

How meaningful are the results of static pile load tests? From the pile load test to the design basis to the pile production of driven piles

Martin Hayden
Product Line Manager Ductile Driven Piles, Keller Grundbau Ges.m.b.H., Austria

Thomas Kirchmaier
Sustainability & Lean Manager Keller SEN, Head of Team Planet EME, Keller Grundbau Ges.m.b.H., Austria

DI Dr. tech. Roman Marte
Institute of Soil Mechanics, Foundation Engineering and Computational Geotechnics, Graz University of Technology, Austria

ABSTRACT: This article discusses the advantages of the results of the Pile HAY-Proof-System[®] and the significance of the test results regarding pile design and economic optimization. Based on the results of conventional static compression load tests, the problems involved in deriving the design basis are discussed. Subsequently, the static load test with the Pile HAY-Proof-System[®] is presented, which helps to improve the database for meaningful design parameters of pile foundations. Based on a case study, it is shown how design parameters can be derived from test results and prepared for an application suitable for construction sites. Finally, a brief overview of the necessary aspects about the quality of workmanship in pile production will be given.

KEYWORDS: Pile HAY-Proof-System[®], static load test, pile load tests, ductile piles, bidirectional test system.

1 INTRODUCTION

In times of constantly increasing economic pressure in the construction industry, the need to continuously optimise processes and the associated necessity of increasingly pushing the technical limits, economical static pile load tests carried out on the construction site are becoming increasingly important. This article explains the advantages of pile tests and the specific significance of the test results.

When using ductile small pile foundations (displacement piles) experience has shown that static pile load tests are only carried out under the following circumstances:

- Larger construction projects for the purpose of optimising (reducing) pile lengths
- difficult-to-assess subsoil conditions, e.g. in glacial basin sediments
- Lack of/insufficient ground investigations
- Technically "sensitive" construction projects with high settlement requirements, e.g. fully automated high-bay warehouses and machine foundations

In the case of subordinate structures or small construction projects, the piles are manufactured with a longer pile length in case of doubt. This is usually still cheaper than carrying out a static pile load test. Often, there is not enough construction time available to carry out a pile test. To obtain high-quality test results, at least 2-4 weeks of preparation time is required before the start of construction.

In recent years, there have been increasing differences in the assessment between contractors, planners and building owners regarding the required pile lengths and load-bearing capacity when planning and manufacturing ductile piles. Since, in the case of ductile piles, the pile length is not determined in advance by the planner at the drawing board, as e.g. for bored piles, but on site using (often company-specific) pile driving criteria. The specialist contractor has a great deal of responsibility. Depending on the experience of the specialist company, the pile lengths can sometimes vary significantly even when the same equipment, pile type and soil conditions are given.

With the publication of design parameters for ductile driven piles in the 2022 annual report of the "Piles" working

group of the German Geotechnical Society (DGGT) (Moormann, 2022), which derived in a dissertation by Johannes Berndt (Berndt, 2022), it is possible now to design pile lengths based on the design parameters $q_{s,k}$ and $q_{b,k}$ even without internal "experience". The data for $q_{s,k}$ and $q_{b,k}$ have been derived from 338 pile test loads in correlation with subsoil investigation results (n_{10} , q_c , c_u). These design parameters are meanwhile often used as a basis for arbitration proceedings in connection with disagreements between building owners and specialist companies regarding excessive pile lengths.

One would expect that investing in conventional static compression load tests carried out on the construction site would allow an optimal pile design in economic terms by reducing the safety margin to a necessary minimum – unfortunately, many designers and clients does not follow this logic.

2 DUCTILE DRIVEN PILES

The pile system consists of ductile centrifugal cast pipes with a conical socket at the upper end and a conical tapered end at the lower end of the pile pipe. This allows the individual pile pipes

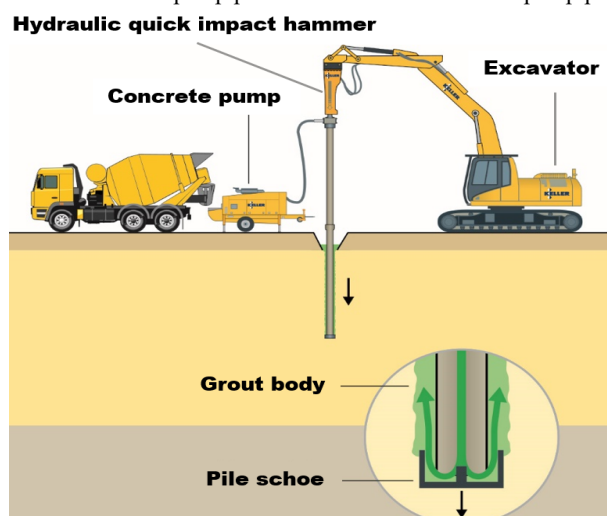


Figure 1 . Installation of ductile driven piles (Hayden, 2024)

to be easily assembled into longer elements during pile driving without the need for special tools. The individual pipe length of the manufacturer Tiroler Rohre GmbH (TRM) is 5.15 m. Thanks to the use of coupling sleeves, shorter pieces can also be used when space (height) is limited. The individual pipe elements are connected securely during the pile driving process due to the special shape of the conical pile ends and the pile sleeve. Depending on the soil conditions, the ductile cast iron pile is designed as mainly an end-bearing pile or a skin-friction pile. The load-bearing capacity of the pile depends on the pile length, the pile shoe diameter (grout body), the local ground conditions and, ultimately, the quality of the pile installation (Hayden, 2024).

3 STATIC CONVENTIONAL COMPRESSION LOAD TEST

3.1 General

In a static conventional compression load test, the test pile is pressed into the ground against an abutment (usually a large steel girder anchored with reaction piles) using a hydraulic jack. The load is applied in stages up to the test load and the deformations are recorded over time (see Figure 2).

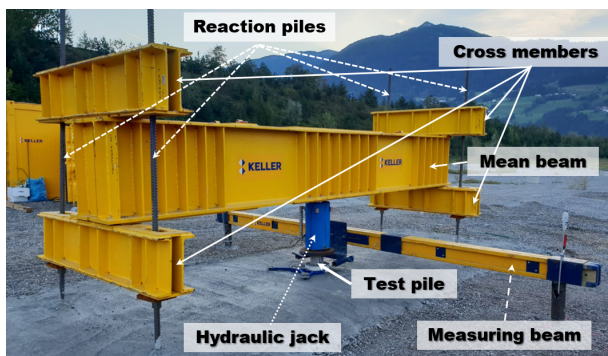


Figure 2. Setup of a static (conventional) compression load test (Hayden, 2024)

3.2 Results

For classical pile load tests the measured pile resistance cannot be differentiated according to the individual pile resistance values – base resistance q_b and skin friction q_s . For a long time, even when evaluating a static compression load test, the base resistance q_b was not considered in the design of small driven piles.

Figure 3 shows the result of a conventional static compression load test (test pile 1) in the form of a load-settlement curve.

Considering a maximum test load of $F_p = 700$ kN, a pile length of $L = 11$ m and an average grouting diameter $D = 0.17$ m, this would result in the following average (failure) of skin friction $q_{s,ult}$ without knowledge or consideration of a base resistance q_b :

$$q_{s,ult} = \frac{700}{11 \cdot 0,17 \cdot \pi} = 119 \text{ kN/m}^2 \quad (1)$$

In this test field with homogeneous cohesive soil conditions, from which the pile test results shown in Figure 3 originates, a second test pile (Test Pile 2) was constructed without using grout, so only the base resistance force F_b was measured under the same manufacturing conditions and at the same depth of the pile base (same pile length – see Figure 3 – red line).

If the base resistance force $F_{p,b} = 200$ kN measured on Test Pile 2 also applies to Test Pile 1 under the same manufacturing conditions, and if this is taken into account in the calculation of the ultimate skin friction $q_{s,ult}$ this results in a more realistic skin friction of

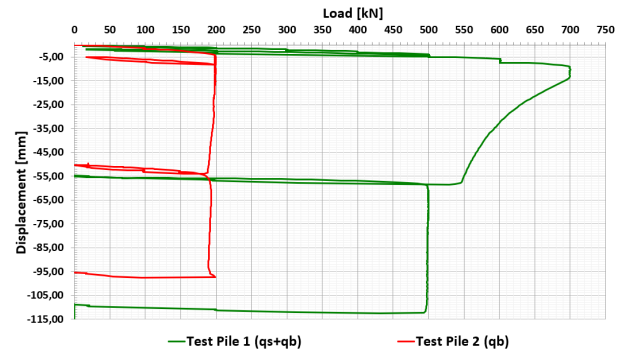


Figure 3. Load-displacement curve test pile 1 and test pile 2

$$q_{s,ult} = \frac{700 - 200}{11 \cdot 0,17 \cdot \pi} = 85 \text{ kN/m}^2 \quad (2)$$

The last example shows that if the actual base resistance of a pile is not considered, the skin friction determined from a static conventional load test can be significantly overestimated.

For this reason, it is very important to determine the two resistance components q_b and q_s separately when deriving the design bases for the pile bearing capacity (Hayden & Kirchmaier, 2010).

4 PILE HAY-PROOF-SYSTEM®

4.1 General

The innovative single pile load test Pile HAY-Proof-System® was designed for grouted ductile piles, developed in 2007 and patented in 2010. It involves a bidirectional pile load test in which the force acting in two directions – upwards against the shear resistance of the pile skin (skin friction) and downwards against the base resistance – allows the both different components of the resistance to be measured separately (Hayden & Kirchmaier, 2010).

4.2 Setup

In the test setup of the Pile HAY-Proof-System®, a tension pipe (5+8 in Figure 4) adapted to the tensile forces is installed to absorb or distribute the tensile forces over the entire pile length, which also serves as a casing tube for the (special) compression member (6). To transfer the jack force to the special compression member, a height-adjustable jack support plate (13) is fixed in the upper end of the (special) compression member (6) using a special thread. The tension pipe (5+8) can be extended as required by means of coupling sleeves (7). Spacers (4) are installed to ensure the required centricity of the tension pipe.

The special driving shoe (1) acts as an abutment in this test system in conjunction with the surrounding ground. In principle, this bidirectional system works similarly to the Osterberg cell (Osterberg, 1998), which is used for testing large bored piles. To prevent bonding between the pile driving shoe, concrete and pile tube, "friction reducers" (2) in the form of foams are installed around the pile driving shoe.

The upper end of the Pile HAY-Proof-System® is formed by the measuring head. This consists of the upper (16) and lower measuring head plates (11) and the six tension elements with the associated anchor nuts (12).

In addition to time and cost optimisation, the main advantage of the system described is that it eliminates the need for reaction piles and the associated potential mutual influence of test and reaction piles. This largely rules out any falsification of the measurement results (Hayden, 2024).

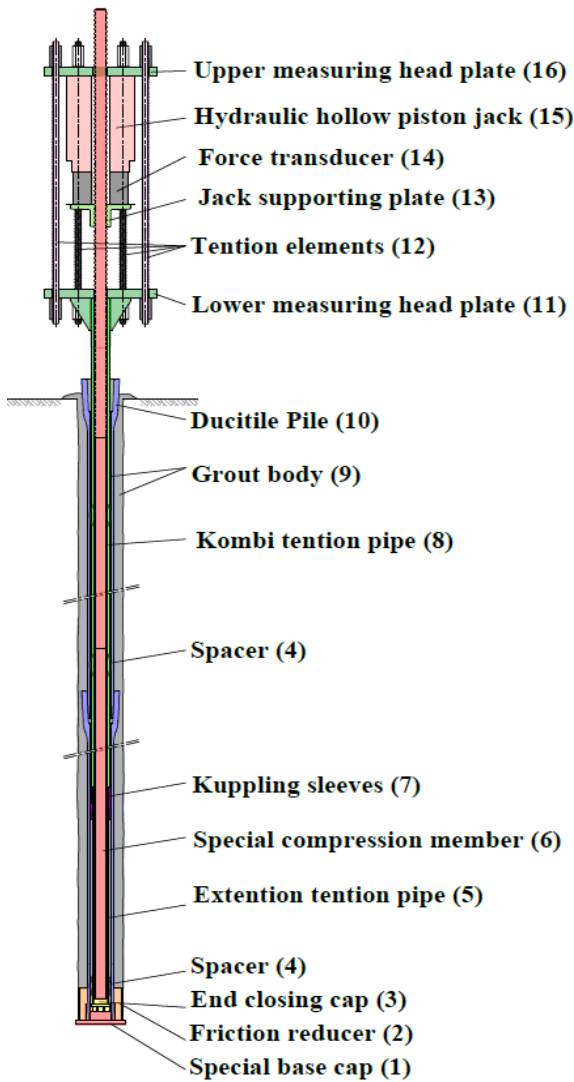


Figure 4. Structure of the HAY Proof System pile® (Hayden,

4.3 Function

Regarding the flow of force, the upper measuring head plate (16) serves as an abutment for the hydraulic jack. The lower measuring head plate (11) is connected to the combination pull tube (8) by means of a special thread.

The jack reaction force is transmitted via the upper measuring head plate (16) and the six pull elements (12) to the lower measuring head plate (11) and thus to the tension pipe (5+8).

The jack pressure force is now transmitted via the jack support plate (13) into the special compression member (6) and transferred to the reinforced special pile driving shoe (1) without significant friction losses.

Since the tension pipe (5+8) is installed immediately after pile production in the still soft concrete up to the lower edge of the pile, i.e. placed on the special pile driving shoe (1), a force-fit connection is created between the grouting mortar, the load-

bearing element (usually ductile pipe) and the tension pipe (5+8). The pile geometry (grouting body) for determining the external load-bearing capacity (grout body) is identical to that of ductile structural piles.

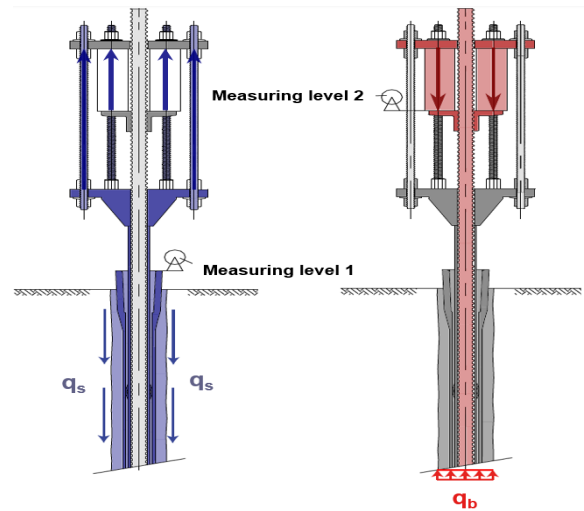


Figure 5. Function adapted from (Dziwok, 2022).

4.4 Evaluation – Determination of the equivalent load-displacement curve

The basis for determining the equivalent load displacement curve is formed by the force-lifting line (friction) and the force-settling line (end bearing) as shown in the German standard for concrete pipes and pipe systems (Figure 6).

The determination is made on the assumption that the pile, consisting of ductile cast iron pipe and the grouting mortar body, is considered rigid over its entire length. The total bearing capacity (equivalent load-displacement curve) is determined by adding the resistance components for the same displacements, with corrections for the pile's own weight (skin friction) and the elastic buckling of the special compression member (base resistance – see Figure 6).

Furthermore, the evaluation assumes that the skin friction from the load-lift curve is independent of the direction of movement (upward for the bidirectional Pile HAY-Proof-System® and downward for the conventional compression load test). In the evaluation of the Pile HAY-Proof-System®, analogous to the evaluation with the Osterberg cell (Osterberg, 1998), it is assumed that the sum of the resistances from load lifting (skin friction) and load settlement (end bearing) are

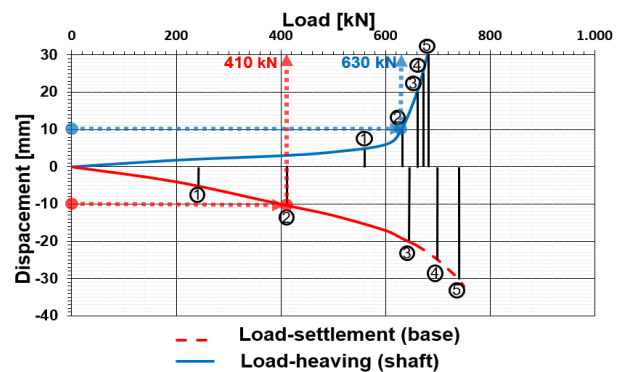


Figure 6. Determination of the load with equal displacement of base resistance (red) and skin friction (blue)

equivalent to the results from a conventional compression load test.

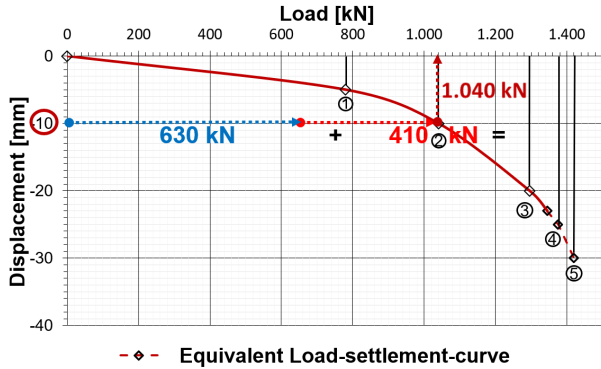


Figure 7. Determination of the equivalent load-displacement curve (dark red) – addition of the loads from the base resistance (red) and pile skin friction (blue) with the same displacement

5 PROPOSAL FOR DERIVING A PILE DRIVING CRITERION FROM THE RESULTS OF A PILE TEST WITH THE PILE HAY-PROOF-SYSTEM®

5.1 General

Based on the results of the test pile PP02 carried out as part of a Pile HAY-Proof-System® test in Rheinland-Pfalz (Germany), the following chapter derives the design resistance of a pile subjected to axial compression and proposes a possible pile driving criterion.

In general, the pile driving criterion must always be determined jointly with the responsible geotechnical expert before the start of pile foundation work (Hayden, 2024).

5.2 Subsoil conditions

Quaternary deposits from the Rhein were found at the test site, i.e. sand and gravel, partly loamy and clayey, to great depths. The gravel and sand are overlaid by several metres of Holocene cover loam and anthropogenic fill (ARCADIS Infrastructure, Environment Construction, 2006).

Due to the approx. 30 m distance between the location of the test pile PP02 and the nearest subsoil investigations (BK2 and DPH2), the lower edges of the layers cannot be directly transferred to the results of the pile driving survey. As shown in Figure 8, there is a significant change in the pile driving time from a depth of 4 m. At this depth, the transition between clay and gravel is assumed (Hayden, 2024).

5.3 Evaluation of the measurement results of test pile PP02 from the Pile HAY-Proof-System®

As can be seen from Figure 9, the ultimate force due to skin friction resistance is $F_{s,ult} = 1590$ kN with a deformation of $s = 32$ mm. The ultimate force of the base resistance is $F_{b,ult} = 460$ kN with a deformation of 23 mm.

Due to the assumption of a rigid supporting structure (foundation slabs/beams) and a structure that is not susceptible to settlement, the breaking forces $F_{b,ult}$ and $F_{s,ult}$ were used for further evaluations.

Figure 9 shows the equivalent load-deformation curve for test pile PP02. With a limit value s_{gr} of 10% of the pile diameter

($s_{gr} = 25$ mm), the total resistance derived from the test is

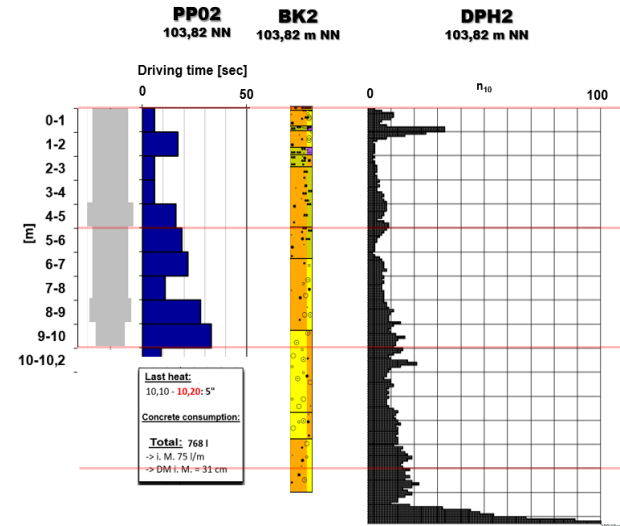


Figure 8. Soil conditions (BK2 and DPH2), grouting geometry and pile driving time per meter from PP02 (Hayden, 2024)

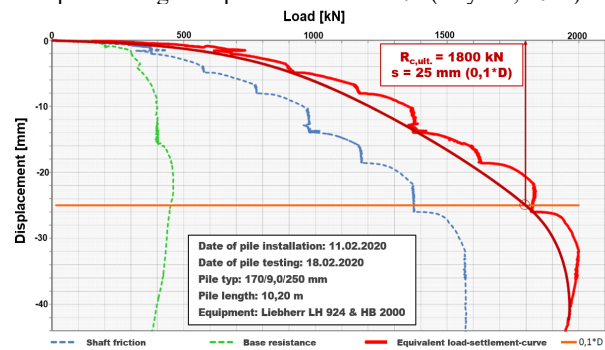


Figure 9. Equivalent load-displacement curve test pile PP02 $R_{c,m} = 1800$ kN.

The characteristic resistances of the axially loaded compression pile with a pile length of $L = 10.20$ m, a mean grouting diameter of $d = 0.31$ m, a total driving time of 173 seconds using the Liebherr LH 924 excavator and the Atlas Copco HB 2000 hydraulic hammer, derived from $n = 1$ load tests, can be derived from the formula (5), as follows:

$$R_{c;k} = \min \left(\frac{(R_{c,m})_{mean}}{\xi_1} \text{ bzw. } \frac{(R_{c,m})_{min}}{\xi_2} \right) = \quad (3)$$

$$R_{c;k} = 1414 \text{ kN} \quad (4)$$

The design value of the total resistance $R_{c;d}$ of the test pile PP02 is calculated using the model factor $\eta_{p;c} = 1.0$ and the partial safety factor $\gamma_t = 1.10$ analogous to (ÖNORM B 1997-1-3, 2015-08-01):

$$R_{c;d} = \frac{R_{c;k}}{\eta_{p;c} \cdot \gamma_t} = \frac{1414 \text{ kN}}{1,0 \cdot 1,10} = 1285 \text{ kN} \quad (5)$$

With the derivation of the design value of the total resistance $R_{c;d}$ shown above, it is not possible to apply the results from the static test load using the Pile HAY-Proof-System®, as experience has shown that the following parameters relating to the manufacturing parameters of the test pile will change continuously during construction:

- Change in the total driving time
- Change in soil conditions and layer boundaries (driving characteristics)
- Change in the actual amount of concrete used and thus the actual pile diameter
- Changes in the loads to be removed (design values of the load) $F_{c;d}$ per pile

For this reason, the following approach was chosen for deriving the design resistances from the results of the Pile HAY-Proof-System® when executing grouted driven ductile piles.

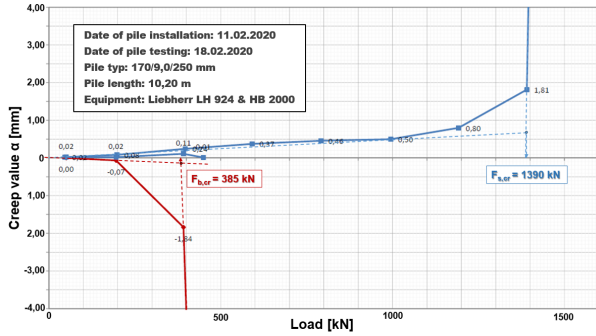


Figure 10 . Derive creep value α from Test Pile PP02

The sum of the creep resistance F_{cr} from the creep resistance of the base $F_{b,cr}$ and the creep resistance of the shaft $F_{s,cr}$ is $F_{cr} = 385 + 1390 = 1775$ kN (see Figure 10). This is in the order of magnitude of the total resistance of $R_{c,m} = 1800$ kN derived from the limit setting $s_{gr} = 0.1 D$.

Using the formula (3), the characteristic base resistance $q_{b;k}$ and the characteristic skin friction $q_{s;k}$ can be determined.

When determining the characteristic base resistance $q_{b;k}$, the creep resistance of the tip $F_{b,cr}$ and the diameter of the pile driving shoe base plate D_{GP} are used as a basis.

$$q_{b;k} = \min \left(\frac{\left(\frac{F_{b,cr}}{D_{GP}^2 \cdot \pi} \right)_{mean}}{\xi_1} \text{ bzw. } \frac{\left(\frac{F_{b,cr}}{D_{GP}^2 \cdot \pi} \right)_{min}}{\xi_2} \right) = \quad (6)$$

$$q_{b;k} = 6173 \text{ kN/m}^2 \quad (7)$$

When determining the average characteristic skin friction $q_{s;k}$, the creep resistance of the pile skin $F_{s,cr}$, the average grouting diameter D_{verp} and the embedment length of the pile $L_{P(fäh)}$ are used as a basis.

$$q_{s;k} = \min \left(\frac{\left(\frac{F_{s,cr}}{D_{gout} \cdot \pi \cdot L_{pile}} \right)_{mean}}{\xi_1} \text{ bzw. } \frac{\left(\frac{F_{s,cr}}{D_{gout} \cdot \pi \cdot L_{pile}} \right)_{min}}{\xi_2} \right) \quad (8)$$

$$q_{s;k} = 110 \text{ kN/m}^2 \quad (9)$$

The design value of the pile base resistance $q_{b;d}$ of the test pile PP02 is calculated using the model factor $\eta_{p;c} = 1.0$ and the

partial safety factor $\gamma_b = 1.10$ analogous to (ÖNORM B 1997-1-3, 2015-08-01):

$$q_{b;d} = \frac{q_{b;k}}{\eta_{p;c} \cdot \gamma_b} = 5612 \text{ kN/m}^2 \quad (10)$$

Considering the pile shoe base plate diameter D_{GP} and a final heat of $LH = 5''/10$ cm (see Figure 8), a design resistance $R_{b;d}$ for the pile base can be calculated as

$$R_{b;d} = q_{b;d} \cdot D_{GP} = 5612 \cdot 0.049 = 275 \text{ kN} \quad (11)$$

can be used.

The design value of the pile skin friction $q_{s;d}$ is calculated using the model factor $\eta_{p;c} = 1.0$ and the partial safety factor $\gamma_s = 1.10$ analogous to (ÖNORM B 1997-1-3, 2015-08-01) :

$$q_{s;d} = \frac{q_{s;k}}{\eta_{p;c} \cdot \gamma_b} = \frac{110 \text{ kN/m}^2}{1.0 \cdot 1.10} = 100 \text{ kN/m}^2 \quad (12)$$

Since the design value of the pile skin friction $q_{s;d}$ represents an average value over the entire pile length and does not correspond to the actual distribution according to the soil conditions encountered, it is possible to weight the skin friction over the driving times.

In the present case, there are continuous non-cohesive soil conditions with a load-settlement behaviour that is similar based on experience. Thus, the creep resistance of the pile skin $F_{s,cr}$ (in this specific case) can be divided in proportion to the driving time per meter of pile $t_{Ramm,i}$ to the total driving time $St_{Ramm,i}$.

$$F_{s,cr,i} = \frac{F_{s,cr}}{\sum_{i=1}^n t_{Ramm,i}} \cdot t_{Ramm,i} \quad [kN] \quad (13)$$

The actual grouting mortar quantity per depth step is used to calculate the grouting diameter and a weighted skin friction per depth step $q_{s,m,i}$ is determined.

$$q_{s,m,i} = \frac{F_{s,cr,i}}{d_i \cdot \pi} \quad [kN/m^2] \quad (14)$$

Since deviations from the calculated mean characteristic skin friction coefficient $q_{s;k}$ may occur when dividing the depth steps, any deviations must be distributed linearly.

Considering the formula (12) , the design value of the pile skin friction per depth step $q_{s;d,i}$ is obtained (see Table 1).

Table 1. Distribution of the pile skin bearing capacity per running metre over the driving time

Depth [m]	Driving Time [sec]	Amount of Grout [l/m]	Grouting Diameter [m]	Weighting: $F_{s,cr,i} = F_{s,cr} / \sum_{i=1}^n t_{Ramm,i}$ per m [kN]	Weighting Shaft friction $q_{s,m,i}$ [kN/m ²]	charact. Shaft friction $q_{s,k}$ [kN/m ²]	Design Shaft friction $q_{s,d}$ [kN/m ²]	Design-Resistance $R_{s,d}$ acc. Driving Criteria [kN/m]
0-1	6	72	0.30	48	52	41	37	31
1-2	17	72	0.30	137	148	118	106	70
2-3	6	72	0.30	48	52	41	37	31
3-4	6	72	0.30	48	52	41	37	31
4-5	16	120	0.39	129	108	85	77	70
5-6	19	72	0.30	153	165	130	118	70
6-7	22	72	0.30	177	191	150	137	140
7-8	11	72	0.30	88	96	75	68	70
8-9	28	96	0.35	225	211	166	151	140
9-10	33	48	0.25	265	351	276	251	140
10-10.2	9	24	0.22	72	108	85	77	28
Sum	173	792						821
Average			0,31	1390	140	110	100	

5.4 Derived pile driving criterion from the test load results of test pile PP02

A possible pile driving criterion based on the measurement results from the Pile HAY-Proof-System® from test pile PP02 for the construction project in Rheinland-Pfalz (Germany) is as follows:

Design values of the skin resistance $R_{s,d}$ for driving times:

- $> 5'' - 10'' /m \Rightarrow q_{s,d} = 40 \text{ kN/m}^2$, DM 250: R_s , $d \approx 31 \text{ kN/m}$
- $> 11'' - 20'' /m \Rightarrow q_{s,d} = 90 \text{ kN/m}^2$, DM 250: R_s , $d \approx 70 \text{ kN/m}$
- $> 21'' /m \Rightarrow q_{s,d} = 180 \text{ kN/m}^2$, DM 250: R_s , $d \approx 140 \text{ kN/m}$

Design values of base resistance $R_{b,d}$ at last heat:

- $> 5''/10 \text{ cm} \Rightarrow q_{b,d} = 5612 \text{ kN/m}^2$, DM 250: $R_{b,d} \approx 275 \text{ kN}$

If a significantly larger grouting diameter is achieved during construction, the design values of the shaft resistance $R_{s,d}$ can be adjusted to the actual diameter.

6 OVERVIEW OF QUALITY ASPECTS

To ensure the sufficient quality of the final ductile pile product, quality criteria must be defined in advance and tools (e.g. test procedures, etc.) must be selected so that these criteria can be implemented, checked and documented. The options and procedures developed by Keller Grundbau Ges.m.b.H in recent years were presented in a paper at the 22nd Austrian Geotechnical Conference in 2022 (Hayden, et al., 2022).

One of the most important "quality assurance tools" – the Pile HAY-Proof-System[®] – is discussed in chapter "4" in this article. A comprehensive description of this test system is summarised in the author's dissertation (Hayden, 2024).

The driving time (synonymous with the driving time per meter of penetration depth) is the central (reference) point for maintaining and ensuring quality in the production of driven piles using hydraulic rapid impact hammers, and can be regarded as an essential measure for estimating the load-bearing capacity. All factors influencing the ramming time must be continuously checked and documented, both internally and externally.

The following parameters can influence the driving time:

- Hydraulic settings on the pile driving equipment (pressure and flow)
- Nitrogen pressure in the storage bladder of the hydraulic hammer
- Pipe materials used (diameter and wall thickness)
- Pile length
- Impact frequency of the hydraulic hammer
- Operating mode of the hydraulic hammer (slow or fast impact)
- Pile driving shoes used (diameter, shape)
- Type and performance of the hydraulic hammer
- Subsoil and groundwater conditions

Special attention must also be paid to concrete consumption. Consumption not only indicates the presence of adequate (simple) corrosion protection but also allows conclusions about the pile cross-section (and subsequently the pile's surface area in contact with the soil) and thus the load-bearing capacity of the pile. This circumstance has been considered in the new edition of the German concrete and rock engineering guidelines LB-VI 006 (Forschungsgesellschaft Straße-Schiene-Verkehr, 01.05.2021) by specifying the amount of concrete used in the specifications and requiring proof by means of delivery notes. This makes it easier for the testing authorities to verify the pile cross-section achieved.

There are also several new options for checking, collecting, displaying and storing all data relevant to pile production (e.g. nitrogen, hammer force, impact frequency, pile length) (e.g. DukiApp, Leica system). This lays the foundation for greater transparency in ductile pile manufacturing and raises the quality of this pile system to a new level (Hayden, 2024).

7 CONCLUSIONS

As discussed in this article, performing a classic static compression load test does not necessarily contribute to an improvement in safety. If the base resistance is considered non-existent and is "transferred" to the pile shaft, the determined skin friction is overestimated.

By using measuring systems that allow separate determination of the resistance parameters base resistance q_b and skin friction q_s (e.g. with the Pile HAY-Proof-System[®]), much more meaningful parameters for the design of the pile bearing capacity can be derived.

The installation of ductile piles also has the advantage that additional information about the bearing capacity of the soil can be obtained during pile production via the driving times or the concrete consumption per meter. This means that the findings from the subsoil investigations, the test load results from the Pile HAY-Proof-System[®], the pile driving resistance and the concrete consumption can be used to guarantee the required load-bearing capacity with the standard safety factors, even if the soil conditions change. Depending on the pile driving resistance, the pile length can be and is adjusted in situ.

Since the driving time is the main influencing parameter for the implementation of a driving criterion based on load tests/experience, a "representative" driving time, i.e. the functioning of all equipment involved in the driving process, is of utmost importance. To be able to guarantee this "representative" driving time on a permanent basis, it is essential to apply and document ongoing strict quality control during the installation of ductile piles. This is the only way to ensure that the required construction specifications can be achieved both economically and technically. Finally, CO₂ emissions can also be reduced through the sustainable and optimal use of resources.

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