Calculation of piles based on CPT results in Poland

Calcul des pieux a partir des résultats de l'essai CPT en Pologne

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ABSTRACT
The paper presents a capacity of driven precast piles prediction method based on the results of CPT tests. The pile settlement equal to 10% of pile diameter is assumed as a criteria of pile capacity. The method gives also a unit skin friction and a unit base resistance for intermediate pile settlements. It allows to simulate the load-settlement curve and to calculate the axial stiffness of the pile in any load range. For the purpose of analysis the calculation file is created which makes it possible to copare the results of calculation and that of the field-test. The comparative analysis of 37 square 0.3x0.3m and 0.4x0.4m piles in clays and sands was carried out. The comparison shows a good agreement between the predicted and actual capacities and a satisfactory agreement between the predicted and actual slope of the load-settlement curve in the range up to 40% of the ultimate pile capacity.

RÉSUMÉ
L'article présente une méthode de calcul de la force portante des pieux préfabriqués battus à partir des résultats de l'essai au penetrometre statique. Comme le critère de la rupture on admet le tassement égal, à 10% de la coté de la section du pieu. La méthode permet à évaluer la pression unitaire sous la pointe du pieu et le frottement latéral unitaire le long du fut de pieu pour les valeurs intermédiaires de tassement. Cela permet à faire une simulation de la courbe du tassement du pieu en fonction de charge et calculer la rigidité axiale du pieu. On a ressemblé les résultats des 37 essais statiques des pieux ou section 0.3x0.3m et 0.4x0.4m encastrés en argiles et en sables. La comparaison donne une bonne concordance des valeurs des forces portantes reçues au chantier et calculées ainsi qu'entre la courbe expérimentale et théorique du tassement évalué pour le chargement jusqu'à 40% de la force portante.

Keywords: driven precast piles, CPT test, pile load test, pile capacity, pile settlement

1 INTRODUCTION

Because of model similarity between a pile during its loading and the CPT cone (White and Bolton 2005) and relatively low costs of a CPT test, it is often used as a base for the calculation of pile bearing capacity. A number of methods had already been developed, which differ fromeachother by a number of assumptions and, of course by their estimation accuracy. The most important differences are the way of the assessment of the unit pile shaft and toe capacity based on the CPT results, the range of the influence zone below the pile tip (the range of averaging of cone tip resistance) and the assumption about what the pile ultimate capacity means. The abovementioned assumptions are essential for both the prediction accuracy and for the complexity of each method. Some proposals allow for estimation of unit resistances directly from CPT results in sands and in clays (Bustamante and Gianeselli 1982, Jardine et al. 2005). There are also methods, which require the undrained shear strength of clay s_u to be used (de Ruiter and Beringer 1979, German Society for Geotechnics 2007). In such approaches engineering judgment has a rather great influence on the results (Haldar and Babu 2008). The range of the influence zone varies between $0.7D_p$ to $4D_p$ below and between 1.5 D_p to 8 D_p over the pile tip, where D_p is the pile diameter. The most often used criterion of the ultimate capacity of a pile is its sttlement equal to 0.1 D_p, though the amount is sometimes argued and the criterion of a plunge in load-settlement characteristic is considered to be more reliable (White and Bolton 2005). Many of those and also other differences between methods have already been described (Haldar and Babu 2008, Eslami and Fellenius 1997). Most of the mentioned methods enable only the pile ultimate capacity to be evaluated. Only one proposal gives guidline for the pile settlements assessment based on the CPT results (German Society for Geotechnics 2007). In the German method the unit pile shaft and tip resistances in clays are given in relationship to the undrained shear strength s_u. Additionally a bottom and upper boundary of unit resistances are given for pile shaft and tip. Both elements require a portion of engineering judgment and as a matter of fact the accuracy is strongly dependent on the decision of a designer. In the paper a method is presented which allows for concrete precast driven piles capacity and settlements calculation based on the results of a CPT test.

2 PROPOSED METHOD

The described method is created on the basical assumption, that maintained load test is capable to reflect the "true" characteristic of a pile. There are several serious doubts regarding this assumption (Fellenius 1980). Some of them are connected with errors arising during measurements but some other reffers to fundamental engineering problems. The questions are covered in the next parts of this paper. A number of additional assumptions are made, which are shortly presented and characterised below.

2.1 Parameters conclusive for shaft and toe resistance

It is assumed the conclusive parameter is CPT cone resistance. Sleeve friction is ignored as relatively sensitive parameter. For the assessment of pile characteristics the cone resistance is not treated, which means the peaks and plunges are not smoothened.

2.2 The range of the influence zone

The influence zone of $3D_p$ below and $1.5D_p$ above the pile tip is admited. It is to be considered whether a varying influence depth below the pile tip should not be taken into consideration especially as dependent on the soil type and strength at that level. For the analysis of the pile shaft unit resistance the cone resistance is used without any treatment.

2.3 Pile settlement versus mobilized resistance

It was assumed that the pile toe unit resistance and the pile shaft unit resistance depend on the pile head settlement. Author is aware that the unit resistance of the pile toe depends on the pile toe settlement and not on the pile head settlement. By analogy the unit resistance of the pile shaft depends on relative movement of pile shaft against the soil. Consequently such parameters like residual post driving stresses and the strain of the pile shaft are ignored in the method. Presented proposal is Theoretically appropriate for analysis of the settlement of piles loaded in tension but through for the lack of data it was not tested in such cases. and it should be noted, that disregard of pile shaft elongation might have a serious influence on the evaluated pile settlement (elevation).

2.4 Link between q_c and unit pile shaft and pile tip resistances

The proposal presented in the paper is to a some extent based on the French (Bustamante and Gianeselli 1982) and German (German Society for Geotechnics 2007) method. A simple relation is given between the CPT cone resistance and the unit pile tip and pile shaft resistances for different pile head settlements. Pile resistances as dependent on the settlements can be evaluated with the Equation 1 and 2 below.

$$R_c(s_i) = A_b \cdot q_b(s_i) + \sum_n A_{sn} \cdot q_{sn}(s_i) \quad (1)$$

$$R_t(s_i) = \sum_n A_{sn} \cdot q_{sn}(s_i) \quad (2)$$

where $R_c(s_i)$ and $R_t(s_i)$ are the pile resistances at the pile head settlement s_i on compression and tension respectively, A_b is pile base area, $q_b(s_i)$ is unit pile base resistance at the pile head settlement s_i, A_{sn} is pile shaft area in layer n and $q_{sn}(s_i)$ is unit pile shaft resistance in layer "n" at the pile head settlement s_i. The unit resistances are directly dependent on the cone resistance of CPT and the type of the soil. They are evaluated with the formulae given below:

$$q_b(s_i) = q_{cavg} \cdot k_b(s_i) \quad (3)$$

$$q_{sn}(s_i) = \frac{q_{cn}}{\alpha_n(s_i)} \quad (4)$$

where $k_b(s_i)$ is a settlement-dependent coefficient for pile toe resistance and $k_s(s_i)$ is a settlement-dependent coefficient for pile shaft resistance in layer "n" according to Table 1. The coefficients enable evaluation of pile shaft and pile toe resistance at ultimate and intermediate settlements which are assessed according to Equation 5 to 7. This in turns allows for simulation of a pile load-settlement curve.

Table 1. Coefficients for unit resistances calculation

Cone tip, q_c, MPa	k_{s1}	k_{s2}	k_{su}	k_{b1}	k_{bu}
Silts, clays, organic clays					
< 2	45	55	150	0.5	0.4
2 ÷ 4	50	63	165	0.45	0.3
4 ÷ 7	55	70	185	0.35	0.25
> 7	60	75	200	0.35	0.25
Sands, silty sands, gravels					
< 7.5	180	200	255	0.6	0.5
7.5 ÷ 15	190	210	270	0.5	0.4
15 ÷ 25	200	220	285	0.4	0.3
> 25	210	235	300	0.3	0.2

2.5 Partial mobilisation of the resistances

The amount of settlements representative for the described method are given in Equation 5 to 7. A number of different possibilities were analysed and for any arbitrary amount of pile head settlement being only a function of pile dimensions the scatter of the relation between predicted and measured pile settlement was very large. In the authors opinion one of the important reasons is that the mobilisation of the unit pile resistances is dependent not only directly on the soil stiffness but also on the residual stresses arising both along the pile shaft and under the pile tip as a result of pile driving (Altaee et al. 1992). As a result any arbitrary settlement for partial mobilisation of unit resistances seems to be inappropriate. The pile head settlements representative for partial mobilisation of both pile shaft and pile toe are given in Equation 5 to 7. The settlements are dependent on the respective partial resistance of the pile shaft and toe and thereby on the type and strength of soil along pile shaft or beneath the pile tip.

$$s_{s1} = \frac{R_{s1}}{300kN} \cdot mm \quad (5)$$

$$s_{s2} = \frac{R_{s2}}{150kN} \cdot mm \quad (6)$$

$$s_{b1} = \frac{R_{b1}}{70kN} \cdot mm \quad (7)$$

where R_{s1}, R_{s2} are resistances of the pile shaft mobilized at the pile head settlements respectively s_{s1}, s_{s2} and R_{b1} is the pile toe resistance mobilized at the pile head settlement s_{b1}. The forces R_{s1}, R_{s2}, R_{b1} should be calculated according to Equation 1 to 4 based on coefficients given in Table 1. The use of the settlements according to Equation 5 to 7 without any limitations induces a clear discrepancy, namely it appears that for very hard clays and very dense sands the pile settlements are relatively large at forces significantly less than the pile capacity. And inversely for soft clays and loose sands the settlements appear to be very little. Both cases are counterintuitive. Consequently additionally a lower and upper bound are imposed for the amount of possible pile head settlements. They are described in Equation 8 to 10.

$$s_{s1} = \begin{cases} 0.0015 \cdot D_p \Leftrightarrow \frac{R_{s1}}{300kN} \cdot mm < 0.0015 \cdot D_p \\ 0.005 \cdot D_p \Leftrightarrow \frac{R_{s1}}{300kN} \cdot mm > 0.005 \cdot D_p \end{cases} \quad (8)$$

$$s_{s2} = \begin{cases} 0.005 \cdot D_p \Leftrightarrow \frac{R_{s2}}{150kN} \cdot mm < 0.005 \cdot D_p \\ 0.02 \cdot D_p \Leftrightarrow \frac{R_{s2}}{150kN} \cdot mm > 0.02 \cdot D_p \end{cases} \quad (9)$$

$$s_{b1} = \begin{cases} 0.0075 \cdot D_p \Leftrightarrow \frac{R_{b1}}{120kN} \cdot mm < 0.005 \cdot D_p \\ 0.02 \cdot D_p \Leftrightarrow \frac{R_{b1}}{120kN} \cdot mm > 0.02 \cdot D_p \end{cases} \quad (10)$$

3 DATABASE

A database of 37 static compression load tests were collated from the years 2005-2009. The detailed data about tested piles are given in Table 2.

Table 2. Tested piles characteristics

No of pile	Pile cross section, D_p, m	Pile embed-ment, L_p, m	Time between driving and testing, T, days	Soils along the pile (*)	Distance between CPT and test pile, B_c, m
1	0.3	9.2	No data	D	8
2	0.3	13	No data	C	11
3	0.3	13.6	46	C	10
4	0.3	8.6	10	A	1
5	0.4	12.1	9	C	8
6	0.4	12.3	23	B	ca 10
7	0.4	12.3	30	B	ca 10
8	0.4	12.3	28	B	ca 10
9	0.4	12.3	71	B	ca 10
10	0.4	14.6	29	B	ca 10
11	0.4	13.3	37	B	ca 10
12	0.4	12.3	40	B	ca 10
13	0.3	11.2	5	D	13
14	0.3	11.2	6	D	13
15	0.3	10.2	6	D	9
16	0.3	12.2	6	D	10
17	0.3	12.4	8	D	14
18	0.4	17.5	19	A	4
19	0.4	20.4	9	A	5
20	0.4	20.4	8	D	5
21	0.4	12.4	22	C	5
22	0.4	16.8	9	A	5
23	0.4	12.8	20	D	6
24	0.4	8.4	7	D	3
25	0.4	8.4	9	A	5
26	0.3	8.6	8	A	4
27	0.3	7.4	9	A	4
28	0.3	13.6	23	D	13
29	0.3	11.6	21	D	2
30	0.3	9.8	20	D	3
31	0.4	14.3	19	D	2
32	0.4	12.5	14	D	3
33	0.4	12.4	10	C	7
34	0.4	12.4	9	D	7
35	0.4	12.4	14	C	7
36	0.4	15.5	29	B	8
37	0.4	15.5	29	B	8

(*): A - only sands; B - only clays; C – layered soils, toe in clay; D – layered soils, toe in sand.

All tests have been performed on square driven concrete piles according to quick maintained load test (Polish Standard 1983). A total number of 16 tests refer to the 0.3x0.3 m piles and 25 to the 0.4x0.4 m piles driven in different types of soils: 7 piles in sands, 9 in clays end the remaining 22 piles in layered soils. No pile was driven in silts or soft clays. The embeddement of the piles was between 7.4 and 20.4 m with the average of 12.6 m. The time elapsed between driving and testing was 5 to 71 days as related to the required (Polish Standard 1983) and widely accepted 28 days (Jardine et al. 2005). In 20 tests the ultimate pile capacity was reached. Two different criteria of the ultimate pile capacity were assumed. The first criterion was a plunge in the load-settlement characteristic of a pile and the second one was total settlement of 0.10 D_p. For 17 tests pile capacity was interpreted by the method of Mazurkiewicz (Polish Standard 1983, Fellenius 1980). All tests have been performed on actual sites and most of them on the construction piles. In all static tests the load was imposed with the aid of reaction piles. The distance between the test pile and the reaction piles was between 2 and 4 m what is in accordance with the minimal distance of required 2 m (Polish Standard 1983). For most of the cases the CPT test with the mechanical cone was carried out. Only in few cases the electric cone or the CPTu test has been implemented. The distance between the performed CPT tests and the loaded piles was between 1 and 14 m.

4 DATABASE ANALYSIS

For the purpose of the method evaluation a simple file in MathCad code has been created. The load-settlement curves simulated in this file are shown below. Note the piles No15 and No26 (Figure 1) are the best predicted ones in terms of the settlements, the pile No5 is the most underpredicted and the pile No23 the most overpredicted in that regard.

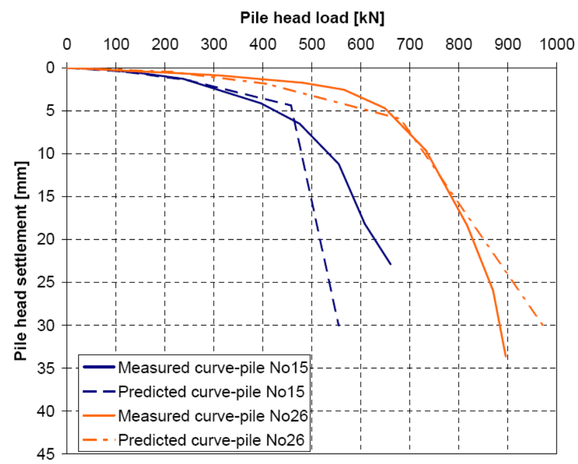

Figure 1. Measured and predicted curves for pile No15 and No26

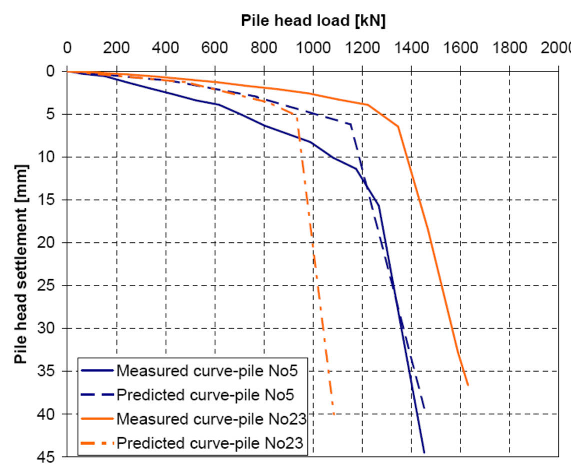

Figure 2. Measured and predicted curves for pile No5 and No23

Results of the pile capacity analysis are presented in Figure 3 and that of the settlements in Figure 4. The settlements refers to the pile head loading equal to 0.4 R_u, where R_u is ultimate pile capacity from the static test. For the pile capacity a good fit between the theoretical and measured results is obtained. Mediana of R^c/R^m is equal 0.994 and standard deviation to 0.154. The prediction for settlements is also good. Mediana of s^c/s^m is equal 0.867 and standard deviation to 0.342, what compares quite well with other methods analysed in the literature (Zhang et al. 2008).

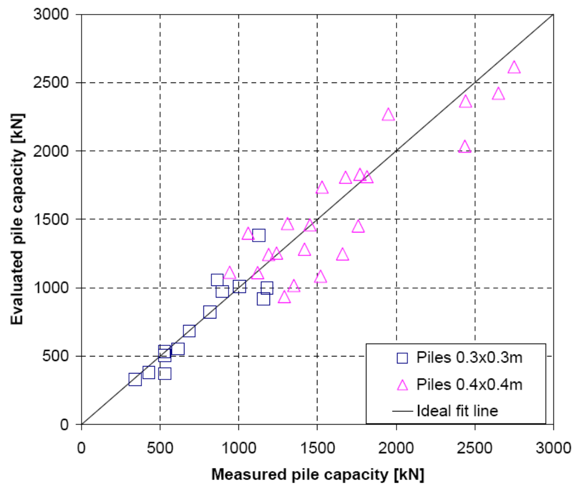

Figure 3. Comparison of the measured and evaluated pile capacities

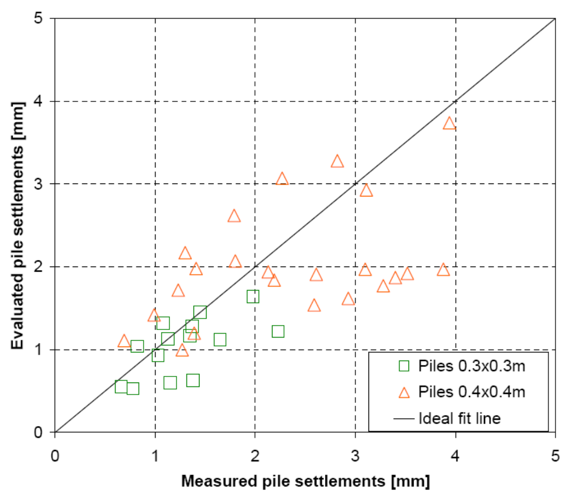

Figure 4. Comparison of the measured and evaluated pile settlements

5 CLOSING REMARKS

In the described method it was assumed a loading test is capable to reflect the true characteristic of a pile. A number of errors arise however during a static test. In all tests analysed in the paper the load was imposed with the use of beam-system and four reaction piles. It is known the reaction piles can influence both the reference base and the tested pile (Fellenius 1980). It is also accepted the temperature can change readings during the pile loading via influence on the reference-base (Fellenius 1980). Some researchers have shown the reaction piles can alter the settlements of the tested pile (Kitiyodom et al. 2004). Some of the inaccuracies can be of course limited but it's clear that the results of a static loading test should be treated with care. Other uncertainties are connected with rather fundamental questions. It is doubtful if a concept of a true settlement or even a true capacity of a pile is reasonable. It cannot be assumed the pile behaviour is independent on the way and time of loading. A typical maintained load test takes a number of hours, whereby in many engineering tasks the load is imposed in the time of months. It is known the pile capacity in clays increases as the time elapses (Yang and Liang 2006). Similar dependence is however valid also in sands (Jardine et al. 2005). One of the piles in Table 2 (Pile No25) was tested twice: in 9 days and in 159 days after driving and its capacity increased by 15%. The opposite case with the time of loading during the static test is significantly longer than in the construction is possible as well. A typical example is a windmill, where the duration of maximal calculated load is probably equal to only a few minutes. The link between instant and long-time pile capacity is not well understood and, as a result, any arbitrary assumption about the relation is not reasonable. It should be realised that any kind of static load test should not be regarded as fully reliable method reflecting the true load-settlement relation of a pile, if the link between the way of loading during the static test and in the future construction is disregarded. The consequence is that even a reliable model of pile-soil interaction doesn't mean the actual behaviour of a pile in the construction can be obtained.

CONCLUSIONS

A method allowing for a capacity and settlements of driven precast piles analysis based on the CPT results is presented. A database of static loading test conducted on 37 square driven precast piles has been collated and the method is evaluated refering to the test results. A good agreement between measured and calculated capacities is obtained. Presented method enables also a reliable analysis of pile settlement up to the pile head loading equal to 0.4 of the pile ultimate capacity. Additionally some engineering remarks are made. It is often believed the static loading tests is able to reflect the true load-settlement characteristic of a pile. For many reasons this assumption should be treated rather as a practical assumption than as a dogma.

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