Axial Pile Resistance of Different Pile Types Based on Empirical Values

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ABSTRACT: This paper presented a comparison of pile capacity from axial load tests and that from empirical equations. Additionally, a correlation was developed based on the load test database to estimate skin friction and end bearing of piles based on cone penetration resistance or undrained shear strength. Up to 1000 pile load tests on displacement piles, such as precast concrete, cast in place, steel, and screwed cast in place piles, micro piles, etc. are evaluated. The result of this study has been already integrated in the national German recommendations for piles "EA-Pfähle".

INTRODUCTION

According to German national standard DIN 1054:2005, analytical calculation methods cannot generally be used for the determination of pile resistance, since no methods are available at present, which describe the mechanical model and the influences of the installation method of the different pile types. Therefore, the resistance-settlement behaviour has to be verified on the basis of pile load tests on the field or comparable pile load test results from the nearby area with similar underground conditions. If no pile load tests are carried out and empirical values from directly comparable load tests are not available, the characteristic axial pile resistance of a single pile can be determined from general empirical values of axial pile resistances according to DIN 1054:2005. Similar specifications can also be found in EN 1997-1:2008 (Euro code EC 7-1).

However, very limited empirical values for pile resistance are available for few pile types in the existing German pile standards DIN 4026, DIN 4014, DIN 4128 and DIN 1054:2005. This deficiency in empirical values has been taken as a motive to form a database of axial pile load tests on different pile types and analyze them statistically. The goal of the study was to derive a range of empirical value of base resistance and skin friction as much as possible for different pile types and hence to contribute to the economical evaluation of the axial resistances of piles.

STATISTICAL METHODS AND RANGE OF EMPIRICAL VALUES

The descriptive and statistical methods used for the derivation of axial pile capacity based on empirical values are widely known. For details, see Hartung et al. (2002) and Kempfert & Becker (2007).

In addition to the scattering of soil strength parameters due to the boundary conditions of the geological process, the pile load bearing behaviour is also influenced by the installation method. Since the empirical values for the pile resistance are available for few pile types in a very limited amount, the scatter of pile bearing capacity can be considered in the statistical analysis by using a range of quantile values as shown in Figure 1.

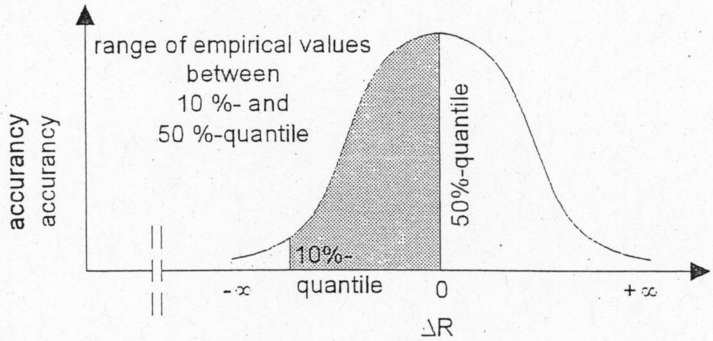

FIG. 1. Range of empirical values of pile resistances.

In the present analysis, empirical values for pile resistance have been derived at 10%, 20% and 50% quantiles. A 10% quantile means that 90% of the cases of the empirical determination of the axial pile resistance lies on the safe side and/or does not exceed the existing measured resistances. In contrast to this, a conservative average value at 50% quantile is usually taken for determination of the characteristic soil properties so far in practice.

The range of empirical values indicated in Figure 1 can vary depending on pile load tests and local boundary conditions and it only serves as first orientation.

PILES TYPES AND DATABASE

Data are collected mainly from static but also from dynamic load tests of different pile types (Table 2) and they are compiled in a database.

Table 2. Overview of pile load tests of the different pile types

Pile types	Construction type	no. of tests	
		static	dynamic
Driven precast piles	Reinforced and prestressed concrete piles	121	-
	Steel piles	98	80
Driven cast in place piles	Simplex pile	70	-
	Franki pile	300	-
Screwed cast in place piles	Atlas pile	124	-
	Fundex pile	52	-
Micro piles	Composite and cast in place piles	38	-

In the derivation of the axial pile resistance, only those pile load test results that have adequate information on the underground conditions, are exclusively used in order to attain a reliable correlation between the soil strength properties and the pile resistance. For details, see Kempfert & Becker (2007).

EMPIRICAL AXIAL PILE RESISTANCE

Determination of Pile Resistance

The characteristic axial bearing capacity of a single pile is given by

$$R = R_b + R_s = q_b \cdot A_b + \sum_{i=1}^{n} \left(q_{s,i} \cdot A_{s,i} \right) \quad (1)$$

where:

A_b area of pile base;
$A_{s,i}$ area of pile shaft in layer i;
q_b base resistance;
$q_{s,i}$ shaft resistance in layer i.

For the definitions of q_b and $q_{s,i}$ refer to Figure 4 and Figure 5 as well as the publication by Kempfert & Becker (2007). In the following the axial pile resistance R is referred to the ultimate limit state (ULS). Additional empirical values for the serviceability limit state (SLS) depending on different settlement criteria are given in EA-Pfähle (2007).

Depending on the qualitative relationships between soil strength and base resistance q_b and/or shaft resistance q_s of the correlation analysis, a regression model is developed to take into account the proportion of the two components of the axial pile bearing capacity depending on the pile type (see Kempfert & Becker (2007) for details). In the regression analysis, the functional relationships between axial pile load capacity and soil strength had been optimized iteratively until the difference between measured and calculated axial pile load capacity becomes or approaches to zero:

$$\Delta R = \frac{R_m - R_{cal}}{R_m} \equiv 0 \quad (2)$$

where:

ΔR Difference between measured and calculated axial pile resistance for the ultimate limit state (ULS),
R_m Measured value of the axial pile resistance from pile load tests,
R_{cal} Calculated value of the axial pile resistance according equation (1).

The results of the lower empirical pile resistances, which are already introduced in EA-Pfähle (2007), are shown in Figure 2 exemplary for driven precast piles. The difference between measured and calculated axial pile resistances ΔR for the ultimate limit state (ULS) falls between –2.38 % and 0.29 % for the lower and upper empirical values (not shown in the diagram) respectively.

Comparison of Empirical Axial Pile Resistance for Different Pile Types

Some issues of the empirical analysis of pile resistance are explained below with a comparative summary for the different pile types. In Figure 3a) a comparison of the total load capacity for the different pile systems is shown. Here, the variation between the results of the static pile load tests R_m and the calculated empirical pile resistances R_{cal} according to equation (1) is displayed with shaded areas for each pile system. The average values of the empirical analysis are indicated by symbols.

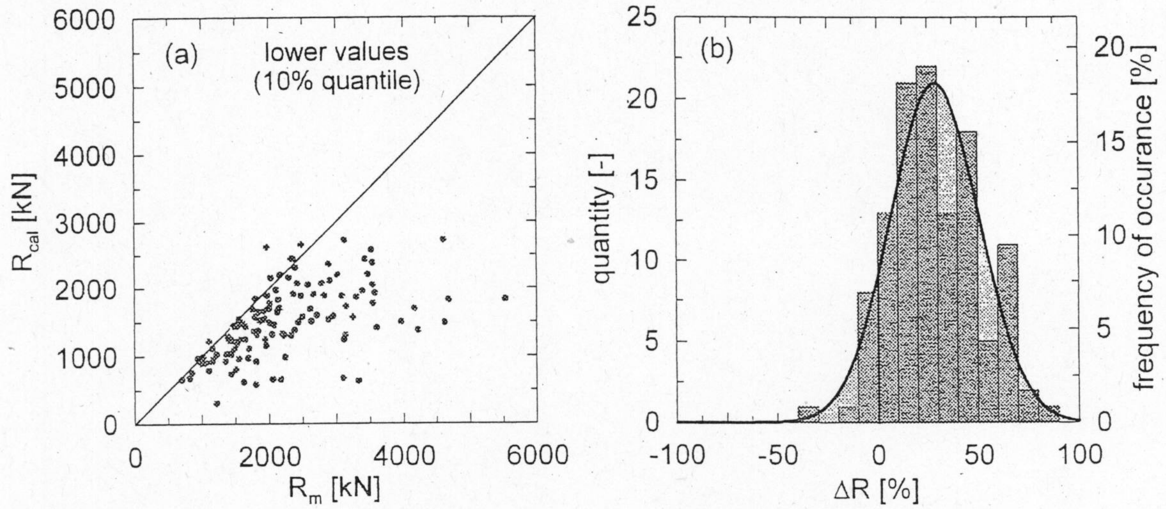

FIG. 2. a) Scatter plot and b) Histogramm of lower empirical values of driven precast piles in noncohesive soils at ULS.

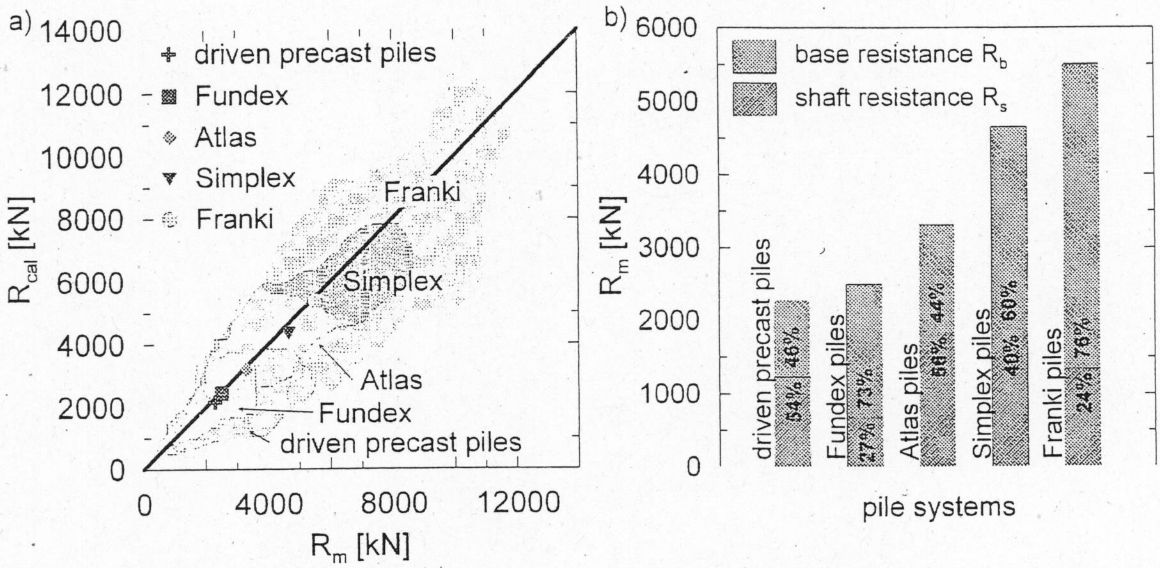

FIG. 3. a) Comparison of total load capacities (symbols = average values) and b) mean proportion of base and shaft resistances for different pile types.

The mean proportion of the base and shaft resistance of the different pile types is shown in Figure 3b). Depending on the installation method of the pile type the ratio of base resistance to the total load varies from 44 % to 76 %.

The comparison of the base resistance separately in Figure 4a) leads to an obvious relationship between the installation method, the pile system and the bearing capacity. Driven displacement piles generate a higher base resistance because of the displacement and compaction of the soil below the pile tip while driving the pile. The empirical values for the base resistance in noncohesive soils for driven precast piles and cast in place simplex piles are similar because the installation method is the same. On the other hand, the shaft resistance of the driven piles is lower than the other pile systems as it can be seen in Figure 4b) and Figure 5. Only the lower values are shown in Figure 5. The ratio between the upper and lower empirical values falls approximately between 1.3 and 1.4.

The empirical values for the base resistance of Fundex piles are smaller than the driven Simplex piles because of the effects of displacement and compaction of the installation method, with rotating and pushing movements. Both pile types have a pile tip with overlap, i.e. the diameter of the pile shaft is smaller than the diameter of the pile tip, which remains in the ground after the pile installation. This overlap leads to a loosening of the ground in the shaft area and a reduction of the empirical shaft resistances.

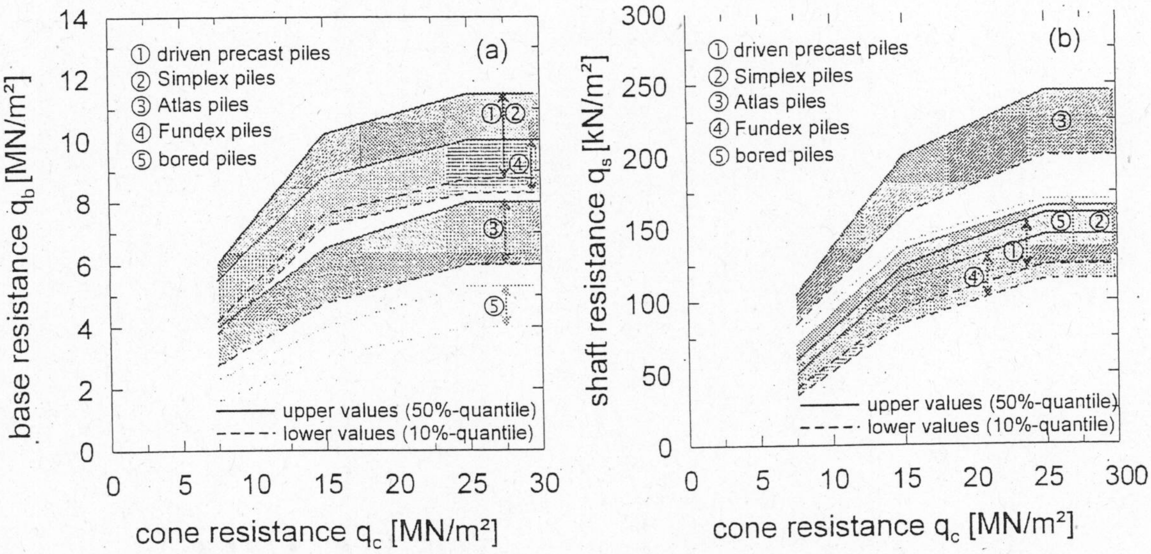

FIG. 4. Upper and lower empirical values of different piles in noncohesive soils for a) base resistance and b) skin friction.

The installation method of Atlas piles is characterised by a cutter head with a single-thread screw blade, which is twisted into the ground in the same way as the Fundex piles by a powerful rotary drive applying a large vertical pressure at the same time. The resulting screw-like shape of the Atlas pile shaft leads to larger values of shaft resistances.

The lower values of base resistances of bored piles and auger piles can be explained by the relaxation of the initial stress conditions in the area of pile tip due to the boring process.

All empirical values for the analysed pile system are given in EA-Pfähle (2007) for both ULS and SLS.

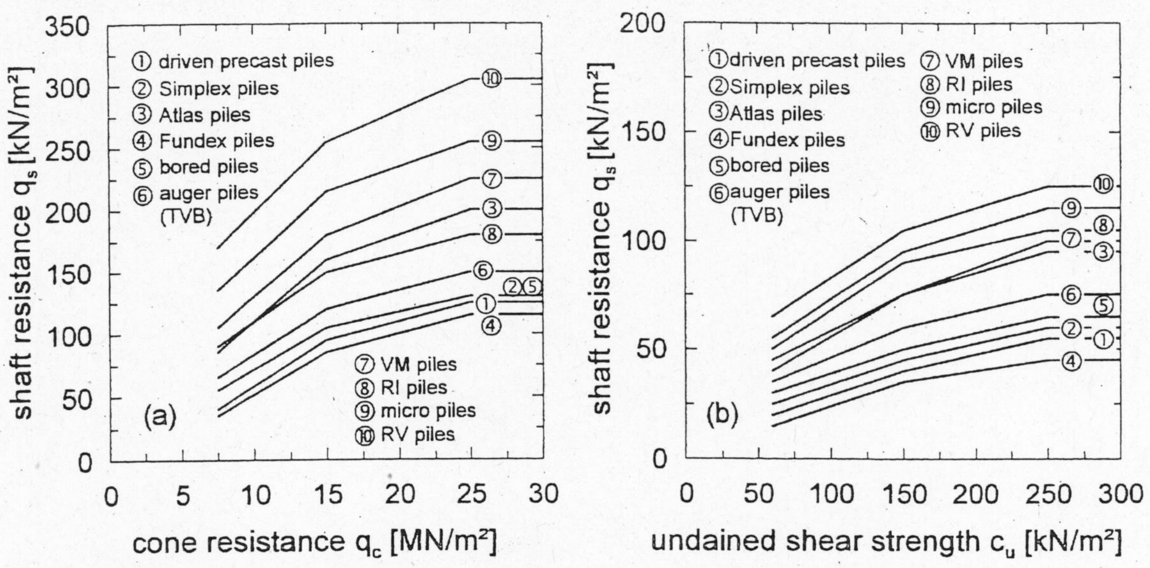

FIG. 5. Lower empirical values of skin friction for different piles in a) noncohesive soils and b) in cohesive soils.

CONCLUSIONS

The study of pile load tests provides to a large extent a secured range of empirical values for the base resistance and the skin friction for the different pile types as a function of the soil strength. Based on comparative statistical analysis of pile load tests on different pile systems, it becomes possible to derive a consistent analysis of bearing behaviour of pile types, which provides a safe and an economical pile bearing capacity depending on the extend of preliminary soil investigations.

The results of this study has been already integrated in the national German recommendations for piles "EA-Pfähle" of the German society of Geotechnics (DGGT).

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