Assessment of the skin friction of large diameter bored piles in sand

Evaluation du frottement latéral maximal des pieux forés des grands diamètres dans le sable

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ABSTRACT
Large diameter bored piles currently represent a major element of deep foundations that can successfully be utilized in different subsurface conditions. However, there is an apparent difficulty in correlating the skin friction and end bearing resistances of such piles with the results of in-situ tests with adequate accuracy. Hence, the need for further research associated with the estimation of the ultimate capacity and load-settlement behavior of large diameter bored piles based on these tests is evident. This paper will focus on the assessment of skin friction of large diameter bored piles in cohesionless soil using correlation with in-situ tests such as standard penetration test (SPT). Traditionally, average SPT blow counts have been used, which invariably involves various degrees of uncertainty. This uncertainty can be attributed to several factors, such as soil spatial variability, effect of construction technique, and model uncertainty. Engineering judgment and reliance on appropriate factors of safety have been the conventional tools adopted in the geotechnical engineering practice to deal with the uncertainty associated with pile design. There is a need, however, to develop theoretically-sound methods to account for the uncertainty in SPT-based pile design especially for large diameter bored piles where pile settlement becomes of significant importance. In this paper, an attempt is made to develop a new SPT-based correlation with the maximum skin friction capacity of large diameter bored piles, in sand, that takes into account the effect of various sources of uncertainty.

RÉSUMÉ
Les pieux forés à grands diamètres occupant un des éléments principaux de la fondation profonde. Il est difficile d'estimer,avec une précession acceptable, la valeur du frottement latéral et de la résistance du bout à partir des résultats des essais in-situ exécutés dans un sol pulvérulent, comme par exemple l'essai de pénétration standard (SPT). Généralement, il y a un degré d'incertitude en utilisant le nombre de coups du SPT à l'étude de la fondation due plusieurs facteurs. L'article présent, donne une corrélation entre le nombre de coups du SPT et le frottement latéral maximal des pieux forés des grands diamètres dans un sol sablé prenant en compte plusieurs sources d'incertitudes.

Keywords : *Bored piles, SPT, Soil variability, Model uncertainty*

1 INTRODUCTION

Deep foundations using large diameter bored piles have proved in the last three decades to be an economic foundation type. This foundation system was successfully applied in different geotechnical conditions. There is still a shortcoming regarding assessment of the bearing capacity and load-settlement behavior of such large diameter bored piles, and how to correlate their skin friction and end bearing resistances with in-situ tests results. This paper will focus on the topic of skin friction of large diameter bored piles in cohesionless soil. The standard penetration test (SPT) is one of the most widely used in-situ tests in cohesionless soils. Therefore, it will be adapted in this research to estimate the ultimate skin friction resistance of large diameter bored piles. The average SPT N-value along the pile shaft is commonly utilized in different previous SPT-based correlations with pile skin friction. Pile design based on these average values may involve a degree of uncertainty associated with the possible soil variability along the pile shaft.

In this paper, SPT-based correlation with the ultimate skin friction resistance of large diameter bored piles under axial compression in sand is investigated. Results of 12 instrumented pile load tests were utilized. The statistic/probabilistic tools were exploited to evaluate the performance reliability of the investigated correlation.

2 INSTRUMENTED PILE LOAD TESTS

Results of 12 pile load tests, conducted on large diameter bored piles in sand, were utilized in this study. These tests were selected from different case histories presented in the literature. The tested piles have shaft diameter between 0.8 and 2.0 m. The piles lengths range between 8 and 38 m, without enlarged base. Geotechnical information, available from adjacent boreholes to the location of the selected piles, indicated that the subsurface profiles generally consisted of medium to very dense sand.

In the chosen 12 case studies, the piles were loaded using the Maintained Loading Test (MLT) method. The maximum measured pile head settlement, at the maximum test load, raged between 7 and 14% of the pile diameter. Field instrumentations of the pile side and base resistances were available. Hence, the load share taken by pile skin friction and end bearing could separately be evaluated. Details of the tested piles, and a summary of the tests results, are shown in Table 1.

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Table 1. Details and results of the selected pile load tests.

Test No.	Pile Information			
	d (m)	L (m)	Location	Supporting technique
T-01	1.2	11.4	Germany	TC
T-02	2.0	38	Japan	BS
T-03	0.81	8.5	Germany	BS
T-04	0.95	8.5	Germany	BS
T-05	1.2	8.2	Germany	TC
T-06	1.0	20	Japan	BS
T-07	1.22	18	Florida	BS
T-08	0.9	10.4	Florida	TC
T-09	1.2	16.5	Argentina	BS
T-10	1.35	18.4	Venezuela	TC
T-11	1.07	8.5	Germany	BS
T-12	1.08	8.5	Germany	TC

Test No.	Results of the Pile Load Test			
	P_{max} (MN)	Q_{sact} (MN)	Q_{bact} (MN)	s_{max}/d (%)
T-01	17	5	12	9.85
T-02	40	21.25	18.75	10
T-03	3.457	0.95	2.507	10.53
T-04	4.04	1.11	2.93	9.47
T-05	5.225	1.525	3.7	7.96
T-06	9.2	6.25	2.95	7.82
T-07	3.24	1.491	1.749	8.03
T-08	7.55	2.3	5.25	10.55
T-09	7.2	4.18	3.02	7.08
T-10	13.43	5.2	8.23	13.63
T-11	4.595	1.575	3.02	8.64
T-12	4.63	1.78	2.85	8.72

BS: bentonite slurry; d: pile shaft diameter; L: pile length; P_{max}: maximum test load; Q_{bact}: load taken by end bearing at the maximum test load; Q_{sact}: load taken by skin friction at the maximum test load; s_{max}: pile head settlement at the maximum test load; and TC: temporary casing.

3 DEVELOPMENT OF PILE SKIN FRICTION

Several attempts have been made to estimate the load-settlement behavior of large diameter bored piles. It is commonly accepted that, the pile skin friction resistance is quickly mobilized at a relatively small settlement. In contrary, pile base resistance is mobilized at larger settlement. Meyerhof (1986) considered that the skin friction resistance can be fully mobilized at a pile head settlement of l2 mm, or ranges between 0.5 and 1.5% of the pile diameter. Furthermore, in the Egyptian Code of Practice (ECP, 2001), it is suggested to consider the full mobilization of pile skin friction at a settlement of 1% of the shaft diameter. On the other hand, in the German Standard (DIN 1054, 2005), the required settlement value to fully mobilize the pile skin friction (s_{mf}) is dependent on the ultimate pile skin friction capacity (Q_{su}), as follows:

$$s_{mf}\,(\mathrm{cm}) = 0.5 + 0.5\, Q_{su}\,(\mathrm{MN}) \;\; \leq 3.0\ \mathrm{cm} \qquad (1)$$

For the 12 pile load tests, the above formula was used, assuming Q_{su} is the maximum measured skin friction load (Q_{sact}). Consequently, values of s_{mf}, in a range of 1 to 3% of the pile diameter, were obtained. Figure 1 demonstrates the normalized skin friction load-settlement curves for the 12 instrumented pile load tests. Supplementary, the range of (s_{mf}/d)% suggested by Meyerhof (1986) and in either the ECP (2001), and that obtained from DIN 1054 (2005), are added for comparison, Figures 1.

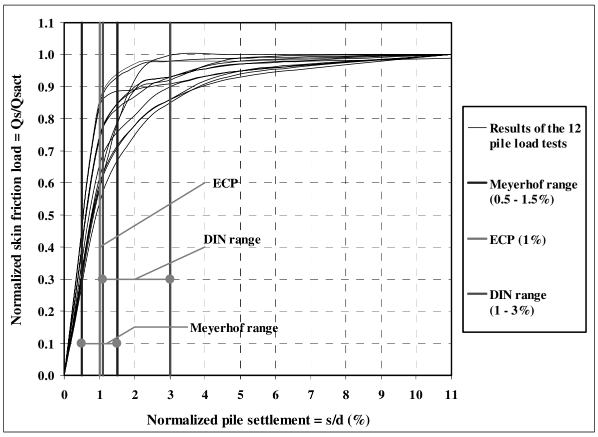

Fig. 1: Normalized skin friction load-settlement curves.

It can generally be noticed from Figure 1 that, 75 to 95% of the piles skin friction was quickly mobilized at a relatively small pile head settlement (s/d ≈ 2%). In some case studies, full mobilization of pile skin friction was observed, at s/d ranged between 2.5 and 3.5%. This may practically be considered matching with the suggestions presented by Meyerhof and in design codes. However, in the other cases, further development of skin friction was observed with continued settlement. The further development of skin friction with increasing settlement in granular soil can be attributed to the soil dilation (Lehane, 2008).

Therefore, in this study, it was suggested to consider a nominal value for the ultimate pile skin friction resistance (f_{su}) at a deterministic pile head settlement of s/d =10%. This postulation may circumvent a possible conservative evaluation of the ultimate skin friction pile capacity. Nevertheless, for such implicated case studies, where the measured settlement did not reach 10% of the pile diameter, the Chin's extrapolation technique (1970) was utilized to extrapolate the measured load-settlement curves to the suggested asymptote.

In addition to the essentially presented 12 case studies, five (5) different cases were utilized to investigate the possible development of pile skin friction with effective overburden pressure. In the additional 5 cases, results of in-situ tests, excluding the SPT, were available. For the 17 cases, the nominal ultimate skin friction resistance (f_{su}), at s/d = 10%, were consequently plotted versus the calculated P_o-values, Figure 2. Where P_o is the calculated effective overburden pressure at the middle of pile shaft.

Figure 2 illustrates that the pile side resistance tends to nonlinearly increase with the overburden pressure. An adequate agreement is present between this finding and that provided in several studies, e.g., Randolph et al. (1994), and Alawneh et al. (2003). Therefore, f_{su} was suggested to be associated with the square root of P_o, to consider the observed nonlinear f_{su}-P_o behavior as shown in Figure 2.

4 SPT-BASED CORRELATION WITH PILE SKIN FRICTION

In this paper, an attempt is made to develop a new SPT-based correlation with the ultimate skin friction capacity of large diameter bored piles in sand. Influences of several factors were considered, including the potential variation of SPT-results along the pile shaft (soil variability), the pile construction technique, and the possible uncertainty in the developed correlation model itself. Out of the 12 case studies, essentially presented in this study, only the first 9 cases were utilized to develop the correlation. The remaining 3 cases (T-10, T-11, and T-12), Table 1, were kept for examining the correlation validity.

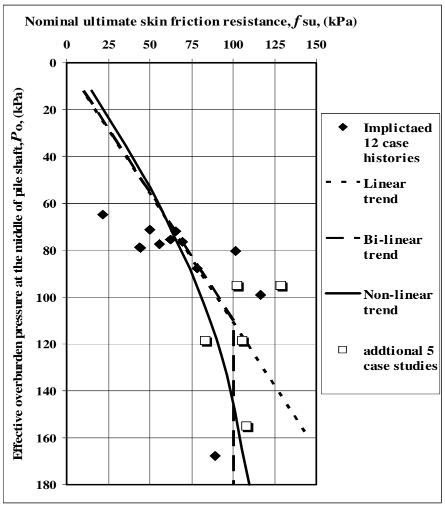

Fig. 2: Side resistance versus effective overburden pressure.

In the present study, the corrected SPT-blow counts, for overburden pressure, were used in order to reliably reflect the potential variability of soil properties along the pile shaft, regardless the relative impact of overburden pressure. The coefficient of variation of the corrected SPT N-values, incorporated along the pile shaft, (COV_L) was utilized to represent and quantify the consequent soil variability.

For the selected 9 case studies, the ratio of $\{f_{su} / N_{fc} \text{ x } \sqrt{P_o / P_a}\}$ was estimated. This ratio represents a converting factor for the tradional average value of corrected SPT-blow counts along the pile shaft (N_{fc}) into nominal ultimate pile skin friction resistance (f_{su}). The conversion factor also implements the impact of the square root of effective overburden pressure at the middle of pile shaft (P_o) that is normalized, to be dimensionless, to the atmospheric pressure (P_a). The estimated conversion factors were subsequently correlated to the coefficient of variation (COV_L) in the 9 cases, as shown in Figure 3. Consequently, the linear regression analysis was utilized and an average correlation trend could be provided as follows:

$$f_{su} = N_{fc} \text{ x } \sqrt{P_o / P_a} \text{ x } [5.73\, COV_L + 0.9] \quad (2)$$

The above average correlation trend is a proposed deterministic model for analysis of pile skin friction. However, it involves a degree of model uncertainty due to the imperfect representation of reality, Figure 3. To minimize such a model uncertainty, upper and lower correlation bounds were added, as illustrated in Figure 3. The correlation bounds were estimated through multiplying the average trend by the model uncertainty statistical criterion of $\mu \pm U\sigma$, provided by Ronold and Bjerager (1992). In which, μ and σ are mean and standard deviation, respectively, of the $\{f_{su(true)} / f_{su(averge\ trend)}\}$ ratios. Whereas, U is a normally distriubted variable, suggested to be associated with a 90% confidence level.

It was considered that, the correlation upper bound represents a best-fit to those case studies where the temporary casing was used to support the excavated hole during drilling of pile shafts. While, the lower bound represents a best-fit to most case studies where the bentonite slurry was used. Thus, the developed upper and lower SPT-based correlation trends can be provided as follows, Figure 3:

Upper correlation bound {for piles with temporary casing}

$$f_{su} = N_{fc} \text{ x } \sqrt{P_o / P_a} \text{ x } [6.46\, COV_L + 1.01] \quad (3.a)$$

Lower correlation bound {for piles with bentonite slurry}

$$f_{su} = N_{fc} \text{ x } \sqrt{P_o / P_a} \text{ x } [4.84\, COV_L + 0.76] \quad (3.b)$$

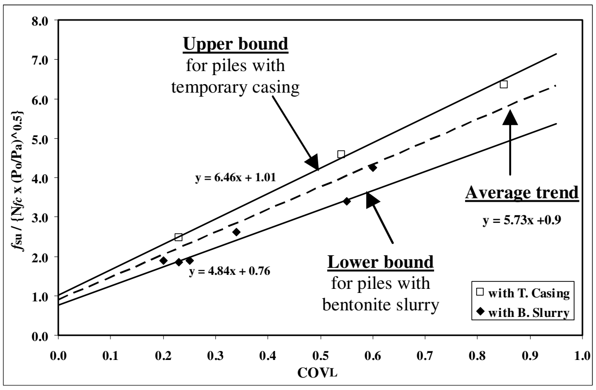

Fig. 3. SPT-based correlation with the ultimate skin friction resistance considering the soil variability along the pile shaft.

Nevertheless, the developed correlation bounds, Equations (3.a and 3.b), may involve potentially truncated model uncertainties. To evaluate these uncertainties, the ultimate pile skin friction capacity (Q_{su}) was predicted, for the nine case studies, using the appropriate correlation bound, associated to the utilized pile construction technique. The predicted values of Q_{su} were then compared with the measured (or extrapolated) ultimate skin friction capacities, from the instrumented 9 pile load tests at s/d = 10%. The uncertainties were represented exploiting the biases of piles capacities. The bias factor (λ) is the ratio between the predicted and the measured ultimate skin friction capacity (Q_p/Q_m).

Figure 4 illustrates the probability histogram of the calculated biases, for the nine case studies. The observed biases ranged between 0.87 and 1.04, corresponding to percents of uncertainty ranged between -13%, i.e., underestimation, and 4%, i.e., overestimation. These uncertainty percents, i.e., prediction errors, correspond to a very good to excellent prediction performance, regarding the estimation quality classes identified by Morgenstern (2000).

Furthermore, the probabilistic tools were utilized to assess the performance reliability of the developed SPT-based correlation bounds. The lognormal distribution was found to best-fit the probability density function (PDF) of the calculated biases in Figure 4, with 0.05 level of significance, as determined from the Chi Square test. An acceptable level of error (uncertainty) of ±10%, was suggested to be adopted in this study. This acceptance criteria is related to a very good to excellent prediction performance (Morgenstern, 2000).

The assigned lognormal PDF for biases, shown in Figure 4, was subsequently used to calculate the probability of satisfactory performance (P_{sp}) of the developed correlation bounds. The probability of satisfactory performance can be defined as the probability of the model to predict the true value within a satisfactory level of error. Hence, in the present study, the P_{sp}-value is the likelihood that Q_p will be within 0.9 to 1.1 of Q_m, i.e., $prob(0.9 \leq \lambda \leq 1.1)$, regarding the proposed performance acceptance criteria associated with ±10% error. At the anticipated level of errors the calculated probability of satisfactory performance was 84%. This P_{sp}-value of a SPT-based correlation may practically be considered superior (Abu-Farsakh and Titi, 2004).

It was considered that ignoring the soil variability along the pile shaft, in an average correlation trend between the ultimate pile side resistance and the mean value of blow counts, may increase the above evaluated uncertainties fourfold.

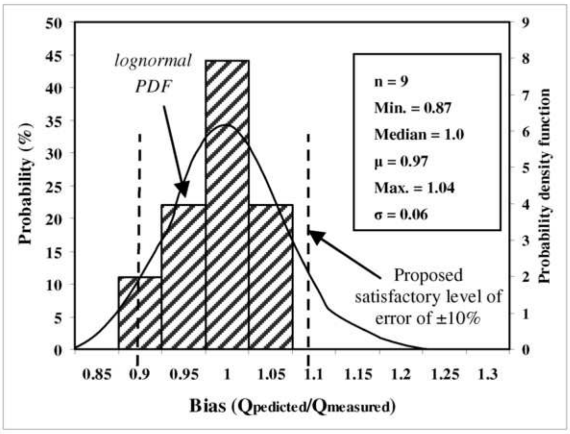

Fig. 4. Histogram and lognormal probability density for biases associated with the developed correlation bounds.

5 VERIFICATION OF THE CORRELATION BOUNDS

Results of the last three pile loading tests, presented in Table (1), were used to reliably assess/verify the developed upper and lower correlation bounds, (Equations 3.a and 3.b). For these 3 case studies, the ultimate pile skin friction capacity (Q_{su}) was predicted using the appropriate correlation bound. The predicted values were compared with the true values of Q_{su}, determined from the measured values of the instrumented 3 pile load tests at s/d = 10%. The biases (λ) of the predicted Q_{su}-values were estimated.

The evaluated biases, of the 3 cases, were found ranging between 0.93 and 0.99, associated with a degree of model uncertainty ranged between -7 and -1% (underestimation). Regarding the proposed acceptable level of error of ±10%, the above verified degrees of uncertainty could be considered trivial and can be neglected.

6 CONCLUSIONS

In this paper, an attempt was made to develop a new SPT-based correlation with the ultimate skin friction resistance of large diameter bored piles in sand. Impact of different sources of uncertainty were considered, including the potential soil variability along the pile shaft, pile construction technique, and the possible uncertainty in the developed correlation model itself. Results of 12 instrumented pile load tests were utilized. In these tests, measurements of the field instrumentations of the pile side and base resistances were available.

A nominal value for the ultimate pile skin friction resistance was considered at a percent of pile head settlement to diameter ratio of 10%. It was observed that, the ultimate pile side resistance tended to nonlinearly increase with overburden pressure, i.e., with depth.

The conversion factor between the tradional average value of corrected SPT-blow counts along the pile shaft and the ultimate skin friction resistance was estimated. These factors also included the impact of the square root of effective overburden pressure at the middle of pile shaft. The estimated conversion factors were correlated to the coefficient of variation of corrected blow counts along the pile shaft. The coefficient of variation was implemented to represent the potenial soil variability. An average linear correlation trend was provided. Upper and lower linear correlation bounds were statsitically identified, to eliminate the possible degrees of model uncertainty due to imperfect representation of reality. The developed correlation bounds were paritcularly associated with the pile construction technique.

The truncated model uncertainties in the developed correlation bounds were evaluated. These uncertainties ranged between 13% underestimation and 4% overestimation. The probability of satisfactory performance of the correlation bounds, within ±10% error, was calculated, and the result could be considered practically accepted. The developed correlation bounds were reliably verified using results of three pile load tests. The assessed uncertainties in these correlation bounds were considered trivial, and the evlauted prediction performance was classified as very good to excellent.

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