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CALCULATION OF PILES BASED ON CPT RESULTS IN POLAND

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Abstract: The paper presents the capacity of driven precast pile prediction method based on the results of CPT tests. The pile settlement equal to 10% of pile diameter is assumed as a criterion of pile capacity. The method gives also a unit skin friction and a unit base resistance for intermediate pile settlements. This allows us 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 compare the results of calculation with those of the field-test. The comparative analysis of 37 square 0.3 m × 0.3 m and 0.4 m × 0.4 m 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 slopes of the load–settlement curve in the range up to 40% of the ultimate pile capacity.

1. INTRODUCTION

Because of model similarity between a pile during its loading and the CPT cone (WHITE and BOLTON [11]) and relatively low costs of a CPT test, it is often used as a basis for the calculation of pile bearing capacity. A number of methods had already been developed, which differ from each other by a number of assumptions and, of course, by their estimation accuracy. The most important differences are the way of assessing 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 above-mentioned assumptions are essential for both the prediction accuracy and for the complexity of each method. Some proposals allow estimation of unit resistances directly from CPT results in sands and in clays (BUSTAMANTE and GIANESELLI [3], JARDINE et al. [7]). There are also methods, which require the undrained shear strength s_u of clay to be used (de RUITER and BERINGER [10], German Society for Geotechnics [6]). In such approaches, engineering judgment has rather a great influence on the results (Haldar and Babu). The range of the influence zone varies between 0.7 D_p and 4 D_p below and between 1.5 D_p and 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 settlement 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 [11]). Many of those and also other differences between methods have already been described (Haldar and Babu, ESLAMI and FELLENIUS [4]). Most of the methods mentioned enable only the pile ultimate capacity to be evaluated. Only one proposal gives guideline for the pile settlement assessment based on the CPT results (German Society for Geotechnics [6]). In the German method, the unit pile shaft and tip resistances in clays are given in relation to the undrained shear strength s_u. Additionally the bottom and upper boundaries 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 greatly dependent on the decision of a designer. In the paper, a method is presented which allows concrete precast driven piles capacity and settlements calculation based on the results of a CPT test.

2. THE METHOD PROPOSED

The method described is developed on the basical assumption that the load test performed is capable of reflecting the "true" characteristic of a pile. Several serious doubts have arisen over this assumption (FELLENIUS [5]). Some of them are connected with errors occurring during measurements, but some other reffer to fundamental engineering problems. The questions are considered in the next parts of this paper. A number of additional assumptions are made and shortly presented and characterised below.

CPT cone resistance is assumed to be a conclusive parameter. Sleeve friction is ignored as relatively sensitive parameter. For the assessment of pile characteristics the cone resistance is not taken into account, which means the peaks and plunges are not smoothened.

The influence zone of 3 D_p below and 1.5 D_p above the pile tip is assumed. It is to be considered whether the influence of a varying 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.

It was assumed that the pile toe unit resistance and the pile shaft unit resistance depend on the pile head settlement. The 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 as residual post-driving stresses and the strain of the pile shaft are ignored in the method. The proposal presented is theoretically appropriate for the analysis of the settlement of piles loaded in tension but because of a lack of data it has not been tested in such cases and it should be noted that disregard of the pile shaft elongation it might have a serious influence on the evaluated pile settlement (elevation).

The proposal presented in the paper is, to a some extent, based on the French (BUSTAMANTE and GIANESELLI [3]) and German (German Society for Geotechnics [6]) methods. A simple relationship 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 as follows:

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

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

where: $R_c(s_i)$ and $R_t(s_i)$ are the pile resistances at the pile head settlement s_i under 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 given by the following formulae:

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

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

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 resistances at ultimate and intermediate settlements which are assessed according to equations (5)–(7). This in turn allows a pile load–settlement curve to be simulated.

Table 1

Coefficients for unit resistance calculation

Cone tip q_c (MPa)	k_{s1}	k_{s2}	k_{s2}	k_{b1}	k_{b2}
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

The amount of settlements representative of the method described are given by equations (5)–(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 relations between predicted and measured pile settlements was remarkably wide. In the authors opinion, one of the important reasons is that the mobilisation of the unit pile resistances is directly dependent not only 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. [2]). As a result, any arbitrary settlement for partial mobilisation of unit resistances seems to be inappropriate. The pile head settlements representative of partial mobilisation of both pile shaft and pile toe are given by equations (5)–(7). The settlements depend 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:

$$s_{s1} = \frac{R_{s1}}{300\ \mathrm{kN}} \cdot \mathrm{mm}, \tag{5}$$

$$s_{s2} = \frac{R_{s2}}{150\ \mathrm{kN}} \cdot \mathrm{mm}, \tag{6}$$

$$s_{b1} = \frac{R_{b1}}{70\ \mathrm{kN}} \cdot \mathrm{mm}, \tag{7}$$

where: R_{s1}, R_{s2} are resistances of the pile shaft mobilized at the pile head settlements s_{s1}, s_{s2}, respectively, 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 equations (1)–(4) based on the coefficients given in table 1. The use of the settlements according to equations (6)–(8) 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 lower than the pile capacity. And vice versa, for soft clays and loose sands the settlements appear to be very small. Both cases are counterintuitive. Consequently, additionally lower and upper bounds are imposed for the amount of possible pile head settlements. They are described by equations (8)–(10):

$$s_{s1} = \begin{cases} 0.0015 \cdot D_p \Leftrightarrow \dfrac{R_{s1}}{300\ \mathrm{kN}} \cdot \mathrm{mm} < 0.0015 \cdot D_p, \\ 0.005 \cdot D_p \Leftrightarrow \dfrac{R_{s1}}{300\ \mathrm{kN}} \cdot \mathrm{mm} > 0.005 \cdot D_p, \end{cases} \tag{8}$$

$$s_{s2} = \begin{cases} 0.005 \cdot D_p \Leftrightarrow \dfrac{R_{s2}}{150\ \mathrm{kN}} \cdot \mathrm{mm} < 0.005 \cdot D_p, \\ 0.02 \cdot D_p \Leftrightarrow \dfrac{R_{s2}}{150\ \mathrm{kN}} \cdot \mathrm{mm} > 0.02 \cdot D_p, \end{cases} \tag{9}$$

$$s_{b1} = \begin{cases} 0.0075 \cdot D_p \Leftrightarrow \dfrac{R_{b1}}{120\ \mathrm{kN}} \cdot \mathrm{mm} < 0.0075 \cdot D_p, \\ 0.02 \cdot D_p \Leftrightarrow \dfrac{R_{b1}}{120\ \mathrm{kN}} \cdot \mathrm{mm} > 0.02 \cdot D_p. \end{cases} \tag{10}$$

3. DATABASE

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

Table 2

Characteristics of the piles tested

No. of pile	Pile cross section, D_p (m)	Pile embedment, 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 the tests have been performed on square driven concrete piles according to quick maintained load test (Polish Standard [9]). A total number of 16 tests refer to the 0.3 m × 0.3 m piles and 25 to the 0.4 m ×0.4 m piles driven into different types of soils: 7 piles into sands, 9 into clays and the remaining 22 piles into layered soils. No pile was driven into silts, nor into soft clays. The embeddement of the piles was between 7.4 and 20.4 m with an average of 12.6 m. The time that had elapsed between driving and testing was 5–71 days as related to the required (Polish Standard [9]) and widely accepted 28 days (JARDINE et al. [7]). In 20 tests, the ultimate pile capacity was reached. Two different criteria of the ultimate pile capacity were adopted. The first criterion was a plunge in the load–settlement characteristic of a pile, and the second one was a total settlement of 0.10 D_p. In 17 tests, the pile capacity was interpreted by the method of MAZURKIEWICZ (Polish Standard [9], FELLENIUS [5]). All the 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 which is in accordance with the minimal required distance of 2 m (Polish Standard [9]). For most of the cases the CPT test with a mechanical cone was carried out. Only in few cases an electric cone or the CPTu test has been implemented. The distance between the CPT tests performed 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 in figure 1. Note the piles No. 15 and No. 26 are the best predicted ones in terms of the settlements, the pile No. 5 is the most underpredicted, and the pile No. 23 the most overpredicted in that regard.

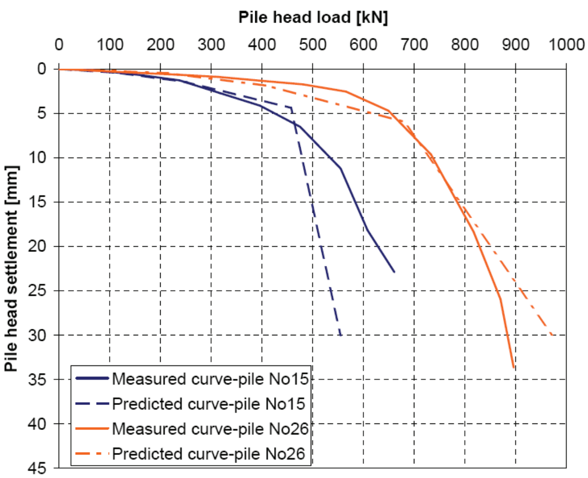

Fig. 1. The curves measured and predicted for piles No. 15 and No. 26

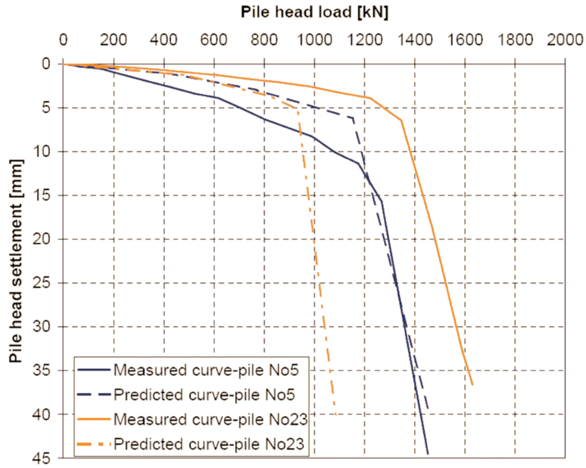

Fig. 2. The curves measured and predicted for piles No. 5 and No. 23

The results of the pile capacity analysis are presented in figure 3 and those of the settlements in figure 4. The settlements refer to the pile head loading equal to 0.4 R_u, where R_u is the 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 to 0.994 and standard deviation to 0.154. The prediction for settlements is also correct. Mediana of s^c/s^m is equal to 0.867 and standard deviation is 0.342, which compares quite well with the results of other methods analysed in the literature (ZHANG et al. [13]).

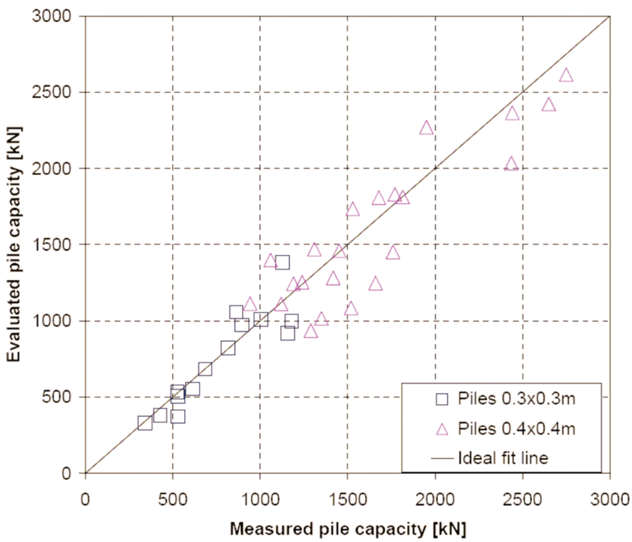

Fig. 3. Comparison of the measured and evaluated pile capacities

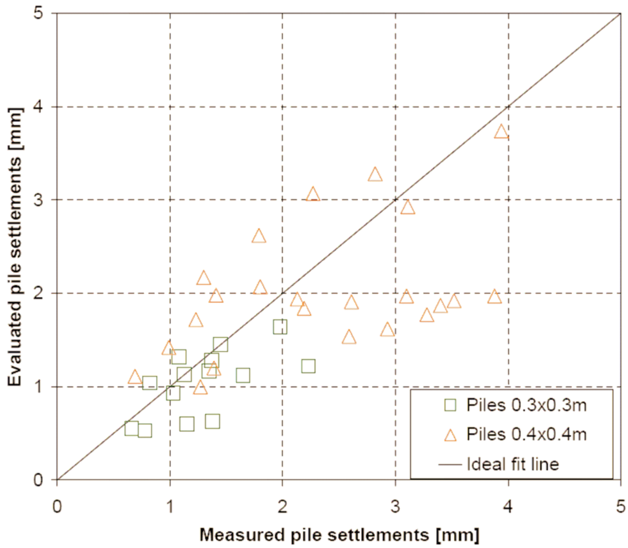

Fig. 4. Comparison of the measured and evaluated pile settlements

5. CLOSING REMARKS

In the method described, it was assumed that a loading test is capable of reflecting the true characteristic of a pile. A number of errors arise, however, during a static test. In all the tests analysed in the paper, the load was imposed with the use of beam-system and four reaction piles. It is known that the reaction piles can influence both the reference base and the pile tested (FELLENIUS [5]). It is also accepted that the temperature can change readings during the pile loading via influence on the reference-base (FELLENIUS [5]). Some researchers have shown that the reaction piles can alter the settlements of the pile tested (KITIYODOM et al. [8]). Some of the inaccuracies can be, of course, limited but it is clear that the results of a static loading test should be treated with care. Other uncertainties are connected with a rather fundamental questions. It is doubtful, however, whether the concept of a true settlement or even a true capacity of a pile makes any sense. It cannot be assumed the pile behaviour is independent of 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 for months. It is known that the pile capacity in clays increases with time (YANG and LIANG [12]). Similar dependence, is however, valid also for sands (JARDINE et al. [7]). One of the piles in table 2 (pile No. 25) was tested twice: 9 days and 159 days after driving and its capacity increased by 15%. The opposite case with the time of loading during the static test significantly longer than in the construction is possible as well. A typical example is a windmill, where the action of maximal calculated load probably takes only a few minutes. The link between instant and long-time pile capacities 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 cannot be regarded as a 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 that in the future construction is disregarded. The consequence is that even a reliable model of pile–soil interaction does not mean the actual behaviour of a pile in the construction can be obtained.

6. CONCLUSIONS

The method allowing capacity and settlements of driven precast piles to be analysed 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 referring to the test results. A good agreement between measured and calculated capacities is obtained. The method presented 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 that the static loading tests can reflect the true load–settlement characteristic of a pile. For many reasons this assumption should be treated as a practical assumption rather than as a dogma.

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