

**A simple approach to predict the load settlement behavior
of precast driven piles with due consideration of the driving process**

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Abstract

To predict the ultimate limit state of precast driven piles, there are different empirical and analytical approaches available. A simple prediction of the resistance-settlement behavior is so far not possible. During field load tests of precast driven piles, commonly measured quantity is the total load on the pile head. Hence, model tests were performed to separate the skin friction and base resistance on the pile. Based on the statistical analysis of more than 200 static load tests on precast driven steel and concrete piles, a simple approach to predict the resistance-settlement behavior of precast driven piles was derived.

Introduction

Economical design of pile foundations requires appropriate methods to predict their load-settlement behavior in preliminary stages of design. In this stage, static loading tests can't be applied, even though they are still the most reliable method to predict the load-settlement behavior of pile foundations. Different approaches are available to predict the ultimate limit state of precast driven piles. According to *Poulos (1989)* they can be divided into three broad categories. Empirical approaches based on correlations with in situ (e.g. CPT, SPT), laboratory or field tests (e.g. α method) are classified as category 1. Category 2 is usually based on simplified theoretical approach like the effective stress (β) method, e.g. *Meyerhof (1976)*. Numerical approaches such as the Finite Element or Boundary Element Method are assigned to category 3.

To predict the ultimate limit state of precast driven piles, the category 1 approach is most commonly used. Most of the methods in category 1 and 2 are based on parameters of the undisturbed soil, although it is commonly known that the installation process of precast driven piles may change the soil properties intensely.

Numerical approaches, e.g. *Desai (1978)*, offer the opportunity to model the effect of pile installation, however, the application of these methods is still too bulky for the standard precast driven pile design.

A remarkable difference between the different design methods is the proportion of the skin friction and the base resistance to the total pile capacity. In static loading tests on driven piles, usually the total pile capacity only is measured. An appropriate evaluation of existing design methods and a true analysis of static loading tests requires a method to divide the measured load settlement curves into skin friction and base resistance.

Pile design according to the European standard *Eurocode 7* demands in addition to the verification of the ultimate limit state, a proof of a sufficient safety in the serviceability limit state of a super structure caused by displacement of the piles. So far there is no simple empirical approach to predict the load settlement behavior of precast driven piles. The paper presents a simple approach to predict a load settlement behavior of precast driven piles with due consideration of the driving process. This is based on the statistical analysis of more than 200 static loading tests on precast driven steel and concrete piles.

Model tests

As aforementioned separate measurement of skin friction and base resistance in static field loading tests were not possible because of the cost factor. Therefore, model tests were carried out to analyze the proportion of the skin friction and the base resistance compared to the total pile capacity of piles driven into dense sand.

Detail (a)

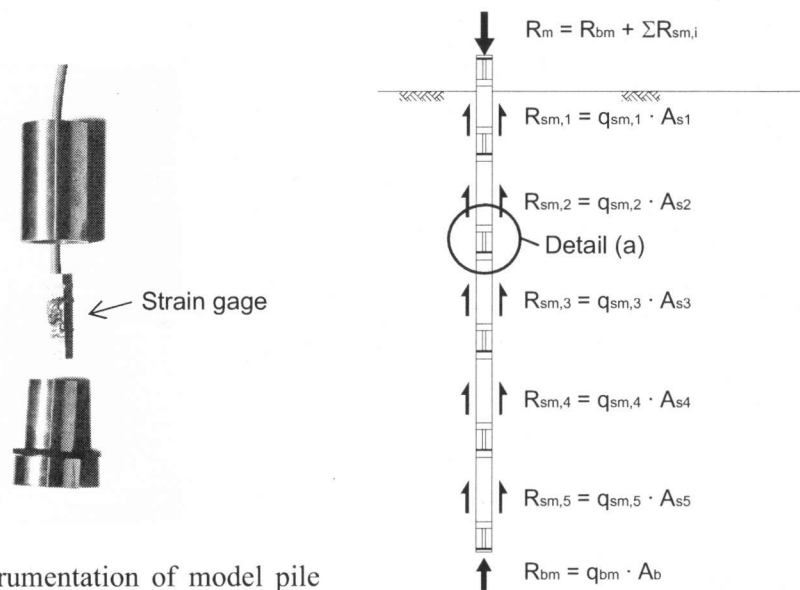


Figure 1. Instrumentation of model pile with strain gages

Beside the separate measurement of the skin friction and the base resistance, the changes in the skin friction along the pile shaft could be determined. The instrumentation of the model pile is shown in Figure 1.

Medium scale steel piles with a diameter of 5 cm and a length of 1,50 m were used for the model tests. The piles were driven into dense sand using a medium heavy driving rod (0,02 kNm/blow). Three days after the driving of the pile a static loading test was carried out.

During the test series the embedded length and the surface texture of the model piles were varied. Ratios of embedded length to pile diameter from 12 to 28 were tested. To analyze the influence of the surface texture a smooth steel pile and a sand coated steel pile with a very rough surface were used.

The model tests confirmed the aforementioned influence of the driving process on the pile capacity. A correlation of the skin friction and the driving energy (Figure 2) and the base resistance pressure and the sum of the driving energy on the last $8 \cdot D_b$ (Figure 3) shows a rise of the pile capacity with the driving energy.

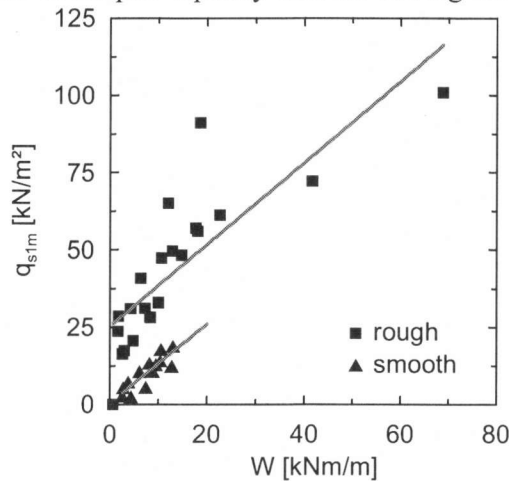


Figure 2. Correlation between the skin friction and the driving energy

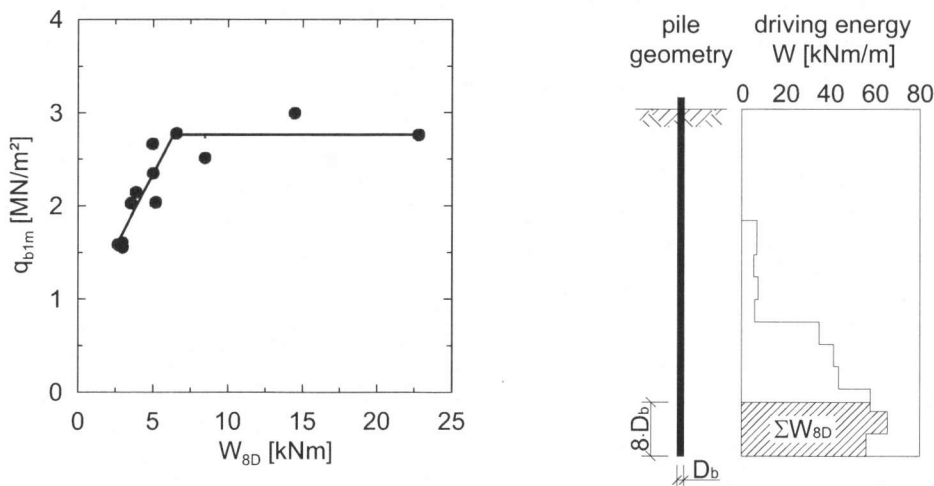


Figure 3. Correlation between the base resistance and the driving energy W_{8D}

Based on the results of the model tests, a correlation between the ratio of base to skin area A_b/A_s and the ratio of shaft to total pile capacity R_{sm}/R_m can be made (Figure 4). The two model piles had the two extreme possible pile surface textures. An optical 3D analyzer was used to define the surface roughness of the model piles and full scale concrete piles, with the principle of the chromatic aberration.

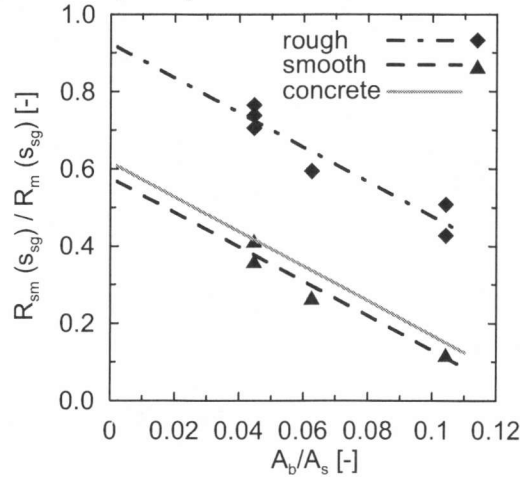


Figure 4. Correlation of A_b/A_s and R_{sm}/R_m at skin friction failure

The correlations in Figure 4 were used to divide the resistance-settlement curves of precast concrete piles predominantly driven into dense sand into base and shaft resistance.

Statistical analysis of in situ static pile load tests

The statistical analysis is based on a dataset of more than 200 in situ static pile loading tests. Only those fully documented loading tests were used in the analysis. At least the following information was required for full documentation:

- a) *general information*: reference, project, location, date of driving and loading test;
- b) *pile information*: material, geometry (cross section, diameter, length), embedment length and base and shaft area;
- c) *driving information*: type of pile driver and hammer, weight of ram, weight of pile, height of drop, sum of driving energy, maximum driving energy per blow, driving chart and rate of penetration during the last 30 blows;
- d) *subsoil information*: soil profile, static penetration test, c_u -value for cohesive strata and groundwater;
- e) *pile loading test*: distribution of the resistance-settlement curve.

The intention of the statistical analysis was to isolate and quantify the different factors that influence the pile capacity. Therefore, the multiple regression analysis method was used. First, the two components of the resistance-settlement curve of precast concrete piles predominantly driven into dense sand were analyzed separately.

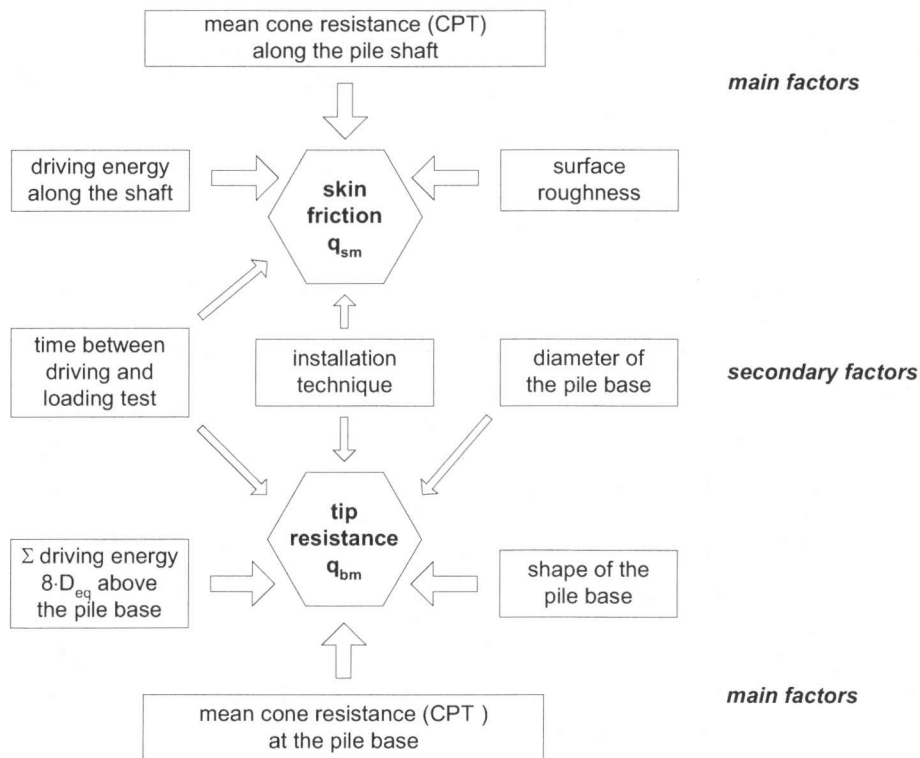


Figure 5. Factors that had been considered in the statistical analysis of the pile capacity

The statistical analysis of in situ pile loading tests leads to a wide scatter of the results. In the first step of the statistical analysis of the pile capacity, the main influencing factors shown in Figure 5 are identified.

Based on the first results of the analysis the whole data of resistance-settlement curve of precast concrete piles was reviewed. The values of skin friction and base resistance pressure for precast concrete piles were derived as functions of the factors mentioned above. Using the derived values of the skin friction and the base resistance pressure for precast concrete piles, adjustment factors for other pile types were developed.

Prediction of the load-settlement behavior

The simplified approach to predict the load-settlement behavior of precast driven piles based on the statistical analysis is presented below. Figure 6 shows the elements of the resistance-settlement curve of precast driven piles up to a settlement of $s_l = s_g$, where s_l is the settlement at the ultimate limit state and s_g the limit settlement or the settlement at failure. The presented approach differentiates between the settlement-dependent pile base resistance $R_b(s)$ and the pile shaft resistance $R_s(s)$.

The limit settlement for $R_{b,k}$ ($s_l = s_g$) can be estimated from:

$$s_g = 0,10 \cdot D_{eq} \tag{1}$$

where D_{eq} is the equivalent diameter of a round shaped pile base coextensive to the pile base area. Pile base areas for steel piles may be assumed as shown in Figure 7.

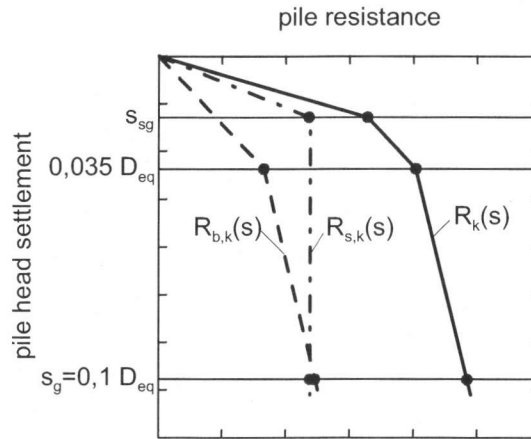


Figure 6. Elements of the resistance-settlement curve of precast driven piles

The limit settlement at failure for $R_{s,k}(s_{sg}) = R_{s1,k}$ in MN is given by:

$$s_{sg} [mm] = 5 \cdot R_{s1,k} [MN] + 0,5 [mm] \leq 10mm \tag{2}$$

The characteristic axial pile resistance is determined from:

$$R_k(s) = R_{b,k}(s) + R_{s,k}(s) = \eta_b \cdot q_{b,k} \cdot A_b + \sum_i \eta_{s,i} \cdot q_{s,k,i} \cdot A_{s,i} \tag{3}$$

where:

- A_b is the nominal value of the pile base area;
- $A_{s,i}$ is the nominal value of the pile shaft area in layer n;
- $q_{b,k}$ is the characteristic pile base resistance pressure according to Tables 1 and 2;
- $q_{s,k,i}$ is the characteristic pile skin friction in layer n according to Tables 3 and 4;
- η_b is an adjustment factor of the pile base resistance according to Table 5;
- η_s is an adjustment factor of the pile shaft resistance according to Table 5;
- $R_k(s)$ is the settlement-dependent characteristic pile resistance;
- $R_{b,k}(s)$ is the settlement-dependent characteristic pile base resistance;
- $R_{s,k}(s)$ is the settlement-dependent characteristic pile shaft resistance.

The characteristic values of pile base resistance pressure and pile skin friction given in Tables 1 to 4 are valid for:

- precast reinforced concrete and pre-stressed concrete piles with $D_{eq} = 0,28$ to $0,47$ m;
 - steel girder piles with flange width of 300 to 500 mm and a profile height of 290 to 1000 mm;
 - pipe piles up to $D_b = 0,80$ m
- and are embedded at least 2,50 m into a load bearing stratum.

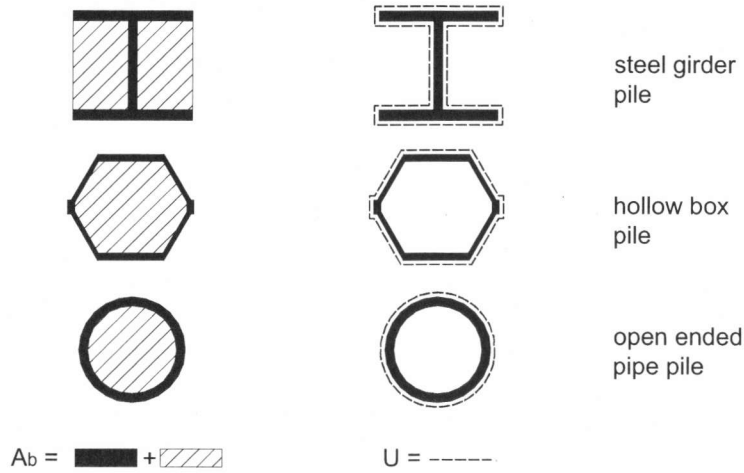


Figure 7. Pile base and shaft area of different types of steel piles

The characteristic values of pile base resistance pressure and pile skin friction given in Tables 1 to 4 are given as functions of:

- the mean cone resistance q_c (CPT) in cohesionless soil;
- the driving energy W in cohesionless soil, and
- the undrained shear strength $c_{u,k}$ in cohesive soil.

Table 1. Pile base resistance pressure $q_{b,k}$ in cohesionless soils

Relative settlement of the pile head s/D_{eq}	Pile base resistance pressure $q_{b,k}$ MN/m ²							
	mean cone resistance q_c (CPT)							
	$1 \cdot D_{eq}$ above and $4 \cdot D_{eq}$ below the pile base							
	MN/m ²							
	7,5	10	15	20				
	sum of driving energy W_{8D} on the last $8 \cdot D_{eq}$ m							
	MNm							
	≤ 15	> 15	≤ 25	> 25	≤ 25	> 25	≤ 25	> 25
0,035	5,70	5,90	6,67	6,90	8,10	8,33	9,29	9,52
0,100	6,05	8,52	8,86	10,48	11,81	13,52	14,95	16,67

Intermediate values may be linearly interpolated. For piles driven by vibration the table values may be adopted at 75 %. This is not necessary, if the pile is driven by impact for the last $8 \cdot D_{eq}$ length of the pile.

Table 2. Pile base resistance pressure $q_{b,k}$ in cohesive soils

Relative settlement of the pile head s/D_{eq}	Pile base resistance pressure $q_{b,k}$ MN/m ²	
	undrained shear strength $c_{u,k}$	
	MN/m ²	
	0,10	0,20
0,035	0,57	1,14
0,100	0,86	1,71

Intermediate values may be linearly interpolated.

Table 3. Pile skin friction $q_{s,k}$ in cohesionless soils

Mean cone resistance q_c (CPT) MN/m ²	Mean driving energy W MNm/m	Pile skin friction $q_{s,k}$ at failure MN/m ²
0		0
5	$\leq 6,5$	0,029
	$> 6,5$	0,038
10	$\leq 6,5$	0,048
	$> 6,5$	0,057
15	$\leq 6,5$	0,067
	$> 6,5$	0,076
≥ 20	$\leq 6,5$	0,086
	$> 6,5$	0,095

Intermediate values may be linearly interpolated. For piles driven by vibration the table values may be adopted at 75 %.

Table 4. Pile skin friction $q_{s,k}$ in cohesive soils

Undrained shear strength $c_{u,k}$ MN/m ²	Pile skin friction $q_{s,k}$ at failure MN/m ²
0,025	0,024
0,100	0,043
0,200	0,057

Intermediate values may be linearly interpolated.

Table 5. Adjustment factors of the pile base η_b and shaft resistance η_s

Pile type	η_b	η_s
precast reinforced concrete and pre-stressed concrete	1,0	1,0
steel girder piles ¹⁾	$s = 0,035 \cdot D_{eq}$	$0,83 - 0,34 \cdot h/b$
	$s = 0,10 \cdot D_{eq}$	$1,03 - 0,34 \cdot h/b$
open ended pipe piles and hollow box piles	0,55	1,00
closed pipe piles	0,90	1,00

¹⁾ h = profile height, b = flange width

Case study

The empirical approach to predict the resistance-settlement behavior of precast driven piles is illustrated below. For the case study a square shaped precast concrete pile (35 · 35 cm) with a length of 21 m was chosen. Refer to Figure 8 for details of the pile geometry, the subsoil and the driving process.

Characteristic pile base resistance at $s = 0,035 \cdot D_{eq} = 13,65$ mm:
 using $q_{b,k} = 8,22$ MN/m² and interpolation from Table 1,
 $R_{b,k}(s = 13,65\text{mm}) = 0,35^2 \cdot 8,22 = 1,007$ MN

Characteristic pile base resistance at $s = 0,10 \cdot D_{eq} = 39,00$ mm:
 using $q_{b,k} = 12,12$ MN/m² and interpolation from Table 1,
 $R_{b,k}(s = 39,00\text{mm}) = 0,35^2 \cdot 12,12 = 1,485$ MN

- 3.) Characteristic pile resistance R_k :
 $R_k(s = 13,65\text{mm}) = 1,007 + 1\,376 = 2\,383$ MN
 $R_k(s = 39,00\text{mm}) = 1,485 + 1\,376 = 2\,861$ MN

The measured and predicted resistance-settlement curves are displayed in Figure 9.

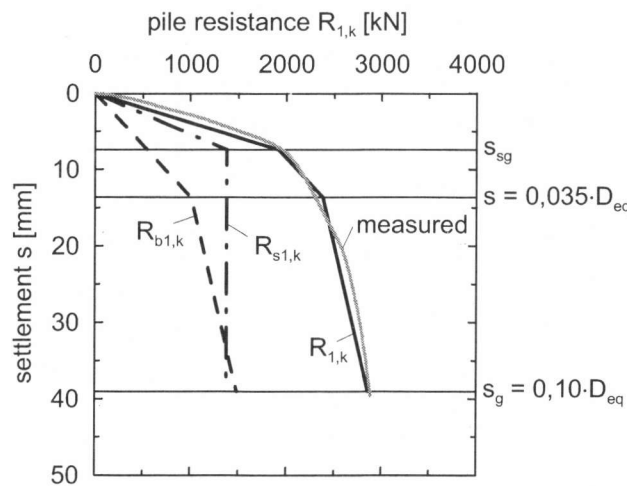


Figure 9. Calculated characteristic resistance-settlement curves and result of the static loading test

Verification

The new approach was used to predict the resistance-settlement curves of more than 200 driven steel and concrete piles. To verify the reliability of the approach, the percentage of the difference between measured and predicted pile resistance at ultimate limit state ΔR_l is shown in Figure 10.

The standard deviation of ΔR_l using conventional approaches for pile capacity prediction leads, in the analyzed cases, to a large scatter of the standard deviation ($s = 25$ to 50 %). With the new approach, however, the standard deviation of ΔR_l can be reduced to $s = 19,52$ %. This is mainly due to the consideration of the driving process, because conventional approaches use parameters of the undisturbed soil only.

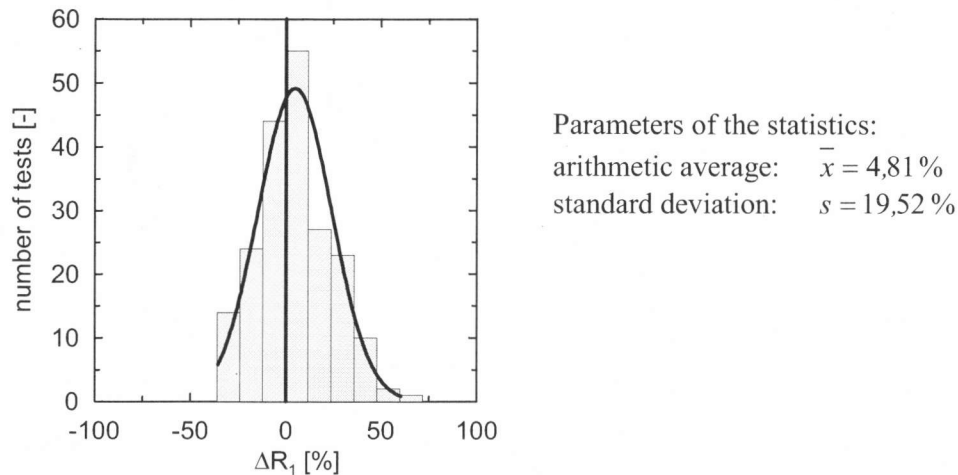


Figure 10. Frequency distribution of the difference between measured and predicted pile resistance ΔR_I from static loading tests

Conclusion

The model tests had shown, that the driving energy has a significant influence on the pile capacity. Based on a statistical analysis of more than 200 static loading tests, a new approach to predict the load settlement behavior of precast driven piles was derived. Unlike common approaches for pile capacity prediction, the new approach takes the disturbance of the soil as a result of the driving process into account. The application of the new approach was demonstrated and its reliability was confirmed.

The new approach offers a simple way to predict the load settlement behavior of precast driven piles.

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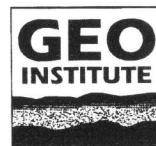
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