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Numerical simulation of the lateral bearing behavior of open steel pipe piles with regard to their installation method

Simulation numérique de la capacité portante lateral des pieux tabulaires en acier ouvert en fonction de leur méthode d'installation

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ABSTRACT: Open steel pipe piles are used for various applications in coastal engineering and port structures as well they are getting more and more important for offshore structures. Especially in Europe there are already many offshore wind energy parks realized and more are planned. When designing these piles, different aspects influencing the axial and lateral bearing behavior have to be considered. Among others, the pile diameter, the installation method and the soil state variables after installation have a significant influence on the bearing behavior. In this paper, a simplified approach to simulate the lateral bearing behavior of open steel pipe piles with regard to the installation method is shown. In section 2, the different installation methods and their influence on the soil are described. In section 3, the numerical simulation is presented. The constitutive model with its parameters as well as the numerical model itself are shown and explained. Section 4 documents the results of the numerical study and discusses the results. The last section comprises a résumé of the simplified approach presented in this paper.

RÉSUMÉ: Des pieux tubulaires en acier ouvert sont utilisés pour diverses applications dans l'ingénierie côtière et portuaire ainsi qu'ils deviennent de plus en plus important pour les structures. Surtout en Europe, il existe déjà de nombreux parcs d'énergie au large éolienne en mer réalisés et d'autres sont prévues. Lors de la conception de ces pieux, les différents aspects qui influencent le comportement portant axial et latéral doivent être considérés. Entre autres, le diamètre du pieu, le méthode d'installation et les variables d'état du sol après l'installation ont une influence notable sur le comportement de portant. Dans cet article, l'influence de la méthode d'installation sur le comportement portant latéral sera montré à l'aide de simulations numériques. Dans la section 2, les différentes méthodes d'installation et leur influence sur le sol sont décrites. Dans la section 3, la simulation numérique est présentée. Le modèle constitutif avec ses paramètres ainsi que le modèle numérique lui-même sont présentés et expliqués. La section 4 documente les résultats de l'étude numérique et examine les résultats. La dernière section est un résumé de la dans ce document présenté approche simplifiée.

KEYWORDS: Monopiles, lateral bearing behavior, vibratory-driven piles, impact-driven piles, numerical simulation, hypoplasticity.

1 INTRODUCTION

Open steel pipe piles are used for various applications in coastal engineering and port structures as well they are getting more and more important for offshore structures. Especially in Europe there are already many offshore wind energy parks realized and more are planned. When designing these piles, different aspects influencing the axial and lateral bearing behavior have to be considered. Among others, the pile diameter, the installation method and the soil state parameters after installation have a significant influence on the bearing behavior. In this paper, a simplified approach to simulate the lateral bearing behavior of open steel pipe piles with regard to its installation method is shown. Based on the influence of the pile installation method on the soil, different zones of influence are defined in the numerical model. This simplified numerical approach should serve as a guidance for the engineer to estimate the lateral bearing behavior.

2 PILE INSTALLATION

Open steel pipe piles in general can be installed in various ways. They can be jacked, impact-driven or vibratory-driven. Monopiles, which are used as foundation for offshore wind power plants, are usually installed impact-driven. This installation method guarantees reaching of the final embedment depth. Furthermore it allows the use of state-of-the-art methods, as the p-y method provided in national and international standards, to determine the lateral bearing behavior. Nevertheless, this installation method comes along with several disadvantages. During impact-driving the noise level around the pile reaches such a high level, that an expensive noise mitigation shield has to be used. Another aspect is the installation time, which is relatively long. Furthermore, a high level of fatigue is introduced to the pile with every impact. Thus, monopiles should be installed vibratory-driven in the future. This installation method has been investigated for monopiles in the VIBRO project (Moormann et al. 2016). An installation 10 times faster than for the impact-driven pile could be observed. Also the level of noise during installation was lower than for the impact-driven pile, i.e. no noise mitigation shield might by necessary for vibratory-driven piles. The pile installation method has not only an influence on the installation time and the noise emissions, but influences also the soil around the pile significantly. The influence of the installation method has been investigated among others by (Hartung 1994), (Wienholz 1998), (Viking 2002), (Massarsch and Fellenius 2005), (Lammertz 2008), (Stahlmann and Fischer 2013), (Moormann et al. 2015), (Labenski et al. 2016) and (Moormann et al. 2016). In this paper, only vibratory-driven and impact-driven monopiles are compared.

2.1 Impact-driven piles

During the impact-driven installation of piles, the stress in the soil as well as the soil state parameters are horizontally influenced up to a distance of 7 to 12 times the pile diameter D and vertically influenced up to a depth of 3 to 5 D underneath the pile toe (Hartung 1994).

In the area around the pile toe, the soil is compacted. Thus, the vertical and horizontal stresses increase. Around the pile shaft, the soil is contracting if the relative density of the soil is loose. If the relative density of the soil is dense, the soil around the pile shaft is dilating during installation. If the soil is dilating, the radial stress acting on the shaft is increasing. However, if
the displacement of the sand grains is exceeding a certain limit, this effect is inverted and the radial stress is decreasing.

Numerical simulations of the pile installation process by (Labenski et al. 2016) show loosening directly at the pile shaft around the impact-driven pile. Furthermore at the top of the soil layer the soil is slightly influenced and densified up to a distance of 1.5 D from the pile shaft while at the pile toe a strong influence is visible up to a distance of 1 D.

2.1 Vibratory-driven piles

During the vibratory-driven installation the pile is vertically excited by a dynamical force acting down- and upwards. This vertical excitation of the pile leads to an excitation of the soil grains which are moved not only vertically, but also horizontally or in all directions respectively (Hartung 1994). This way the soil around the pile shaft is transformed into a Newtonian fluid, which is not able to resist shear forces. Thus, the pile is able to sink to the desired embedment length just by its own weight and an optional surcharge.

In accordance with findings by Hartung (1994) for piles vibratory driven with a frequency of 40–50 Hz, the soil around the pile shaft during installation can be divided into two different zones: a liquefaction zone and a compaction zone. Due to the dynamical excitation the soil grains in the liquefaction zone are moving with high velocities leading to a higher volume of the soil in this area. Also the horizontal stress is significantly lowered. In the compaction zone the horizontal stress in the soil shows high values. After pile driving, the relative density in the liquefaction zone is low while there is a high relative density in the compaction zone. In the area around the pile toe, the soil is behaving similarly.

Numerical simulations of the pile installation process by (Labenski et al. 2016) show a loosening directly at the pile shaft. In comparison to the impact-driven pile, the soil is strongly influenced and densified up to a distance of 5.5 D to the pile shaft. This distance is almost constant over the whole embedment length. Underneath the pile toe, the soil is densified up to 12 D.

(Massarsch and Fellenius 2005) document the influence of the vibration frequency on the compaction of granular soils. Vibrating with a frequency higher than the resonance frequency of the adjacent soil leads to a low compaction of the soil, as most of the vibration energy is converted into heat along the pile shaft. Vibrating with a frequency close to the resonance frequency of the adjacent soil leads to an efficient transfer energy between pile shaft and soil grains, as both move “in phase”. This causes a densification of the surrounding soil.

3 NUMERICAL SIMULATION

To compare the lateral bearing behavior of open steel pipe piles with regard to their installation method, several numerical simulations have been carried out. In the numerical simulations a simplified approach is used to take the different installation methods into account. Based on the review of the different pile installation methods in the previous section, different zones around the pile with varying relative density $R_0$ are defined.

The numerical model was validated by back-analysing one of the scaled model tests (scale 1:20) investigating the lateral bearing behavior of vibratory-driven monopiles documented in (VIBRO-II 2016).

The numerical simulations were carried out using the commercial software ABAQUS (Dassault Systèmes 2014). An implicit time integration algorithm is used.

3.1 Constitutive model

The hypoplastic constitutive model from (von Wolffersdorff 1996), with the small-strain extension by (Niemunis and Herle 1997) is used to simulate the behavior of the soil. This constitutive model is able to adequately represent the nonlinear and anelastic behavior of granular materials. The hypoplasticity possesses of a rate dependent formulation. It is consistent with mechanical soil properties, e.g. contractibility, dilatancy and the change of stiffness due to the actual stress state, the void ratio and cyclic loading. The ABAQUS implementation was done using a user subroutine provided by (Gudehus et al. 2008).

In Table 1, the constitutive parameters used for the numerical simulation are shown. The granular hardness $h_s$ has been reduced by the factor 10 in comparison to the original value to take the low stress state in the scaled model test into account.

The pile was modeled using an elastic constitutive model with a Young’s modulus of 50 GPa and a Poisson number of 0.25 and is based on the pile used in the scaled model test. Corresponding scaling laws have been respected.

Table 1. Hypoplastic parameters with intergranular strain for Berlin Sand according to (Le 2015).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi_i (\degree)$</td>
<td>31.5</td>
</tr>
<tr>
<td>$h_s (\text{MN/m}^2)$</td>
<td>230</td>
</tr>
<tr>
<td>$\alpha (-)$</td>
<td>0.30</td>
</tr>
<tr>
<td>$\omega_i (-)$</td>
<td>0.391</td>
</tr>
<tr>
<td>$\omega_e (-)$</td>
<td>0.688</td>
</tr>
<tr>
<td>$\omega_m (-)$</td>
<td>0.791</td>
</tr>
<tr>
<td>$\alpha (-)$</td>
<td>0.13</td>
</tr>
<tr>
<td>$\beta (-)$</td>
<td>1.00</td>
</tr>
<tr>
<td>$R (-)$</td>
<td>0.0001</td>
</tr>
<tr>
<td>$m_e (-)$</td>
<td>4.4</td>
</tr>
<tr>
<td>$m_i (-)$</td>
<td>2.2</td>
</tr>
<tr>
<td>$\beta_s (-)$</td>
<td>0.2</td>
</tr>
<tr>
<td>$\chi (-)$</td>
<td>6.0</td>
</tr>
</tbody>
</table>

3.2 Numerical model

The numerical model is shown in Figure 1. In order to reduce computational time, symmetry conditions were used and only half of the model was simulated. The numerical model consists of 80,000 elements. C3D8R elements were used in ABAQUS. These are 8-noded elements with reduced integration.

The numerical model has the shape of a cylinder and has a diameter of 2.0 m with a height of 2.5 m. The pile has a diameter of 0.2 m and a wall thickness of 3 mm leading to a flexural stiffness of 0.55 MNm² in the full model, 545 x 10³ MNm² in prototype scale respectively. The ratio of embedment length to pile diameter L/D is 4.2 and is based on usual values for offshore monopiles. The force is applied in a height of 1.5 D above the soil surface and has a maximum value of 450 N, which corresponds to 900 N in the full model and 9 MN in the full model in prototype scale.
The zones are used to simulate the different installation methods. Zone 3 has a width of 0.25 D around the pile shaft and zone 2 has a width of 1.75 D which results in a total distance of 0.25 D to 2.0 D to the pile shaft. Zone 1 describes the part of the soil which is not influenced by the installation method. Based on the investigated installation method, the relative density $I_D$ of the zone is adapted. The corresponding relative densities $I_D$ for each of the installation methods are documented in Table 2. One simulation has been also carried out with the same $I_D$ for every zone. This simulation serves as reference simulation and is marked as "None" in Table 2. As the zones of the vibratory-driven pile are highly influenced by the vibration frequency, four different vibratory-driven piles have been defined.

### Table 2. Definition of the different zones corresponding to the different installation methods.

<table>
<thead>
<tr>
<th>Installation method</th>
<th>$I_D$ Zone 1</th>
<th>$I_D$ Zone 2</th>
<th>$I_D$ Zone 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>75 %</td>
<td>75 %</td>
<td>75 %</td>
</tr>
<tr>
<td>VDr (1)</td>
<td>75 %</td>
<td>80 %</td>
<td>55 %</td>
</tr>
<tr>
<td>VDr (2)</td>
<td>75 %</td>
<td>80 %</td>
<td>10 %</td>
</tr>
<tr>
<td>VDr (3)</td>
<td>75 %</td>
<td>90 %</td>
<td>10 %</td>
</tr>
<tr>
<td>VDr (4)</td>
<td>75 %</td>
<td>70 %</td>
<td>10 %</td>
</tr>
<tr>
<td>IDr</td>
<td>75 %</td>
<td>99 %</td>
<td>70 %</td>
</tr>
</tbody>
</table>

VDr: Vibratory-Driven; IDr: Impact-Driven.

## 4 RESULTS AND DISCUSSION

In Figure 2 the load-displacement curves for the different idealized pile installation methods are documented. On the y-axis the horizontal load $F_y$ is shown, on the x-axis the horizontal displacement $U_y$ of the pile at the soil surface in relation to the pile diameter D. The reference pile has a maximum displacement of $3 \times 10^{-3}$ D. In comparison to the reference pile, the impact-driven pile has a smaller maximum displacement, whereas all of the vibratory-driven piles have a higher maximum displacement. All of the curves have in common, that they qualitatively behave similar. Up to a horizontal displacement of $1 \times 10^{-3}$ D, the curves have almost the same inclination. Starting from $1 \times 10^{-3}$ D, all of the curves change their inclination drastically.

Based on the load-displacement curve, the influence of the defined zones can be evaluated as follows: The definition of zone 3 might have the highest influence on the lateral bearing behavior. Only taking into account the reference pile and the vibratory-driven piles, the reference pile has the smallest displacement with the highest definition of $I_D$ for zone 3, whereas vibratory-driven piles 2 to 4 with the smallest definition of $I_D$ for zone 3 have higher horizontal displacements than the vibratory-driven pile 1 and the reference pile. Nevertheless, the impact-driven pile with a slightly reduced definition of $I_D$ for zone 3 has a smaller horizontal displacement than the reference pile.

Considering also zone 2, the vibratory-driven piles show an increase of horizontal displacement with a decrease of $I_D$, i.e. the vibratory-driven piles can be ordered as follows: VDr (1) < VDr (3) < VDr (2) < VDr (4). This is also coherent with the reference pile and the impact-driven pile, showing a decrease of horizontal displacement with an increase of $I_D$.

Figure 3 shows the relative displacement in relation to the relative applied force. The relative displacement is defined as the displacement of the reference pile divided by the displacement of the pile being compared. Thus, a value greater than one means that the horizontal displacements are lower compared to the reference pile and a value smaller than one that the horizontal displacements are higher compared to the reference pile. The relative force is defined as the actual horizontal force divided by the maximum applied force, which corresponds to 450 N.

Figure 3 is coherent with the findings based on Figure 2. All of the vibratory-driven piles show a weaker lateral bearing behavior than the reference pile and the impact-driven pile. It can be also seen, that up to a relative force of 40%, the behavior between the piles remains constant. With a relative horizontal...
force higher than 40%, the piles behave differently. The impact-driven pile behaves even stiffer in comparison to the reference pile. The vibratory-driven piles 2 to 4 behave even softer. Even though vibratory-driven pile 1 behaves slightly weaker, its behavior compared to the reference pile is almost constant. It can be summarized, that a decrease of relative density in the near field of the pile mainly influences the bearing behavior, if the decrease is significant in comparison to the overall density (zone 1). If the decrease is small, the in-respectively decrease in a distance up to 2 D to the pile shaft has the main influence on the horizontal bearing behavior.

5 RÉSUMÉ

In this paper, a simplified approach to simulate the lateral bearing behavior of monopiles based on their installation method has been presented. After clarifying the theoretical soil mechanical mechanisms during installation, a numerical study was presented. The numerical study picks up to the soil mechanical mechanisms during pile installation in a simplified manner. Different zones with different relative densities have been introduced around the near and far field of the pile. It has been shown, that a decrease of density does not inescapably lead to a weaker lateral bearing behavior. The combination of de-and increase of density in the near and far field around the pile controls the lateral bearing behavior.

This leads to the conclusion, that a correct determination of the different zones of influence is important in order to simulate the correct lateral bearing behavior. In this paper, these zones have been defined based on documented scaled model tests, theoretical approaches and numerical simulations of the pile penetration process. Nevertheless, further investigation of these zones of influence is necessary, especially for vibratory-driven monopiles.

Still, this simplified approach shows a possibility for engineering practice to estimate the lateral bearing behavior of monopiles based on their installation method, without conducting expensive computational simulations of the installation process (as shown by e.g. Labenski et al. 2016) or timeconsuming large scale model tests (as shown by e.g. Moormann et al. 2016). Though, such simulations and scaled model tests are necessary to further validate this approach.

6 REFERENCES


