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Evaluation of reliability index and safety factors for pile load capacity estimation using CPT results

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ABSTRACT: The reliability index is an important reliability parameter that is necessary for the development of reliability-based geotechnical design. Both the factor of safety (FS) and the reliability index (β) represent safety margin of structures against either failure or limit state. In this study, the reliability index is analyzed and evaluated in reference to the factor of safety currently adopted in working stress design for pile foundation. Evaluation of the reliability index focuses on CPT-based pile resistance method. Various load-settlement criteria including the 0.1B, Chin, De Beer, and Davisson's methods were adopted to determine pile load capacity from pile load test results. As a CPT-based pile load capacity estimation method, LCPC method was adopted. Using load-settlement curves and CPT results obtained from literature, FOSM analysis was performed for the determination of the reliability index. Based on FOSM analysis, safety margin given by current factor of safety used for the allowable and ultimate condition of pile load capacity are evaluated and compared with values of the reliability index for each load-settlement criterion.

1 INTRODUCTION

In allowable stress design (ASD), deterministic values of load and resistance are used to define safety margin of structures with adoption of the safety factor. It has been widely recognized that the conventional design procedure of ASD doest not fully reflect uncertainties associated with actual distribution of load and resistance that is affected by various soil factors. This has in turn raised the need of introducing reliability-based design concept in geotechnical engineering, such as limit state design and geotechnical load-resistance factor design.

For the determination of load capacity of foundation, uncertainties from soil itself due to non-linear soil behaviour and spatial variability of soil properties are important consideration. Uncertainty from application of different design methods is also an important factor that affects overall reliability of foundation design. There have been a number of methods and criteria for the design of foundation and interpretation of field load test results. Each of this represents different level of load capacity and reliability. Optimized foundation design therefore requires quantification and reflection of the difference from design and interpretation methods to maintain the consistency of overall reliability.

The reliability index is an important reliability parameter that is necessary for the load and resistance factor design (LRFD). Both the factor of safety and the reliability index represent safety margin of structures against either failure or limit state. In this study, the reliability index is analyzed and evaluated in reference to factors of safety currently adopted in allowable stress design for pile foundation. Evaluation of the reliability index focuses on CPT-based pile load capacity estimation. Load capacity of axially loaded piles in sands is addressed with different load-settlement criteria that are used to determine pile load capacity from pile load test results.

2 RELIABILITY-BASED DESIGN

2.1 Limit State Function

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

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

where p_f = probability of failure; p_s = probability of survival; P = probability function. If distributions of Q and R are known, the probability of failure and actual safety margin can be evaluated using Eq. (1).

Since exact distributions of Q and R are hardly identified, particularly for geotechnical problems, approximated reliability analysis methods based on representative reliability parameters are often used (Becker 1996; Withiam et al. 2001; Scott et al. 2003). In the present study, the first-order second-moment (FOSM) method, assuming the log-normal distribution of Q and R, is adopted. This method is based on the first order approximation of Taylor expansion using the mean and the standard deviation. While distributions of Q and R 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 (Scott et al. 2003; Christian 2004). For log-normally distributed Q and R, the limit state function g can be written as:

$$g = \ln(R) - \ln(Q) = \ln(R/Q) \tag{2}$$

where g = limit state function; R = resistance; and Q = load. The condition of $g < 0$ corresponds to failure, hence $g = 0$ represents a limit state condition. Fig.1 shows a typical distribution curve of the limit state function.

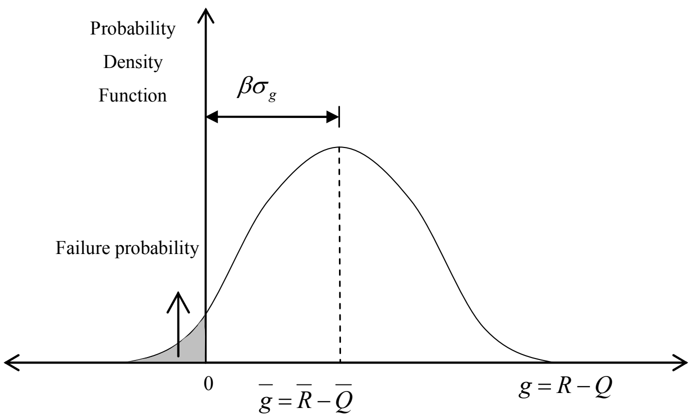


Fig.1 Limit state function and reliability index

2.2 Reliability Index

In load resistance factor design (LRFD), inequality relationship between load and resistance using the load and resistance factors is given as follows:

$$\phi R_n \geq r_D Q_D + r_L Q_L = \sum r_i Q_i \tag{3}$$

where ϕ = resistance factor; R_n = nominal resistance; r_D = dead load factor; r_L = live load factor; Q_D = dead load; and Q_L = live load. The reliability index β is defined as the mean of g normalized with the standard deviation σ_g. As shown in Fig.1, β corresponds to distance of the mean from the origin, and thus represents statistically the same meaning as p_f. If Q and R are uncorrelated each other and are log-normally distributed, β is given as (Withiam et al. 2001):

$$\beta = \frac{\ln\left(\dfrac{\lambda_R R_n}{\lambda_{QD}\dfrac{Q_D}{Q_L}+\lambda_{QL}}\right)\sqrt{\dfrac{1+COV_{QD}{}^2+COV_{QL}{}^2)}{1+COV_R{}^2}}}{\sqrt{\ln(1+COV_R{}^2)(1+COV_{QD}{}^2+COV_{QL}{}^2)}} \tag{4}$$

where λ_{QD} = bias factor for dead load; λ_{QL} = bias factor for live load; λ_R = bias factor for resistance; COV_{QD} and COV_{QL} = coefficients of variation for L and Q, respectively; and COV_R = coefficient of variation for resistance. The bias factor λ is defined as a ratio of the mean to the nominal value. The coefficient of variation (COV) is given as follows:

$$COV_{QD} = \frac{\sigma_{QD}}{\overline{Q}_D}, COV_{QL} = \frac{\sigma_{QL}}{\overline{Q}_L}, COV_R = \frac{\sigma_R}{\overline{R}} \tag{5}$$

where σ_{QD}, σ_{QL}, and σ_R = standard deviations of dead load, live load, and resistance; and $\overline{Q}_D$, $\overline{Q}_L$, $\overline{R}$ = means of Q_D, Q_L, and R, respectively.

As indicated in Eq. (4), the reliability index β is defined in terms of various factors that are related to load and resistance. While values of factors associated with loads have been differently proposed by different institute, in the present study, those presented by AASHTO (1994) were adopted as follows:

$$\lambda_{QD} = 1.08, \lambda_{QL} = 1.15, r_D = 1.25, r_L = 1.75, COV_{QD} = 0.13, COV_{QL} = 0.18 \tag{6}$$

Values of λ_R and COV_R for resistance should be obtained from reliability analysis with actual pile load test and other relevant testing results. Other than variability associated with pile load capacity estimation method, those from pile load test itself and other related in-situ tests are also factors that should be considered (Scott 2002). If these testing uncertainties are taken into account, overall COV for CPT-based pile design methods can be obtained as:

$$COV = \sqrt{COV_{\mathrm{model}}{}^2 + COV_{CPT}{}^2 + COV_{PLT}{}^2} \tag{7}$$

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).

2.3 Relationship between Reliability Index and Factor of Safety

Both the factor of safety (FS) in allowable stress design (ASD) and the reliability index (β) in limit state design represent a level of safety margin for a given structure design. In terms of FS, the nominal resistance R_n can be written as follows:

$$R_n = FS \cdot Q_n \tag{8}$$

where R_n = nominal resistance; FS = factor of safety; and Q_n = nominal load, which is composed of dead load Q_D and live load Q_L. The nominal load on the other hand can be expressed using the bias factors as follows:

$$\lambda_n Q_n = \lambda_{QD} Q_D + \lambda_{QL} Q_L \tag{9}$$

where λ_n = bias factor for nominal load; λ_{QD} = bias factor for dead load; λ_{QL} = bias factor for live load; Q_n = nominal load; Q_D = dead load; Q_L = live load.

From Eqs. (4), (8), and (9), the reliability index β is given by following equations for the normally distributed load and resistance (Zhang et al. 2001):

$$\beta = \frac{\lambda_R FS\left(\frac{Q_D}{Q_L}+1\right) - \left(\lambda_{QD}\frac{Q_D}{Q_L}+\lambda_{QL}\right)}{\sqrt{\sigma_R{}^2+\sigma_{QD}{}^2+\sigma_{QL}{}^2}} \tag{10}$$

and for log-normally distributed load and resistance:

$$\beta = \frac{\ln\left[\left(\frac{\lambda_R FS\left(\frac{Q_D}{Q_L}+1\right)}{\lambda_{QD}(\frac{Q_D}{Q_L})+\lambda_{QL}}\right)\sqrt{\frac{(1+COV_{QD}{}^2+COV_{QL}{}^2)}{(1+COV_R{}^2)}}\right]}{\sqrt{\ln[(1+COV_R{}^2)(1+COV_{QD}{}^2+COV_{QL}{}^2)]}} \tag{11}$$

All the symbols are the same as appearing in previous equations.

3 PILE LOAD CAPACITIES FROM LOAD-SETTLEMENT CURVES AND CPT

3.1 Load-settlement criteria

For the determination of the pile load capacity on load-settlement curves from field pile load tests, four different load-settlement criteria were adopted and used in the analysis of the reliability index and factor of safety. These include methods of 0.1B (Franke 1989), Chin (1970), De Beer (1967), and Davison (1972). All these methods are commonly adopted in piling engineering practice. Detailed description of each method is given in Fig.2. The pile load capacity determined from load-settlement curves will be referred to as "measured" pile load capacity.

The 0.1B method defines the pile load capacity (P_L) at a settlement equal to 10% of the pile diameter (B). This is based on the assumption that a settlement of 10% pile diameter is likely to cause the ultimate limit state for most structures supported by piles. Chin's method on the other hand defines P_L from the hyperbolically transformed load-settlement curve. In this method, P_L is equal to a reciprocal of slope C_1 shown in Fig.2(b). Chin's method can be regarded as an extrapolation method for estimating limit pile load capacity assuming that load-settlement curve is defined with hyperbolic function. However, it may not provide realistic yield load if a constant time increment is not sustained in the pile load test. Extrapolation for hyperbolic load-settlement curves also requires that the load test be extended sufficiently far.

De Beer (1967) defined P_L as the load corresponding to the point of maximum curvature on the load-settlement curve. In this method, the load-settlement curve is plotted using log-log scale as shown in Fig.2(c). The failure load is then determined as the load corresponding to the point at which two straight lines intersect. This method was, however, originally proposed for the slow maintained pile load test. In Davisson's method (Davisson 1972), P_L load is defined as the load leading to a deformation equal to the summation of the pile elastic compression and a deformation equal to a percentage of the pile diameter. This relationship is given by:

$$s_f = \frac{QL}{AE} + 0.00381B^* + \frac{1}{3.05}\cdot\frac{B}{B^*} \tag{12}$$

where s_f = settlement at failure; Q = applied load; L = pile length; E = Young's modulus of pile; A = cross sectional area of pile; B^* = reference length = 1 m; and B = pile diameter. Since this method is, in general, regarded conservative, it appears to work best with data from quick maintained load tests. Due to the dynamic effect, loads obtained from the quick maintained load tests tend to be higher than loads obtained from the slow maintained load tests, sometimes significantly so in clayey material. It may, therefore, lead to overly conservative results when applied to data from the slow maintained load tests resulting in considerable underestimation of a pile failure load.

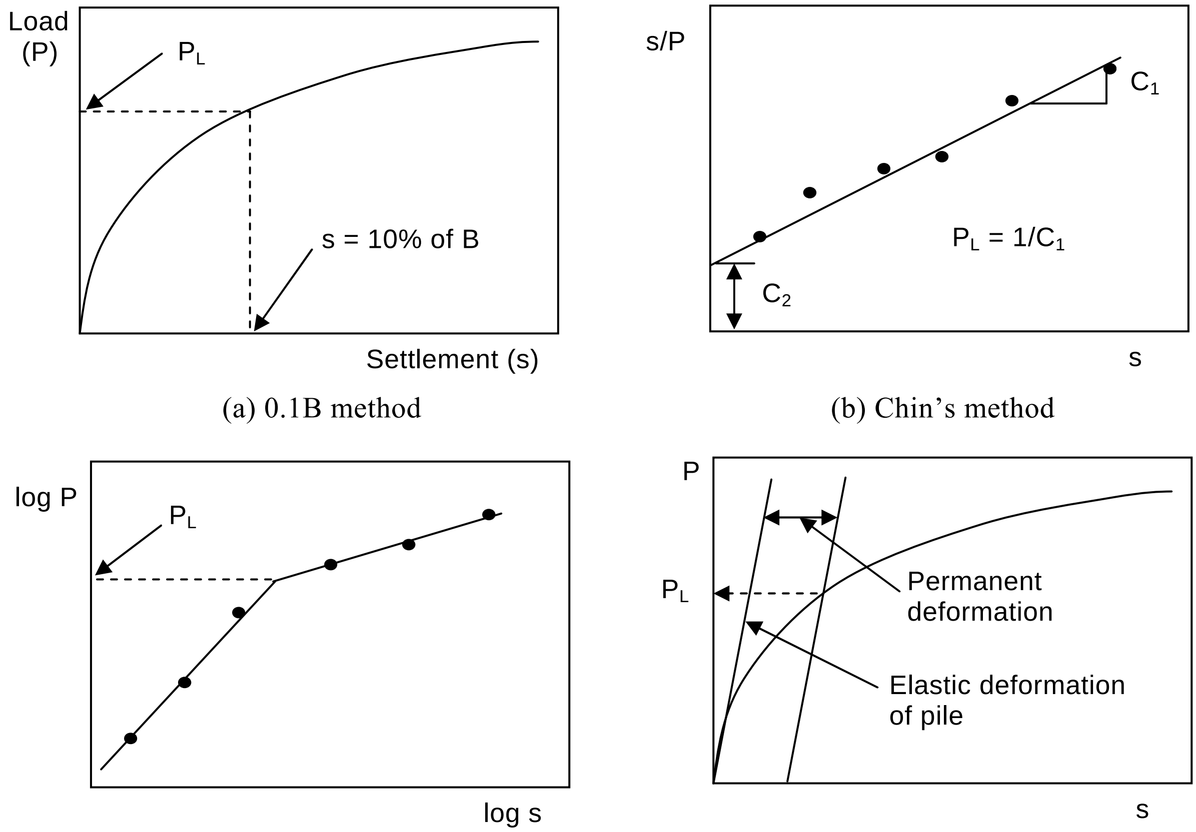
3.2 CPT-based Pile Load Capacity Estimation

The CPT is a superior test for pile design purposes. In this test, a cylindrical penetrometer with a conical tip is pushed into the ground as if it were a scaled pile load test. In addition to the similarity between the pile loading and cone penetration testing mechanisms, the possibility of simultaneous measurement of shear wave velocities makes it possible to estimate elastic properties of subsurface soils, which may improve the quality of the design with more accurate in-situ soil properties. Determination of pile load capacity based on CPT results can be expressed as:

$$q_b = c_b q_c \tag{13}$$

$$q_s = \sum c_{si} q_{ci} \tag{14}$$

where q_b = base resistance; c_b = empirical parameter to convert q_c to base resistance; q_c = cone resistance at the pile base level; q_s = shaft resistance; c_{si} = empirical parameter to convert q_c to shaft resistance; and q_{ci} = representative cone resistance for layer i.



(a) 0.1B method (b) Chin's method

(c) De Beer's method (b) Davison's method

Fig.2 Load-settlement criteria used in reliability analysis of pile load capacity

Values of c_b and c_{si} have been proposed mostly based on empirical correlations developed between pile load test results and CPT results. Because different authors proposed different values of c_b and c_{si}, the use of such parameters should be applied under conditions similar to those under which they were determined. Although most expressions were based on cone resistance q_c, some authors (Price and

Wardle 1982, Schmertmann 1978) suggested the use of cone sleeve friction f_s for the estimation of shaft resistance with the following general expression:

$$q_s = c_{sfi} f_{si} \tag{15}$$

where c_{sfi} is a empirical parameter to convert cone sleeve friction to shaft resistance and f_{si} is a representative cone sleeve friction for layer i.

In the present study, LCPC method proposed by Bustamante and Gianeselli (1982) was adopted and used in the reliability analysis of pile load capacity. The basic formula for the LCPC method can be written as:

$$q_b = k_c q_{ca} \tag{16}$$

$$q_s = \frac{1}{k_s} q_c \tag{17}$$

where k_c = base resistance factor; q_{ca} = equivalent cone resistance at pile base level; k_s = shaft resistance factor; and q_c = representative cone resistance for the corresponding layer. The values of k_c and k_s depend on the nature of soil and its degree of compaction as well as the pile installation method. The equivalent cone resistance q_{ca} used in Eq. (16) represents an arithmetical mean of the cone resistance measured along the distance equal to 1.5B above and below the pile base, where B = pile diameter.

4 RELIABILITY ANALYSIS OF PILE LOAD CAPACITIES

4.1 Measured and Estimated Pile Load Capacities

A series of load test results for axially loaded bored and driven piles and CPT results performed at test sites were collected from literature and used in reliability analysis. Detailed test conditions of collected cases are given in Table 1. Soils at test sites were of various types and conditions, but bearing layers at pile base levels for all the cases consisted of granular soils. This is a common situation in routine piling practices, as placing a pile on a firm bearing layer is the main goal of pile foundation, unless entirely floating friction piles are used.

Table 1 Summary of data sets for pile load tests

Pile type	Reference	Pile length (m)	Pile diameter (m)	No. of CPT	Pile material	Site
Driven Pile	Van Impe et al. (1988)	12.02	0.60	3	Steel pipe (CE)	Belgium
	Briaud et al. (1989[a])	9.14	0.27	4	Steel pipe (CE)	U.S.A
	Lee et al. (2003)	6.87	0.36	2	Steel pipe (OE)	U.S.A
		7.04	0.36		Steel pipe (CE)	
	Vesic (1970)	3.01	0.46	2	Steel pipe (OE)	U.S.A
		6.13	0.46			
		8.87	0.46			
		11.98	0.46			
	Kautsoftas (2002)	14.02	0.42	2	Steel pipe(OE)	U.S.A
	Briaud et al. (1989[b])	16.46	0.37	2	Steel H-pile	U.S.A
		16.15	0.37			

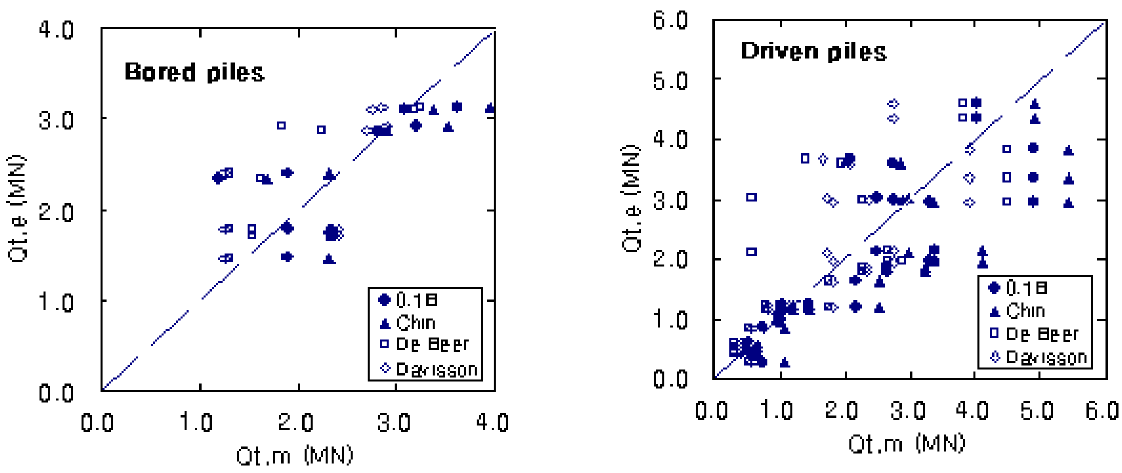
		17.68	0.37	1		
		17.98	0.37			
	Witzel & Kempfert (2005)	21.00	0.35	1	Concrete squre	Germany
	Altaee et al. (1992)	11.00	0.29	2	Concrete squre	Iraq
Bored Pile	Van Impe et al. (1988)	11.76	0.60	3	Concrete	Belgium
	Mayne & Harris (1993)	16.76	0.76	1	Concrete	U.S.A
	Matsui (1993)	36.30	1.20	1	Concrete	Japan
	Mandolini et al.(2002)	24.00	0.84	2	CFA	Italy
		22.50	0.61			
	Kruizinga (1975)	12.55	0.59	1	Concrete	Netherlands
		18.40	0.59			
	Kruizinga et al. (1985)	22.50	0.60	1	Steel pipe (OE)	Netherlands

OE : Open-ended pile; CE : Closed-ended pile

For each case collected in this study, measured and estimated pile load capacities were obtained using load-settlement criteria described previously and LCPC method. Fig.3 shows pile load capacities measured from load-settlement curves versus estimated from LCPC method. From Fig.3, it is observed that adoption of different load-settlement criteria affects both the accuracy (i.e., degree of match between measured and estimated results) and the consistency (i.e., degree of data scatter).

4.2 Reliability index versus Factor of Safety

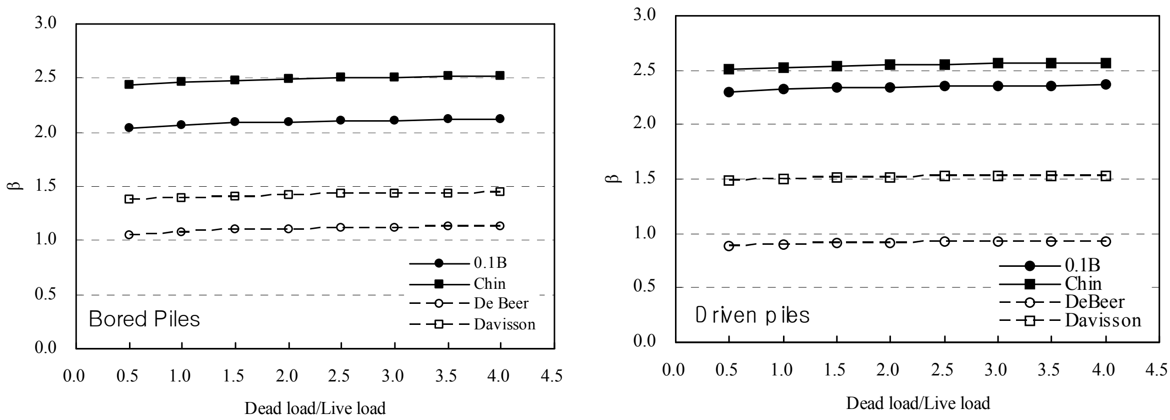
As described previously, determination of the reliability index β requires several reliability factors, including the load ratio defined by a ratio of dead load to live load Q_D/Q_L. Values of load ratios differ for different types and sizes of structures. Hansell and Viest (1971) presented values of load ratio with span length. Their result are used the AASHTO ASD specifications. In this study, more detailed effect of the load ratio on the reliability index, values of load ratio from 0.5 to 4.0 were considered and analyzed. Values of COV_R and λ_R in Eq. (11) were obtained from reliability analysis using results in Fig.3.



(a) Bored piles (b) Driven piles

Fig.3 Measured and predicted pile load capacity for different load-settlement criteria

Fig.4 shows values of the reliability index β with load ratio, using pile load test results of driven and bored piles previously described. As shown in Fig.4, while values of β slightly increase with load ratio, no significant variations of β are observed with load ratio. This is in agreement with results by Whitiam et al. (2001), Becker (1996) and Titi et al. (2004). In the present study, therefore, the load ratio equal to 4 was adopted for evaluations of the reliability index and factor of safety.

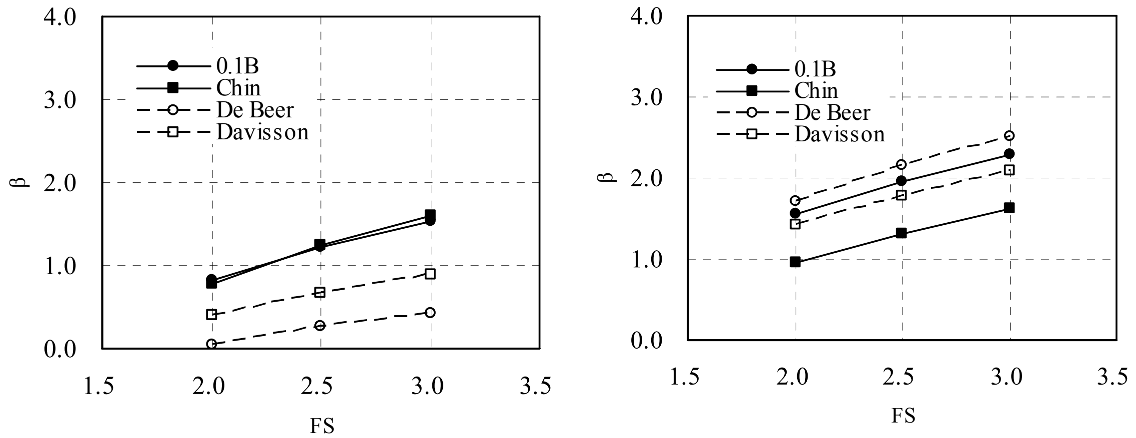


(a) Bored piles (b) Driven piles

Fig.4 Reliability index with load ratio

Fig.5 shows values of the reliability index β versus the factor of safety FS for the total pile load capacity according Eq. (11) using reliability analysis results obtained in this study. For load-related reliability parameters in Eq. (11), such as COV_{LD}, COV_{LL}, λ_{LD}, and λ_{LL}, values reported in the literature were adopted (AASHTO 1994). The load ratio L_D/L_L was 4 based on results given Fig.4.

From Fig.5, it is seen that overall range of the reliability index for bored piles are lower than that for driven piles. This was due to higher degree of data scatter and lower degree of correlation between measured and predicted load capacities observed for bored piles obtained from pile load test and CPT results. This is somewhat unexpected as soil conditions before and after the installation of bored piles are regarded the same and thus predicted load capacities are in general expected to be better correlated to soil properties or in-situ test results. Based on results obtained in study, it can be inferred that uncertainty associated with load capacity estimation for bored pile are greater than conventionally assumed, and that the uncertainty may be primarily from quality of bored pile installation.



(a) Bored piles (b) Driven piles

Fig.5 Relationship between the reliability index and factor of safety with different load-settlement criteria

From Fig.5(a) for bored piles, it is observed that current factor of safety equal to 2 to 3 may not be sufficiently high to guarantee required reliability level of pile design due to uncertainty described above. For driven piles in Fig.5(b), on the other hand, DeBeer's criterion shows the highest range of β values for a given FS while Chin's criterion represents the lowest range. This indicates that relatively lower FS can be applied to the pile load capacity obtained from DeBeer's criterion than from others at a similar design reliability level. It is also noticed that different load-settlement criteria represent considerably different β values at a given FS. Based on results in Fig.5, it can be summarized that current pile design practice based on allowable stress design with fixed FS (typically 2.0 – 3.0) does not guarantee a consistent level of actual safety margin with possible variation of actual FS around 1.

5 SUMMARY AND CONCLUSION

The reliability index is an important reliability parameter that is necessary for the load and resistance factor design. Both the factor of safety and the reliability index represent safety margin of structures against either failure or limit state. In this study, the reliability index is analyzed and evaluated in reference to factors of safety currently adopted in allowable stress design for pile foundation. Evaluation of the reliability index and factor of safety was performed for various load-settlement criteria and LCPC method. Load-settlement criteria adopted in this study include the 0.1B, Chin's, DeBeer's, and Davisson's methods. All these methods are commonly used in piling practice.

A series of load test results for axially loaded bored and driven piles and CPT results performed at test sites were collected from literature and used in reliability analysis. Soils at test sites were of various types and conditions, but bearing layers at pile base levels for all the cases consisted of granular soils. Using pile load capacities from field pile load tests and LCPC method with CPT results, reliability analysis was performed. Values of the reliability index were calculated and compared with a range of factor of safety.

It was seen that overall range of the reliability index for bored piles are lower than that for driven piles due to higher degree of data scatter and lower degree of correlation between measured and predicted load capacities. This indicates that current factor of safety equal to 2 to 3 may not be sufficiently high to guarantee required reliability level for bored pile design. For driven piles, DeBeer's criterion shows the highest range of β values for a given FS while Chin's criterion represents the lowest range. Based on results obtained in this study, it is concluded that current pile design practice based on allowable stress design with fixed FS does not guarantee a consistent level of actual safety margin with possible variation of actual FS around 1.

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