AUT: Geo-CPT & Pile Database Updates and Implementations for Pile Geotechnical Design

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ABSTRACT: Due to uncertainties in geomaterial properties and modelling, a detailed and precise data source can significantly improve reliability indices. Accordingly, to facilitate quantifying the uncertainties, there are currently several databases in the realm of piling and CPT. AUT (Amirkabir University of Technology): Geo-CPT&Pile Database was initially developed in 2015 by 466 case records including pile and CPT records. At present, it is updated to the total number of 600 case records which is partly accessible online. Aiming at pile performance-based design, risk analyses and evaluation of optimum safety factor have been examined based on value engineering by Wasted Capacity Index (WCI). Subsequently, the performance of direct and indirect CPT methods for pile bearing capacity estimation has been assessed focusing on reliability-based approaches. In addition, a methodology was employed to predict the load-displacement and bearing capacity of driven piles interactively. Finally, an algorithm is implemented for pile geotechnical performance-based design through a selected database considering probabilistic, reliability and risk assessments.

KEYWORDS: AUT: Geo-CPT & Pile Database, Pile Capacity, CPT-based Methods, Performance-Based Design (PBD)

1. INTRODUCTION

Assessment and evaluation of geomaterials specifications, known as geotechnical site investigation, is one of the main and primary stages of design procedure. For more complicated projects, factors such as special subsurface conditions, site environment and particular serviceability aspects necessitate wider extent of investigations along with knowledge-based analysis and design at different stages.

Sources of data collection and synthesis mainly include borings, sampling, in-situ and laboratory testing, physical modelling as well as geophysical tests. Empirical, analytical and numerical approaches are employed coupled with these data sources for achieving an optimum design (Fellenius and Eslami, 2000).

For pile geotechnical design, the various approaches used to determine pile axial bearing capacity include static analysis, in-situ testing records, static load tests and dynamic analyses or tests. In static analysis methods, great uncertainties arise in selecting appropriate mechanisms of failure and soil parameters. Full scale pile loading tests are expensive and time-consuming, while reducing uncertainties in pile design profoundly. Dynamic analysis requires input parameters that can significantly bias the results, with a considerable limitation of not having bearing capacity estimations available prior to pile driving. Among these methods, use of in-situ tests, especially cone and piezocone penetration tests (CPT, CPTu) are more favoured and reliable because of their similarities with piles in performance, as well as rapidity and continuous subsurface profiling (Fellenius, 2002; Fellenius and Infante, 2002). This trend is practically well established where deep foundations are to be constructed in soft to medium subsoil deposits (Eslami and Fellenius, 1997; Mayne and Niazi, 2009; Eslami et al., 2017).

Geotechnical databases are known as helpful tools in research and practical applications for optimizing analysis and design. Employing databases facilitates quantifying the uncertainties, and subsequently, considering them in analyses via different statistical approaches. A number of investigations which can be performed by means of piling geotechnical databases are as follows:

- Comparing different soil behaviour classification (SBC) methods with geotechnical logs
- Studying effects of surrounding soil types on piles performance
- Back analysis of load-displacement behaviour and resistance distribution in piles
- Evaluating efficiency of pile design methods
- Validation of static and dynamic methods for bearing capacity estimation
- Interpretation of the ultimate bearing capacity of piles with different approaches.

2. COMMONLY USED CPT DIRECT METHODS

CPT records are applied in two main approaches for pile design: indirect and direct methods. Indirect methods, at first, use CPT measurements to estimate different soil parameters, and then, the bearing capacity is defined by the estimated soil parameters. On the other hand, direct methods employ CPT measurements directly to estimate the pile unit shaft and toe capacity.

More than 30 different CPT and CPTu based methods have been developed for determining the axial bearing capacity of piles. A review of these methods is made by Niazi and Mayne (2013) and Eslami and Fellenius (1997). Using CPT in pile design first started by Begemann (1969) for estimating the maximum pile embedment length. Afterwards, several efforts have been made to correlate the pile unit shaft and toe capacity with CPT measurements and to study different factors affecting the pile bearing capacity, e.g. installation procedure, scale effects, friction fatigue, plugging in low displacement piles, etc. A summary of more commonly used methods is presented in Table 1.

3. REVIEW OF A FEW PILE AND CPT DATABASES

A number of well-established geotechnical databases including piling and cone penetration testing records in literature are presented. Generally, these databases were used to study different aspects of determining pile capacity by means of in-situ tests which have illuminated the performance of some of the current methods.

Briaud and Tucker (1988) used 98 case records to evaluate performance of thirteen methods of estimating settlement and bearing capacity of piles by SPT, CPT and PMT. This database consists of 64 square concrete piles with the widths ranging from 36 to 46 cm, 27 H piles and 7 drilled shafts with the diameters from 30 to 41 cm. The pile embedment lengths vary between 3 and 25 m with the average of 12.2 m. The pile capacities range from 307 to 2890 kN with the average of 1213 kN.

Table 1 Summary of current CPT and CPTu-based methods

No.	Method/references	Pile unit side resistance (rs)	Pile unit end bearing (rt)
1	Meyerhof (1976)	$r_s = kf_s$, $k = 1$ $r_s = cq_c$, $c = 0.5\%$	$r_t = q_{c.a}c_1c_2$, $c_1 = \left(\frac{B+0.5}{2B}\right)^n$, $c_2 = \frac{D_b}{10B}$ D_b bearing embedment depth $n = 1\ (loose), 2\ (medium\ dense), 3\ (dense)$
2	LCPC (Bustamante and Gianeselli, 1982)	$r_s = \frac{1}{k_s}q_c$ $k_s = 30 - 150$	$r_t = \mathrm{k_b q_{eq}}$ $k_b = 0.4 \sim 0.55$
3	Dutch method (de Ruiter and Beringen 1979)	Compression: $r_s = \min[f_s, \frac{q_c}{300}, 120\ kPa]$ $Tension$: $r_s = \min[f_s, \frac{q_c}{400}, 120\ kPa]$	Similar to Nottingham (1975) and Schmertmann (1978)
4	Nottingham (1975) Schmertmann (1978)	$r_s = C_s q_c$, $r_s = Kf_s$ $C_s = 0.8\sim1.8\%$, $K = 0.8\sim2 (sand)$	$r_t = q_{ca}$
5	Unicone (Eslami and Fellenius, 1997)	$r_s = c_{se} \times q_E$ $q_E = q_t - u_2$, $c_{se} = 0.3\sim8\%$	$r_t = c_{te} \times q_{Eg}$ $q_{cg} = (q_{c1} \times q_{c2} \times q_{c3} \times \ldots \times q_{cn})^{\frac{1}{n}}$, $c_{te} = 1$
6	UWA-05 method (Lehane et al., 2005)	$r_s = \frac{f_t}{f_c}\left[0.03q_c A_{rs,eff}{}^{0.3}\left[\max\left(\frac{h}{B}, 2\right)\right]^{-0.5} + \Delta\sigma'_{rd}\right]\tan\delta_f$ $A_{rs,eff} = 1 - IFR\left(\frac{B_i}{B}\right)^2, \frac{f_t}{f_c} =$ $1\ in\ compression, 0.75\ in\ tension$ $IFR_{mean} \approx min\left[1, (\frac{B_i(m)}{1.5(m)})^{0.2}\right]$	$\frac{r_{t0.1}}{q_{c,avg}} = 0.15 + 0.45A_{rb,eff}$ $A_{rb,eff} = 1 - FFR\left(\frac{B_i{}^2}{B^2}\right)$ $FFR \approx min\left[1, (\frac{B_i(m)}{1.5(m)})^{0.2}\right]$
7	Fugro-05 method (Kolk et al., 2005)	Compression Loading: $h/R^* \geq 4 : r_s = 0.08q_c\left(\frac{\sigma'_{v0}}{p_{ref}}\right)^{0.05}\left(\frac{h}{R^*}\right)^{-0.90}$ $h/R^* \leq 4 : r_s = 0.08q_c\left(\frac{\sigma'_{v0}}{p_{ref}}\right)^{0.05}(4)^{-0.90}\left(\frac{h}{4R^*}\right)$ Tension Loading: $r_s = 0.045q_c\left(\frac{\sigma'_{v0}}{p_{ref}}\right)^{0.15}\left(\max(\frac{h}{R^*}, 4)\right)^{-0.85}$	$r_{t0.1} = 8.5q_{c,avg}(\frac{p_{ref}}{q_{c,avg}})^{0.5}A_r{}^{0.25}$ $A_r = 1 - \left(\frac{B_i{}^2}{B^2}\right)$
8	ICP-05 method (Jardine et al., 2005)	$r_s = a\left[0.029bq_c(\frac{\sigma'_{v0}}{p_{ref}})^{0.13}\left[\max(\frac{h}{R^*}, 8)\right]^{-0.38} + \Delta\sigma'_{rd}\right]\tan\delta_f$ a = 0.9 (OE piles in tension), 1.0 (all other cases) b = 0.8 (tension), 1.0 (compression) δ_f measured or estimated as fctn(d50)	$\frac{r_{t0.1}}{q_{c,avg}} = max\left[1 - 0.5\log\left(\frac{B}{B_{CPT}}\right), 0.3\right]$ The pile is fully plugged if: $B_i < 0.02(D_r - 30)$ or $B_i < 0.083\left(\frac{q_{c,avg}}{p_{ref}}\right)B_{CPT}$ $Fully\ Plugged$: $\frac{r_{t0.1}}{q_{c,avg}} = max\left[0.5 - 0.25\log\left(\frac{B}{B_{CPT}}\right), 0.15, A_r\right]$ Coring: $\frac{q_{b0.1}}{q_{c,avg}} = A_r$
9	NGI-05 method (Clausen et al., 2005)	$r_s = \left(\frac{z}{Dp_{ref}F_{D_r}F_{sig}F_{tip}F_{load}F_{mat}}\right) \geq 0.1\sigma'_{v0}$ $F_{D_r} = 2.1(D_r - 0.1)^{1.7}$ $F_{sig} = (\frac{\sigma'_{v0}}{p_{p_a}})^{0.25}$ $F_{tip} = 1.0\ (driven\ OE), 1.6\ (driven\ CE)$ $F_{load} = 1.0\ (tension), 1.3\ (compression)$ $F_{mat} = 1.0\ (steel),\ 1.2\ (concrete)$	Closed ended pile: $\frac{r_{t0.1}}{q_{c,tip}} = \frac{0.8}{1+D_r{}^2}$ Open ended pile $Plugged$: $\frac{r_{t0.1}}{q_{c,tip}} = \frac{0.7}{1 + 3D_r{}^2}$ $Unplugged$: $r_{t0.1} = r_{t,ann}A_r + r_{t,plug}(1 - A_r)$ $r_{t,ann} = q_{c,tip}, r_{t,plug} = \frac{12r_{s,avg}L}{\pi D_i}$ $r_{t0.1} = min(r_{t0.1,plugged}, r_{t0.1,unplugged})$
10	German method (Kempfert and Becker, 2010)	Defined based on the proposed chart of q_c-r_s	Defined based on the proposed chart of q_c-r_t
11	Modified UniCone (Niazi and Mayne, 2016)	$f_{pi} = C_{se} * q_E$; $C_{se} = C_{sei}\theta_{pile\ type}\theta_{tc}\theta_{rate}$; $C_{sei}.\theta_{pile\ type}.\theta_{tc}.\theta_{rate}$ are dependent to soil type; pile installation method, loading direction and loading rate; Defined based on proposed algorithm (Niazi and Mayne, 2016 and Niazi, 2014)	$q_b = C_{te(mean)} * q_E$; $C_{te(mean)} = 10^{0.325I_C - 1.2018}$ Defined based on proposed algorithm (Niazi and Mayne, 2016)

Note: $D = pile\ embedment\ depth$, $B = pile\ diameter$, $B_i = pile\ inner\ diameter$, $R = pile\ radius$, $R_i = pile\ inner\ radius$,
$h = height\ above\ pile\ tip$, $B_{CPT} = 0.036\ m$, $p_{ref} = 100\ kPa$, $R^* = \sqrt{R^2 - R_i{}^2}$, $A_r = 1 - \left(\frac{D_i{}^2}{D^2}\right)$, $\Delta\sigma'_{rd} = \frac{2G}{R^*}\Delta y$; $\Delta y \approx 2\ R_a \approx 0.02\ mm$,
$G = 185q_c q_{c1N}{}^{-0.7}$, or $G = q_c[0.0203 + 0.00125q_{c1N} - 1.216e^{-6}q_{c1N}{}^2]^{-1}$, $q_{c1N} = \frac{(q_c/p_{ref})}{(\sigma'_{v0}/p_{ref})^{0.5}}$, $D_r = 0.4\left[\ln\frac{q_{c,tip}}{22(\sigma'_{v0}p_{ref})^{0.5}}\right]$,
$\delta_f = friction\ angle\ between\ soil\ and\ pile$
OE= Open ended, CE= Closed ended

Alsamman (1995) presented a database of 95 full scale drilled shaft load tests from 29 sites in 8 countries (mainly in Germany and the United States) in order to evaluate five methods of bearing capacity estimation and to develop a new procedure of determining capacity by CPT. Records include 48 pile load tests in cohessionless soils, 16 load tests in cohesive soils and 31 load tests in mixed soils. Diameter of drilled shafts vary between 30 to 213 cm and the shaft lengths between 4.6 and 42 m. CPTs were mainly performed with mechanical cones and contain the cone tip resistance with depth. Ultimate loads were defined at shaft displacement of 5 percent of the diameter plus the elastic compression of the shaft. For shafts in tension the axial load at 12.7 mm of displacement were used to define ultimate load.

The **Eslami & Fellenius (1997)** database consists of 102 case records of 40 sites from 13 countries but mainly in the United States. The soils of the sites consisted of sediments of clay, silt and sand. Most of the CPT cases included in the data were obtained by electrical cone. Most of the CPT measurements were at a vertical spacing of 300 mm or smaller. Most of the piles have a square or round cross section and the pile materials are steel and concrete. All but 10 of the piles were installed by driving. The pile embedment lengths range from 5 to 67 m, the pile diameters from 200 to 900 mm, and the pile capacities from 80 to 8000 kN. 14 case records were instrumented and the toe and shaft resistances were determined separately. This database was used to evaluate and compare 6 methods of determining pile bearing capacity by CPT and CPTu.

Abu-Farsakh & Titi (2004) compiled results of static load tests on 35 square precast prestressed concrete (PPC) piles to evaluate applicability of 8 CPT based methods of determining bearing capacity. The piles embedment lengths range from 9 to 38 m and piles diameters range from 356 to 762 mm. Of the 35 piles, 26 piles were driven in clay soils and other 9 piles were driven in layered soils. The ultimate pile capacity from the load test was determined using Butler-Hoy tangent method (1977).

The UWA Database (Schneider et al., 2008) consists of 77 case records of impact driven piles and was used to evaluate seven design methods in siliceous sands. All CPT data were digitized to a depth interval of 0.1 m or smaller. The soils include sands with wide range of relative density. Diameters of piles are mainly less than 80 cm and pile lengths vary between 5 to 80 m, most of which are between 10 and 20 m. Pile capacities are mainly less than 5000 kN. In this database load at displacement of 10 percent of the pile diameter was defined as pile capacity in compression, if plunging failure was reached, otherwise hyperbolic extrapolation of Chin (1978) was used to estimate pile capacity. Pile capacity in tension was defined as the maximum uplift load less the pile weight.

The **Van Dijk & Kolk (2011)** database consists of 33 case records of driven piles at 15 different locations. All cases were installed in clay soils. Results of CPTs and equilibrium in situ pore pressure u_0 were determined at 0.1 m depth intervals. Diameters of piles vary between 102 and 812 mm and pile lengths vary between 3.6 and 71.4 m. Among 33 case records, 18 piles were tested in compression and 15 piles in tension. Time interval between pile installation and load tests varies between 0.25 and 134 days. The ultimate capacity of a pile was defined as the maximum resistance measured during the test, corrected for the effective weight of the pile (total weight of the pile minus the weight of the displaced soil).

The **Hassani (2010)** database includes 70 case records obtained from 16 sources, reporting data from 18 sites in 10 countries. The soils at sites consist of sediments of soft and stiff clay, silt, silty sand, and sand. Most of the CPT cases were obtained by electrical cone. All of the CPT measurements were at a vertical spacing of 25 to 300 mm. Most of the piles have a round cross section and the pile materials are steel and concrete. All but two of the piles were installed by driving. The pile embedment lengths range from 8.2 to 75 m, the pile diameters range from 270 to 813 mm, and the pile capacities vary from 485 to 6860 kN. This database was used for training Group Method of Data Handling (GMDH) type neural networks to model the effects of effective cone point resistance and cone sleeve friction on pile unit shaft resistance.

Eslami et al. (2011) employed 13 case records of driven pipe piles from 4 sites of Iran marine environments. The soils of the sites were mainly soft sensitive to stiff clay. Results of electrical piezopenetrometer for all cases were available. The pile embedment lengths range from 41 to 85 m, the pile diameters from 685 to 913 mm, and the pile capacities from 4700 to 16500 kN. This database was used to assess applicability of 5 CPT and CPTu based methods in Iran marine environments and static capacity derived from both static and dynamic load tests was used as reference test.

ZJU-ICL (2015) database was developed by Yang et al. (2015) with cooperation of Zhejiang University and Imperial College London database. It includes 115 records of driven piles in sand and is openly accessible for researchers to use.

Niazi and Mayne (2016) employed a database of piles and piezocone test results to present an enhanced version of the UniCone method (CPTu-based method of determining the axial bearing capacity of piles). The database consists of 153 case records of piles with various installation types including driven, bored, cast-in-situ, and jacked. The piles were constructed in both sandy and clayey soils. All the case records contain the measurements of excess pore pressure.

A summary of these CPT and piling databases characteristics is presented in Table 2

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Table 2 Summary of CPT and pile databases in geotechnical literature

No.	Database	Number of records	Installation	Soil
1	Briaud & Tucker (1988)	98	Driven, bored	Clay, Sand
2	Alsamman (1995)	95	Drilled shaft	Clay, Sand
3	Eslami & Fellenius (1997)	102	Driven, bored	Clay, Sand
4	Abu-Farsakh & Titi (2004)	35	Prestressed driven	Clay
5	UWA (2005)	77	Driven	Sand
6	Van Dijk & Kolk (2011)	33	Circular driven	Clay
7	Hassani (2010)	70	Driven, bored	Clay, Sand
8	Eslami et al. (2011)	13	Driven	Clay
9	ZJU-ICL (2015)	115	Driven	Sand
10	Niazi & Mayne (2016)	153	Driven, bored cast in-situ, jacked	Clay, Sand

4. AUT: GEO-CPT&PILE DATABASE

4.1 Establishment

With the primary aim for assessing different approaches of determining pile static capacity based on cone and piezocone penetration tests, AUT: Geo-CPT&Pile database has been compiled mainly from well-published and documented geotechnical engineering sources. It was first introduced in 2015 under the title of "AUT-CPT&Pile database" (Moshfeghi et al., 2015a,b). The database initially consisted of 466 records of pile loading tests as well as the results of cone or piezocone penetration tests carried out in the vicinity of the pile locations.

4.2 Updates and Accessibility

The AUT: Geo-CPT&Pile database is now further upgraded to the total number of 600 records. The case records have been obtained from 68 sources and are from 24 countries and the majority of cases are located in the United States.

All the case records include results of axial load tests and CPT records. CPT logs were digitized at depth intervals of 0.05, 0.1, 0.2, 0.3 and rarely 0.5 and 1 m using GetData Graph Digitizer 2.24. About 46% of CPT results include measurements of cone tip resistance (q_c) and sleeve friction (f_s), 29 % include only qc measurement, 21% include q_c, f_s, and pore pressure (u_2 or u_3) and other 4% include measurements of q_c and u_2 or u_3. Site soils include wide ranges of clayey, silty and sandy deposits.

Load tests records include head-down static load tests in compression or tension, static O-cell tests, dynamic load tests (PDA and CAPWAP) and statnamic load tests. Approximately 96% of load test results contain load-displacement diagrams, while for the rest of 4% of cases only the ultimate capacity is reported.

Case records consist of different pile types including driven piles, auger cast piles, drilled displacement piles, continuous flight auger piles (CFA), driven cast in-situ piles (DCIS), post grouted piles, jacked piles, vibro driven piles and helical piles. The pile materials are steel, concrete, composite (steel and concrete) and CFG (cement fly ash gravel) and the shapes of piles are round, square, pipe, triangular, octagonal, H, X and helical. Embedment lengths of the piles vary between 3.0 and 100 m, but mainly less than 50 m and the pile diameters range from 50 to 2500 mm with an average of 450 mm. The pile capacities range from 50 to 36000 kN with an average of 1620 kN.

A limited version of this database is currently accessible through the website of civil and environmental engineering Department of the Amirkabir University of Technology, AUT: (http://civil.aut.ac.ir/Default,en-US,Civil,Content,Document,Name,GeoData,TabID,273.aspx).

4.3 Organization

This database has been organized via Microsoft Access software, consisting of different sections allotted to general information, CPT data, pile characteristics, data sources, as well as a section for searching through the database for data with specified characteristics. Various sections of the database are shown in Figure 1 and described below:

- ***Figure 1a: General records form:*** As depicted, the first section of the database includes the list of all the records. Each record is given a unique identification name by which its source, CPT profiles and pile loading test can be distinguished. In this form, a summary of the records characteristics is presented as well. More detailed information on each record can be accessed through the "Details" button at the end of each row.
- ***Figure 1b: CPT data:*** the CPT profiles as well as the digitized results for each case can be found in this section of the database. The data are presented in MS Excel file which can be accessed by clicking on the preview link provided.
- ***Figure 1c: Piles characteristics:*** this part is allocated to the information on pile geometry, installation type, along with the results of pile loading tests, both diagram and digitized formats. The time interval between pile installation and performing the load tests and the separated shaft and toe capacities, if available, are also provided. As shown in Figures 1c, this part is divided into some subsections in terms of pile installation types. Similar to the "CPT results" section, the MS excel files for the pile load test results can be accessed through the preview links.
- ***Figure 1d: pile load tests:*** demonstrates the information on pile load tests and the load-displacement diagrams.
- ***Figure 1e: Information sources:*** In this part of the database, the original sources of the data are provided for more detailed reference. It should be mentioned that the name of the reference file for each case is the three digit number at the beginning of the case ID. For instance the source file for the case with the ID "064-SANDPOINT" is "064".
- ***Figure 1f: Search form :*** In this part, searching through the database is provided based on different factors and specifications including pile type and characteristics, soil type, available CPT and load test data, etc.

5. APPLICATION OF THE DEVELOPED DATABASE

AUT: Geo-CPT&Pile database, similar to other well-established databases, can be employed as a helpful tool in research and practical applications for optimizing pile analysis and design mainly in soft to medium deposits which dictates deep foundations as substructure. Considering the extent of the case records in terms of soil diversity, pile installation types and properties, this database facilitates the evaluation and comparing different CPT and CPTu-based methods of determining pile capacity considering uncertainties, probabilistic as well as reliability-based approaches, or any other performance-based design approaches.

A number of investigations performed by means of this database are briefly introduced.

5.1 Comparison of Load-Displacement Interpretation Criteria

It is necessary to apply a unique failure criterion in defining the ultimate capacity to make the load test results comparable. Six failure criteria have been summarized by Fellenius (2001). Among these approaches, the Davisson offset limit (Davisson, 1972), the Brinch-Hansen 80% criterion (Hansen, 1963) and the Chin-Kondner extrapolation (Chin, 1978) are more commonly used. The Davisson limit load usually reports loads in lower part of load-displacement diagram, while, the Chin-Kondner extrapolation assumes an asymptotic curve, and the load is defined by extrapolation, and therefore the results are always greater than the maximum load applied in the test. The Brinch-Hansen 80% criterion normally agrees well with the intuitively perceived “plunging failure” of the pile (Fellenius, 2001). Comparison of different interpretation criteria confirms this trend as well (Moshfeghi et al., 2015b).

Forty-three records of piles driven in sand deposits were employed to investigate the effect of ultimate capacity interpretation criteria from load displacement diagrams. In this regards, four criteria were selected: load at 10% of pile diameter, Brinch Hansen 80% criterion, Chin-Kondner, and Davisson Limit. Compariosons indicate that the Brinch Hansen 80% criterion and the load at the displacement of 10% of the pile diameter were the two most consistent criteria as far as CPT-based approaches are concerned. However, the Brinch Hansen 80% criterion showed less scatter than the 10% diameter criterion. Figure 2 shows an example of interpreting the load-displacement diagram using these four criteria for a closed-end driven pipe pile with the diameter of 356 mm and the embedment length of 7 m.

5.2 Risk Analysis and Optimum Safety Factor

In engineering, risk is defined as the product of probability of occurrence of an unwanted situation and its adverse consequences. However, in geotechnical engineering risk is evaluated in terms of probability of failure rather than the way risk is described due to the priceless value of human life (Fenton and Griffith, 2008). The study performed by Moshfeghi and Eslami (2018a) deals with risk, cost optimization approach and optimum safety factors for the axial bearing capacity of driven piles in sand using CPT-based methods. The database of seventy six records is employed to evaluate the performance of nine commonly used direct CPT-based methods was evaluated against the database. Analysis of different failure criteria shows that the Hansen 80% criterion leads to more consistent results with the CPT-based methods. In addition, almost all of the investigated methods showed promising performance in estimating

(a) (b) (c) (d) (e) (f)

Figure 1 Different sections of the AUT: Geo-CPT&Pile database: (a) General records form, (b) CPT data, (c) Pile characteristics, (d) Pile loading test results, (e) Data sources, (f) Search section

the axial bearing capacity of driven piles. The attained safety factors range from 1.6 to 3.1 for all records, 1.4 to 3.1 for piles in compression, and 1.4 to 2.2 for the piles in tension. In this approach, the lower factor of safety does not necessarily show either better performance or more precision, but the safety factors consider both accuracy and precision of the methods simultaneously. For instance, the Schmertmann (1978) method underestimates the tensile pile capacity by about 30% and as a result the factor of safety of 1.68 is attained. It means a lower safety factor is needed to reach a certain level of safety because the predictions of this method were already conservative. On the other hand, take UniCone, for instance. The average Q_p/Q_m is 1.178 for this method, which means it tends to overpredict the pile capacity and its predictions are unconservative. Therefore, the safety factor of as high as 2.5 is attained. From this point of view, it may be derived that standard deviation, that is, scatter in results is of primary importance rather than the average of the predicted to the measured ratios, because in this approach the average Q_p/Q_m ratios are more or less modified by imposing the recommended safety factors.

In the next step, to make the values of the safety factors more perceptible and comparable with common values of safety factor used in geotechnical practice, the optimum safety factors can be divided by the corresponding average Q_p/Q_m ratios obtained from the same database. Table 3 presents the values of the optimum safety factors divided by the Q_p/Q_m ratios. In this way, it was concluded that the optimum safety factor can be broken into two factors, one of which

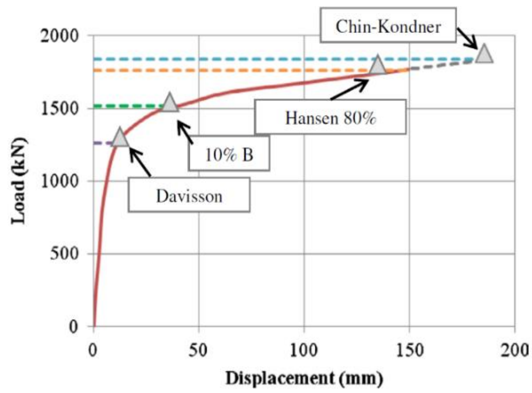

Figure 2 Example of interpretation of load-displacement diagram (Moshfeghi and Eslami, 2016)

allows for overprediction or underprediction of the methods. And, the other factor takes the uncertainties and scatter of the results into account. As can be conceived from Table 3, these factors are within or close to commonly used safety factor ranges in practice. Albeit, it is apparent that for the methods of which the average of the Q_p/Q_m ratios was close to unity, the optimum safety factors will not change significantly.

Table 3 Optimum safety factors divided by the geometric average of Q_p/Q_m ratios (Moshfeghi and Eslami, 2018a)

Methods	All	Compression	Tension
Meyerhof (1983)	2.26	2.05	2.05
Schmertmann (1978)	2.67	2.31	1.68
LCPC (1982)	1.99	2.01	1.63
Unicone (1997)	2.12	2.09	1.53
UWA (2005)	2.51	2.43	1.78
NGI (2005)	2.36	2.77	2.24
Fugro (2005)	2.61	2.37	1.97
ICP (2005)	3.27	3.07	1.96
German (2010)	2.01	2.12	1.68

Then, the efficiency of the methods was evaluated via Wasted Capacity Index (WCI) proposed by Long et al. (1999) as depicted in Figure 3. WCI is calculated by Eq. (1).

$$WCI = \int_0^{\left(\frac{Q_p}{Q_m}\right)_{required}} P(x) \frac{\left(\frac{Q_p}{Q_m}\right)_{required}}{x} dx \qquad (1)$$

where, $(Q_p/Q_m)_{required}$ is a desired level of uncertainty, and P(x) is the log-normal distribution function. The x is the ratio of (Q_p/Q_m). The distribution of probability for x, P(x), and $(Q_p/Q_m)_{required}$ is independent of bias.

The WCI is a measure of how inefficiently a method predicts capacity. A precise method will be very efficient and accordingly has a low WCI. On the other hand, a less precise method requires a more conservative design, thus a greater WCI. Wasted capacity is simply referred to the extra capacity for which a foundation must be designed to account for uncertainties, that is, the higher the level of uncertainties, the higher the wasted capacity. Assessments indicate that the German (2010), LCPC (1982), Meyerhof 1983), UniCone (1997) and UWA (2005) methods have shown the most efficient predictions at their optimum factor of safety.

5.3 Non-Stationary Reproduction of CPT Data

Jamshidi et al. (2018) developed an algorithm for realisation of CPT data based on non-stationary random field. The proposed algorithm

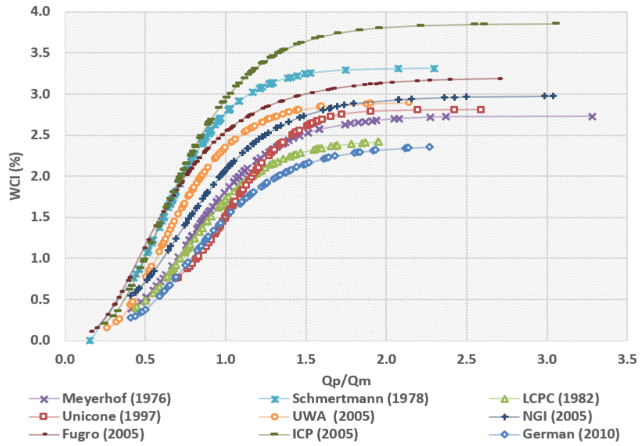

Figure 3 Variation of Wasted Capacity Index (WCI) with the predicted to the measured capacity ratio (Moshfeghi and Eslami, 2018a)

imposes soil layering alongside soil inherent variability based on Eslami and Fellenius (2004, 2006) soil classification chart. After detection of soil layering based on the simplified proposed approach, the statistical characteristics of soil are defined as multi-criteria functions, assembled into the non-stationary auto-covariance matrix and the routines continue in Monte Carlo scheme. Figure 4 provides the efficiency of the method in realisation of CPT record (q_c) for four cases. The ability of reproducing CPT records enables geotechnical engineers to consider the effect of uncertainties associated with soil spatial variability in their designs.

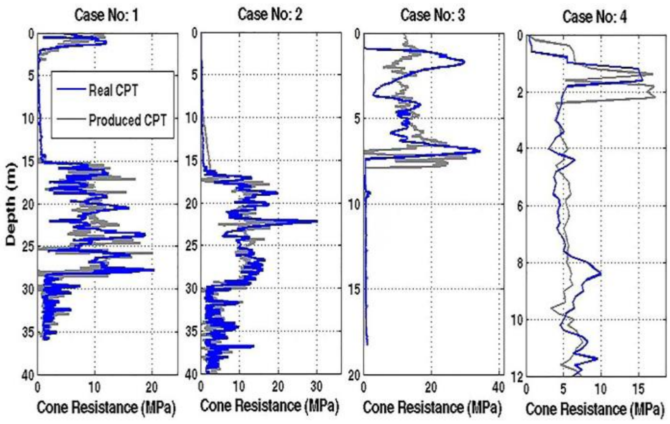

Figure 4 Representative simulation of CPT record (q_c) (Jamshidi et al., 2018)

5.4 Statistical and Probabilistic Assessment

Due to different sources of uncertainty, there are several methods developed for estimation of pile axial capacity since the very first employment of piles in foundation systems. All these methods render a wide range of estimations. Several studies by Briaud and Tucker (1988), Schneider et al. (2008), Dithinde et al. (2011) and Moshfeghi and Eslami (2016) confirm the effect of uncertainties associated with the pile bearing capacity prediction as a result of inherent soil variability, measurement error, model errors and transformation uncertainty (Phoon and Kulhawy, 1999 a,b). Since uncertainties are unavoidable in pile design, it is noteworthy to evaluate performance of different predictive methods.

Heidari et al. (2019 a,b) investigated the effect of uncertainties (model error and transformation uncertainty) on pile axial bearing capacity for various methods in terms of efficiency ratio, i.e. the ratio of resistance factor to mean resistance bias factor; φ/λ_R and actual factor of safety, i.e. the product of resistance bias factor to factor of safety; FS×λ_R introduced by Paikowsky et al. (2004). Model factor or in other words resistance bias factor, i.e. λ_R, is defined as the ratio of measured to predicted capacity and its statistical and probabilistic properties have been the measure of accuracy and performance of different predictive methods. In order to compare the performance of different static analyses, SPT and CPT-based methods, a database of 60 driven piles was selected including different pile and soil types. It was shown in Figure 5 that in-situ-based methods predict the bearing capacity more reliably than static analyses.

Also, CPT-based methods predict the bearing capacity more efficiently than SPT-based methods for the current database. Furthermore, Figure 5 suggests that the efficiency ratio has little sensitivity to different dead to live ratios. In addition, higher target reliabilities for safer designs result in lower resistance factors and consequently lower efficiency ratios.

Furthermore, the resistance factors calibrated by FORM approach is presented in Figure 6.

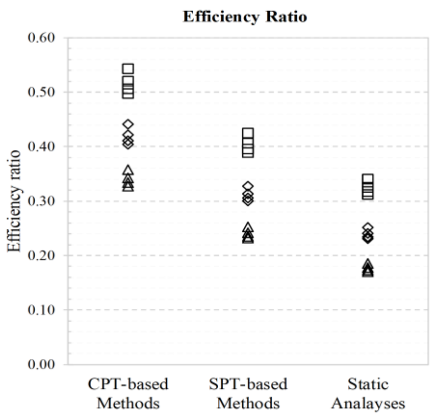

Figure 5 Efficiency ratio (φ/λ_R) for different methods and target reliabilities (Q_D/Q_L=3)

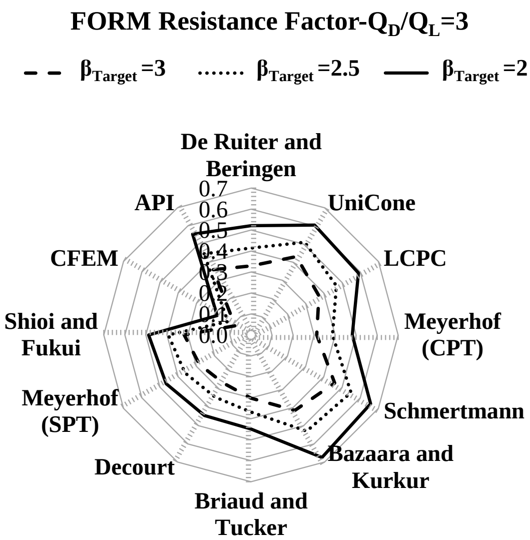

Figure 6 Resistance factor for different methods and reliability indices (Heidarie et al., 2019b)

Figure 7 provides the comparison of efficiency ratios and actual factors of safety for the investigated methods. Figure 7 shows that the more accurate and precise a method (i.e. lower COV value and bias closer to unity) is, the higher its efficiency ratio and the lower its actual factor of safety will be.

Comparisons show that conservative methods, due to their built-in safety, attain higher resistance factors. However, efficiency ratio, a distinct measure of reliability, considers both resistance factor and resistance bias factor to evaluate performance of different methods. Therefore, the Bazaara and Kurkur (1986) method does not predict the axial pile bearing capacity efficiently for the investigated database although it has had the greatest resistance factor. Moreover, the UniCone method (1997) and the Schmertmann (1978) method were the most consistent prediction approach with the lowest COV.

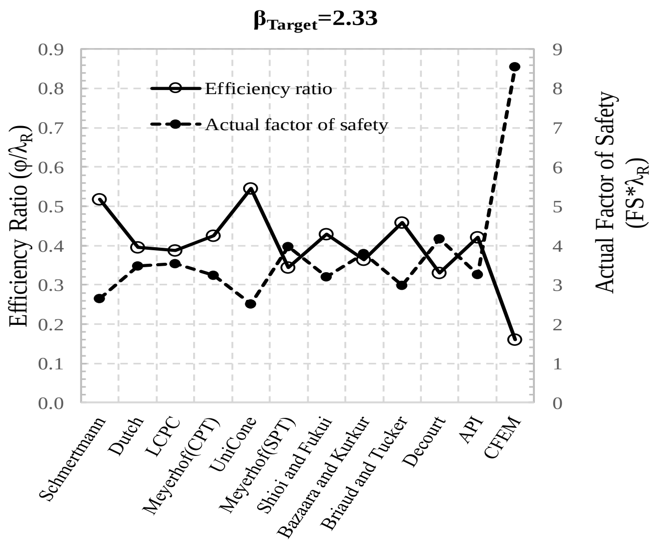

Figure 7 Efficiency ratio and actual factor of safety for different methods (Heidarie et al., 2019 a)

Predicting more efficiently than other investigated methods as depicted in Figures 5 and 7, CPT-based methods were subjected to more study. In this regard, more CPT-based methods were considered to be assessed based upon a subtly different database of 62 driven piles.

In addition to efficiency ratio and actual factor of safety, several different statistical and probabilistic measures have been employed to assess model parameter (Long et al., 1999; Abu-Farsakh and Titi, 2004; Eslami et al., 2011, 2014; Moshfeghi and Eslami, 2018b) including (1) Arithmetic mean and standard deviation of model parameter (2) Best fit line (3) Cumulative probability (4) 20% accuracy level (5) Model error (6) Confidence interval and (7) Efficiency ratio. All these criteria were implemented for assessing the model factor for each method, the results of some of which are presented in Figure 8.

In this assessment, the scores vary from 12 to 1 for the method with the best and the poorest performance based on each criterion, respectively. The method occupying larger area is realized to perform better than the others.

5.5 Reliability-Based Assessment of Pile Capacities

Although CPT-based methods provide more reliable results for prediction of axial pile bearing capacity, the question arises which method provides more reliable results for a specific project, or what factors should be considered for selection of a suitable CPT-based method.

The detailed investigations on different methods reveal that the variety of criteria and assumptions, implemented for each method, lead to a wide range of predictions. These criteria can be categorized as follows:

- **Input variables:** various CPT-based methods employ different data as their input variables. Some methods rely solely on q_c or both q_c and f_s; while only limited methods consider u_2 in addition to q_c and f_s values.
- **Data processing:** another field of difference among methods is whether or not q_c is corrected for the effect of pore water pressure on cone shoulder (u_2).

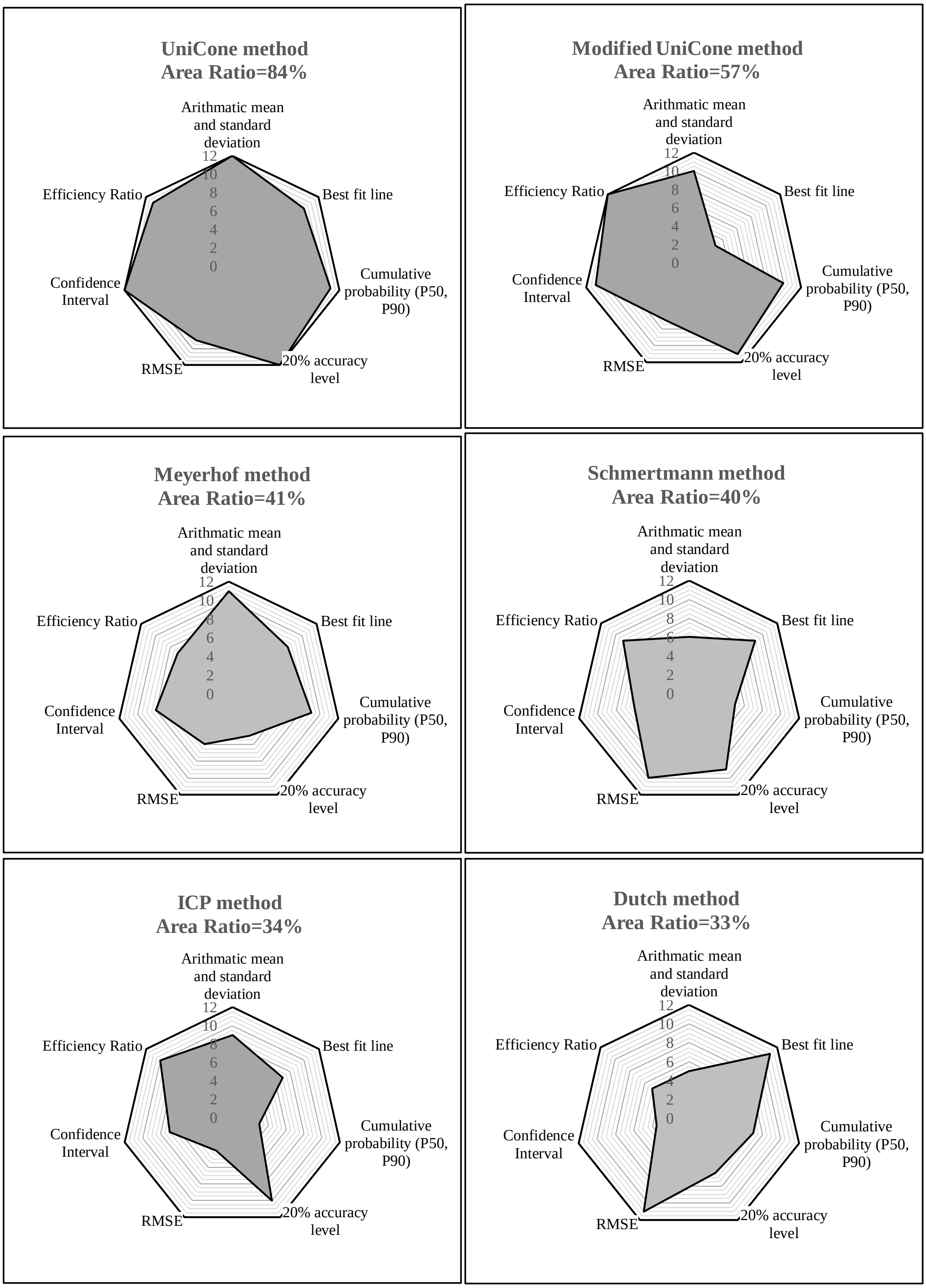

Figure 8 Performance of different methods based on various statistical and probabilistic criteria

- **Model assumptions:** a fundamental difference among approaches is this criterion. Some are based on total stress approach, or empirical correlations, while others apply effective stress directly or indirectly.
- **Failure criterion:** several interpretation approaches are used for pile failure load. The fact that which criterion is considered in the development of a method as the reference load can significantly affect the results of the estimations by that method.
- **Time frame:** another important criterion is the time elapsed between pile installation and pile load test. Generally, the longer this duration, more capacity is gained due to soil setup. There are only limited methods that have taken this factor into account.
- **Soil classification system:** for prediction of toe and shaft capacities, some methods classify soil roughly as sand and clay without considering precise CPT records. While, some

other methods apply more complicated soil classification schemes based on direct or indirect application of CPT records.

- **Influence zone:** other subject of uncertainties is the failure mechanism considered around the pile base and the averaging technique.
- **Friction fatigue:** it is an important factor, especially in sandy soils, that may govern the shaft capacity. This effect is considered in some methods by imposing an upper limit for shaft capacity.
- **Loading direction:** the shaft capacity differs in tension and compression loadings due to the Poisson's effect and the lateral deformation of the pile. The fact that whether or not a method considers loading direction is another distinctive criterion.
- **Installation method:** it can significantly influence the pile behavior owing to the impact on the surrounding soil and performance of pile. Consequently, addressing this phenomena can notably improve the capacity predictions.
- **CPT records interval:** there are several types of CPTs, recording in different intervals. This exerts an influence on model parameter of a predictive method or not is another area of studying model uncertainty.

The summary of these factors is presented in Figure 9. All these criteria can be assessed in terms of reliability-based approaches. Considering each criterion, there are several subsections that each method belongs to. In this regard the efficiency ratio for each method, placed in a subsection, is evaluated based on that group efficiency. Finally, these efficiency ratios are gathered in a radar chart for all the criteria and the ratio of shaded area to total chart area is introduced as the area ratio. The more the area ratio, the better the performance of that specific method.

Figure 10 presents the performance of the six methods for the database of 62 driven piles.

5.6 Displacement-Based Bearing Capacity

In view of principles of the plasticity theory, the stress field is not independent of the displacement and/or deformation fields. Therefore, a more reliable analysis will be achieved if the bearing capacity and load-displacement behavior of piles are analyzed simultaneously (Fellenius, 1989). Recently, Valikhah et al. (2018a,b) proposed a new analytical-numerical method to estimate the bearing capacity and axial load-displacement behavior of driven piles in granular soils using CPT records. They used the method of stress characteristics to analyze the stress field below and around the pile and in effect, the failure mechanism. This failure mechanism has been then used by implementation of the kinematical approach of the limit analysis to compute the displacement field. This procedure is employed in a step-wise manner to gradually calculate the stress and displacement field as the pile is assumed to penetrate into the ground. In their proposed method, the mobilization of the friction angle is linked to the gradual increase in shear strains in the field. This is done by making use of the CPT results which are both continuous and reliable in comparison to standard laboratory tests often conducted on disturbed samples at discrete intervals (Eslami and Fellenius, 1997). Hence, the step-wise procedure is expected to give rise to a complete load-displacement behavior of driven piles shown in a practical case. The proposed approach procedure comprises three different elements. First, the stress state at every point around the pile was computed using the slip lines equations. Then, an admissible velocity field can be found corresponding to the failure mechanism already obtained by the stress characteristics method. Construction of the displacement increment or the velocity field is done by making the velocity hodographs corresponding to the velocities of different rigid blocks enclosed by slip lines (which was previously presented by Veiskarami et al., 2014). Figure 11 shows the failure pattern obtained by the method of stress characteristics and the velocity vectors acting on the slip lines.

When the velocity field has been found, the maximum shear strains can be determined. The soil shear strength is assumed to be a function of the maximum shear strain and the residual shear resistance of the soil. This relationship can be found by direct use of CPT data based on which the residual shear strength of the soil can be found.

For this purpose, a database of case histories from the results of 98 full-scale pile load tests was employed with complete information on the soil type and the results of CPT soundings performed close to the pile locations. In the investigated database, all piles are of "driven pile" type. Most of the cases are in sand and some in silt and mixed soils.

The hyperbolic relationship between $\sin\phi_{mob.}$ and the maximum shear strain can be assumed (Lade and Duncan, 1975). Therefore, the following equation has been chosen as a basis for the functional dependency of the mobilized friction angle:

$$\sin\phi_{mob.} = \frac{\gamma}{a + b\gamma} \tag{2}$$

In this equation, two parameters of a and b can be considered as representatives of the geotechnical (or mechanical) parameters, i.e. the modulus of elasticity, E, and the critical state (or the residual) friction angle, $\phi_{c.s.}$ For instance, a is some measure of E and $b = 1/\sin\phi_{c.s.}$. Therefore, the load-transfer relations for pile tip and shaft can be found based on the presented hyperbolic equation as follows:

$$q = \frac{\zeta}{a_t + b_t\zeta} \tag{3}$$

$$t = \frac{\zeta}{a_s + b_s\zeta} \tag{4}$$

In these equations, q is the effective overburden pressure of soil at pile tip, t is shear stress at the pile shaft and ζ is vertical movement of the pile.

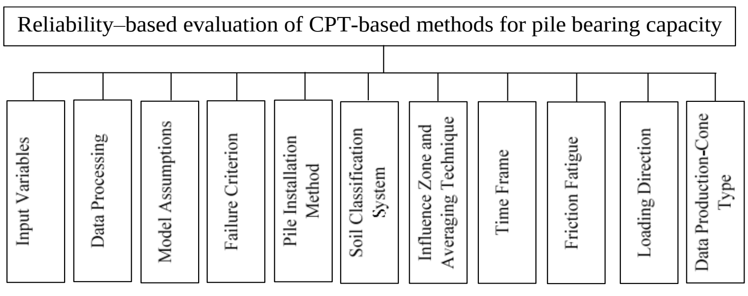

Figure 9 Different assessment criteria for reliability based evaluation of predictive methods

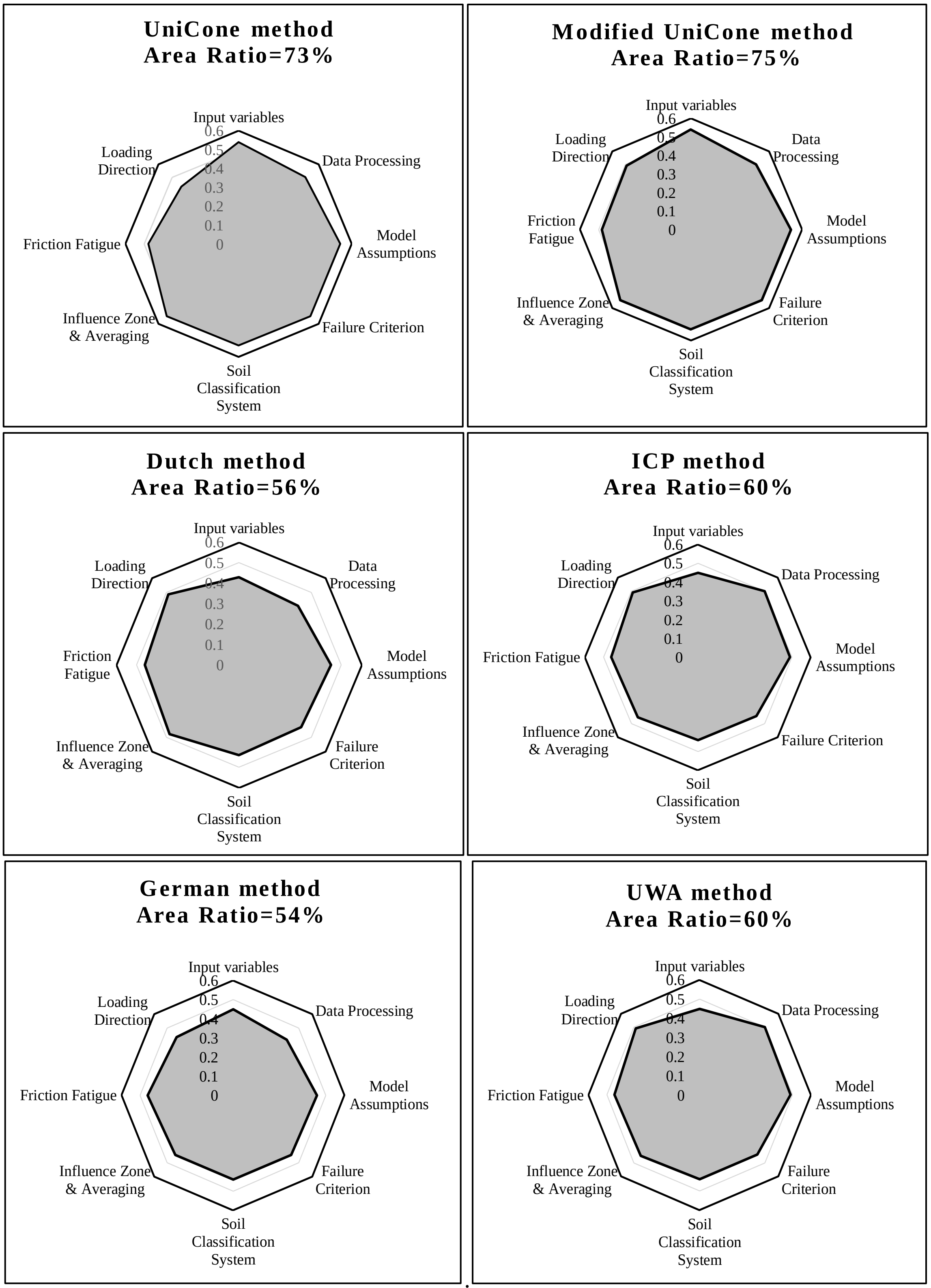

Figure 10 Reliability based assessment of different methods for a compiled database

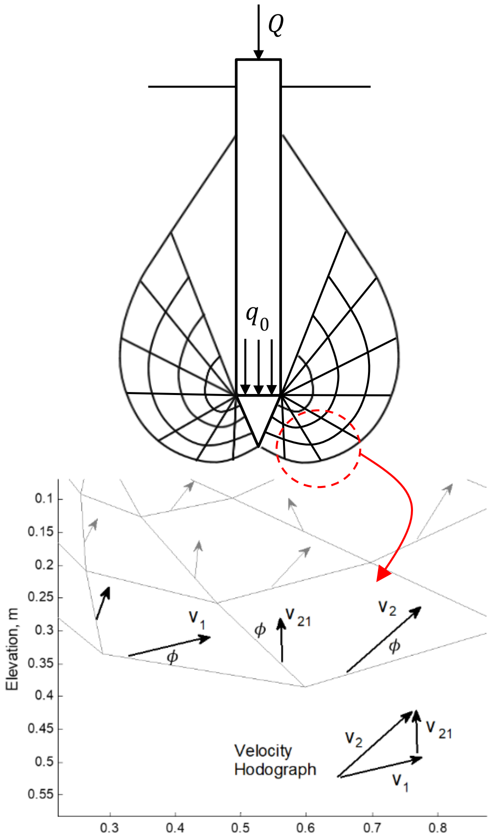

Figure 11 Failure mechanism around the pile and the velocity vectors acting on the slip lines (Valikhah et al., 2018b)

Valikhah et al. (2018a) with study on the properties of the collected database proposed the relations for a and b parameters for pile tip and shaft based on CPT results as follows:

$$a_t = 0.03\left(\frac{q_c}{\sigma_0}\right) + 0.012 \tag{5}$$

$$b_t = 0.006\,\sigma_0 + 1.39 \tag{6}$$

$$a_s = 0.55\,(f_s) + 0.01 \tag{7}$$

$$b_s = 21\,f_s + 0.21 \tag{8}$$

where, σ_0 is the initial vertical stress at the depth at which the load-transfer curves are required.

The results of the load-displacement response of the proposed procedure for some arbitrary case studies are shown in Figure 12. The piles are 350 mm and 400 mm wide and 14.4 m and 14.6 m long, respectively. Both piles are steel closed-ended pipe type. As shown, the results obtained by the proposed approach are in acceptable agreement with the measured load-displacement curve for the piles.

As stated before, the bearing capacity of piles is a strain-based concept. In the other words, the bearing capacity and the displacement occurred in the soil are not distinct from each other. However, other common direct and indirect CPT-based methods for estimation of the bearing capacity of piles do not consider the soil strains and are based exclusively on the ultimate loads. In the proposed study, the researchers tried to estimate the pile load in each increment of soil displacement based on CPT records. Finally, the ultimate pile load or bearing capacity of pile can also be estimated using predicted load-displacement curve and the Brinch Hansen 80%-criterion (Hansen, 1963).

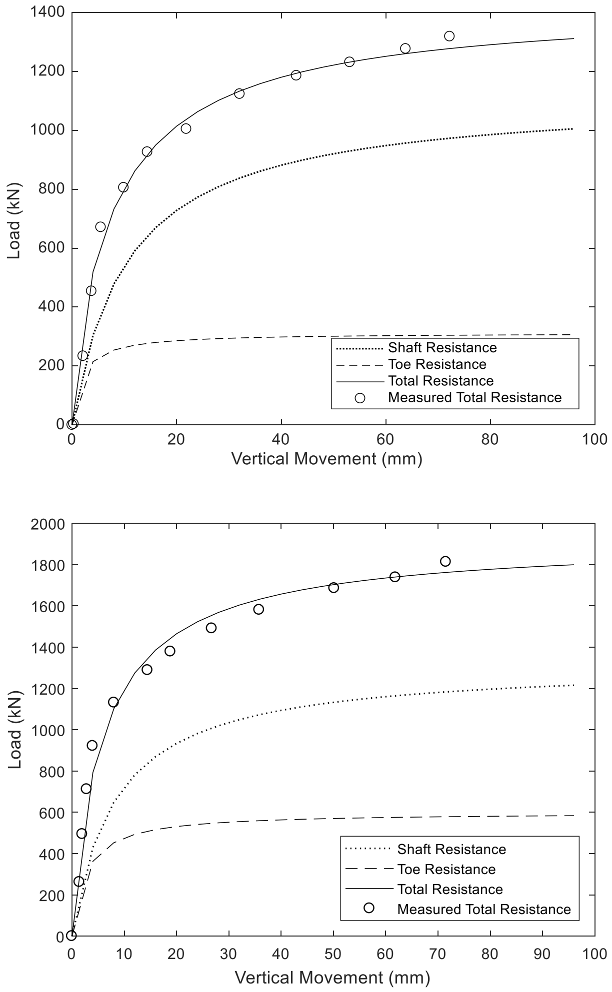

Figure 12 Predicted load-displacement responses of piles using proposed approach by Valikhah et al. (2018a)

5.7 Capacity Assessment of Special Piles

5.7.1 Helical Piles

The feature that CPT prepares the continuous data of soil geotechnical properties per inch in depth was used to modify plate helix locations to achieve higher capacity for helical piles in various soils. In the study carried out by Askari Fateh et al. (2017), axial capacity prediction of thirty-seven cases of helical piles by ten direct CPT methods was considered and the results were compared with the measured capacity of the piles from static pile load tests at different sites. Figure 13 presents failure mechanism of helical piles and their different types. For this purpose, the records consisting of about twenty CPT profiles and thirty-seven cases of pile load displacement curves were employed. Fifteen cases were considered into sandy soils and the rest was into clayey or intermediate soils. The accuracy of initial assumption for the mechanism of failure was determined by the comparison between pile capacity from common static analysis and measured piles' load test under compression or tension.

Also, a new CPT-based method was developed by Askari Fateh et al. (2017), as shown in Figure 14, to estimate the bearing capacity of helical piles.

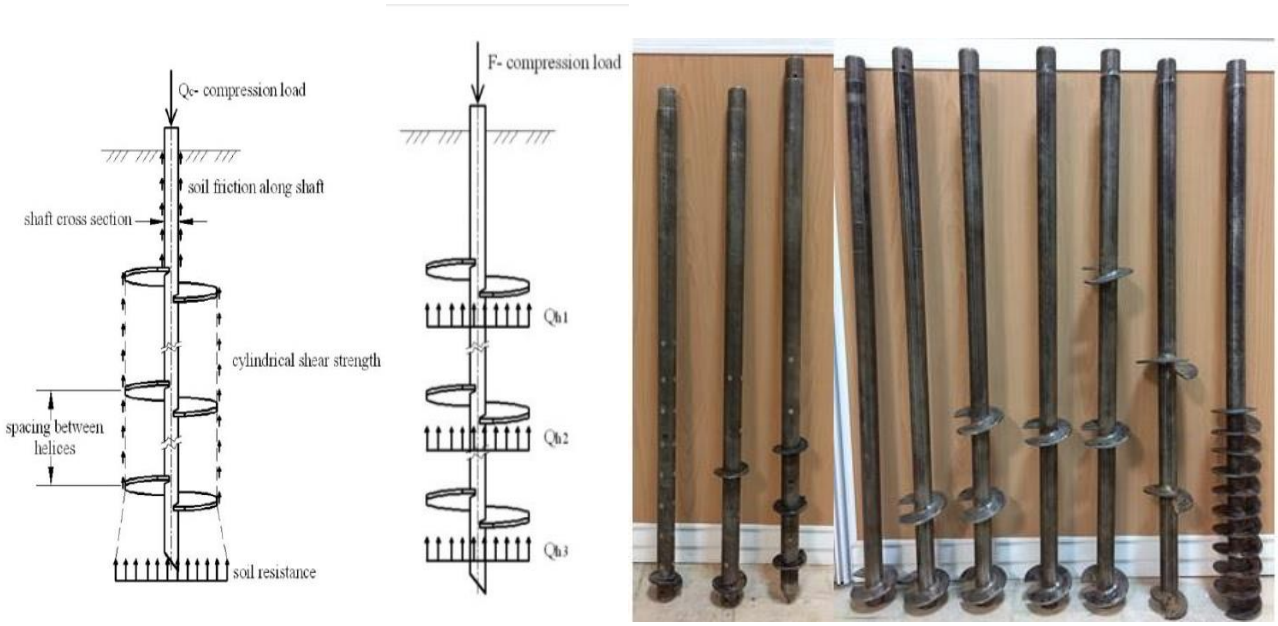

Figure 13 Failure mechanism and different types of helical piles (Askari Fateh et al., 2017)

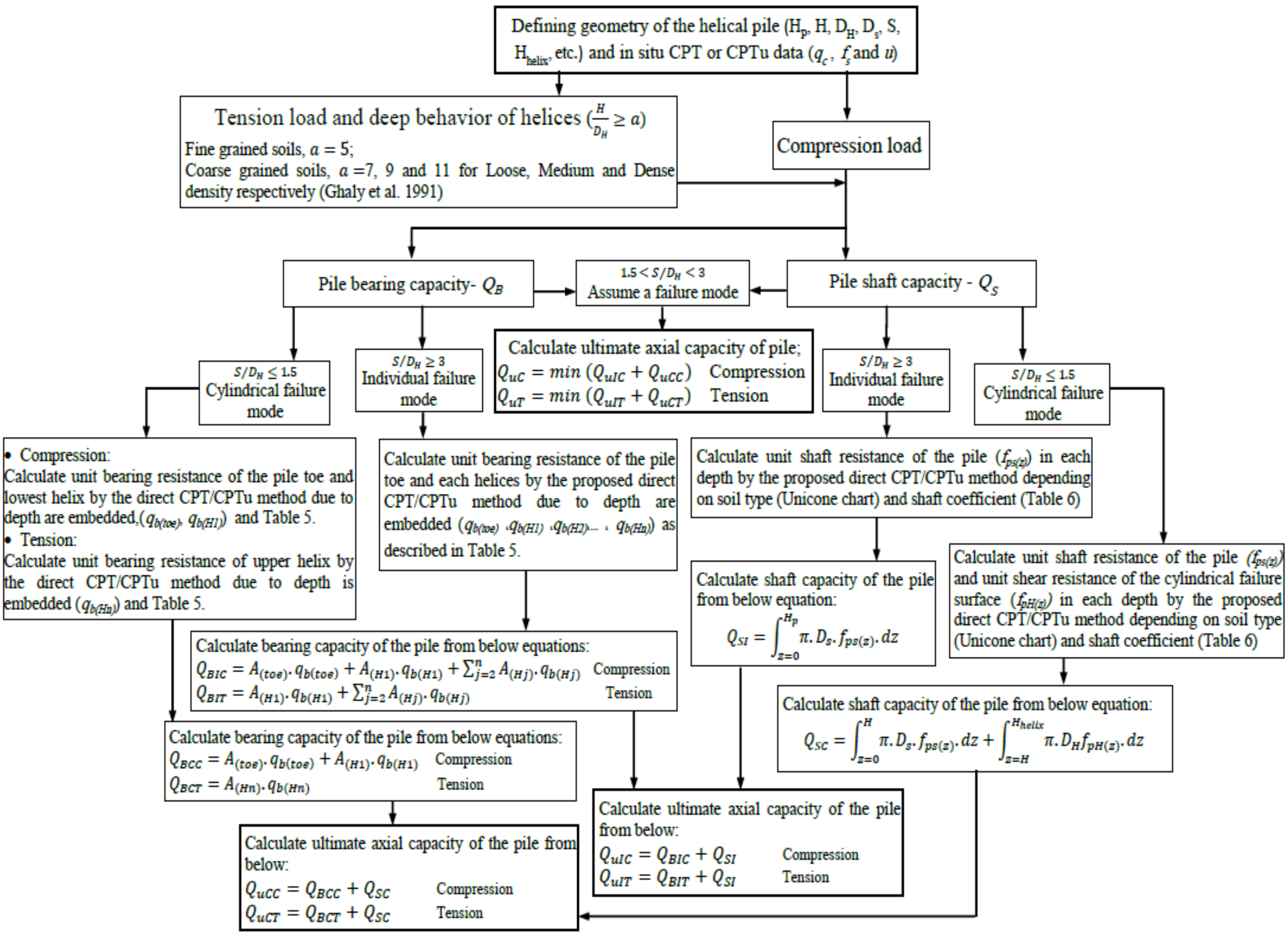

Figure 14 The proposed flowchart for estimating the bearing capacity of helical piles (Askari Fateh, 2017)

5.7.2 Drilled Displacement Piles

Drilled displacement (DD) piles are a type of bored piles constructed using a helical drilling tool with both a vertical force and torque. In the construction process of these piles, soil is displaced laterally, and therefore, minimal spoil is generated. The void will be then filled with either grout or concrete. An example of construction of drilled displacement piles is depicted in Figure 15. Despite several advantages and the increasing application of these piles, the design procedure used for these piles still requires more investigations for an optimum design. The primary approach of determining the bearing capacity of drilled displacement piles are in-situ-based methods including SPT, CPT as well as PMT.

A database of sixty five records were employed in this study including static load tests on drilled displacement piles in addition to the adjacent CPT profiles.

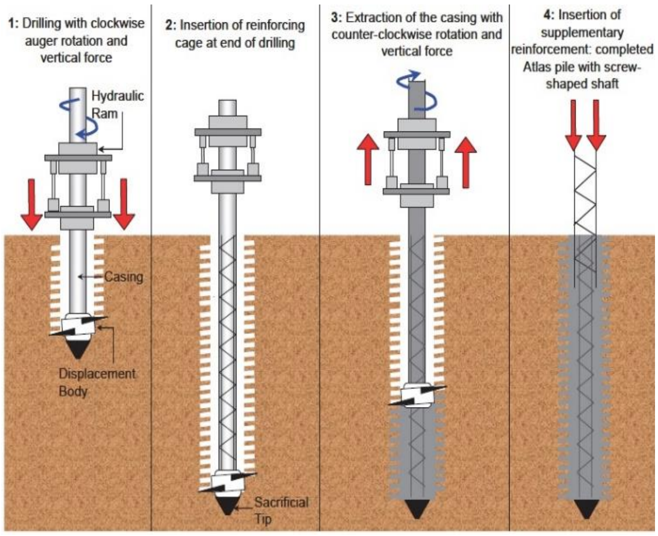

Figure 15 Drilling displacement procedure of a screw shaped DD pile (Atlas) (Basu et al., 2010)

Statistical reliability-based assessments, focusing on soil-pile specifications, have been conducted for six current CPT-based methods of determining the piles bearing capacity by Moshfeghi and Eslami (2018b). Overall, almost all of the investigated methods have shown the most consistent results in q_c range of 5 to 15 MPa. The more commonly used CPT-based methods which have not been developed or calibrated for DDPs, especially Togliani (2008) and Eslami and Fellenius (1997) showed a great potential to have reasonable estimations. Moreover, they have shown more reliability in various categories. However, in their current form, they seem to be applicable to a certain ranges of q_c values, and they require some modifications or calibration to have more promising performance. The lack of upper limits for pile resistance can be considered as the main flaw of these methods. Another shortcoming of the current methods is the lack of considering the shaft shape (screw or smooth) in pile design (Figure 16). They also concluded that compilation and employment of a more extensive database can be beneficial for further assessment of these methods, so as to impose the required modification to reach more optimum and reliable predictions.

6. IMPLEMENTATIONS AND REMARKS

In the procedure of pile geotechnical design, either of these two conditions are encountered: (1) sufficient site investigations are performed due to low variability in a specific site, and there is adequate information on site conditions such as CPT records, pile load test results, etc.; and (2) Due to economical aspects or project limitations, it is not possible to perform in-situ testing as many that fully represent the site conditions. This especially applies to the site with high inherent variability.

For either case, geotechnical databases can enter the design procedure accompanied by performance-based approaches such as those mentioned in this paper including WCI (as a measure of capacity prediction efficiency), serviceability criteria, value engineering prospects, probability and reliability assessments. The procedure of employing such geotechnical databases through smart data selection is presented in Figure 17.

The databases can provide the opportunity to reproduce data, such as CPT and pile load-displacement records, similar to the ones encountered in the project site. Considering the availability of these data, the need for performing the time-consuming or expensive loading tests diminishes, and consequently, it can help the efficiency of the project. Moreover, the ability of considering soil inherent variability enhances the geotechnical engineer's understanding of the site conditions.

In the next step, after acquiring necessary data, design approaches must be opted. For commonly-used CPT methods of determining pile axial capacity, several evaluation criteria must be employed to assess and compare the performance of each method in a given site condition so as to select the most compatible method with the reasonable performance. In this regard, the more well-known approaches which can be used for assessments are as follows:

- Statistical and probabilistic
- Reliability-based
- Risk

Then, by employing the superior method or methods (screening) and LRFD approach, the optimum design can be achieved.

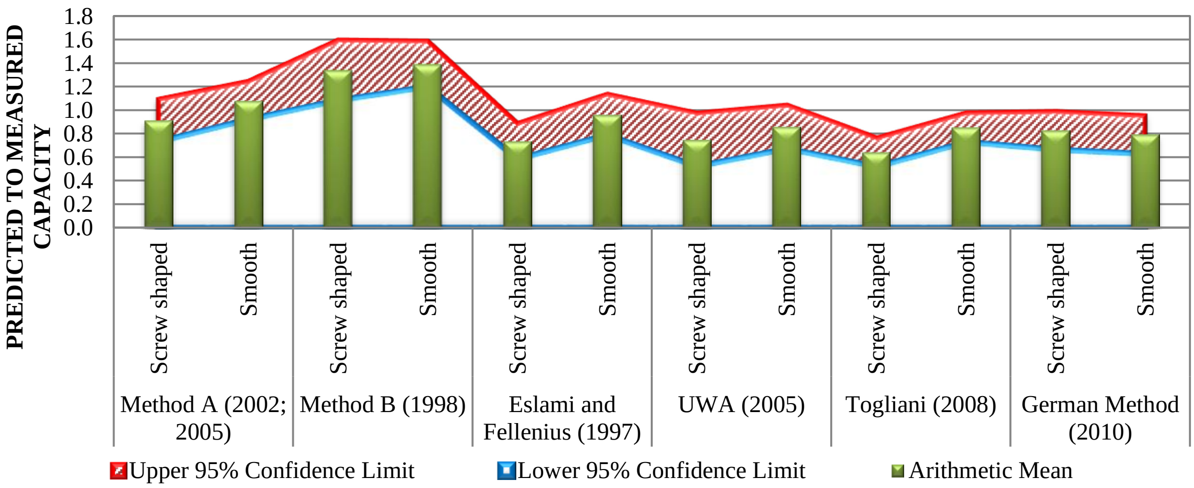

Figure 16 Example of evaluation results of CPT-based methods based on shaft shapes: mean, upper and lower confidence limits (Moshfeghi and Eslami, 2018b)

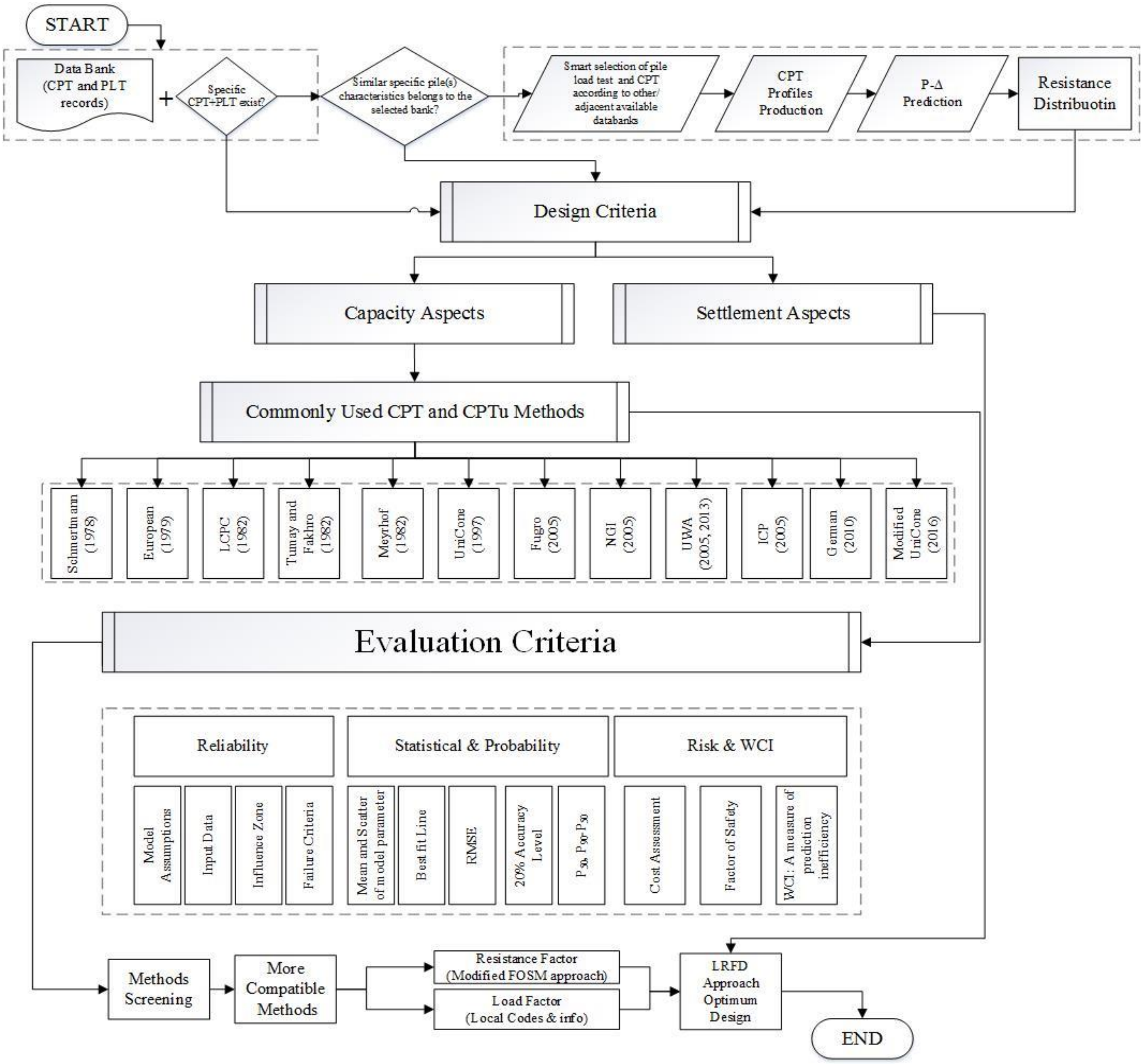

Figure 17 The procedure of designing a pile using geotechnical databases

As stated by Fellenius (2015), design of a pile foundation for axial load starts with an analysis of how the load is transferred to the soil, often thought to be limited to determining only the pile capacity, sometimes separating the capacity on components of shaft and toe resistances. However, the load-transfer is also the basis for a settlement analysis, because in contrast to the design of shallow foundations, settlement analysis of piles cannot be separated from a load-transfer analysis. Therefore, it is evident that evaluating the bearing capacity must be based upon load-displacement behaviour, which can be considered through the employment of such geotechnical databases.

Also, in pile design, Serviceability Limit State (SLS) aspect is significant and occasionally decisive over ultimate limit state. SLS deals with settlements and differential settlements not exceeding the allowable limits. Due to uncertainties, both tolerable and estimated settlements can be considered as random variables and it would be better to consider the effect of these factors in pile design, as well. Additionally, it is recommended to account for system reliability in pursuance of efficient practice.

7. CONCLUSIONS

In the realm of optimum pile geotechnical design by means of CPT, there have been several databases compiled, a few of which have been reviewed. However, these databases are either limited in terms of number of case records and soil or pile properties, or they have been locally developed based upon the records of a specific area.

A recently-developed geotechnical piling database along with the data of the CPT and CPTu performed in the adjacency of pile location, namely AUT: Geo-CPT&Pile Database which includes 600 records, has been introduced and presented. Thus far, several investigations have been performed on this database as discussed in this paper.

Generally, for interpretation of pile failure or ultimate capacity based on load-displacement diagrams, the Brinch Hansen 80% criterion was shown to be the most consistent when dealing with CPT-based approaches, since it mainly targets the bearing capacities at larger strains which is more compatible with the CPT large strain penetration mechanism. However, the bearing capacity is a strain dependant issue and cannot be studied without considering displacement occurred in the soil-pile interactions. Therefore, it is necessary to simultaneously analyze the capacity and the load-displacement response of pile. Accordingly, the CPT records have been used and formulated to a proposed CPT-based approach to realize both load-displacement and capacity response of driven piles. When it comes to risk assessment and efficiency of the methods, the derived optimum safety factors varied from 1.6 to 3.1 for all the case records, 1.3 to 2.2 for the piles in tension and 1.4 to 3.1 for the piles in compression loading. In addition the values of WCIs corresponding to the optimum safety factors indicate that the German (2010), LCPC (1982), Meyerhof (1983), UniCone (1997) and UWA (2005) methods have shown the most efficient predictions. Their efficient performance regardless of their accuracy is due to lower scatter reflected in their predictions which can be attributed to various factors considered in for their development such as pore pressure, extensive and high quality database, effects of partial plugging in open ended piles.

Furthermore, it was demonstrated through statistical and probabilistic approaches that the direct CPT methods perform better than the investigated indirect methods due to their lower dispersion and scatter of data. Indirect CPT-based methods, SPT-based methods and static analyses are based mainly on empirical and analytical correlations resulting in a wider range of inaccuracies and scatter of predictions for axial pile bearing capacities.

In terms of reliability-based approaches, different safety levels or acceptable risk is defined based on the importance of the superstructure. Hence, different values of resistance factor are attained for different target reliabilities. Also, these resistance factors are dependent on the resistance bias factor and coefficient of variation for each predictive method. Results depicted that the conservative methods attain higher resistance factors. Applying these resistance factors will not lead to optimum design and for better engineering judgement, it is proposed to consider efficiency ratio and actual factor of safety. In this regard, eight criteria have been introduced for assessment of assumptions as well as the basis of various methods. Overall, according to both statistical-probabilistic and reliability-based assessments, the UniCone (1997) and modified UniCone (2016) methods showed more promising performance.

Considering special piles such as helical and drilled displacement piles, it was perceived that the CPT-based methods potentially show reasonable performance provided that required modifications are applied to account for the installation effects. Additionally, a relatively new direct CPT-based method was introduced which was developed for determining the bearing capacity of helical piles.

Finally, via implementing the database approach, an algorithm is proposed for the pile geotechnical design procedure considering serviceability and capacity requirements emphasizing on probability and reliability as well as risk assessments. Consequently, through these comprehensive data sources and performance-based design consideration, it would be promising to reach a more optimum and simultaneously safe design dependent on value engineering prospects.

8. NOTATIONS

a, a_t, a_s b, b_t, b_s	Coefficients of hyperbolic soil behaviour model for proposed pile tip and shaft load transfer curve
AUT	Amirkabir University of Technology
CFA	Continuous Flight Auger
CFG	Cement Flyash Gravel
COV	Coefficient of Variation
CPT	Cone Penetration Test
DCIS	Driven Cast In-situ
DDP	Drilled Displacement Pile
FORM	First Order Reliability Method
FOSM	First Order Second Moment Method
f_s	Cone friction
FS	Factor of Safety
ICP	Imperial College Pile
LCPC	Laboratoire Central des Ponts et Chauses
LRFD	Load and Resistance Factor Design
NGI	Norwegian Geotechnical Institute
PBD	Performance-Based Design
PMT	Pressure Meter Test
PPC	precast prestressed concrete
q	Effective overburden pressure of soil at pile tip
q_c	Cone resistance
Q_D/ Q_L	Dead to Live load ratio
Q_m	Measured capacity
Q_p	Predicted capacity
q_t	Corrected cone resistance for pore pressure
RMSE	Root Mean Square Error
SBC	Soil Behavior Classification
SLS	Serviceability Limit State
SPT	Standard Penetration Test
t	Shear stress at the pile shaft
UWA	University of Western Australia
WCI	Wasted Capacity Index
β	Reliability index
β_{Target}	Target reliability index
γ	Soil shear strain
ζ	Vertical movement of the pile
λ_R	Resistance bias factor
σ_0	Initial soil pressure
φ	Resistance factor
ϕ_{mob}	Mobilized friction angle

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