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Bearing capacity of open-ended piles based on empirical values – recommendations according to the German approach

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ABSTRACT: During driving of open-ended pipe piles, H-Piles and double H-Piles a plugging effect between opposite areas can occur. However, in the main calculation methodologies this plugging effect is considered as fully plugged or not plugged at all. Based on a huge number of static and dynamic pile test results a new calculation methodology is derived for open-ended piles, H-Piles and double H-Piles considering the plugging effect based on geometry boundary conditions. Furthermore, the pile resistance and the pile resistance curve can be calculated based on the derived range of values of experiences for the ultimate limit state (ULS) and the serviceability limit state (SLS). Because of the huge database, the calculation methodology can be said to be verified and was adopted by the Recommendations on Piling (EA-Pfähle).

1 INTRODUCTION

During driving of open-ended pipe piles the soil enters the profile, which can lead to a plugging effect. This plugging effect can occur in a fully plugged condition, partially plugged condition or in an unplugged condition. Reason for the plugging effect is an increased inner shaft resistance during driving or in a later condition during static loading of the pile. This plugging effect is not limited to open-ended pipe piles only but can also occur between opposite areas (i.e. flanges) of H-Piles or double H-Piles. Figure 1 shows an example. Furthermore, the areas for the load transfer regarding the calculation methodology as described in Chapter 2.2 and 2.3 are also displayed.

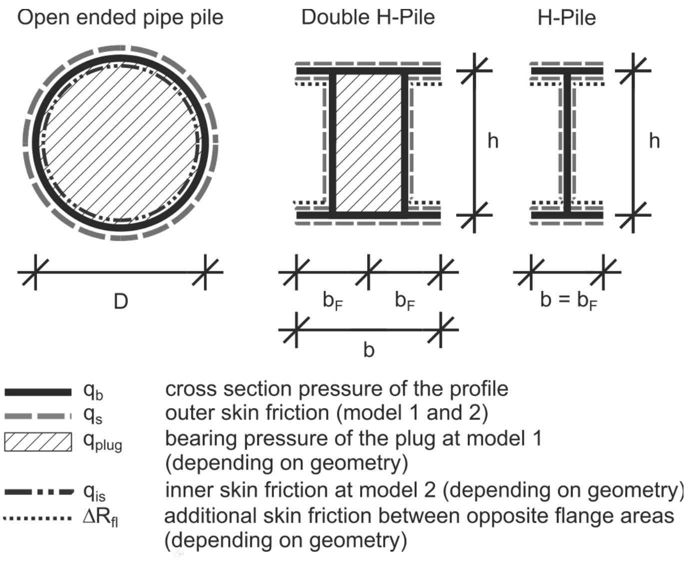

Figure 1. Profiles with different areas of possible plugging

Based on an own database (see Lüking & Becker, 2015, Kempfert & Becker, 2007 and Kempfert & Becker, 2010) of different static and dynamic pile load tests a new calculation methodology was derived, which will be explained in detail in the following chapters. Based on this methodology the full load bearing behaviour of an open-ended pile can be calculated.

Furthermore, a comparison with other available methodologies like ICP-05 (Jardine et al., 2005), NGI-05 (Clausen et al., 2005), UWA-05 (Lehane et al. 2005a, b) and FUGRO-05 (Kolk et al. 2005) is given. A general overview of CPT based calculation methods can be found in Niazi & Mayne (2013).

2 GERMAN CALCULATION METHODOLOGY FOR OPEN-ENDED PILES

2.1 *General*

The plugging effect is not defined in general. As stated previously, plugging describes an increase in the inner shaft resistance near the pile toe on a limited area. The changeover between the fully plugged conditions (and reacting like a monolith), the partially plugged condition and an unplugged condition are fluently and cannot be defined exactly, see Lüking (2010).

The plugging effect depends on the pile diameter, relative density of the soil and the installation methodology. Schenk (1966) describes based on experience that a fully plugged condition can occur to a pile diameter up to 0.5m. On the other hand, at a pile diameter bigger than 1.5 m no plugging effect shall occur, see Lehane et al. (2005c).

Lüking (2010) describes that an excessively high driving energy might lead to slipping of the plug (in case of a fully plugged condition). Lammertz (2008) investigated that likely no plugging effect will occur in case of vibrating the pile.

However, the load transfer is shown in Figure 2 based on the investigations of Lüking (2010). Furthermore, a numerical calculation is given in which the distribution of the inner skin friction over pile length is shown. The lower the pile diameter, the greater the increase in inner skin friction near the pile toe, which is the reason for the arching effect and finally the plugging of the soil inside. Details are described in Lüking (2010) and Lüking & Kempfert (2012). Therefore, the inner skin friction near the pile toe can be many times higher than the outer skin friction.

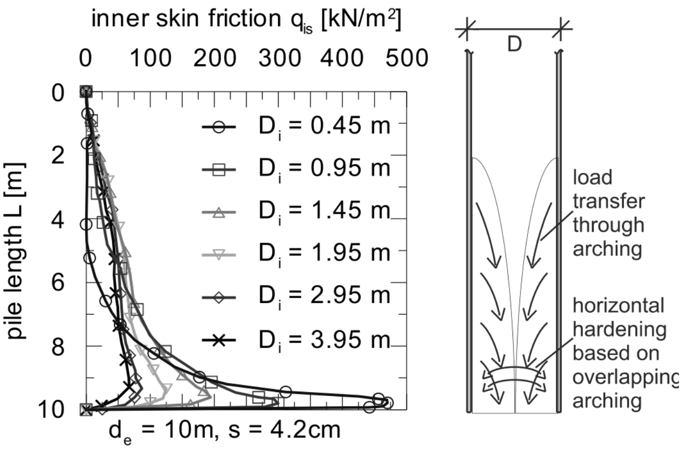

Figure 2. Inner skin friction for different pile diameter and model load transfer after Lüking (2010) and Lüking & Kempfert (2012)

2.2 *Calculation Methodology for open-ended piles*

The calculation methodology is based on a database of 113 static and dynamic pile loadings of open-ended pipe piles mainly performed in northern Germany with pile diameters of D = 0.32 m to 1.42 m and pile embedded depths of d_e = 7 m to 32 m in medium dense to very dense sand layers. Details of the database and the following calculation methodology is given in detail in Lüking & Becker (2015) and Kempfert & Becker (2007).

Based on the soil mechanical relations described in Chapter 2.1 two calculation models were defined, see Figure 3.

According to EA-Pfähle (2012) two quantiles were defined. The 10 % quantile is for general use in which 90 % of the results are on the so called "safe side". The 50 % quantile is an average for all results and should be used by geotechnical experts only. Furthermore, values for serviceability limit state (SLS) and ultimate limit state (ULS) are given. The ULS is defined as a pile settlement equal to 10% of the diameter, see equation (1).

$$s_{ult} = s_g = 0.1 \cdot D \tag{1}$$

where s_{ult} = pile settlement for ULS and D = pile diameter.

In general, the pile resistance will be calculated after the models already described in Figure 3.

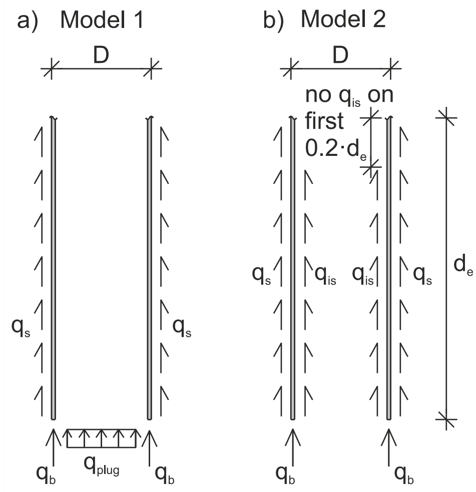

Figure 3. Calculation models for open-ended pipe piles,
a) Model 1: Fully plugged condition, b) Model 2: No plugging

2.2.1 *Model 1*

Model 1 considers a fully plugged condition and the load transfer takes place over an outer skin friction q_s and a bearing capacity on the steel cross section itself q_a and the bottom of the pile plug q_{plug}.

The characteristic pile resistance of model 1 $R_{c,k,Model\ 1}$ is calculated after Equation 2.

$$R_{c,k,Model\ 1}(s) = \eta_{plug} \cdot q_{plug,k} \cdot A_{plug} + q_{b,k} \cdot A_b + \Sigma\ \eta_s \cdot q_{s,k,j} \cdot A_{s,j} \tag{2}$$

where $\eta_{plug} = 2{,}52 \cdot e^{-1{,}85 \cdot D}$ [-], $q_{plug,k}$ = characteristic bearing pressure of the plug [kN/m²] after table 1, A_{plug} = bottom of plug [m²], $q_{b,k}$ = cross section pressure of the profile [kN/m²] after table 3, A_b = cross section of profile [m²], $\eta_s = 1{,}53 \cdot e^{-0{,}85 \cdot D}$ [-], $q_{s,k,j}$ = characteristic outer skin friction of soil layer j [kN/m²] after table 2, $A_{s,j}$ = outer shaft area of soil layer j [m²], D = outer pile diameter [m].

2.2.2 *Model 2*

In model 2 an inner skin friction q_{is} is acting instead of a bearing pressure on the plug. Based on settlement effects during pile installation on the first 20% of the pile length no inner skin friction is considered. The characteristic pile resistance of model 2 $R_{c,k,Model\ 2}$ is calculated after Equation 3.

$$R_{c,k,Modell\ 2}(s) = q_{b,k} \cdot A_b + \Sigma\ q_{s,k,j} \cdot A_s + \Sigma\ q_{is,k,j} \cdot A_{is,j} \tag{3}$$

where $q_{b,k}$ = cross section pressure of the profile [kN/m²] after table 3, A_b = cross section of profile

$[m^2]$, $q_{s,k,j}$ = characteristic outer skin friction of soil layer j $[kN/m^2]$ after table 4, $A_{s,j}$ = outer shaft area of soil layer j $[m^2]$, $q_{is,k,j}$ = characteristic inner skin friction of soil layer j $[kN/m^2]$ after table 5, $A_{is,j}$ = inner shaft area of soil layer j $[m^2]$.

The total characteristic pile resistance will be calculated after equation (4), in which both pile models will be combined with each other depending on the pile diameter and therefore considering the plugging effect of the pile.

$$R_{c,k}(s) = \psi \cdot R_{c,k,Model\,1}(s) + \chi \cdot R_{c,k,Model\,2}(s) \quad (4)$$

where $R_{c,k,Model\,1}(s)$ = characteristic pile resistance after model 1 [kN] in compression after equation (2), $R_{c,k,Model\,2}(s)$ = characteristic pile resistance after model 2 [kN] in compression after equation (3), parameter ψ and χ are based on $\psi = 1$ for $D < 0.5$ m, $\psi = -D + 1.5$ for $0{,}5\ m \leq D \leq 1{,}5$ m, $\psi = 0$ for $D > 1.5$ m, $\chi = 0$ for $D < 0.5$ m, $\chi = -0.52 \cdot D^2 + 2.04 \cdot D - 0.89$ for $0.5\ m \leq D \leq 1.5$ m, $\chi = 1$ for $D > 1.5$ m, D = outer pile diameter [m].

2.3 *Calculation Methodology for H-Piles and Double H-Piles*

The methodology for calculating the bearing capacity of H-Piles and double H-Piles consider the soil mechanics described in Chapter 2.1. For H-Piles a skin friction $q_{s,k}$ around the pile is acting. Furthermore there is a pile bearing capacity $q_{b,k}$ on the pile steel cross section area only and an additional increase of skin friction based on a plugging effect between the inner flange areas called ΔR_{fl}. Regarding the double H-Piles there is an additional capacity on the bottom of the plug $q_{plug,k}$ acting. Details can be found in figure 1. Only model 1 is used for the double H-Piles.

For the statistical analysis the results of 31 pile tests for the H-Piles and 26 pile tests for the double H-Piles with pile embedment depth of around 5 m to 25 m in mainly medium dense to very dense sand layers were analysed.

The characteristic pile resistance in compression $R_{c,k}$ for H-piles and double H-Piles is calculated after Equations 5 and 6.

$$R_{c,k}(s) = R_{b,k}(s) + R_{s,k}(s) + \Delta R_{Fl,k}(s)$$
$$R_{c,k}(s) = q_{b,k} \cdot A_b + \Sigma q_{s,k,j} \cdot A_{s,j} + \eta \cdot \Sigma q_{s,k,j} \cdot A_{s,Fl,j} \quad (5)$$

$$R_{c,k}(s) = R_{b,k}(s) + R_{plug,k}(s) + R_{s,k}(s) + \Delta R_{Fl,k}(s)$$
$$R_{c,k}(s) = q_{b,k} \cdot A_b + \eta \cdot q_{plug,k} \cdot A_{plug} + \Sigma q_{s,k,j} \cdot A_{s,j} + \eta \cdot \Sigma q_{s,k,j} \cdot A_{s,Fl,j} \quad (6)$$

where $q_{b,k}$ = cross section pressure of the profile $[kN/m^2]$ after Table 3, A_b = cross section of profile $[m^2]$, $q_{s,k,j}$ = characteristic outer skin friction of soil layer j $[kN/m^2]$ after Table 2, $A_{s,j}$ = outer shaft area of soil layer j $[m^2]$, $A_{s,Fl,j}$ = inner flange area $[m^2]$, $q_{plug,k}$ = characteristic bearing pressure of the plug $[kN/m^2]$ after Table 1, A_{plug} = bottom of plug $[m^2]$, η = parameter after Equation 7 and Figure 4.

$$\eta = 0.65 \cdot e^{-2.2 \cdot h \cdot b} \quad (7)$$

where h = height of H-profile with 300 mm < h ≤ 1000 mm, b_f = width of flange with 290 mm < b_f ≤ 500 mm.

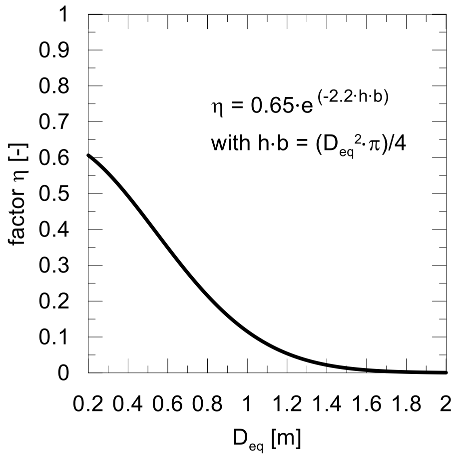

Figure 4. Factor η after equation (7) for considering the plugging effect for H-piles depending on the equivalent pile diameter D_{eq}

2.4 *Pile Resistance Curve*

The deriving of the pile resistance curve for the SLS condition is based on EA-Pfähle (2012). Therefore, the pile resistance will be calculated based on different pile settlements as stated below.

$R_{b,k}(s = 0{,}035 \cdot D_{eq})$	$R_{b,k}(s = 0{,}1 \cdot D_{eq})$
$R_{plug,k}(s = 0{,}035 \cdot D_{eq})$	$R_{plug,k}(s = 0{,}1 \cdot D_{eq})$
$R_{is,k}(s = s_{sg*})$	$R_{is,k}(s = s_{sg})$
$R_{s,k}(s = s_{sg*})$	$R_{s,k}(s = s_{sg})$
$\Delta R_{fl,k}(s = s_{sg*})$	$\Delta R_{fl,k}(s = s_{sg})$

where s_{sg*} = characteristic pile settlement for activating the failure skin friction after Equation 8, s_{sg} = pile settlement in ULS ($s_{sg} = s_g$) after Equation 1.

$$s_{sg*} = 0.5 \cdot R_{s,k}(s = s_{sg*}) \leq 1.0\ cm \quad (8)$$

Equation 8 is empirical, in which $R_{s,k}$ has to be used in [MN] units.

The ranges for the values of experiences are given in Table 1 to Table 5. The first value (lower bound) is for the 10 % quantile and can be adopted for the preliminary design. The second value (50 % quantile for upper bound) may only be selected for the specific application by the designer if they are expressly confirmed by a geotechnical expert. Additional details can be found in EA-Pfähle (2012).

3 STATISTICAL RESULTS

As stated before, the calculation methodology was derived in Lüking & Becker (2015). The statistical results like scatter diagrams and histograms for the open-ended pipe piles are given in Figure 5 for the open-ended pipe piles, Figure 6 for the H-Piles and Figure 7 for the double H-Piles.

The standard deviation is in a range of 20 to 34.3 and therefore in a satisfactory range for a geotechnical analysis considering the natural scatter of the data.

Table 1. Range of values of experiences for the characteristic bearing capacity on plug $q_{plug,k}$ in non-cohesive soils for model 1

Related pile settlement s/D_{eq}	Characteristic base pressure on plug $q_{plug,k}$ [kN/m²] Cone penetration resistance q_c [MN/m²]		
	7.5	15	25
0.035	1200÷3300	2100÷4000	2500÷4750
0.100	2250÷4000	4000÷6250	4750÷7250

Table 2. Range of values of experiences for the characteristic outer skin friction $q_{s,k}$ in non-cohesive soils for model 1

Pile settlement	Characteristic outer shaft friction $q_{s,k}$ [kN/m²] Cone penetration resistance q_c [MN/m²]		
	7.5	15	25
s_{sg}*	15÷25	35÷50	40÷70
$s_{sg}=s_g=0.1\cdot D$	25÷35	50÷70	60÷90

Table 3. Range of values of experiences for the characteristic bearing capacity on cross section of the profile $q_{b,k}$ in non-cohesive soils for model 1 and model 2

related pile settlement s/D_{eq}	characteristic base pressure on plug $q_{b,k}$ [kN/m²] cone penetration resistance q_c [MN/m²]		
	7.5	15	25
0.035	3900÷7500	7900÷11500	10300÷16300
0.100	7500÷9000	15000÷18000	20000÷25000

Table 4. Range of values of experiences for the characteristic outer skin friction $q_{s,k}$ in non-cohesive soils for model 2

Pile settlement	Characteristic outer shaft friction $q_{s,k}$ [kN/m²] Cone penetration resistance q_c [MN/m²]		
	7.5	15	25
s_{sg}*	15÷20	30÷45	35÷60
$s_{sg}=s_g=0.1\cdot D$	20÷30	40÷60	50÷80

Table 5. Range of values of experiences for the characteristic inner skin friction $q_{is,k}$ in non-cohesive soils for model 2

Pile settlement	Characteristic outer shaft friction $q_{is,k}$ [kN/m²] Cone penetration resistance q_c [MN/m²]		
	7.5	15	25
s_{sg}*	5÷10	10÷20	15÷25
$s_{sg}=s_g=0.1\cdot D$	10÷15	20÷30	25÷40

Values between shall be interpolated linearly.

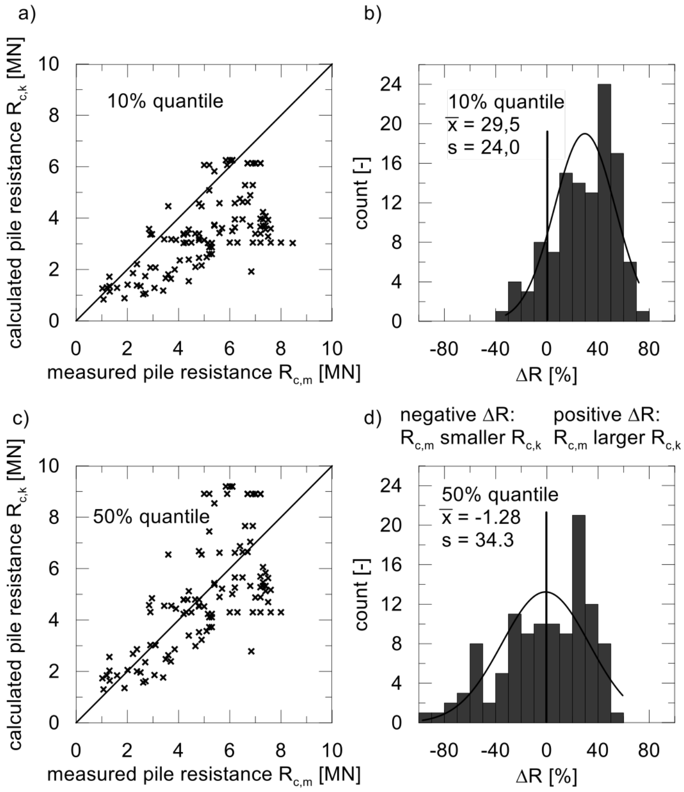

Figure 5. Results of the statistical calculation for the whole database of open-ended pipe piles for both quantiles; a) Scatter diagram (10 % quantile); b) Histogram (10 % quantile); c) Scatter diagram (50 % quantile); d) Histogram (50 % quantile)

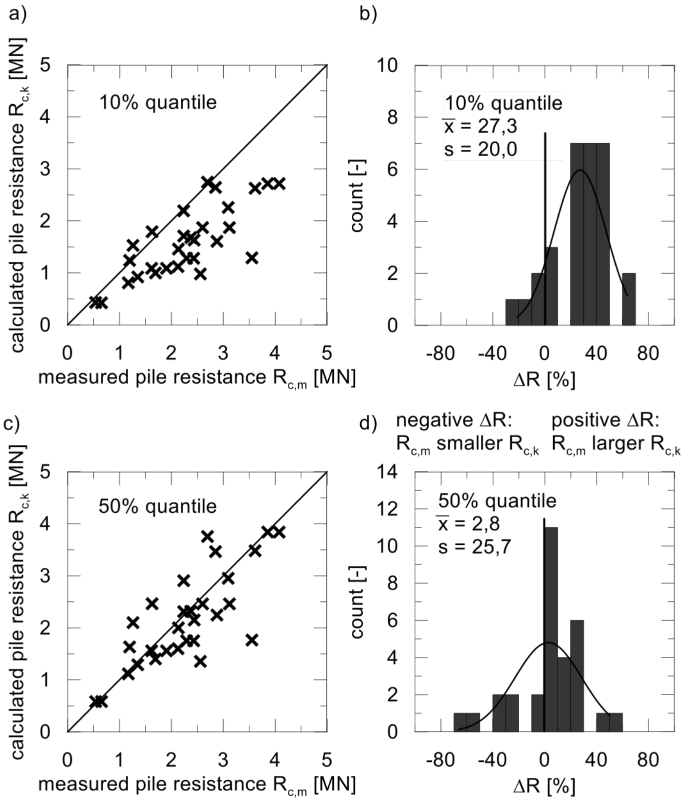

Figure 6. Results of the statistical calculation for the whole database of H-piles for both quantiles; a) Scatter diagram (10 % quantile); b) Histogram (10 % quantile); c) Scatter diagram (50 % quantile); d) Histogram (50 % quantile)

4 EXAMPLE OF USE

To show the applicability of the new calculation methodology in addition to the statistical analysis, the calculation of the pile resistance curve is demonstrated for open-ended pipe piles, H-piles and double H-piles. Table 6 summarizes the parameters for the calculation of the pile resistance curve for open-ended piles, which is illustrated in Figure 8. Table 7 and Figure 9 show the results for H-piles and double H-piles. These four examples show a good agreement between the measurements and the calculations in particular for the shape of the pile resistance curve.

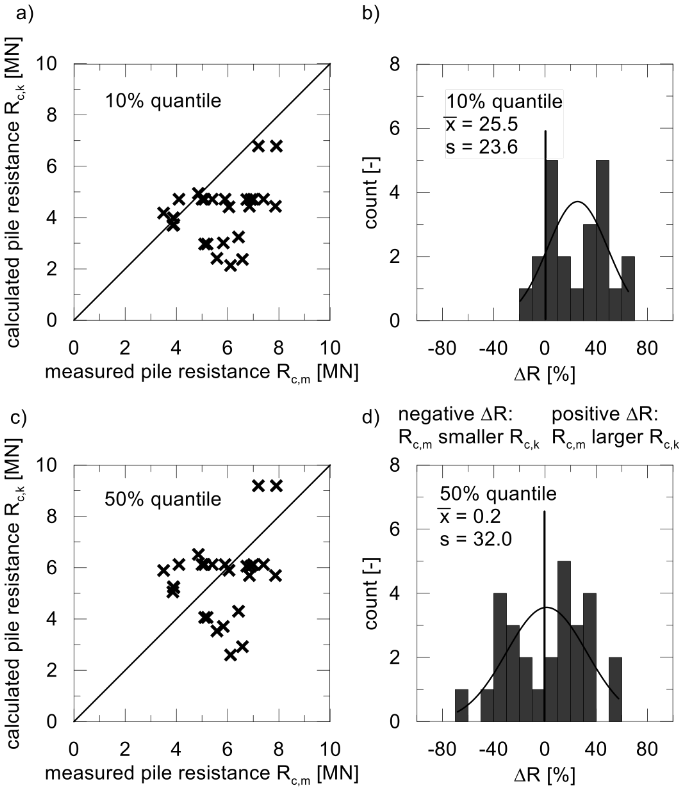

Figure 7. Results of the statistical calculation for the whole database of double H-piles for both quantiles; a) Scatter diagram (10 % quantile); b) Histogram (10 % quantile); c) Scatter diagram (50 % quantile); d) Histogram (50 % quantile)

Table 6. Documentation of the soil parameters for the calculations as shown in Figure 8 (open-ended pipe piles)

	Figure 8a	Figure 8b
$q_{c,s,1}$ [MN/m^2]	11	4
h_1 [m]	2.8	4
$q_{c,s,2}$ [MN/m^2]	9	14
h_2 [m]	7	7
$q_{c,s,3}$ [MN/m^2]	18	./.
h_3 [m]	2	./.
$q_{c,b}$ [MN/m^2]	18	14

5 COMPARISON WITH OTHER CALCULATION METHODOLOGIES

As described in Becker & Lüking (2017) and shown in Figure 10 the database was calculated with different calculation methods. Figure 10 shows the results of the different methods for the prior used database, whereas the UWA-05, NGI-05 and FUGRO-05 results are higher than the 50% quantile. On the other hand the ICP-05 methodology is between both quantiles of the described calculation methodology.

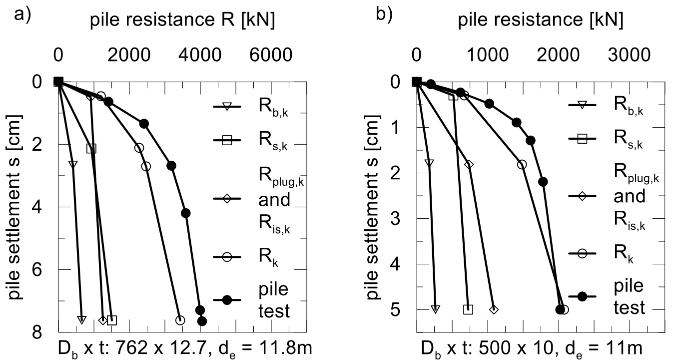

Figure 8. Comparison of a static pile testing with the calculations based on the values of experience (50% quantile)

Table 7. Documentation for the soil parameters and geometry for the calculations as shown in Figure 9 (H-pile and double H-pile)

	H-pile Figure 9a	Double H-pile Figure 9b
Profile	PSt 370/88	PSp 700/3
h [m]	0.37	0.70
b_F/b [m]	0.38 / 0.38	0.46 / 0.98
A_b [m^2]	0.014	0.060
A_{plug} [m^2]	./.	0.343
$A_{s,j}$ [m^2]	2.25	4.61
$A_{s,fl,j}$ [m^2/m]	0.73	0.98
d_e [m]	18.5	13.0
D_{eq} [m]	0.42	0.94
$q_{c,s,1}$ [MN/m^2]	11	4
h_1 [m]	2.8	4
$q_{c,s,2}$ [MN/m^2]	9	14
h_2 [m]	7	7
$q_{c,b}$ [MN/m^2]	18	14

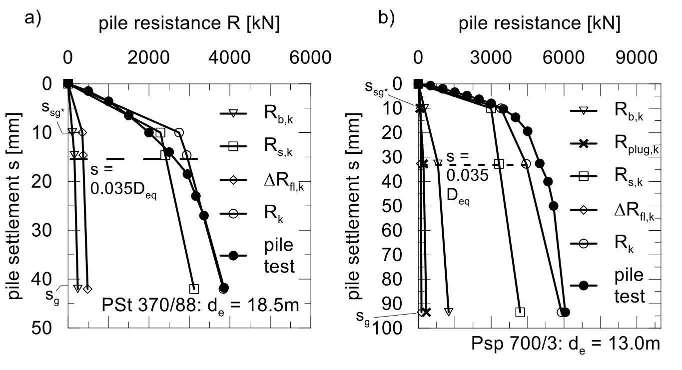

Figure 9. Comparison of a static pile testing with the calculations based on the values of experience (50 % quantile); a) H-piles; b) double H-piles

6 LIMIT OF APPLICABILITY

The limit of applicability is mainly defined as the range of the values within the database. As a lower limit the pile diameter must not be smaller than 0.3 m and the minimum pile embedment depth must be ≥

2.5 m according to EA-Pfähle (2012). As an upper limit the pile slenderness shall be around 30. Theoretically model 2 is usable for pile diameters greater than 1.5 m but currently there is not enough data available to confirm the results.

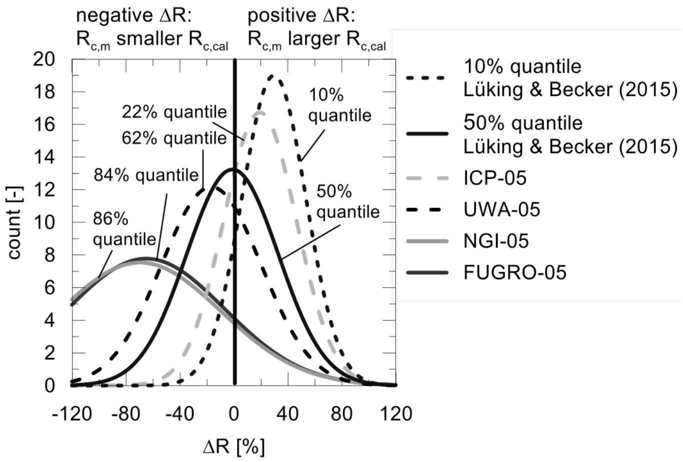

Figure 10. Histogram for different calculation methodologies after Becker & Lüking (2017) based on the database

The values are limited to driven piles in compression loading. Transferring the results to other installation methodologies like vibrating or piles in tension loading or different areas of applicability like offshore-engineering is not possible without further investigations.

The Recommendations on Piling (EA-Pfähle 2012) are frequently updated on annual basis. In one of these updates the described calculation methodology was adopted by the EA-Pfähle, see Moormann & Kempfert (2014). Additionally, in the Recommendations on Piling (EA-Pfähle) Special edition for Southern Africa (2018) the updated calculation methodology has not been considered so far. It is based on an older methodology and shall be updated by this one as it has been in Germany.

7 SUMMARY

Based on a large number of static and dynamic pile testing results a new calculation methodology for open-ended pipe piles, H-Piles and double H-Piles was derived. Here the plugging effect is considered based on geometry boundary conditions. Furthermore, based on the derived range of values of experiences the pile resistance and the pile resistance curve can be calculated for the ultimate limit state (ULS) and the serviceability limit state (SLS). Because of the huge database the calculation methodology can be said to be verified and was adopted by the Recommendation on Piling (EA-Pfähle).

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