Verification of empirical values for skin friction and base resistance of precast driven steel piles

M. Witzel
University of Kassel, Institute of Geotechnics and Geohydraulics (IGG), Germany
now: Dr. Hug Geoconsult GmbH, Oberursel, Germany

ABSTRACT: A new approach to predict the load settlement behavior of precast driven piles is briefly discussed. The described method is used to predict the results of a independent loading test on a steel girder pile. A comparison between the measured and predicted results is drawn.

The example is used to verify the derived values of skin friction and base resistance and to confirm the assumed proportion of skin friction and base resistance on the total pile capacity for steel piles.

1. INTRODUCTION

For efficient pile design a reliable method to predict the ultimate capacity and the load-settlement behavior of pile foundations in early stages of design is required.

To predict the ultimate limit state of precast driven piles, different approaches are available. According to Poulos (1989) the methods can be divided into three broad categories.

1. Empirical approaches based on correlations with in situ (e.g. CPT, SPT), laboratory or field tests (e.g. α-method).
2. Approaches usually based on simplified theoretical approaches like the effective stress (β) method.
3. Numerical routines such as the Finite Element or Boundary Element Method.

In order to predict the ultimate limit state of precast driven piles category 1 approaches are the most commonly used. A pile load settlement prediction with simple empirical values is so far not available.

Pile design according to the European standard Eurocode 7 demands in addition to the verification of the ultimate limit state, a proof of sufficient safety in the serviceability limit state of a super structure caused by displacement of the piles.

2. PREDICTION OF PILE CAPACITY

In order to derive values of skin friction and base resistance for different stages of pile head settlement, a research project was carried out at the University of Kassel, Germany.

The research project comprises three stages: Model tests, a statistic analysis of in situ static loading tests and the derivation and verification of values for skin friction and base resistance of precast driven piles based on the in situ loading tests.

2.1. Model tests

Usually, in static field loading tests on driven piles, only the total pile capacity is measured. However, a true analysis of static loading tests requires a method to divide the measured load settlement curves into skin friction and base resistance.

A main objective of the model test series was to analyze the proportion of skin friction and base resistance on the total pile capacity of piles driven in dense sand.

Based on the results of the model tests, a correlation between the ratio of base to skin area and the ratio of shaft to total pile capacity was derived.

2.2. *Statistical analysis*

The statistical analysis is based on a dataset of more than 200 in situ static pile loading tests. To begin with load settlement curves of precast piles driven into dense sand were divided into skin and base resistance using the correlation derived from model tests.

For two stages of relative settlements of the pile head s/D_{eq}, a correlation between the base resistance and the mean cone resistance (CPT) at the pile base, the sum of the driving energy in a certain area above the pile base, and the shape of the pile base was observed.

The influence of the mean cone resistance (CPT) and of the driving energy along the pile shaft on the ultimate skin friction were also be quantified.

2.3. *Prediction approach*

The results of the model tests and the statistical analysis were summarized into a simplified approach to predict the load-settlement behavior.

Figure 1 shows the components of the simplified resistance-settlement curve of precast driven piles up to a settlement of s_g, where s_g is the limit settlement or the settlement at failure.

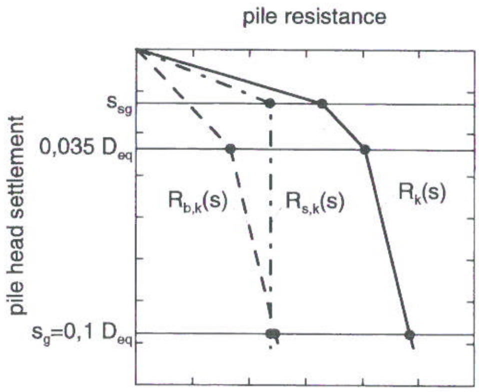

Figure 1. Elements of the resistance-settlement curve of precast driven piles

For a simple use the values of skin friction and base resistance for driven piles are listed in tables dependent on the results of the cone penetration test (CPT) and the driving process. Additionally factors η_b and η_s are introduced to adjust the values of base resistance and skin friction for different pile types.

The characteristic axial pile resistance is determined from Equation (1).

$$R_k(s) = R_{b,k}(s) + R_{s,k}(s) = \eta_b \cdot q_{b,k} \cdot A_b + \sum_i \eta_{s,i} \cdot q_{s,k,i} \cdot A_{s,i} \qquad (1)$$

The complete research work and the values of skin friction, base resistance and the adjustment factor for precast driven piles can be found in Witzel (2004).

3. VERIFICATION OF THE PREDICTION APPROACH

De Beer et al. (1981) presented the results of dynamic and static loading tests performed on steel girder piles. Four piles were tested. One pile (pile 1) was an ordinary beam without a lagging like the piles analyzed during the research project at the University Kassel. Piles 2 to 4 are not considered in this article.

The natural underground conditions at the test site were used to predict the resistance settlement curve of this pile. By using the approach of Witzel (2004) the proportions of skin friction and base resistance on the total pile capacity were also predicted.

In the following sections the tests results of pile 1 and the predicted values will be compared and discussed.

3.1. *Test pile*

Test pile 1 is a ordinary steel girder pile with a height of 375 mm and a width of 394 mm.

The pile has a embedment length of 18 m and is equiped with three strain gauges to measure the load distribution along the pile shaft. The arrangement of the strain gauges is shown in Figure 4.

3.2. *Underground conditions*

A representative boring profile and the result of a cone penetration test (CPT) from the test site are shown in Figure 2.

The underground conditions are described downwards from the surface. The first meter of the soil profile consists of fill, followed by 4 m of holocene soft clay and peat. From 5 to 8,5 m beneath the surface a layer of loamy sand is present, followed by a 13 m thick layer of dense to very dense sand (tertiary Pliocene scaldisian) is underlying the loamy sand. The deepest layer of the natural underground explored with the boring is tertiary Oligocene Boom clay.

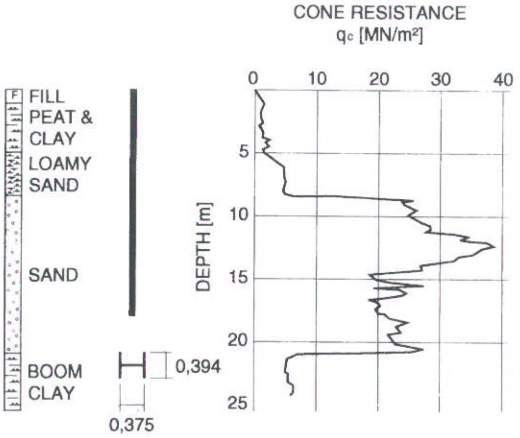

Figure 2. Boring profile and CPT test according to De Beer et al. (1981)

3.3. *Static loading test*

Beneath dynamic pile tests during driving a static loading test has been carried out in a classical way two month after driving. The measured load settlement curve up to a settlement of 27 mm respectively $0{,}062 \cdot D_{eq}$ is shown in Figure 3. The separation of the measured load into base resistance and skin friction is taken from different load distribution curves presented by De Beer et al. (1981).

Using the information of the pile geometry and the underground conditions the resistance settlement curve of test pile 1 is predicted applying the approach of Witzel (2004).

The mean values of the cone resistances for each layer used for the pile resistance prediction are summarized in Table 1.

Table 1. Mean values of the cone resistance (CPT)

Soil Type	Fill, Peat & Clay	Loamy Sand	Sand
Mean cone resistance q_c [MN/m²]	~ 0	5	> 20

By comparing the resistance settlement lines of Figure 3, there is a good agreement between the measured and predicted pile capacity. Considering the complete load settlement curve the measured total pile capacity ($R_{mea.}$) is slightly underestimated by the predicted ($R_{cal.}$).

With increasing settlement the correspondence between measured ($R_{mea.}$) and predicted total pile capacity ($R_{cal.}$) can be optimized, up to a difference of 1,86 % (59 kN) at the point of maximum settlement.

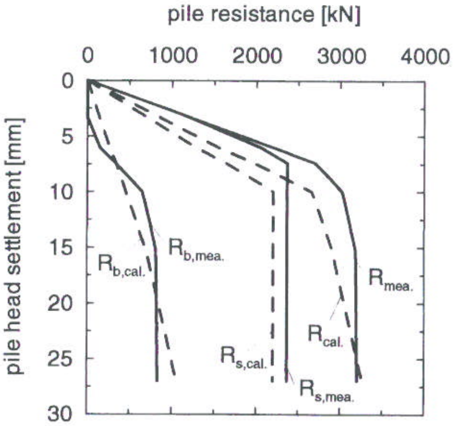

Figure 3. Measured and predicted pile resistances

Especially in the upper part of the load settlement curve the predicted shaft capacity ($R_{s,cal.}$) underestimates the measured ($R_{s,mea.}$) a little bit. The difference between measured and predicted shaft capacity in the ultimate limit state results in to 6,94 % (164 kN).

The measured load settlement curve shows, that the main part of the imposed load is carried by skin friction up to a pile head settlement of approximately 6 mm. The empirical prediction approach simplifies the load settlement curve between the characteristic points as linear (see Fig. 1). This leads to base resistance values right from the beginning of the load settlement test. Even if the base resistance prediction in the upper part of the load settlement curve deviates by a minor amount from the results measured, the general proportion of predicted base resistance to total pile capacity is true for the complete loading test.

In conclusion it has been shown, that the measured load settlement curves can be predicted very well by using the available information of pile geometry, underground conditions and the approach of Witzel (2004). Additionally, the approach for separating load settlement curves for the statistical analysis was proved and leads to correct values for skin friction and base resistance.

3.4. Pile resistance along the pile shaft

Trying to complete the satisfactory results of the comparison between measured and predicted load settlement curves, the load distribution along the pile shaft is analyzed.

Therefore the load distribution along the pile shaft at maximum load is used. Table 2 summarizes the predicted shaft resistance values for the different soil layers.

Table 2. Predicted values of pile skin friction according to Witzel (2004)

	η_s [-]	$q_{s,k,i}$ [kN/m²]	$A_{s,i}$ [m²]	$R_{s,i}$ [kN]
Fill, Peat & Clay	1	0	11,6	0
Loamy Sand	1	29	7,0	202
Sand	1	86	23,3	2000

During the dynamic loading tests the load distribution along the pile shaft of test pile 1 was measured up to a depth of 12 m below the surface. The skin friction of the deepest 6 m is assumed as equivalent to the skin friction measured in the same soil layer, therefore the load distribution is linear extrapolated. The measured and predicted load distribution curves are shown in Figure 4.

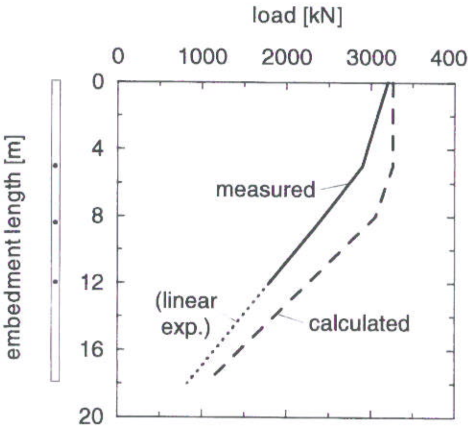

Figure 4. Measured and predicted load distribution curve

The prediction approach assumes, that the skin friction in the first soil layers of fill and soft clay and peat is to neglect. With the dynamic loading test a total skin resistance of approximately 300 kN in the upper 5 m were measured.

Omitting the upper soil layers there is also a good agreement between the measured and predicted load distribution along the pile shaft.

4. CONCLUSIONS

A new empirical approach to predict the load settlement behavior of precast driven piles is presented. Using an independent loading test the calculated values of skin friction and base resistance for steel piles were confirmed.

5. ABBREVATIONS

$R_k(s)$	the settlement-dependent characteristic pile resistance
$R_{b,k}(s)$	the settlement-dependent characteristic pile base resistance
$R_{s,k}(s)$	the settlement-dependent characteristic pile shaft resistance
s_{sg}	limit settlement at failure for $R_{s,k}(s)$
D_{eq}	the equivalent diameter of a round shaped pile base coextensive to the pile base area
A_b	the nominal value of the pile base area
A_{si}	the nominal value of the pile shaft area in layer n
$q_{b,k}$	the characteristic pile base resistance pressure
$q_{s,k,i}$	the characteristic pile skin friction in layer n according
η_b	an adjustment factor of the pile base resistance
η_s	an adjustment factor of the pile shaft resistance

6. REFERENCES

De Beer, E. et al., 1981. H Steel Piles in Dense Sand. Proceedings of the 10th ICSMFE, Stockholm, Vol. 2, pp. 693-698.

Poulos, H. G., 1989. Pile behaviour – theory and application. Géotechnique 39, p. 365-415

Witzel, M., 2004. Zur Tragfähigkeit und Gebrauchstauglichkeit von vorgefertigten Verdrängungspfählen in bindigen und nichtbindigen Böden. University of Kassel, PhD-thesis.