Impact and vibratory driven pipe piles: the difference in soil stresses and bearing capacities due to the installation method

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ABSTRACT

The influence of the installation of open-ended pipe piles on soil stresses is studied by means of scale model tests in sand. Variants with different pile diameters, soil densities and installation methods are investigated. Measurements of pile dynamics and soil stresses are carried out as a basis for further analysis. During impact pile driving, the radial soil stresses acting on the pile wall increases to a peak value as the pile tip approaches a soil element and decrease to a residual value afterwards ('friction fatigue'). The peak value of soil stresses increases with soil density. The residual value was found to be close to the earth pressure at rest. In case of vibratory pile installation, soil stress developments range from 'very similar to impact pile driving' to 'no effect', depending on vibratory driving parameters. High soil stress changes due to vibro-driving correlate with high permanent displacements per vibration cycle. Both peak and residual radial soil stresses need to be considered for pile driving simulations, as they are the basis for the pile shaft friction. A novel formulation for the 'friction fatigue' phenomenon during impact pile driving is presented. In contrast to current practice, the authors suggest using different approaches to calculate the peak skin friction for impact and vibratory driven piles. The soil stress at the end of driving is a key driver for the pile's load bearing behaviour. As increased soil stresses may remain after pile installation, especially near the pile tip, different soil stress developments have implications for the axial or lateral pile design.

Keywords: pipe piles, installation, impact driving, vibratory driving, friction fatigue

1 INTRODUCTION

Open-ended steel pipe piles are the predominantly used foundation elements for offshore, nearshore or port structures. Depending on the type of foundation (monopiles, jackets, dolphins or supporting structures for combined sheet pile walls) these piles are exposed to different loadings, as for example axial, lateral, static, dynamic or cyclic loading. In the past, the commonly used installation method for these piles was impact driving. Due to several positive effects such as noise reduction, installation time, or the reduction of material fatigue during pile installation, the wish for a gentler installation method such as vibratory driving increased. The selection of the installation method is also driven by its influence on the axial and lateral pile bearing capacity after installation.

Over the last few years the influence of the installation method on the pile bearing capacity was investigated in depth at the test facility of the Institute of Geomechanics and Geotechnics of Technische Universität Braunschweig (IGG-TUBS). As part of two different research projects model pipe piles (diameter varying between 35 to 61 cm) were driven into sandy soils at varying states of compaction and water saturation. For the installation a model scale impact hammer and different vibratory hammers were used. To measure the change in the soil stresses before, during, and after pile installation numerous earth pressure and pore water pressure sensors were pre-installed in the soil whilst it was built up. For further analyses like the effect of the vibration frequency, the dynamic unbalance during vibratory driving or the energy during impact driving, additional parameters such as strain, acceleration or displacement of the pile were recorded during driving.

2 SCALE MODEL TESTS

2.1 Test Pit

Model scale tests are an appropriate method for holistic investigations e. g. on the pile installation effects. In order to keep scaling effects as low as possible, a large-scale model testing facility was erected at IGG-TUBS in 2013. The test facility mainly consists of two cylindrical containers with a volumetric capacity of about 60 m³ (diameter = 4 m; height = 5 m) each.

The main task for all model tests carried out is the preparation of predefined, homogenous, and reproducible soil conditions. For the model tests presented here, fine to medium, moist sands were emplaced in layers of about 25 cm and optionally compacted by use of a vibratory plate. Thus, very loose to very dense packing could be achieved. Quality control of the model soil was carried out by cone penetration testing (CPT) and dynamic probing (DPM). Figure 1 shows CPT (left) and DPM (right) results from different tests with the same procedure for sand emplacement. The curves prove a good reproducibility of the tests.

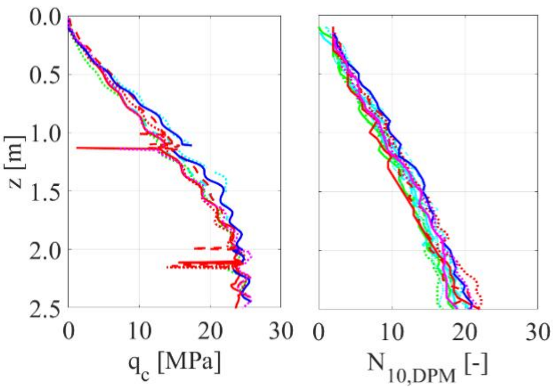

Fig. 1. CPT (left) and DPM (right) readings carried out before pile installations within research project #2

2.2 Testing scheme

The results from two research projects related to the installation of open-ended pipe piles into fully saturated sandy soils will be presented in the following sections.

During the first project, the influence of impact pile driving on the changes in effective soil stresses acting radially on the pile wall was investigated. Furthermore, possible correlations between stress changes and soil density, or stress changes and pile diameter were examined (Fischer, 2021).

The focus of the second research work was to assess the influence of changing installation methods on the development of the soil stresses during pile driving (Stein et al., 2020). Besides impact driving, 'free' and 'crane-guided' variants of vibratory pile driving were used. In case of the crane-guided vibro-installation, the pile-vibro assembly (pile, vibratory hammer, base frame) was attached to the crane hook. A constant driving frequency (sufficient to drive the pile to target penetration) was used and the pile penetration was defined by the crane speed. In case of free vibratory driving, the driving frequency was manually increased with increasing pile penetration to achieve a more or less constant penetration speed throughout the whole pile installation process. Besides the changing frequency, the penetration speed was driven by the self-weight of the pile-vibro assembly and the soil reaction.

The following table gives an overview of the test conditions. All piles used are made of stainless steel (1.4301), have a wall thickness of 3 mm and a pile length of 3 m.

Table 1. Test conditions.

installation method	pile diameter	soil density	water content
impact	0.36 m 0.51 m	very loose dense	fully saturated
impact vibro (free) vibro (guided)	0.61 m	dense	fully saturated

Impact pile driving was executed with a Delmag D2 diesel hammer allowing for a maximum rated energy of 2.45 kJ. For vibratory pile driving, an APE J&M Model 23 hydraulic vibro hammer with an eccentric moment of 2.33 kg·m and a driving frequency of up to 27 Hz was used. The following figure shows impact (left) and vibratory (right) pile driving in the test pit. For more information on the installation equipment please refer to Fischer (2021) and Stein et al. (2020).

Fig. 2. Impact hammer Delmag D2 and vibratory hammer APE J&M Model 23.

2.3 Measurements

At the pile head, accelerometers and strain sensors were installed to measure the pile motions and the forces in the pile. Measurements at the pile were carried out at sample rates of up to 50 kHz.

During pile installation (impact and vibratory driving), the pile penetration was observed by use of markings at the pile wall in combination with video recordings. To be able to compare all additional measurements in relation to the actual pile penetration, the time was synchronized for all recording devices. During vibratory pile driving, a wire transducer was also used to measure the pile penetration.

In the soil, press-in total stress spades and pore water pressure sensors were installed while building up the sand in the test pit. The sensors were placed in various depths along the planned pile penetration at distances between 10 to 20 cm next to the pile wall. The total stress sensors were adjusted to measure the radial soil stresses acting towards the pile wall during pile installation. Due to the arrangement of the sensors, the change in effective soil stresses caused by the pile installation could be derived. Pressure measurements in the soil were carried out at sample rates of up to 100 Hz.

3 MODEL TEST RESULTS

3.1 Pore water pressure

The results from the pore water pressure sensor recordings showed that during all tests no significant accumulation of pore water pressure took place in a distance or approx. 10 cm outside the pile wall during installation.

3.2 Impact driven piles

Within the scope of the first research project focusing on impact driving, piles with two different diameters were driven into fully saturated sand. During installation of the soil in the test pit, the sand was built up at two different degrees of compaction (see Table 1). For both soil densities (loose and dense) results from the recorded stress measurements during pile installation are shown in Figure 3.

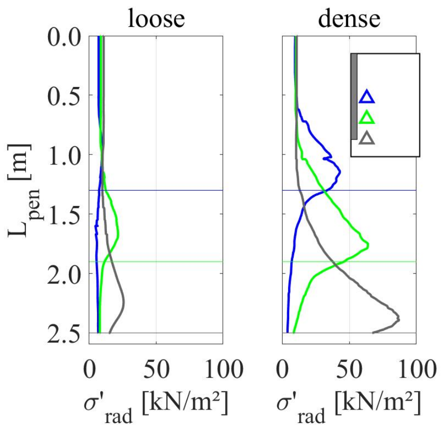

Fig. 3. Soil stress developments during impact driving into loose (left) and dense (right) saturated sand.

During both tests the effective radial stresses were measured at three different depths below ground (1.3 m, 1.9 m, 2.5 m), each located 10 cm outside the pile wall.

All results shown were filtered to remove peaks from dynamic impacts. Measurements at different sensor levels are shown in different colours. Horizontal lines and the pictogram in the upper right corner of the figure indicate the location of the sensors.

As shown in Figure 3, the effective radial soil stresses σ'_{rad} increases as the pile tip penetration L_{pen} approaches the corresponding measuring section at depth z. From the first contact with the pile wall onwards, a decrease in the effective radial stresses was observed. These phenomena are well known, and the latter is usually described as 'friction fatigue' in the literature.

For the entire period where the pile wall is in contact with a soil element at depth z the measured effective radial soil stresses can directly be converted into skin friction using Mohr-Coulomb's failure criterion:

$$\tau_s(z, L_{pen}) = \sigma'_{rad}(z, L_{pen}) \cdot \tan\delta \qquad (1)$$

Where τ_s (z, L_{pen}) is the skin friction at depth z in relation to the pile tip location L_{pen}, σ'_{rad} (z, L_{pen}) is the effective radial soil stress at the depth z in relation to the pile penetration L_{pen} and δ is the interface friction angle.

Transferring Equation 1 to the installation of the test piles, skin friction is only generated from the moment the pile penetration L_{pen} is equal to the depth z of the soil element in focus (here: sensor level) and onwards. Therefore, the measured increase in radial effective soil stresses is only relevant to define the skin friction at the moment of the first contact between soil element and pile τ_s (L_{pen} = z). In the following, this shall be denoted as peak skin friction $\tau_{s,pk}$. The subsequent decrease in skin friction acting at the soil element considered can then be given e. g. in percent of the peak skin friction.

For each soil density and pile diameter the recorded decrease in relative skin friction was calculated. In Figure 4, the recorded bandwidth of measured decreases in effective radial stress are displayed where the minimum and maximum are given by exponential functions.

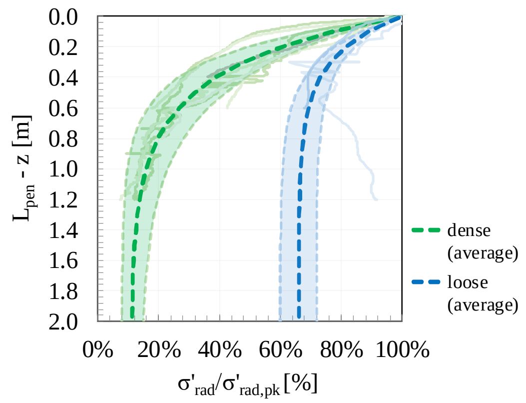

Fig. 4. Measurement results, spread width and average value of decrease in effective radial stresses for two different soil densities.

The mean value highlighted as a dotted green line for dense sand and dotted blue line for very loose sand was then defined as relevant for the test condition considered.

From the literature (Heerema, 1978) it is well known that the decrease in skin friction or the 'friction fatigue' phenomenon can be described by an exponential function (see section 4.2).

Looking at the further course of the measured soil stresses or derived skin friction it is evident that with increasing amount of shear cycles (blows) the skin friction is approaching a lower limit. In the literature the lower limit is often described as residual skin friction $\tau_{s,res}$. Looking at the measured residual effective radial stresses $\sigma'_{rad,res}$ recorded during the model tests it was found that the residual stresses are equal to the theoretical earth pressure at rest. Figure 5 shows the measured values of the peak (blue) and the residual radial stresses (green) as well as the theoretical earth pressure at rest (grey) for all tests carried out within the research project #1.

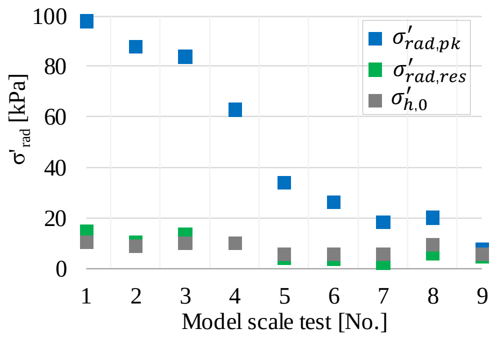

Fig. 5. Comparison of measured soil stress and residual radial soil stresses and theoretical earth pressure at rest

By use of Equation 1 and based on the tests carried out, the residual skin friction can be calculated using:

$$\tau_{s,res} = (\gamma' \cdot z \cdot (1 - \sin\varphi')) \cdot \tan\delta \qquad (2)$$

In terms of the two varying pile diameters used, no significant difference in the development of stresses during pile installation were observed. Thus, it was concluded that pile diameter effects can be neglected for the tests carried out.

3.3 Vibrated piles

The effects described above could be reproduced using a larger pile diameter of $D_{pile} = 0.61$ m in a somewhat coarser, fully saturated sand at dense packing within the second research project. The following Figure 6 shows the development of the effective radial soil stresses σ'_{rad} over pile penetration L_{pen} in analogy to Figure 3.

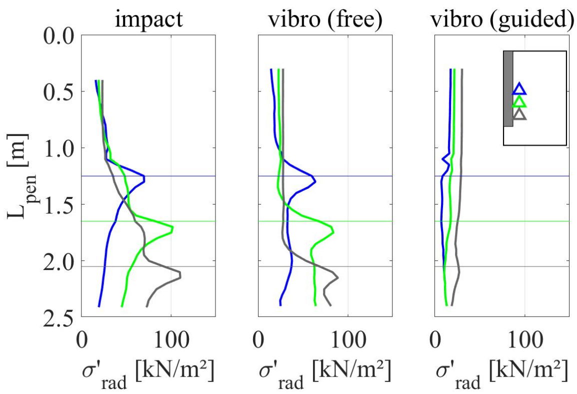

Fig. 6. Soil stress developments during impact driving (left) free vibratory driving (middle) and crane-guided vibratory driving (right).

The left diagram shows the soil stress development of an impact driven pile. The middle diagram shows a very similar outcome, resulting from <u>free</u> vibratory driving. In both cases, peak values of similar height are observed in all measuring sections and increased radial stresses remain after end of driving near the pile tip. The right diagram shows results from a crane-guided vibratory pile installation with almost no influence on the radial soil stresses.

Concerning the differentiation of vibratory driving variants, a closer look at the response parameters of the system vibro-pile-soil is necessary. From 16 pile installations in dense, saturated sand with different installation methods (including impact driving) and parameters, measures were isolated when the pile tip passed each soil sensor. Figure 7 shows the effective radial stresses σ'_{rad} related to the overburden pressure $\gamma' \cdot z$ over the set per blow/cycle s_{set} divided by the total downward directed motion per blow/cycle $s_{\downarrow}$.

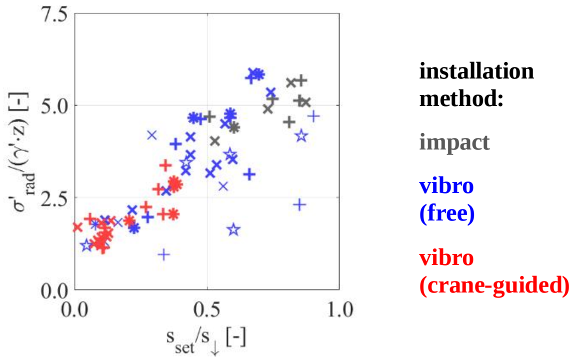

Fig. 7. Soil stress developments during impact driving (left) free vibratory driving (middle) and crane-guided vibratory driving (right).

Each marker represents one observation, i. e. measurements taken as the pile tip reaches a certain measurement level. Different colours indicate different installation methods. The same markers indicate measurements taken during one test.

The comparison of system response parameter $s_{set}/s_{\downarrow}$ and soil stress enhancement factor $\sigma'_{rad}/\gamma' \cdot z$ shows impact pile driving (grey) has a great effect on soil stresses while crane-guided vibratory pile driving (red) has not. In case of free vibratory driving (blue), a wide range of possible effects on the soil's stress state can be observed. Independent from the used installation technique, a larger value of $s_{set}/s_{\downarrow}$ leads to higher radial soil stresses as the pile tip passes a soil element. Increased soil stresses during and after pile installation have a severe influence on the pile resistance to driving and the axial and lateral pile bearing behaviour, as will be discussed in the following section.

4 DISCUSSIONS OF THE FINDINGS

4.1 Skin friction at yield

For impact and vibratory driven piles, the peak skin friction $\tau_{s,pk}$ represents the state of a soil element at first contact with the pile at $L_{pen} = z$. For pile driving predictions for example, the peak skin friction is usually entered into the software's soil model as default value.

As can be seen from the stress measurements during pile installation (see Figure 3 and Figure 6) the peak stresses do not represent the soil stresses at primary stress state before the start of pile installation. Usually, the peak stresses are higher than the primary soil stresses and strongly affected by the initial density of the soil, the overburden pressure and the installation method.

When looking at the installation method only (see Figure 6) three different types of installation were used:

I impact driving
II free vibratory driving (zero hook load)
III crane-guided vibratory driving

As already described in section 3.3, at the same boundary conditions (soil, density, saturation, pile) similar stress developments were measured for the installation types I and II whereas for type III significantly different results were observed. For this, increased radial soil stresses (in comparison with the initial stress state) at $L_{pen} = z$ cannot be assumed in any case for a vibrated pile. As shown in Figure 7, even 'free' vibratory driving is not a configuration to guarantee a soil stress development comparable to impact driven piles as this depends on several factors such as the permanent displacement per vibration-cycle.

4.2 Skin friction degradation

From the literature it is known that the measured decrease in soil resistance, following the first contact between soil element and pile ($L_{pen} > z$), is directly linked to the amount of shear cycles applied to the soil element next to the pile wall (Airey et al., 1992; Boulon & Foray, 1986). With increasing amount of shear cycles (caused by each hammer blow or revolution of the vibro) the skin friction will approach a residual value or lower limit. Once reached, even at a continuation of the pile installation the skin friction will remain constant. In commercially available software for pile driving simulations, the decrease in soil resistance is often considered by use of reduction factors, decay functions, or similar.

For the research project focusing on impact driving, to describe the measured decrease in soil resistance, the exponential function as suggested by Heerema (1978):

$$\sigma_{h_d}^{0.7} = \sigma_{h_i}^{0.7} \cdot e^{n \cdot (d-p)} \tag{3}$$

was used and extended by the term β_{res} to include the residual skin friction:

$$\beta(z, L_{pen}) = \beta_{res}(z) + (1 - \beta_{res}(z)) \cdot \mathrm{e}^{-\alpha \cdot (L_{pen} - z)} \tag{4}$$

Doing so for each soil element at depth z, the skin friction can be calculated in relation to pile tip penetration L_{pen} using:

$$\tau_s(z, L_{pen}) = \tau_{s,pk}(z) \cdot \beta(z, L_{pen}) \tag{5}$$

Taking into account that the residual resistance was found to be related to the theoretical earth pressure at rest (see Figure 5), the residual value can be defined in percent of the peak skin friction by:

$$\beta_{res}(z) = \frac{\tau_{s,res}(z)}{\tau_{s,pk}(z)} \tag{6}$$

For fully saturated sands, the following definition of the shape factor α depending on the soil's relative density D (calculated based on the void ratio n) was found based on the model tests:

$$\alpha = 4.2 - 1.4 \cdot D = 4.2 - 1.4 \cdot \frac{\max n - n}{\max n - \min n} \tag{7}$$

4.3 Impact on pile driving predictions

Transferring the findings from both research projects e. g. to the simulation of pile installations, different approaches to calculate the peak skin friction $\tau_{s,pk}$ need to be used depending on the installation method and mode. In engineering practice however, for vibratory driving predictions (VDP) often the same approach as for impact pile driving predictions (PDP) is used to calculate the peak skin friction $\tau_{s,pk}$. According to the findings presented (see Figure 6), this may lead to an overprediction of the peak skin friction at least for the guided installation case. To correct for a wrong initial condition also the reduction factor or decay function needs to be increased. The combination of both assumptions may lead to a reasonable simulation result but is geomechanically incorrect.

A common approach used for vibratory predictions is the instantaneous application of the residual value (e. g. Jonker, 1987), assuming an immediate drop caused by the high amount of shear cycles applied to the soil element considered. Thus, the residual skin friction is effectively assessed over the complete installation process. When compared with the research findings, this may be justified for crane-guided installations (which can be assumed as the standard method for vibratory pile driving) but may underestimate the actual resistances in some cases (see Figure 6). In addition, and as mentioned before, the validity of the reduction factor selected always needs to be aligned with the calculation approach used to define the peak skin friction.

For the simulation of impact driven piles, several approaches can be found in the literature whilst the approach suggested by Alm & Hamre (2001) might be the most used for open-ended pipe piles, especially in the offshore environment. Comparing this approach with the research findings, the shape factor as defined by Equation 7 results in a (much) faster decay of the skin friction. Furthermore, the residual value for sand is based on the theoretical horizontal earth pressure at rest and not given as a constant reduction in percent of the peak skin friction (Equation 6). In this context it needs to be considered that this is valid for the test conditions, and that a validation for full-scale pile installations is still outstanding. On the other hand, it should be considered that the Alm & Hamre (2001) approach is based on back calculations for which it is known that an almost perfect match with the pile driving protocol can be achieved for different possible distributions between skin friction and tip resistance – as long as the total amount of resistance is equivalent with the situation on site.

5 SUMMARY AND CONCLUSIONS

The results from the pile installation tests carried out in the test pit at IGG-TUBS and presented in this paper can be summarised as follows:

The stress development during pile installation and next to the pile wall can vary significantly when comparing different installation techniques and parameters as: impact driving, 'free' and 'crane-guided' vibratory driving.

Currently, for both impact and vibratory driving, often the same approach is used to calculate the peak skin friction at first contact between soil element and pile tip $\tau_{s,pk}$. According to the research results however, different calculation approaches need to be used here to correctly represent the soil mechanical phenomena occurring. The compensation for a 'wrong' peak skin friction value might then be balanced by using an incorrect correction factor to calculate the residual skin friction.

In case of a vibratory driven pile where the pile penetration is 'guided' by the crane the results demonstrate that the concept of 'friction fatigue' or soil degradation (in combination with a previous increase of stresses) during pile installation may not always be applicable.

In contrast, in case of a 'free' installation – especially along with rather large permanent displacements per cycle (see Figure 7) – a similar approach as known from impact driven piles might be useful. Also, increased radial soil stresses near the pile tip remain after pile installation in case of impact driving and certain variants of 'free' vibratory driving. This implies that vibratory driven piles may have a similar load-bearing behaviour as impact driven piles if appropriate vibratory parameters are used.

The paper lacks methods to calculate the peak skin friction and the tip resistance for the installation methods and modes presented. As a workaround, CPT-based approaches from current practice may be used for the peak skin friction of impact and certain cases of 'free' vibratory driving. For 'crane-guided' vibratory driving, Equation 1 may be used.

Regarding the situation on site, it might be challenging to predict the actual vibratory driving mode applied during installation and thus which method to be used to determine the actual skin friction.

To transfer the current results to the installation of full-scale offshore piles, the authors strongly suggest to increase the amount of impact driving and vibratory driving monitoring and analysis (PDA/VDA: dynamic high frequency measurements of pile forces and motions) during pile installation. This data could then be used for further investigations such as the development of soil models.

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REFERENCES

Airey, D.; Al-Douri, R.; Poulos, H. (1992): Estimation of Pile Friction-Degradation from Shearbox Tests. Geotechnical Testing Journal, Vol. 15(4), Philadelphia, USA.

Alm, T.; Hamre, L. (2001): Soil model for pile driveability predictions based on CPT interpretations. Proceedings of the 15th International Conference on Soil Mechanics and Geotechnical Engineering (ISSMGE), Istanbul, Turkey, 27-31.

Boulon, M.; Foray, P. (1986): Physical and Numerical Simulation of Lateral Shaft Friction Along Offshore Piles in Sand, Proceedings of the third International Conference on Numerical Methods in Offshore Piling, Nantes, France.

Fischer, J. (2021): Ramminduzierte Spannungsfeldänderungen im Nahbereich von Rohrprofilen großen Durchmessers (in German). PhD Thesis, Braunschweig, Germany.

Heerema, E. (1978): Predicting Pile Driveability: Heather As An Illustration Of The "Friction Fatigue" Theory, European Offshore Petroleum Conference & Exhibition (SPE 8084), S. o. Limited, London, UK.

Jonker, G. (1987): vibratory pile driving hammers for pile installations and soil improvement projects. Offshore Technology Conference, Houston/Texas, USA, OTC 5422, S. 549–559.

Ohde, J. (1939): Zur Theorie der Druckverteilung im Baugrund. Der Bauingenieur, S. 451–459

Stein, P.; Gattermann, J.; Daumlechner, E.; Hinzmann, N.; Stahlmann, J. (2020): ZykLaMP – Großmaßstäbliche Modellversuche zur lateralen Tragfähigkeit offener Stahlrohrpfähle unter zyklischer Belastung bei verschiedenen Einbringverfahren (in German). Research report, FKZ 0324133, Braunschweig, Nov. 2020, doi.org/10.2314/KXP:1757076