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Physical Modelling in Geotechnics

On the application of analytical methods and empirical values for the determination of the pull-out resistance of driven steel piles

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ABSTRACT: During the construction of the new ship lift in Niederfinow (Germany), the lower outer harbours bank walls are to be rear-anchored with driven steel piles. The characteristic pile shaft resistance is calculated using empirical values for the preliminary design according to the Recommendations of EA-Pfähle (2013). These are in the range of typical empirical values for driven piles. Several pile loading tests are applied to vertical driven steel piles to verify the tensile pull-out resistance. The resistances measured against the extraction of the piles fall significantly short of the assumed values and correspond to only 20% to 49% of the resistances based on the relevant recommendations. Within the initial cause analysis framework, international approaches and methods for determining skin friction values are compared with the results of load tests. Published approaches for the analytical calculation of the ultimate tensile strength of tension piles can be divided into three groups. One group assume that a soil body is activated around the pile in the ultimate limit state of the pile. The second group is essentially based on Coulomb's shear law. Purely empirical derived values form the third group. A comparison of the calculation methods shows a considerable scatter and thus uncertainties in the design of tension piles, which mobilize their resistance only via skin friction and therefore the design depends significantly on the model conceptions of the pile-soil contact.

Keywords: pile loading tests, pull-out resistance, Coulomb’s law, ultimate limit state

1 INTRODUCTION

In geotechnical engineering in Germany, either load tests or approaches based on empirical values are used to determine the pull-out resistance of piles. However, it is often difficult to carry out load tests. Empirical methods simplify the complex load-bearing behaviour and can lead to uncertainties and discrepancies between the calculation and the measurements. According to the recommendations of EA-Pfähle (2013), the frictional influence between the pile surface and the surrounding soil is only indirectly included in determining the pull-out resistance via skin resistance. The roughness of the surface is not considered directly. For tension piles, this method should not be used at all. This can lead to incorrect design of piles and thus affect the economic efficiency of construction projects. Tension piles generally fulfil the same task as anchors and are sometimes referred to in the same way but have several advantages. Tension piles can also be loaded in compression - if planned - have greater stability against lateral effects and are cheaper and easier to manufacture. Therefore, tension piles are found in many structures that apply tensile forces and other loads to the piles. In Germany, the determination of the axial pull-out resistance of tension piles is only possible through load tests, which are much more time-consuming and expensive than mathematical models. The background to this work is the absence of guidelines for designing single tension piles using calculation methods in Germany. This paper deals with determining the pull-out resistance according to the current state of the art. In addition, an attempt is made to find a suitable calculation method for the pull-out capacity of tension piles. Different methods were selected from the literature and tested for practical applicability. A long-term goal is to develop a suitable calculation method that can replace the expensive and time-consuming load tests that are currently still required for the design. In this regard, methods from Germany, as well as methods from abroad, were examined. Another objective is to improve the understanding of the load-dependent behaviour of tension piles. Overall, there is a significant need for research on tension piles. The application and comparison of the different methods to calculate the behaviour of conducted pile load tests are presented in this paper. One method is selected to predict the resistance-heave curve (RHC) of a planned load test.

2 BEARING BEHAVIOUR OF SINGLE PILES

The load-bearing behaviour of compression piles is generally described by the resistance-settlement line (RSC), which results from the dependency of the pile resistance on the total settlement of the pile. The pile resistance depends on the soil near the pile, which must have specific strength and deformation properties. The forces introduced by the pile into the ground should be transferred without inadmissible settlements (Witt, 2011). The total resistance has two components: the skin resistance and the base resistance. These two components behave differently when a load is applied. Fig. 1 shows the bearing behaviour of a compression pile (a) and a tension pile (b). In the case of a compressive load, the pile is axially loaded with a monotonic force F and the skin friction and the base pressure act in the opposite direction to the load F. The skin friction occurs alongside the embedded skin surface and the peak pressure at the base of the pile. This results in the total resistance of the pile to $R_{c,k} = R_{b,k} + R_{s,k}$. The state of fracture or failure of a compression pile is characterised by the total pile resistance not increasing any further. As soon as this decrease or stagnates, the limit settlement and thus the maximum pull-out resistance is reached (Vesic, 1975). The failure of the soil at the pile base occurs through lateral expansion and a strong compression of the soil material under the pile base. The failure is thus essentially limited to the pile base resistance.

The described RSC can deviate due to many factors. A significant deviation can occur with driven steel piles according to the installation method (Witzel, 2004). In addition, the RSC is also dependent on the stresses in the steel that occur during installation. Another factor is time. Many researchers have found, including Chow et al. (1996), that the skin resistance of driven steel piles in the sand can be increased by up to 250 % due to corrosion of the pile surface, ageing of the surrounding sand or a general increase in horizontal stress. This can cause large deviations in the axial pull-out resistance. Furthermore, according to Witzel (2004), adequate predictions can be made in cohesive soils at the beginning of loading due to the undrained cohesion. However, for calculations after some time, the effective shear angle and cohesion seem to be the better choice.

In contrast to compression piles, tension piles can only transfer the loads into the soil through skin resistance (see Fig. 1). For tension piles, the skin resistance is also dependent on the movement of the pile. In this case, the displacement is characterised by the heave. It is not regulated in EA-Pfähle (2013) if the development of the skin resistance of tension piles is similar to that of compression piles. When determining a characteristic resistance-heave curve based on empirical data, the limit heave S_{sgt} may be approximately determined from the limit settlement of a corresponding compression pile using $S_{sgt} = 1.3 \cdot S_{sg}$.

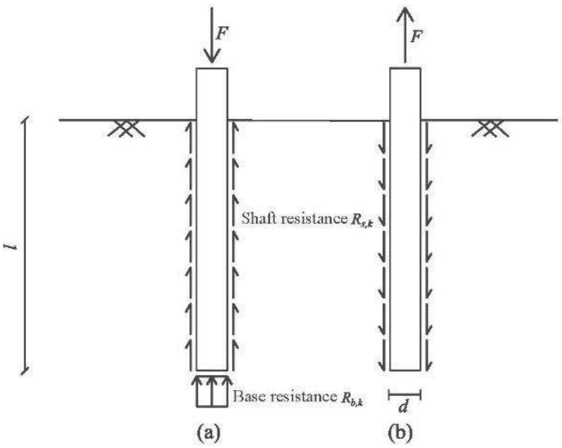


Fig. 1. Axial load-bearing behaviour of (a) compression piles and (b) tension piles

The skin resistance is calculated from the skin friction and the outer pile shaft area. Open pile cross-sections can have inner skin friction and outer skin friction, which according to Jardine (2005), is mainly concentrated near the pile toe.

A lack of increase in resistance also characterises the failure state of a tension pile. The failure at this stage is described by Quarg-Vonscheidt (2000) as the lifting out of an attached soil body that no longer has a hold to the surrounding soil. However, this idea only applies to sand. For cohesive and non-cohesive soils, API (2002), among others, describes failure by simply pulling out the pile. The approach of the failure mode is essential for the calculation of the maximum resistances. The dependence on time and the influences of pile installation also apply to the load-bearing behaviour of tension piles. The skin resistance can be highly increased after a period and influence the RHC. The already mentioned displacement during installation also leads to uncertainties for tension piles. Overall, no procedures can be found in the literature with which the RHC of a tension pile could be depicted and calculated. This raises the question of whether it is possible to develop a general calculation guideline or whether there are too many dependencies that are difficult to capture. The area of load-dependent load-bearing behaviour generally has a great need for research. On the other hand, the maximum pull-out resistance has already been investigated extensively. It is an essential component of the RHC and will be examined in detail in the following.

3 DETERMINATION OF THE MAXIMUM PULL-OUT RESISTANCE OF SINGLE TENSION PILES

In Germany, the EA-Pfähle (2013) and the Handbuch Eurocode 7 (2011) allows the estimation of tension pile resistances from empirical data only in exceptional cases. For the calculation of the tension pile resistance, there is currently no generally applicable method. Depending on the common practice of the countries or the construction measure, other procedures are recommended. This explains the differences in the calculation practice of different countries, which will be discussed in this paper. The methods can be divided into cohesive (c) and non-cohesive (nc) soils. More detailed classifications can be found in the corresponding explanations of the methods in the literature. If no information is given below, it can be assumed that the method has been designed for round profiles. A problem-free application to other profiles cannot always be assumed.

3.1 Pile load tests

During static test loading, the pile is subjected to static axial loads. With the help of a hydraulic cylinder, the loading and unloading phases are applied in stages. The forces acting on the pile and the pile head displacement are measured, and the resistance-heave curve RHC is determined. (Kolymbas, 2011).

3.2 Empirical calculation methods

Since it can be expensive to conduct load tests, calculation methods have been developed over the years, which are not approved in Germany but promise good predictions (Quarg-Vonscheidt, 2000). The empirical calculation methods of the maximum load-pull-out resistance form a large part of the existing calculation methods. This includes all procedures that determine values for the skin friction or the total shear resistance with the help of empirical correlations. The skin area of the pile depends on the profile, which many methods assume to be round. In the following, the main methods are presented in Table 1.

Table 1. Empirical calculation methods.

Method	Soil type	Limitations
EA-Pfähle (2013)	c + nc	No Tension piles
Gwizdala (1997)	c + nc	-
Fascicule 62-V:1993	c + nc	Round, PMT[1]
NGI-05	nc	Round
Holeyman et. al (1997)	c + nc	Round
Skov (1997)	c + nc	Round
Manoliu (1997)	c + nc	Round
Simonsen und Athansiu (1997)	c + nc	Round
API (2002)	c	Round
Prakash und Sharma (1990)	c	-

[1]The Pressuremeter Test (PMT)

3.3 Methods based on an attached soil body

Earth static approaches calculate the maximum tensile load capacity by assuming an attached soil body. In all methods, a soil mass is attached to the pile in a specific form, and thus the failure state can be represented by lifting out the soil body. However, these methods can only be applied to piles in non-cohesive soils with constant properties over the pile length. Consequently, the application of the methods is very limited in practice and will not be further investigated.

3.4 Method based on Coulomb's shear law

Many authors also developed calculation methods based on Coulomb's shear law and derived the skin friction from horizontal stresses. Generally, this approach is only chosen for non-cohesive soils. The corresponding calculation methods for cohesive soils are also included, which are typically empirical (see Table 1). The most common methods are listed below in Table 2.

Table 2. Calculation methods based on Coulomb's shear law

Method	Soil type	Limitations
API (2002)	nc	Round
Prakash und Sharma (1990)	nc	-
ICP-05	c + nc	-

4 COMPARISON OF CALCULATION METHODS WITH LOAD TESTS

The applicability will be tested on a current construction project. The old ship's lift in Niederfinow will be replaced by a new one. The new construction involves the application of tension piles in the lower forebay. A total of six load tests were carried out, which took place at three different locations. Steel sections of the type HP320 x 88.5 were used. For the sake of simplicity, only the Location 1 will be shown in this paper, where the piles were driven vertically into the ground up to 16 m. Site 1 has Holocene fill, silt, and peat up to 6.30 m below ground surface. This is followed by coarse-grained sands to 13.40 m below ground surface, with occasional weak silt bands. Between 13.40 m and 15.50 m below ground surface, there are alternating layers of sand and basin silt with one to three centimeter thick layers of basin silt and five to ten centimeter thick sand layers. Below this, the silt layers reach a thickness of 20 cm. From 16.60 m below ground surface to the end of the borehole, coarse-grained sands were identified. The installation was conducted up to the bottom edge of the turf at level 6.3 m below ground surface with a vibratory hammer and then with a hydraulic impact hammer. The layer distribution of the Location 1 is listed in Table 3. The soil properties were derived from CPT soundings according to Robertson and Cabal (2015) and can be found in Tables 3 and 4. The averaged measured maximum pull-out resistance of the piles was determined to R = 473 kN (see Fig. 2).

Table 3. Layers and average values for Location 1

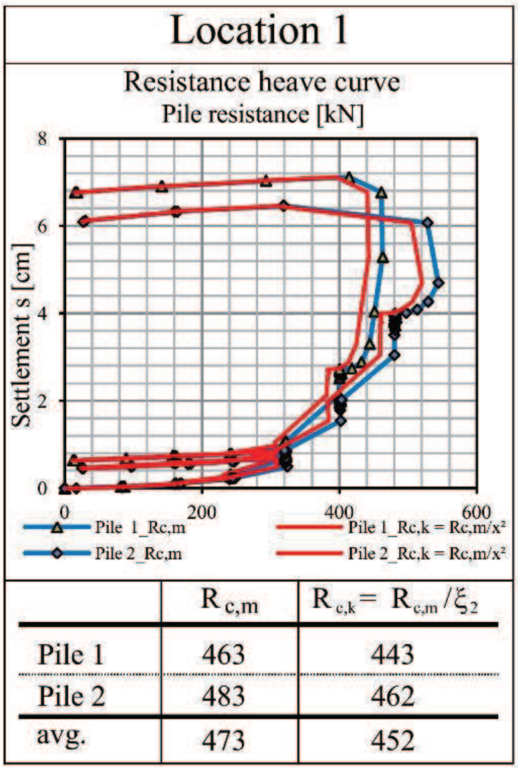
Layer	Top (m)	Bottom (m)	q_c (MPa)	f_s (MPa)	R_f (%)
1	0	1.9	9.66	0.100	1.1
2	1.9	4.0	1.15	0.047	4.47
3	4.0	6.3	0.51	0.058	11.56
4	6.3	13.0	11.84	0.127	1.14
5	13.0	16.0	11.89	0.153	1.41

Table 4. Soil parameters from the evaluation of the CPT sounding of the sand layers.

Layer	γ' (kN/m^3)	σ' (kPa)	D_r (-)	φ' (°)	D_{50} (mm)	G (Mpa)
1	9.62	15.64	0.8	42.9	1.4	26.49
4	9.98	99.25	0.6	40.4	0.7	60.42
5	10.24	148.03	0.5	39.0	0.6	78.02

Table 5. Soil parameters from the evaluation of the CPT sounding of the soft layers

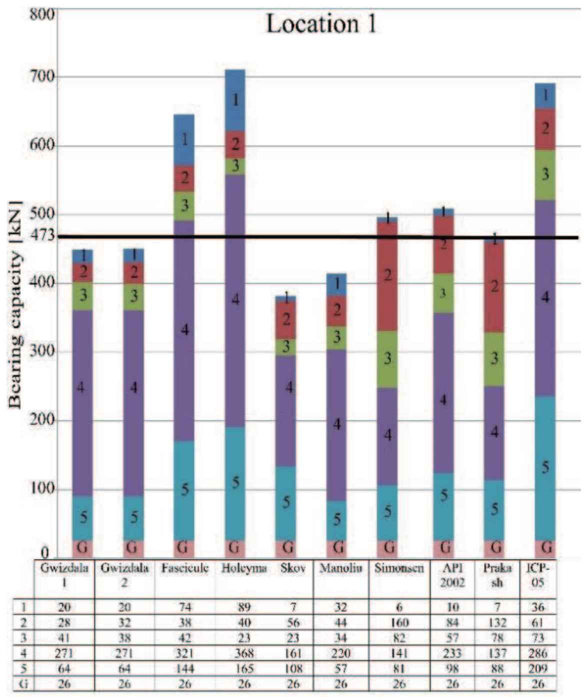
Layer	γ' (kN/m^3)	σ'(kPa)	s_u (kPa)	S_t (-)	I_c (-)	YSR (-)	I_p (%)
2	7.94	39.61	78.27	1.68	0.74	5.14	20
3	7.77	56.88	29.54	0.51	0.58	2.40	30



	$R_{c,m}$	$R_{c,k} = R_{c,m}/\xi_2$
Pile 1	463	443
Pile 2	483	462
avg.	473	452

Fig. 2. Resistance-heave curve (RHC) of the pile load test.

From the results of all selected methods in Fig. 3, no better prediction can be determined from either group (Empirical and Coulomb). Thus, the empirical procedures according to Gwizdala (1997), Skov (1997), Manoliu (1997) and Simonsen and Athansiu (1997) give relatively good estimates, while the empirical procedures according to Fascicule 62-V:1993 and Holeyman et al. (1997) exceed the measured pull-out resistance. Furthermore, suitable and unsuitable predictions are also obtained for the procedures using Coulomb's law approach. The Methods according to API (2002) and Prakash and Sharma (1990) can be described as suitable. The ICP-05 method, according to Jardine et al. (2005), yields values that are too large. It can be seen that the method, according to Prakash and Sharma (1990), is best suited for determining the maximum pull-out resistance, as it has no restrictions regarding the empirical values and soil types. The influence of the pile type and the effective vertical stress as a function of depth are also considered. The predictions of the maximum pull-out resistance of the new Location 4 was obtained from the layer distributions and CPT values from Table 6. In addition to the exact calculation, a maximum and minimum value should be determined, between which the result of the test load will lie with a very high probability. The minimum value of the pull-out resistance is calculated by the reduction of the shell area in the cohesive layer. The maximum value of the pull-out resistance according to Prakash and Sharma (1990) can be determined by choosing a higher earth pressure coefficient. Values of 0.5 to 1.0 are given for steel beam sections. For the exact calculation, the earth pressure coefficient Ks = 0.5 has proven itself at site 1 and 2 and was accordingly also used here. With Ks = 1.0, the maximum value of the pull-out resistance is determined, which the test load will most probably not exceed. The predicted pull-out resistance is estimated to R = 550 kN.



	Gwizdala 1	Gwizdala 2	Fascicule	Holeyma	Skov	Manoliu	Simonsen	API 2002	Prakash	ICP-05
1	20	20	74	89	7	32	6	10	7	36
2	28	32	38	40	56	44	160	84	132	61
3	41	38	42	23	23	34	82	57	78	73
4	271	271	321	368	161	220	141	233	137	286
5	64	64	144	165	108	57	81	98	88	209
G	26	26	26	26	26	26	26	26	26	26

Fig. 3. Calculated tensile load capacities of the individual layers for Location 1

Table 6. Layers and average values for Location 4

Layer	Top (m)	Bottom (m)	q_c (MPa)	f_s (MPa)	R_f (%)
1	0	1.8	7.07	0.091	1.58
2	1.8	6.2	0.51	0.048	9.40
3	6.2	9.0	4.16	0.030	0.83
4	9.0	12.0	22.54	0.208	0.92
5	12.0	17.0	5.72	0.071	1.32
6	17.0	18.3	22.83	0.191	0.85

5 CONCLUSIONS

This work investigated the bearing behaviour and the maximum pull-out resistance of tension piles. Since the EA-Pfähle (2013) is only allowed to be used for compression piles, various methods from the literature were presented with which the maximum pull-out resistance of tension piles could be determined. However, no method was able to derive the RHC. Only the EA-Pfähle (2013) with the limit heaving for tension piles S_{sgt} offers a reference point for estimating the course of the WHL. The methods presented were primarily taken from the practice in European countries and the USA. Overall, it was found that the empirical and Coulomb's law approaches can provide similar results. The methods for offshore piles are not suitable for an application for tension piles on land.

Furthermore, the dependency of vertical stress in the soil was very significant. The best results are provided using the method according to Prakash and Sharma (1990), which was utilised for a prognosis at Location 4. However, due to the low basis for comparison with load tests and the derivation of the parameters via CPT sounding the results can only be regarded as of low significance. Further investigation of these factors in practice can increase the significance. Overall, there is still a great need for research in tension piles in multi-layered soil. This can be reduced by further load tests, recalculations, and investigations of stress changes in the soil during driving. In addition, numerical simulations must be conducted to simulate the load-bearing behaviour with the consideration of installation-related influences.

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