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Reliability analysis and evaluation of LRFD resistance factors for CPT-based design of driven piles

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Abstract. There has been growing agreement that geotechnical reliability-based design (RBD) is necessary for establishing more advanced and integrated design system. In this study, resistance factors for LRFD pile design using CPT results were investigated for axially loaded driven piles. In order to address variability in design methodology, different CPT-based methods and load-settlement criteria, popular in practice, were selected and used for evaluation of resistance factors. A total of 32 data sets from 13 test sites were collected from the literature. In order to maintain the statistical consistency of the data sets, the characteristic pile load capacity was introduced in reliability analysis and evaluation of resistance factors. It was found that values of resistance factors considerably differ for different design methods, load-settlement criteria, and load capacity components. For the total resistance, resistance factors for LCPC method were higher than others, while those for Aoki-Velloso's and Philipponnat's methods were in similar ranges. In respect to load-settlement criteria, 0.1B and Chin's criteria produced higher resistance factors than DeBeer's and Davisson's criteria. Resistance factors for the base and shaft resistances were also presented and analyzed.

Keywords: LRFD; resistance factor; reliability index; pile load capacity; driven pile; cone penetration test.

1. Introduction

While insufficient confidence and considerable reluctance to the full adoption of geotechnical reliability-based design (RBD) still exist, there has been growing agreement that geotechnical RBD

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is necessary for establishing more advanced and integrated design. Current practices of geotechnical RBD are differently adopted in Europe and North America. In Europe, limit state design (LSD), as specified in EUROCODE 7 (1993), based on partial factors of safety or factored strengths is used, while the load and resistance factor design (LRFD) based on factored load and resistance is employed in North America. For geotechnical LRFD, key component, which is yet the most challenging task, is determination of resistance factors. Load factors have been relatively well established and can be applied in common to both foundations and superstructures.

For a given geotechnical project, different design methods are available, each of which represents different degrees of uncertainty and reliability. For the estimation of the pile load capacity, for example, different design methods would result in different values of pile load capacities. This indicates that type of design method is an important consideration for geotechnical LRFD and thus should be properly addressed for the evaluation of resistance factors. Estimation of the pile load capacity can be based on either soil properties or in-situ test results such as SPT blow count N or CPT cone resistance q_c. While SPT-based methods have long been used, CPT-based methods have become increasingly popular due to less experimental uncertainties associated with continuous and automated data acquisition system (Philipponnat 1980, Bustamante and Gianeselli 1982). Although resistance factors for both SPT- and CPT-based methods have been presented (AASHTO 1998), further investigation is still necessary, addressing more detailed design methodology.

Other uncertainty or variability for the estimation of the pile load capacity arises from load-settlement criteria that are often adopted for verifying and calibrating estimated pile load capacity. Reference pile load capacity measured from a pile load test can vary depending on load-settlement criterion adopted for the interpretation of measured load-settlement curves. According to limit state design, a settlement equal to 10% of pile diameter is likely to lead ultimate limit state (Franke 1989). Since various load-settlement criteria other than the 10% criterion are also commonly used, the effect of load-settlement criteria on the reliability of the pile load capacity estimation needs to be taken into account for LRFD pile design.

In this study, a series of data sets for pile load test and CPT results are collected from the literature and used in reliability analysis of CPT-based load capacity estimation for driven piles. Based on results from reliability analysis, resistance factors for CPT-based pile load capacity estimation are evaluated and presented. Various CPT-based methods, which are frequently adopted in practice, are selected and used for development and evaluation of resistance factors. Different load-settlement criteria are also addressed and considered in reliability analysis.

2. Estimation of pile load capacity

2.1 Pile load capacity based on CPT results

Estimation of the pile load capacity is key component in the pile design process. In general, the total pile load capacity is composed of the base and shaft capacities as follows

$$Q_t = Q_b + Q_s \tag{1}$$

where Q_t = total pile load capacity; Q_b and Q_s = base and shaft capacities. Following conventional LRFD framework, target resistance component is the total pile load capacity. As indicated by Eq. (1), estimation of the total pile load capacity requires individual estimation of the base and shaft load capacities, similarly to the LRFD load component consisting of dead (L_D) and live (L_L) loads. In this study, all the pile load capacity components of the total, base and shaft load capacities are addressed for evaluation of resistance factors.

In a reliability point of view, CPT-based approach may be less uncertain and more straightforward than property-based approach, since the cone resistance q_c is the only required design parameter. There have been several CPT-based methods for estimating the pile load capacity (Aoki and Velloso 1975, Schmertmann 1978, Bustamante and Gianeselli 1982, Philipponnat 1980). For most CPT-based methods, the base and shaft capacities are given as

$$Q_b = q_b \cdot A_b = (c_b \cdot q_{c,avg})A_b \tag{2}$$

$$Q_s = \sum (q_{si} \cdot A_{si}) = \sum [(c_{si} \cdot q_{ci})A_{si}] \tag{3}$$

where Q_b and Q_s = base and shaft capacities; q_b and q_{si} = based and shaft resistances; A_b and A_{si} = base and shaft areas; $q_{c.avg}$ = average cone resistance at pile base level; q_{ci} = representative cone resistance for a certain sub-layer i; and c_b and c_{si} = correlation parameters.

In the present study, 4 different methods of Aoki and Velloso (1975), Schmertmann (1978), Philipponnat (1980), and Bustamante and Gianeselli (1982) were selected as representative CPT-based methods, and used for evaluation of resistance factors. The method by Bustamante and Gianeselli (1982) is also known as LCPC method. Typical ranges of c_b and c_s values in Eqs. (2) and (3) for driven piles are given in Table 1. From Eq. (3), it can be inferred that determination of q_{ci} is quite straightforward, as a simple average value of q_c for a given sub-layer can be taken as q_{ci}. For the average cone resistance $q_{c,avg}$ in Eq. (2), on the other hand, different methods specify different influence zones, within which $q_{c,avg}$ is determined. Fig. 1 shows the influence zones in terms of the pile diameter (B) as specified in each method adopted in this study.

2.2 Load-settlement criteria for measured pile load capacity

As the ultimate pile load capacity at plunging failure state is not in general achieved in conventional pile load tests, the pile load capacity is often defined at a certain settlement level specified on a load-settlement curve. Therefore, "measured" pile load capacity from a pile load test is not unique, but varies depending on load-settlement criterion adopted. In the present study, four load-settlement criteria were selected and used to define "measured" pile load capacities. These are criteria by Chin (1970), Davisson (1972), DeBeer (1988), and Franke (1989), all of which are commonly used in piling practice. Different load-settlement criteria were considered as local practices of pile design may introduce different load-settlement criteria to determine measured pile load capacities.

Table 1 Values of c_b and c_s for CPT-based Methods for pile load capacity estimation

Method	Driven piles		Bored piles	
	c_b	c_s	c_b	c_s
Aoki and Velloso (1975)	0.40-0.57	0.0040-0.0171	0.28-0.33	0.0020-0.010
Schmertmann (1978)	0.60-1.00	0.0080-0.0180	–	–
Bustamante and Gianeselli (1982)	0.30-0.55	0.0050-0.033	0.20-0.45	0.0050-0.033
Philipponnat (1980)	0.35-0.50	0.0030-0.0250	–	0.0015-0.0170

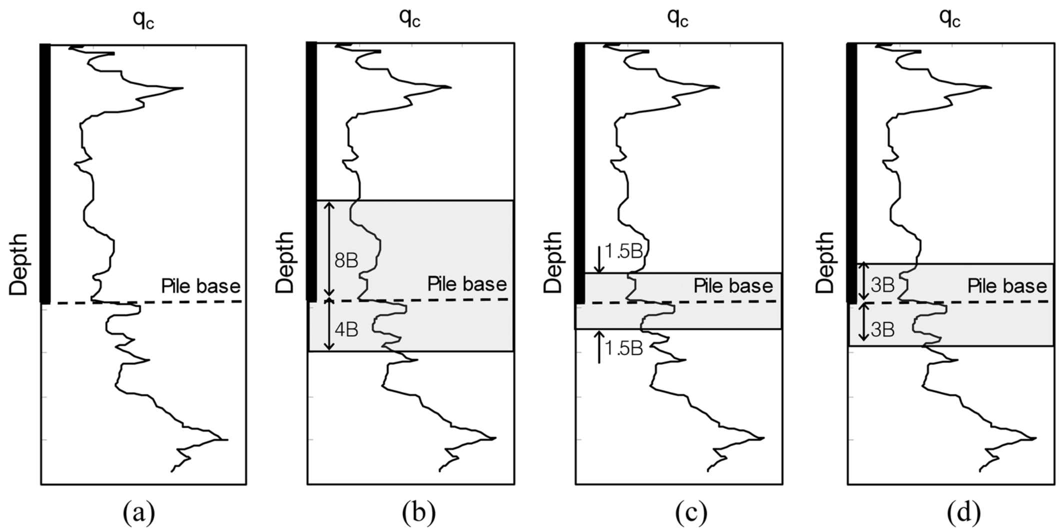


Fig. 1 CPT influence zones for (a) Aoki and Velloso's; (b) Schmertmann's; (c) LCPC's; and (d) Philipponnat's methods

For DeBeer's criterion (DeBeer 1988), a load-settlement curve is transformed into log-scale, and then the pile load capacity is defined at the maximum curvature point on a transformed load-settlement curve. Chin's criterion (Chin 1970) defines the pile load capacity at an asymptotic value from hyperbolically transformed load-settlement curves, assuming that measured pile load-settlement curves follow well the hyperbolic function. The most common load-settlement criterion in current piling practice may be that of Franke (1989). This is also called 0.1B criterion as it specifies the pile load capacity at a settlement equal to 10% of pile diameter B. For Davisson's criterion (Davisson 1972), the pile load capacity is defined as a load leading to deformation equal to summation of pile elastic compression and deformation equal to a certain percentage of the pile diameter.

For all the pile load test results collected in this study, measured pile load capacities were obtained using above described load-settlement criteria and used for reliability analysis. It should be noted that the pile load capacities obtained from CPT-based methods and load-settlement criteria described in this study are commonly treated as those corresponding to ultimate limit state. Reliability analysis results and resistance factors that will be presented in this study therefore represent those for ultimate limit state.

3. Reliability analysis and resistance factors

3.1 Reliability parameters and target reliability index

In working stress design (WSD), the factor of safety is defined as a function of deterministic values of load L and resistance Q. Values of L and Q, however, are not deterministic, and thus actual safety margin is given by probability of failure based on statistical distributions of L and Q. The probability of failure p_f can be written as

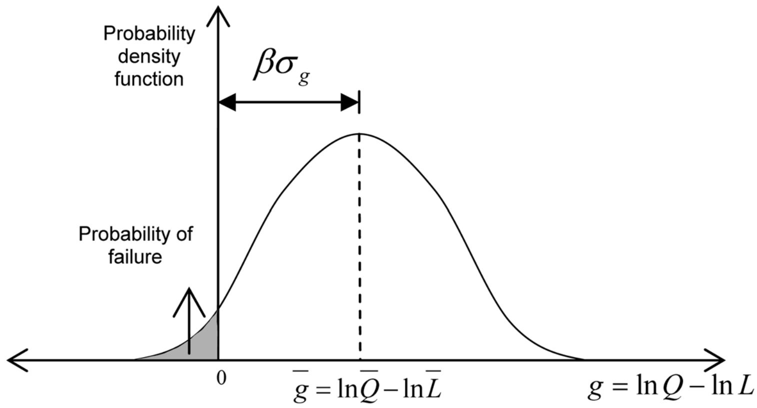


Fig. 2 Distribution curve of limit state function

$$p_f = 1 - p_s = 1 - P(Q \geq L) = P(Q < L) \tag{4}$$

where p_f = probability of failure; p_s = probability of survival; P = probability function. If distributions of L and Q are known, p_f and actual safety margin can be evaluated using Eq. (4).

Since exact distributions of L and R are hardly identified, particularly for geotechnical problems, approximated reliability analysis methods using representative reliability parameters are often adopted (Withiam *et al.* 2001). In the present study, the first-order second-moment (FOSM) method, assuming the log-normal distribution of L and Q, was adopted. While distributions of L and Q other than the log-normal distribution may exist, it has been suggested that the log-normal distribution reasonably well reflects actual distributions of considered variables for geotechnical reliability analysis. For log-normally distributed L and Q, the limit state function g can be written as

$$g = \ln(Q) - \ln(L) = \ln(Q/L) \tag{5}$$

The condition of $g < 0$ corresponds to failure, hence $g = 0$ represents a limit state condition. Fig. 2 shows a typical distribution curve of the limit state function. In Fig. 2, the reliability index β is defined as the mean of g (i.e., $\bar{g}$) normalized with the standard deviation σ_g.

If L and Q are uncorrelated each other and are log-normally distributed, β is given as

$$\beta = \frac{\ln\left[\left(\frac{\bar{Q}}{\bar{L}}\right)\sqrt{\frac{(1+COV_L^2)}{(1+COV_Q^2)}}\right]}{\sqrt{\ln[(1+COV_Q^2)(1+COV_L^2)]}} \tag{6}$$

where $\bar{L}$ and $\bar{Q}$ = means of L and Q; and COV_L and COV_Q = coefficients of variation for L and Q, respectively. The coefficient of variation COV is defined as the standard deviation σ normalized with the mean (i.e., $\bar{L}$ or $\bar{Q}$). Values of $\bar{L}$ and $\bar{Q}$ can also be given in terms of the bias factor λ that defines a ratio of the mean to the nominal value as follows

$$\bar{L} = \lambda_L L_n \text{ and } \bar{Q} = \lambda_Q Q_n \tag{7}$$

where λ_L and λ_Q = bias factors for L and Q; $\bar{L}$ and $\bar{Q}$ = means of L and Q; L_n and Q_n = nominal values of L and Q. From Eqs. (6) and (7), β can be rewritten as

$$\beta = \frac{\ln\left[\left(\frac{\lambda_Q Q_n}{\lambda_L L_n}\right)\sqrt{\frac{(1+COV_L^2)}{(1+COV_Q^2)}}\right]}{\sqrt{\ln[(1+COV_Q^2)(1+COV_L^2)]}} \tag{8}$$

As shown in Fig. 2, β corresponds to distance of $\bar{g}$ from the origin, and represents statistically the same meaning as p_f. In the literature, different ranges of target reliability index β_T for piles can be found. According to AASHTO (1998), values of β_T vary between 1.5 and 4.7, depending on length of bridge span, while β_T = 3.5 was suggested as a typical value for $p_f = 2.33 \times 10^{-4}$. Bea (1983), on the other hand, recommended values of β_T for offshore piles in 3.0 to 4.0 and 2.0 to 3.0 ranges at an annual probability of failure and lifetime side, respectively. It should be noticed that these values of β_T are for group piles. For group piles, failure of a single pile does not necessarily mean entire structural collapse. According to Bea (1983), the probability of failure of a single pile can be 100 times smaller than for group piles. For a single driven pile, Withiam *et al.* (2001) suggested β_T = 2.0 to 2.5. Accordingly, values of β_T equal to 2.0 and 2.5 will be adopted in this study, as proposed by Withiam *et al.* (2001).

3.2 Formulation of resistance factor

Considering the load combination of dead and live loads, the inequality equation for LRFD is given by

$$RF \cdot Q_n \geq \sum LF \cdot L = LF_{LD} \cdot L_D + LF_{LL} \cdot L_L \tag{9}$$

where RF = resistance factor; Q_n = nominal resistance; LF, LF_{LD}, and LF_{LL} = global, dead and live load factors; L, L_D, and L_L = global, dead, and live loads. From Eq. (9), RF is obtained as

$$RF \geq \frac{LF_{LD} \cdot L_D + LF_{LL} \cdot L_L}{Q_n} \tag{10}$$

From Eqs. (8) and (10), if L (or L_D and L_L) and Q are log-normally distributed at a statistically independent condition, the resistance factor RF for a given target reliability index β_T can be given as follows

$$RF = \frac{\lambda_Q\left(LF_{LD}\frac{L_D}{L_L} + LF_{LL}\right)\sqrt{\frac{1+COV_{LD}^2+COV_{LL}^2}{1+COV_Q^2}}}{\left(\lambda_{LD}\frac{L_D}{L_L} + \lambda_{LL}\right)\exp \beta_T\sqrt{\ln[(1+COV_Q^2)(1+COV_{LD}^2+COV_{LL}^2)]}} \tag{11}$$

where β_T = target reliability index, λ_{LD}, λ_{LL}, and λ_Q = bias factors for L_D, L_L, and Q; and COV_{LD}, COV_{LL}, and COV_Q = COVs for L_D, L_L, and Q, respectively.

From Eq. (11), it can seen that determination of RF requires detailed knowledge of various reliability-related and design parameters, including COVs of load and resistance, dead-to-live load ratios, bias factors, and target reliability index. Evaluation of theses parameters for different pile design methods and load-settlement criteria described previously will be presented in next section.

4. Evaluation of uncertainties for CPT-based pile load capacity estimation

4.1 Measured and Estimated Pile Load Capacity

A series of field load test results for axially loaded driven piles and CPT results were collected from the literature and used in reliability analysis for the evaluation of resistance factors. A total of 32 datasets from 13 sites were collected. Detailed test conditions for each case are given in Table 2. Load test results for all the cases in Table 2 were obtained from static axial pile load tests with separate measurements of shaft and base load responses. While soils at the test sites showed various types from fine to granular soils, most of them were sandy soils, and, in particular, bearing layers near the pile base were granular soils for all the cases. Considering that granular soils are less compressible than cohesive soils and are regarded as typical foundation soils, this is a common

Table 2 Summary of data sets used in reliability analysis

Reference	Pile length (m)	Pile cross-section (m)	Pile type	Soil type	Location
Van Impe *et al.* (1988)	12.02	0.60	Steel pipe (CE[a])	Dense sand	Belgium
Briaud *et al.* (1989[a])	9.14	0.27	Steel pipe (CE)	Sand	USA
Lee *et al.* (2003)	6.87	0.36	Steel pipe (OE[b])	Gravely sand	USA
	7.04	0.36	Steel pipe (CE)		
Vesic (1970)	3.01	0.46	Steel pipe (OE)	Medium to dense sand	USA
	6.13	0.46			
	8.87	0.46			
	11.98	0.46			
Kousoftas (2002)	14.02	0.42	Steel pipe (OE)	Loose to dense sand	USA
Briaud *et al.* (1989[b])	16.46	HP 14 × 73	Steel H-pile	Gravely sand & gravely clay	USA
	16.15	HP 14 × 73			
	17.68	HP 14 × 73			
	17.98	HP 14 × 73			
Witzel and Kempfert (2005)	21.00	0.35 × 0.35	Concrete squre	Clay & medium sand	Germany
Altaee *et al.* (1992)	11.00	0.29 × 0.29	Concrete squre	Silty sand	Iraq
Harris *et al.* (2003)	45.00	0.41	Steel pipe (CE)	Silty sand	USA
Rollins *et al.* (1999)	23.20	0.324	Steel pipe (CE)	Sand	USA
Fellenius *et al.* (2004)	45.00	0.406	Steel pipe (CE)	Clay & silty sand	USA
Décourt and Niyama (1994)	6.00	0.50	Steel pipe (OE)	Sand	Brazil
	8.68	0.50	Steel pipe (OE)		
Kruizinga and Nelissen (1985)	18.00	0.355	Steel pipe (CE)	Sand & clay	Netherland

[a]CE: Closed-ended pile, [b]OE: Open-ended pile;

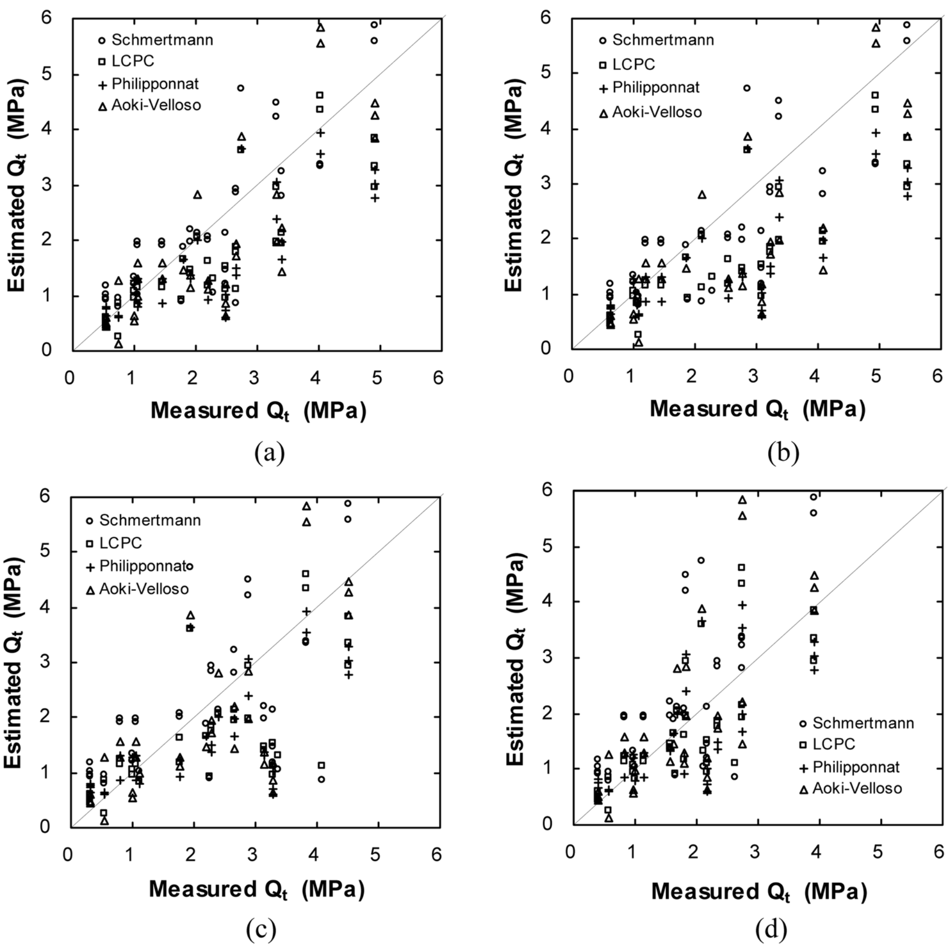


Fig. 3 Measured versus estimated total load capacities with (a) 0.1B; (b) Chin's; (c) DeBeer's; and (d) Davisson's criteria

situation in routine piling practices, as placing a pile on a suitable bearing layer is the main goal of pile foundation, unless entirely floating friction piles are used.

For each of collected cases, measured and estimated pile load capacities were obtained using the load-settlement criteria and CPT-based methods described previously. Fig. 3 shows measured versus estimated total pile load capacities. Those for the base and shaft load capacities were also obtained and analyzed. From Fig. 3, it is certainly observed that adoption of different design methods and load-settlement criteria produce different degrees of the accuracy (i.e., degree of match between measured and estimated data) and the consistency (i.e., degree of data scatter). This confirms that resistance factors should be evaluated such that specific types of design methods and load-settlement criteria are properly taken into account.

4.2 Characteristic pile load capacity

While not explicitly stated in Eq. (9) through Eq. (11), target random variables (i.e., pile load capacity or resistance) that are to be analyzed and quantified statistically should be of the same or sufficiently close geotechnical background. In other words, pile load capacities estimated from entirely different soil conditions cannot be regarded in the same frame of statistical distribution. For example, load capacities of two geometrically identical piles embedded in looser and denser sands would be certainly lower and higher, respectively. The difference of pile load capacities in the denser and looser sands is not due to geotechnical uncertainty; rather it is clearly expected due to obviously different soil conditions. This aspect would not be a matter if target data sets, such as measured and estimated pile load capacities, were from the same test location. If data sets are from different locations and soil conditions, however, target variables that are to be used in reliability analysis should be adjusted such that the statistical consistency is maintained.

In order to maintain the statistical consistency of data sets collected from different sites, characteristic pile load capacity, as defined as the following relationship, was newly introduced and used in reliability analysis

$$Q_{ch} = \frac{Q_e}{Q_r} = \frac{Q_{CPT}}{Q_{PLT}} \tag{12}$$

where Q_{ch} = characteristic pile load capacity; Q_e = estimated pile load capacity; and Q_r = reference pile load capacity. In Eq. (12), Q_e corresponds to the pile load capacity obtained from a certain CPT-based method (Q_{CPT}), whereas Q_r is that measured from pile load test results (Q_{PLT}) using a certain load-settlement criterion.

As Eq. (12) is given in a form normalized with Q_{PLT} at a given load or settlement level, the statistical consistency of data sets from different source locations can be maintained irrespective of soil conditions and pile geometries. It is certain that use of data sets from a single location would be more straightforward and statistically consistent. However, such a case would represent a condition of underestimated uncertainties due to limited variability of soil and test conditions. Using values of Q_{ch} obtained from the datasets given in Table 2, log-normal distribution curves of Q_{ch} for the total, base, and shaft capacities were obtained and plotted in Fig. 4. Results in Fig. 4 were for the case using LCPC method and 0.1B criterion. Distribution curves of Q_{ch} for other CPT-based methods and load-settlement criteria were also obtained and used in reliability analysis.

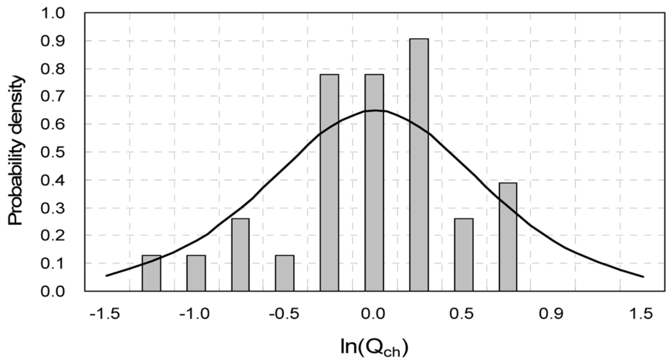
4.3 Bias factors for characteristic pile load capacity

The bias factor (λ) is defined as a ratio of the mean to the nominal value for considered random variables, indicating the accuracy or correctness of estimated nominal resistance with respect to measured resistance. In terms of the characteristic pile load capacity Q_{ch}, λ can be given as follows

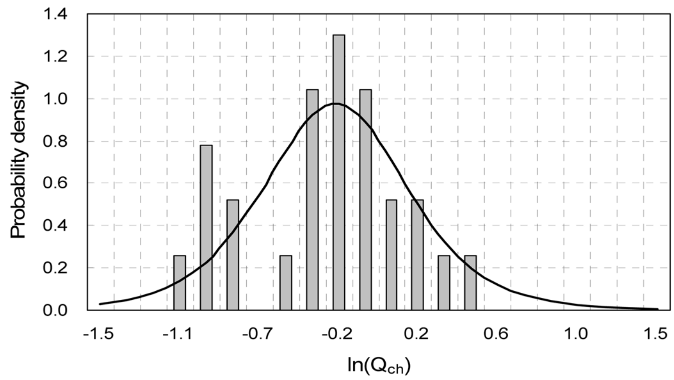
$$\lambda = \frac{\overline{Q_{ch}}}{(Q_{ch})_n} = \frac{(Q_{PLT}/Q_{PLT})}{(Q_{CPT}/Q_{PLT})} = \frac{Q_{PLT}}{Q_{CPT}} \tag{13}$$

where λ = bias factor; $\overline{Q_{ch}}$ = mean of Q_{ch}; $(Q_{ch})_n$ = nominal value of Q_{ch}; Q_{PLT} = measured pile load capacity from pile load test; and Q_{CPT} = estimated pile load capacity using CPT results.

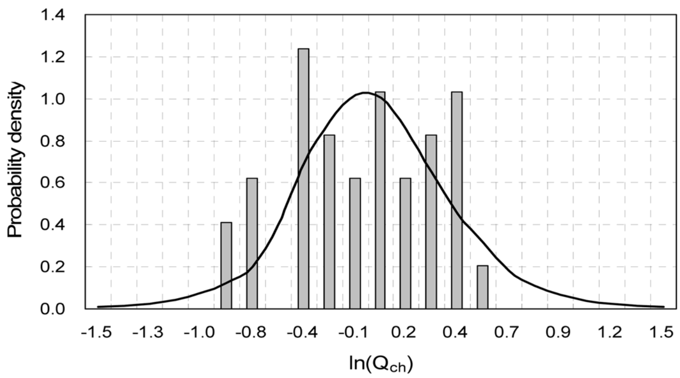
Fig. 5 shows mean values of λ for each load capacity component obtained from different CPT-based design methods and load-settlement criteria. For manufactured materials such as concrete or steel, nominal strengths specified by manufacturers are in general similar to measured mean strengths with λ close to 1. From Fig. 5, however, it is seen that values of λ for the pile load capacity differ considerably for different design methods and load-settlement criteria adopted.



(a)



(b)



(c)

Fig. 4 Statistical distributions of ln(Q_{ch}) for (a) base; (b) shaft; and (c) total load capacities

Variation of λ according to load capacity component is also observed to be quite large. For the base load capacity, Philipponnat's method (i.e., PH in Fig. 5) shows upper ranges of λ values while Schmertmann's (i.e., SC in Fig. 5) and Aoki-Velloso's (i.e., AV in Fig. 5) methods represent lower λ values. In terms of load-settlement criteria, Chin's criterion (i.e., CH in Fig. 5) is observed to give higher λ values while Davisson's criterion (i.e., DA in Fig. 5) shows relatively lower λ values.

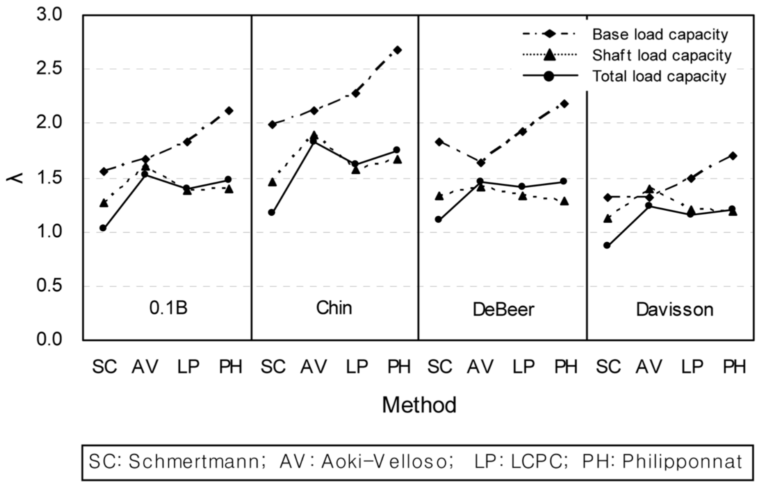


Fig. 5 Values of bias factor (λ) for base, shaft, and total load capacities

These results appear to be reasonable because Chin's criterion, which defines the pile load capacity at ultimate state, tends to produce larger load capacities than other criteria.

For the shaft load capacity, values of λ were in relatively narrow range of 1.1 to 1.9, representing less sensitiveness to design methods and load-settlement criteria. This can be explained as the shaft resistance is typically mobilized at settlements of around 1-2% of pile diameter, which are much smaller than for the base resistance to be mobilized. This in turn indicates that settlement levels specified by most load-settlement criteria are likely to exceed the settlements required for the mobilization of the shaft resistance. In cases of the total load capacity, values of λ are observed to vary in 0.87-1.8 range, showing similar trends to those of the shaft load capacity. For all the cases of the total load capacity, Schmertmann's method represents the lowest range of λ values. In particular, when measured pile load capacity from Davisson's criterion is adopted, the value of λ is observed to be slightly smaller than 1.0, since Davisson's criterion tends to produce lower pile load capacity than other load-settlement criteria.

Values of λ for the pile load capacity of different design methods can also be found in the literature. According Orchant *et al.* (1988), the value of λ for CPT-based pile design methods can be taken as 1.03 while that for SPT-base methods is 1.30. Compared to results obtained in this study, however, λ = 1.03 for CPT-based pile load capacity estimation appears to be excessively small, and thus may lead to underestimated variability of pile load capacity estimation than actually observed.

4.4 Coefficient of Variation

The coefficient of variation COV is a statistical index that quantifies uncertainties in terms of the standard deviation and the mean, representing the precision or consistency of variables. Since uncertainties associated with testing or measurement errors from cone penetration test (CPT) and pile load test (PLT) also affect reliability of target datasets, overall COV for CPT-based pile design methods can be given as follows

$$COV = \sqrt{COV_{model}^2 + COV_{CPT}^2 + COV_{PLT}^2} \tag{14}$$

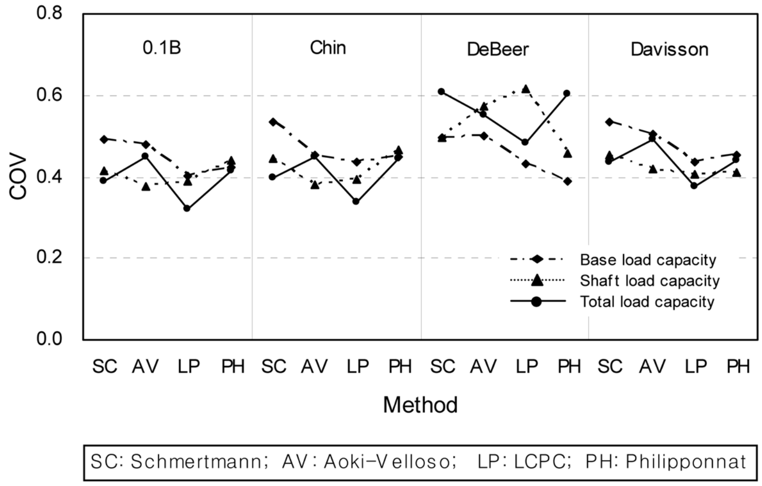


Fig. 6 Values of coefficient of variation (COV) for base, shaft, and total load capacities

where COV_{model} = COV for pile design methods and load-settlement criteria; COV_{CPT} = COV for CPT measurements; COV_{PLT} = COV for PLT measurements. In this study, COV_{CPT} = 0.05 and COV_{PLT} = 0.08 were adopted based on results obtained by Matsumoto *et al.* (1993) and Kulhawy and Trautman (1996).

From statistical analysis results and Eq. (14), COVs for each CPT-based method and load-settlement criterion were obtained and plotted in Fig. 6. For the base load capacity, values of COVs fall within 0.39-0.54 range, whereas those for the shaft and total load capacities are found to be in 0.38-0.62 and 0.32-0.61 ranges, respectively. While values of COVs differ for different design methods and load-settlement criteria, 0.1B and Chin's (i.e., CH in Fig. 6) criteria appear to give, in average, lower values of COVs. It is also seen that, for the total load capacity, LCPC method (i.e., LP in Fig. 6) represents the lowest range of COVs.

5. Resistance factors for CPT-based pile load capacity estimation

5.1 Comparison of reliability index and factor of safety

Both the factor of safety (FS) and the reliability index (β) represent safety margin of structures against either failure or limit state. Based on Eq. (8) using FOSM, the relationship between FS and β can be given as the following relationship

$$\beta = \frac{\ln\left[\left(\frac{\lambda_Q FS\left(\frac{L_D}{L_L}+1\right)}{\lambda_{LD}\left(\frac{L_D}{L_L}\right)+\lambda_{LL}}\right)\sqrt{\frac{(1+COV_{LD}^2+COV_{LL}^2)}{(1+COV_Q^2)}}\right]}{\sqrt{\ln[(1+COV_Q^2)(1+COV_{LD}^2+COV_{LL}^2)]}} \tag{15}$$

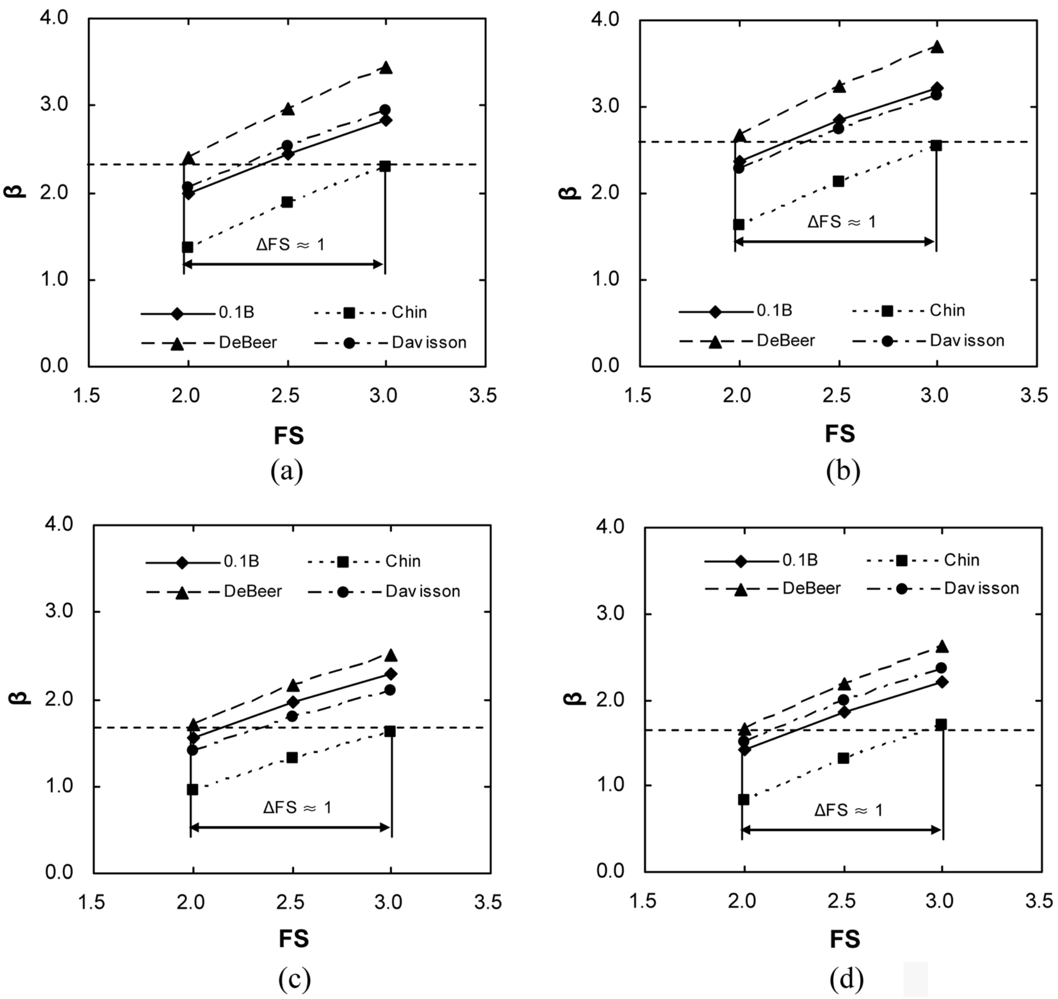
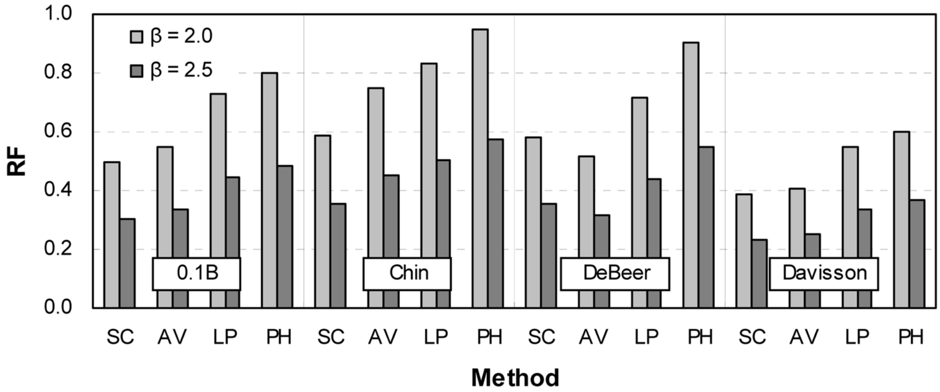


Fig. 7 Reliability index (β) versus factor of safety (FS) for (a) Schmertmann's; (b) Aoki and Velloso's; (c) LCPC's; and (d) Philipponnat's methods

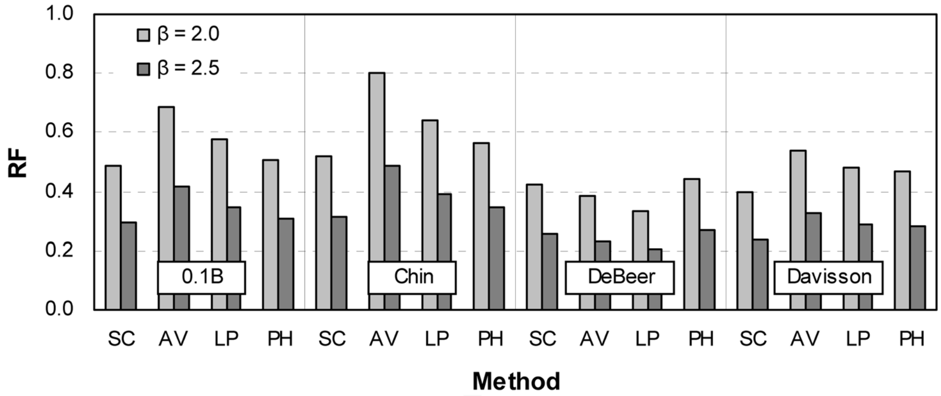
where FS is the factor of safety and others are the same as those in Eq. (11).

Fig. 7 shows values of β versus FS for the total pile load capacity according to Eq. (15) using reliability analysis results obtained in this study. In Eq. (15), values of load-related reliability parameters, such as L_D/L_L, COV_{LD}, COV_{LL}, λ_{LD}, and λ_{LL}, were adopted as those previously reported in the literature (AASHTO 1998, Withiam *et al.* 2001). These are $L_D/L_L = 4$, $COV_{LD} = 0.13$, $COV_{LL} = 0.18$, $\lambda_{LD} = 1.08$, and $\lambda_{LL} = 1.15$. For resistance-related parameters, such as COV_Q and λ_Q, values obtained in this study were used.

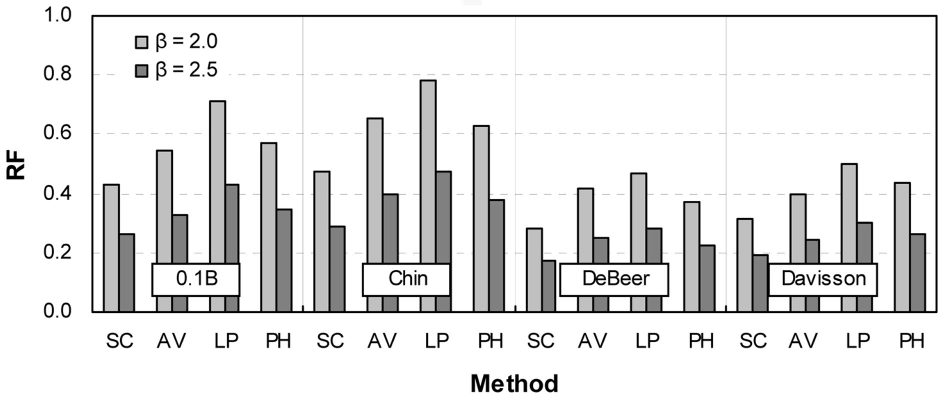
From Fig. 7, it is seen that DeBeer's criterion gives the highest range of β values for a given FS while Chin's criterion represents the lowest range. This implies that relatively lower FS can be applied for the pile load capacities obtained from DeBeer's criterion than those from other criteria at a comparably similar design reliability level. As shown in Fig. 7, difference of FS (i.e., ΔFS) between DeBeer's and Chin's criteria for a given β is observed to be approximately 1. It is also noticed that different design methods and load-settlement criteria represent considerably different β



(a)



(b)



(c)

Fig. 8 Resistance factors (RF) at $\beta = 2.0$ and 2.5 for (a) base load capacity; (b) shaft load capacity; and (c) total load capacity

values at a given FS. Based on results in Fig. 7, it can be summarized and confirmed that actual safety margin of the pile load capacity differs depending on selected design method and load-settlement criterion for a given factor of safety.

Table 3 Values of resistance factor at $\beta_T = 2.0$ and 2.5

Load	Method	$\beta_T = 2.0$				$\beta_T = 2.5$			
		(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
Total	0.1B	0.55	0.50	0.73	0.80	0.33	0.26	0.43	0.35
	Chin	0.75	0.59	0.83	0.95	0.40	0.29	0.47	0.38
	DeBeer	0.52	0.58	0.72	0.90	0.25	0.17	0.28	0.23
	Davisson	0.41	0.39	0.55	0.60	0.24	0.19	0.30	0.26
Base	0.1B	0.55	0.50	0.73	0.80	0.33	0.30	0.44	0.48
	Chin	0.75	0.89	0.83	0.95	0.45	0.35	0.51	0.58
	DeBeer	0.52	0.58	0.72	0.90	0.31	0.35	0.44	0.55
	Davisson	0.42	0.39	0.55	0.60	0.25	0.24	0.33	0.36
Shaft	0.1B	0.69	0.49	0.57	0.30	0.42	0.30	0.35	0.31
	Chin	0.80	0.52	0.64	0.57	0.49	0.32	0.39	0.35
	DeBeer	0.38	0.42	0.33	0.45	0.23	0.25	0.20	0.27
	Davisson	0.54	0.40	0.48	0.47	0.35	0.24	0.29	0.28

(1): Aoki-Velloso's method; (2): Schmertmann's method; (3): LCPC method; (4): Philipponatt's method

5.2 Resistance factors for CPT-based methods and load-settlement criteria

Based on the results from reliability analysis, resistance factors (RF) for driven piles were obtained for CPT-based design methods and load-settlement criteria considered in this study. Figs. 8(a), (b), and (c) show RFs at target reliability indices of $\beta_T = 2.0$ and 2.5 for the base, shaft and total pile load capacities. Values of $\beta_T = 2.0$ and 2.5 were adopted following Withiam *et al.* (2001) as described previously. As shown in the figures, for the base load capacity, LCPC and Philipponnat's methods overall represent higher RFs than Aoki-Velloso's and Schmertmann's methods. In terms of load load-settlement criteria, Davisson's criterion shows the lowest range of RFs while the highest range of RF is observed for Chin's criterion. For the shaft resistance, on the other hand, Aoki-Velloso's method shows the highest range of RFs.

For the total resistance, RFs for LCPC and Schmertmann's methods show the highest and lowest ranges, respectively, while those for Aoki-Velloso's and Philipponnat's methods are in similar ranges. It is also seen that 0.1B and Chin's load-settlement criteria result in higher RFs than those for DeBeer's and Davisson's criteria. This is because DeBeer's and Davisson's criteria tend to produce lower values of measured pile load capacity, and thus estimated pile load capacity should be reduced more conservatively than for other criteria at a given reliability level. Values of RFs for each case shown in Fig. 8 were also summarized in Table 3.

6. Conclusions

In this study, LRFD resistance factors for pile design using CPT results were investigated for axially loaded driven piles. A total of 32 data sets from 13 sites for axially loaded driven piles were collected from the literature. The data sets consisted of load-settlement curves obtained from pile load tests and CPT q_c profiles. In order to maintain the statistical consistency of data sets collected from different sites, the characteristic pile load capacity was introduced as the target variable and used in the reliability analysis.

It was observed that values of the bias factor (λ) for the base load capacity varied considerably depending on pile design methods and load-settlement criteria. For the shaft capacity, on the other hand, values of λ were relatively less sensitive to design methods and load-settlement criteria. Based on reliability analysis results, COVs for each CPT-based method and load-settlement criterion were obtained and analyzed. For the base load capacity, values of COVs were within a range of 0.39-0.54, while COVs for the shaft and total load capacities were found to be in 0.38-0.62 and 0.32-0.61 ranges, respectively.

Using reliability parameters obtained in this study, resistance factors (RF) for driven piles were obtained and presented in terms of CPT-based design methods and load-settlement criteria. Target reliability indices of β_T = 2.0 and 2.5 were considered for the evaluation of RF. For the base load capacity, LCPC and Philipponnat's methods overall represented higher RFs than Aoki-Velloso's and Schmertmann's methods. In terms of load load-settlement criteria, Davisson's and Chin's criteria showed the lowest and highest ranges of RF, respectively. For the shaft load capacity, on the other hand, Aoki-Velloso's method showed the highest range of RF. For the total load capacity, RFs for LCPC method were found to be higher than others while those for Aoki-Velloso's and Philipponnat's methods were in similar ranges. Regarding load-settlement criteria, 0.1B and Chin's criteria resulted in higher RFs than those for DeBeer's and Davisson's criteria.

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List of Symbols

A_b : base area of pile
A_s : shaft area of pile
COV : coefficient of variation
c_b : CPT correlation factor for estimation of pile base resistance
c_s : CPT correlation factor for estimation of pile shaft resistance
FOSM : First-order second-moment method
FS : Factor of safety
L : load
LF : load factor

LRFD	: Load and resistance factor design
LSD	: Limit state design
Q	: resistance
Q_b	: pile base load capacity
Q_{ch}	: characteristic pile load capacity
Q_n	: nominal resistance
Q_s	: pile shaft load capacity
q_c	: CPT cone resistance
q_b	: base resistance of pile
q_s	: shaft resistance of pile
RBD	: Reliability-based design
RF	: resistance factor
WSD	: working stress design
λ	: bias factor
β	: reliability index

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