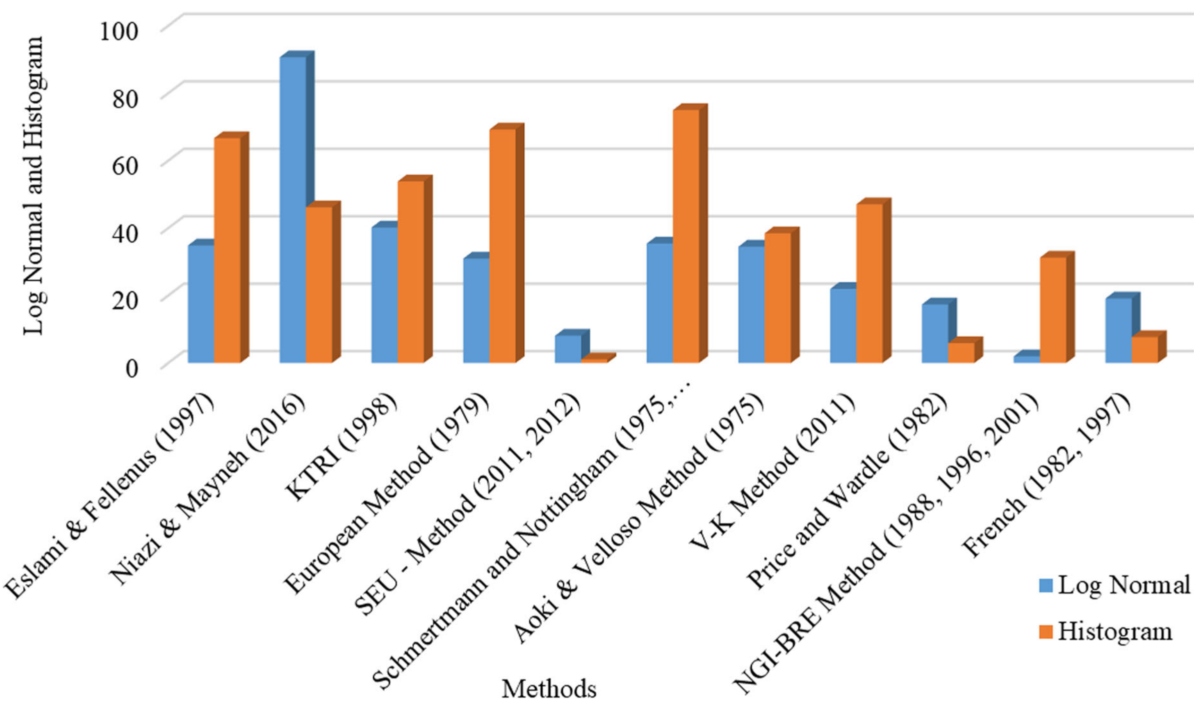


Fig. 14 Comparison of methods based on the accuracy of 20 percent of the histogram and the lognormal distribution curve for the ratio Q_E/Q_M in clay

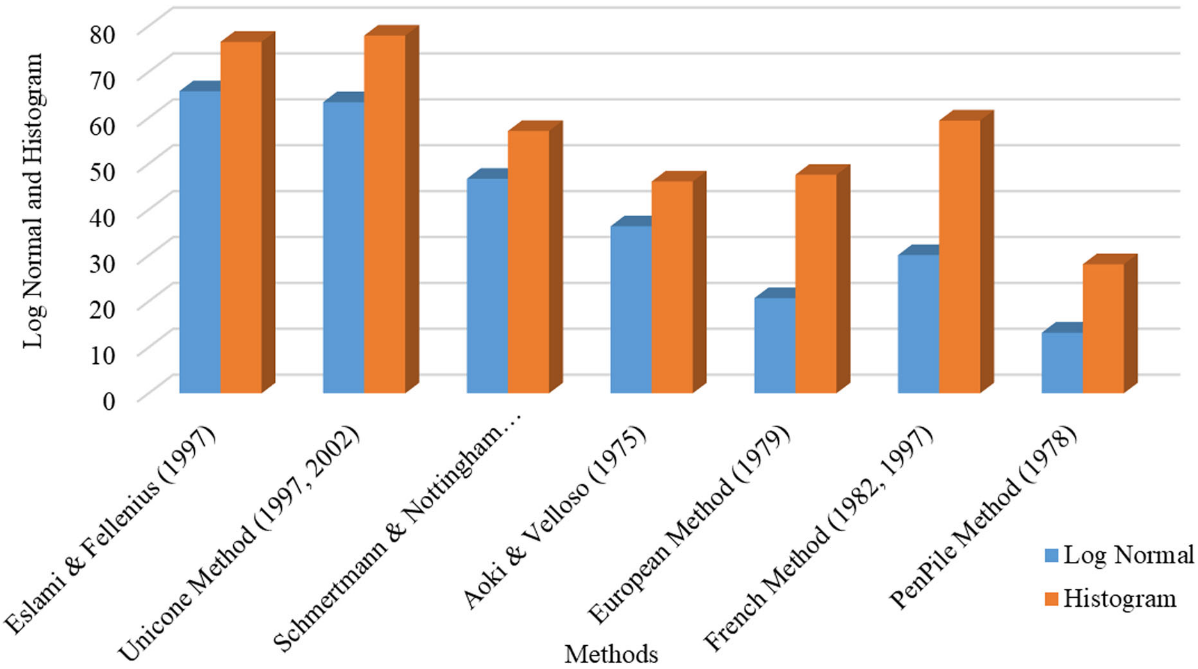


Fig. 15 Comparison of methods based on the accuracy of 20 percent of the histogram and the lognormal distribution curve for the ratio Q_E/Q_M in mixed soils

Appendix: Direct CPT and CPTu Methods

For more details about these 25 methods refer to "Cone Penetration Test-Based Direct Methods for Evaluating Static Axial Capacity of Single Piles: A State-of-the-Art Review" (Niazi and Mayne 2013) (Table 5).

Table 5 Summary of direct CPT and CPTu based pile design methods

No.	Methods	Design equations		Comments
		Pile unit side resistance (f_s)	Pile unit end bearing (q_b)	
1	Bogdanovic (1961)	$f_s = q_s \cdot \left[\frac{(\pi \cdot d_{CPT})}{(\pi \cdot d)}\right]$	$q_b = q_{ca(tip)}$	For driven and jacked concrete piles in dense sand
2	Begemann (1963, 1965, 1969)	f_s is the function of cone tip resistance (q_c) and sleeve friction (q_s)	$q_b = \frac{q_{c1}+q_{c2}}{2}$	For driven piles in sandy soils
3	Aoki and Velloso (1975)	$f_s = \frac{q_{ca(side)} \cdot \alpha_s}{F_s} \leq 120kPa$	$q_b = \frac{q_{ca(tip)}}{F_b} \leq 15MPa$	For piles in all soil types depends on soil type $\alpha_s(\%) = 1.4$ in sand; $\alpha_s(\%) = 2.0$ in silty sand; $\alpha_s(\%) = 2.2$ (sandy silt); $\alpha_s(\%) = 2.4$ (silty sand with clay or sandy clay); $\alpha_s(\%) = 2.8 - 3.0$ (clay-sand-silt mix); $\alpha_s(\%) = 3.4$ (clayey silt); $\alpha_s(\%) = 4.0$ (silty clay); $\alpha_s(\%) = 6$(clay) Empirical factor F_s depends on pile type: F_s = 7.0 (drilled shafts); F_s = 5.0 (driven cast-in-situ); F_s = 3.5 (steel and PCC) Empirical factor F_b depends on pile type: F_b = 3.5 (drilled shafts);F_b = 2.5 (driven cast-in-situ);F_b = 1.75 (steel and PCC)
4	Nottingham (1975), Schmertmann (1978)	In Clay: $f_s = \alpha_c.q_s$ In Sand: $f_s = \alpha_s.q_s \leq 120kPa$ or $f_s = C.q_c \leq 120kPa$	In Sand: n$q_b = \frac{q_{c1}+q_{c2}}{2} \leq 15MPa$In Silty Sand: $q_b = \frac{q_{c1}+q_{c2}}{2} \leq 10MPa$	For driven concrete, steel and timber piles, and drilled shafts in all soil types $\alpha_c = fctn(f_s) = 0.2 - 1.25\alpha_s = fctn(z/d)$ $C(\%) = 0.8 - 1.8$
5	Penpile (Clisby et al. (1978)	$f_s(MPa) = \frac{q_s}{(1.5+14.47q_s)}$	In Sand: $q_b = 0.125q_{ca(tip)}$ In Clay: $q_b = 0.25q_{ca(tip)}$	For piles in all soil types
6	European De Ruiter and Beringen (1979)	In Clay: $f_s = \propto .S_{u(side)} \leq 120kPa$In Sand: $f_s = \min[q_s, \frac{q_{ca(side)}}{300}(compresion), \frac{q_{ca(side)}}{400}(tension), 120kPa]$	In Clay: $q_b = N_c.S_{u(tip)} \leq 15MPa$ In Sand: Nottingham (1975), Schmertmann (1978)	For offshore piles in all soil types $\propto = 1$ (NC clay); $\propto = 0.5$ (OC clay)

Table 5 continued

No.	Methods	Design equations		Comments
		Pile unit side resistance (f_s)	Pile unit end bearing (q_b)	
7	Philipponnat (1980)	$f_s = \frac{q_{ca(side)} \cdot \propto_s}{F_s} \leq f_{p(max)}$	$q_b = K_b \cdot q_{ca(tip)}$	For all pile types in all soil types $\propto_s$ = 1.25 (driven PCC piles and drilled shaft with casing); $\propto_s$= 0.85 [drilled shaft (d < 1.5 m)]; $\propto_s$= 0.75 [drilled shaft (d > 1.5 m)]; $\propto_s$= 1.10 [H-piles (circumscribed perimeter)]; $\propto_s$= 0.6 (driven/jacked steel pipe piles); $\propto_s$= 0.3 (OE steel pipe pile) $F_s = 50$ (clay and calcareous clay); F_s = 60 (silt, sandy clay and clayey sand); $F_s = 100$ (loose sand); $F_s = 150$ (medium dense sand); $F_s =$ 200 (dense sand and gravel) $f_{p(max)} = 120$ [driven PCC piles, H-piles (circumscribed perimeter) and drilled shaft with casing]; $f_{p(max)} = 100$ [drilled shaft (d < 1.5 m)]; $f_{p(max)} = 80$ [drilled shaft (d > 1.5 m)]; $f_{p(max)} = 50$ (driven/jacked steel pipe piles); $f_{p(max)} = 25$ (OE steel pipe pile) depends on soil type: $K_b = 0.35$ for gravel; $K_b =$ 0.4 for sand; $K_b = 0.45$ for silt; $K_b = 0.5$ for clay
8	Tumay and Fakhroo (1981)	$f_s = K.q_s$	Schmertmann and Nottingham method (1975, 1978)	For all pile types in all soil types
9	Price and Wardle (1982)	$f_s = K_s.q_s$	$q_b = K_b.q_{ca(tip)}$	For driven and jacked piles, and drilled shafts in stiff clay K_s = 0.53 (driven piles); K_s = 0.62 (jacked piles); K_s = 0.49 (drilled shafts) K_b = 0.35 (driven piles) and K_b = 0.3 (jacked piles)
10	Mayerhof (1976), Meyerhof (1956, 1983)	$f_s = n_{sf} \cdot q_s$ or $f_s = 0.5 \cdot n_{sq} \cdot q_c$	$q_b = q_{ca(tip)} \cdot C_1 \cdot C_2$	For driven piles and drilled shafts in sandy soils n_{sf} = 1 (driven piles); $n_{sf} = 0.7$ (drilled shafts) n_{sq} = 1 (driven piels); $n_{sq} = 0.5$ (drilled shafts)
11	French Bustamante and Frank (1997), Bustamante and Gianeselli (1982)	$f_s = \frac{q_s}{K_s} \leq f_{s(max)}$	$q_b = K_b \cdot q_{eq(tip)}$	for all pile types in all soil types $K_s = 30$–150 depending on soil type, pile type, and installation procedure

Table 5 continued

No.	Methods	Design equations: Pile unit side resistance (f_s)	Design equations: Pile unit end bearing (q_b)	Comments
				for non-displacement pile: K_b = 0.375 (clay and/or silt); K_b = 0.15 (sand and/or gravel); K_b = 0.20 (chalk) for displacement pile: K_b = 0.60 (clay and/or silt); K_b = 0.375 (sand and/or gravel); K_b = 0.40 (chalk)
12	Eslami and Fellenius (1997)	$f_s = C_s \cdot q_E$	$q_b = q_{Eg}$	For all pile types in all soil types $C_s(\%) = 0.4 - 8.0$
13	KTRI Takesue et al. (1998)	f_s is the function of measured q_s and Δu_2	This method does not indicate a means for evaluating q_b	For all pile and soil types
14	Lee and Salgado (1999)	This method does not indicate a means for evaluating f_s	$q_b \approx \frac{q_t}{\left[1.90 + \frac{0.62}{\left(\frac{w_b}{d}\right)}\right]}$	For piles in sands
15	UWA-99 Nicola and Randolph (1999)	This method uses practical stress approach (β – method)	For closed-ended piles: $q_{b,0.1} = \frac{q_c.\lambda.m.\left(\frac{w_b}{d}\right)}{\left(\frac{w_b}{d}+c\right)}$ For open-ended piles: based on Variation of normalized q_b with effective overburden stress for $w_b/d = 0.1$	For driven pipe piles in medium to very dense homogeneous sand m = 0.7; c = 0.03; λ = 1.75 – 0.5 $\sigma'_{v0}/\sigma_{atm}$ (for $\sigma'_{v0} < 200kPa$) λ = 0.75 (for $\sigma'_{v0} \geq 200kPa$)
16	NGI-BRE Almeida et al. (1996), Powell et al. (2001), Powell and Quarterman (1988)	$f_s = \frac{q_{t(net)}}{K_1}$	$q_b = \frac{q_{t(net)}}{K_2}$	For driven and jacked piles in clay k_1 = 10.5 + 13.3log[$q_{t(net)}/\sigma'_{v0}$] k_2 = N_{kt}/9; N_{kt} = 15 (soft – firm intact clays); N_{kt} = 25 to 35 (fissured to hard clays)
17	Unicone Eslami and Fellenius (1997), Fellenius (2002)	$f_s = C_s.q_E$	$q_b = C_t.q_{Eg}$	For all pile types in all soil types $C_s(\%) = 0.4 - 8.0$ If d $\leq$ 0.4 m $C_t = 1$ If d > 0.4 m $C_t = \frac{1}{3d}$
18	Cambridge White and Bolton (2005)	This method does not indicate a means for evaluating f_s	$q_b \approx 0.9q_{c,ave}$	Based on CE pipe piles, and PCC piles, jacked or driven through upper soft into a lower hard sand layer
19	Fugro-05 Kolk et al. (2005)	For compression loading: $\frac{h}{r^*} \geq 4 \quad f_s = 0.08q_c\left(\frac{\sigma'_{v0}}{\sigma_{atm}}\right)^{0.05}\left(\frac{h}{r^*}\right)^{-0.9}\frac{h}{r^*} \leq 4f_s = 0.08q_c\left(\frac{\sigma'_{v0}}{\sigma_{atm}}\right)^{0.05}(4)^{-0.9}\left(\frac{h}{4r^*}\right)$ For tension loading: $f_s = 0.045q_c\left(\frac{\sigma'_{v0}}{\sigma_{atm}}\right)^{0.15}\left[\max\left(\frac{h}{r^*},4\right)^{-0.85}\right]$	$q_{b,0.1} = 8.5q_{c,ave}\left(\frac{\sigma_{atm}}{q_{c,ave}}\right)^{0.5}A_r^{0.25}$	For driven piles in silica sands, mostly for offshore piling $A_r = 1 - \left(\frac{d_i}{d}\right)^2$

Table 5 continued

No.	Methods	Design equations		Comments
		Pile unit side resistance (f_s)	Pile unit end bearing (q_b)	
20	UWA-05 Lehane et al. (2005)	$f_s = \left(\frac{f_t}{f_c}\right) \cdot \left[\frac{0.03 \cdot q_c \cdot A_{rs,eff}^{0.3}}{\left[\max\left(\frac{h}{d}, 2\right)^{-0.5}\right]} + \Delta\sigma'_{rd}\right] \cdot \tan\delta_{cv}$	$q_{b,0.1} = q_{c,ave} \cdot (0.15 + 0.45 \cdot A_{rb,eff})$	For driven piles in sandy soils $A_{rs,eff} = 1 - IFR \cdot \left(\frac{d_i}{d}\right)^2$ $IFR = \frac{\Delta L_p}{\Delta z}$ $A_{rb,eff} = 1 - FFR \cdot \left(\frac{d_i}{d}\right)^2$
21	NGI-05 Clausen et al. (2005)	$f_s = \left(\frac{Z}{L}\right) \cdot \sigma_{atm} \cdot F_{Dr} \cdot F_{sig} \cdot F_{tip} \cdot F_{load} \cdot F_{mat} \geq 0.1\sigma'_{v0}$	For Close-ended piles: $q_{b,0.1} = q_{c,tip} \cdot \left[\frac{0.8}{(1+D_r^2)}\right]$ For Open ended piles: $q_{b,0.1} = min\begin{bmatrix} q_{b,0.1}(Plugged), \\ q_{b,0.1}(unplugged) \end{bmatrix}$	For driven piles in sandy soils $F_{Dr} = 2.1(D_r - 0.1)^{1.7}$ $F_{sig} = \left(\frac{\sigma'_{v0}}{\sigma_{atm}}\right)^{0.25}$ F_{tip} = 1(driven OE), F_{tip} = 1.6(driven CE) F_{load} = 1(tension), F_{load} = 1.3(compression) F_{mat} = 1(steel), F_{load} = 1.2(concrete)
22	German Kempfert and Becker (2010)	f_s is the function of cone tip resistance (q_c) and installation of piles	q_b is the function of cone tip resistance (q_c) and installation of piles	For piles in sandy soils
23	V-K Kempfert and Becker (2010)	$f_s = K_{s(z)} \cdot q_{t(net)}$,	$q_b = 0.7q_{t(net),ave}$	$K_{s(z)} = 0.16(h/ul)^{-0.3}[Q_{tz}]^{-0.4} \leq 0.08$ ul = 1 m $Q_{tz} = q_{t(net),z}/\sigma'_{v0}$ at z
24	SEU Cai et al. (2011, 2012)	f_s is the function of q_s and Δu_2	Similar to Unicone Method	For PCC thin-wall and high-strength caissons, cement fly- ash grave pile in soft clays
25		$f_s = C_{se} \cdot q_E$	$q_b = C_{te} \cdot q_{Eg}$	For all piles in all soils

Table 5 continued

No.	Methods	Design equations		Comments
		Pile unit side resistance (f_s)	Pile unit end bearing (q_b)	
	Niazi and Mayne (2016)			$C_{se} = C_{se(mean)} \cdot \theta_{pile-type} \cdot \theta_{tc} \cdot \theta_{rate}$ $I_c = \sqrt[2]{\begin{bmatrix} (3.47 - LogQ_{tn})^2 \\ +(LogF_r + 1.22)^2 \end{bmatrix}}$ Q_{tn}: stress normalized cone resistance = $[(q_t - \sigma_{v0})/\sigma_{atm}]$. $\left(\sigma_{atm}/\sigma'_{v0}\right)^n$ $q_t = q_c + u_0(1-a)$ $q_E = q_t - u_2$ σ_{v0}: Total overburden stress. σ_{atm}: A reference stress = 100 kPa. σ'_{v0}: Effective overburden stress. $n = 0.381(I_c) + 0.05\left(\sigma'_{v0}/\sigma_{atm}\right) - 0.15 \leq 1.0$ $F_r = \left[q_s/(q_t - \sigma_{v0})\right] \cdot 100\% C_{te} = C_{te(mean)}$ $C_{te(mean)=10^{[0.325(I_c)-1.218]}}$ $C_{se(mean)=10^{[0.732(I_c)-3.605]}}$

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