Numerical modeling of pile installation

Simulation numérique de l'enfoncement des pieux

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ABSTRACT

Pile installation leads to significant changes in the main state variables of the surrounding soil. Furthermore, the installation process may have an influence on adjacent or intersecting structures. In this paper, three-dimensional numerical analyses are presented to investigate the effect on the surrounding soil and on adjacent structures due to driving piles with open and closed cross-section into the subsoil. Two different installation methods are used: quasi-static pile jacking and vibratory pile driving. The numerical models are validated using measurement data of in-situ field tests during the construction of the quay wall CT4 in Bremerhaven.

Concluding a parametric study is fulfilled to show the effect of the installation method, the cross-section and the distance on the effect of installing a pile next to an adjacent building.

RÉSUMÉ

L'installation des pieux conduit à un changement significant des paramètres caractéristiques du sol. En plus, l'installation des pieux peut influencer les structures avoisinantes ou croisées. Dans cette contribution, des analyses tridimensionelles sont présentées pour investiguer l'influence de l'enfoncement des pieux avec une coupe transversale ouverte ou fermée aux paramètres caractéristiques du sol et aux structures avoisinantes. Deux méthodes d'installation différentes sont utilisées: L'enfoncement quasi-statique et le vibrofonçage. Les modèles numeriques sont verifiés en utilisant des résultats d'un mesurage pendant la construction du mur de quai CT4 à Bremerhaven.

En conclusion, une recherche paramétrique est exécutée pour montrer l'effet de la méthode d'installation, de la coupe transversale et de la distance à l'effet de l'enfoncement d'un pieux près d'un bâtiment avoisinant.

Keywords: Finite-Element-Method, pile installation, numerical simulation, hypoplasticity, pile group, pile jacking, vibrodriving

1 INTRODUCTION

Pile installation leads to significant changes in the main state variables of the surrounding soil depending on the cross-section of the driven piles and the installation method. Mainly, the void ratio distribution and the stress state around the driven piles are influenced. Although, the use of piles for deep foundations is state-of-the-art for many years, the influence of pile driving on the surrounding soil has not been fully investigated.

Numerical methods like Finite-Element-Method are a helpful tool to investigate the mechanisms that occur during pile installation. With the help of these simulations it is possible to describe the changes in void ratio and stress state around the driven piles in dependance of the installation method (Mahutka et al. 2006, Henke and Grabe 2006, Henke and Grabe 2007) and the cross-section of the installed piles (Henke and Hügel 2007). Even the mechanisms of soil plugging in open-ended piles can be examined (Henke and Grabe 2008) using Finite-Element-Method.

Another aspect is that piles are often driven next to existing structures. This may influence these structures. In-situ measurements at a quay wall at the port of Hamburg showed that the inclined piles of the pile grillage experienced more than 20 cm of extra deformation due to the installation of the intersecting vertical piles (Gattermann et al. 2005). This endangered the bearing capacity of the whole construction so that the installation method of the vertical piles had to be changed.

The intention of this paper is to use Finite-Element-Method to investigate the main factors which influence the additional loading on structures if a pile is driven next to it. The investigated parameters are installation method, cross-section, soil density and distance of the installed pile to the adjacent structure.

2 NUMERICAL MODELING OF PILE INSTALLATION

First, the numerical modeling of pile driving using Finite-Element-Method is shortly described. For a deeper insight into the special modeling techniques refer to Henke (2008).

2.1 *Modeling of pile penetration in continuous material*

The penetration of an object into a continuous material like the soil in the present study is only possible using a special numerical technique. In the axis of penetration a rigid tube with a thickness of 1 mm representing the shape of the penetrating object is modeled in frictionless contact with the surrounding soil. During pile penetration, the pile slides over the tube so that the soil is separated from the tube and contact between pile and soil can be established, see Fig. 1.

2.2 *Contact formulation*

The contact between soil and pile is discretized using Abaqus' built-in kinematic contact formulation based on a *master-slave-principle.* The Coulomb friction law is used as contact law.

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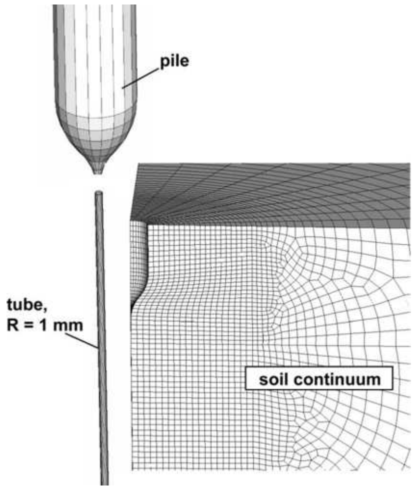

Fig. 1. Modelling technique to simulate pile penetration into a soil continuum

2.3 *Constitutive model*

In this study the penetration into non-cohesive, granular materials like sand is investigated. For this purpose the constitutive equation of hypoplasticity after Gudehus (1996) and von Wolffersdorff (1996) is used for the soil in the analyses. Hypoplasticity suits well the non-linear and anelastic behaviour of granular materials. This constitutive law is well suited to describe mechanical soil properties like dilatancy, contractancy and different stiffness for loading and unloading.

The rate dependant formulation depends on the current stress state $\mathbf{T}$ and the void ratio e.

In order to model the accumulation effects and the hysteretic material behaviour under cyclic loading Niemunis and Herle (1997) proposed the intergranular strain $\boldsymbol{\delta}$. This enhancement is used in the present study. Pore pressure effects have not been taken into account in this analysis.

2.4 *Finite-Element discretisation – investigated profiles*

Fig. 2 shows exemplarily the Finite-Element discretisation for the installation of a displacement pile using vibatory pile driving. The near field around the installed pile is discretised with solid continuum elements. The far field is modeled using infinite elements to minimize wave reflections at the boundary. The pile is modeled as a rigid body.

In the present study a parametric study is fulfilled investigating the installation of different profiles, see table 1.

Table 1. Investigated profiles

profile	pile toe area A_s [cm²]	outlined area A_u [cm²]	ratio $\xi=A_s/A_u$
Displacement pile, D = 16 cm	201	201	1.0
Displacement pile, D = 30 cm	706.9	706.9	1.0
Tubular pile, D_a = 61 cm	188.5	2922.5	0.065
HEM 200	131	453.2	0.289
PSt 600/159	203	2737	0.074

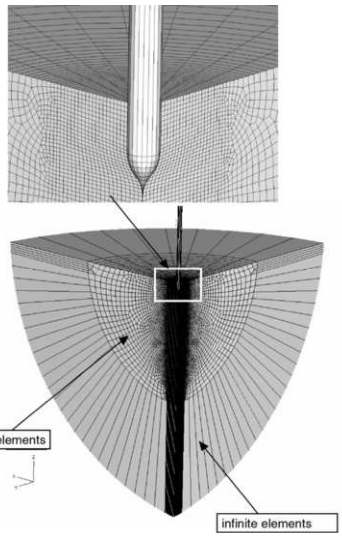

Fig. 2. Finite-Element mesh to simulate vibratory pile driving of a displacement pile

2.5 *Installation methods*

Two different installation methods are distinguished. On the one hand pile jacking which is modeled displacement controlled and on the other hand the dynamic installation method vibratory pile driving. Vibrodriving is simulated force-controlled by applying the dynamic force and the excitation frequency on the reference point of the rigid pile. The excitation is simulated using a sinusodial amplitude.

3 VALIDATION

The numerical simulations are validated by comparison with in-situ measurement results from field tests at the newly constructed container terminal CT4 in Bremerhaven. In the framework of these field tests ground vibration measurements have been carried out. During vibratory pile driving of one vertical pile of the quay wall construction the ground vibration velocities in several distances from the pile (2, 5, 10, 20, 40 and 70 m) are recorded.

In Fig. 3 the numerical model for back-calculation of the ground vibration measurements is depicted.

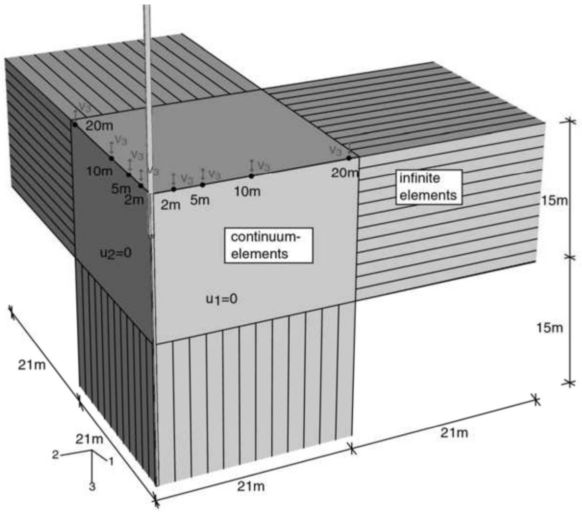

Fig. 3. Numerical model for back-calculation of the ground vibration measurements at CT4 Bremerhaven

In Fig. 4 the frequency spectrum of the ground vibration velocities of the measurement data and the numerical data are compared.

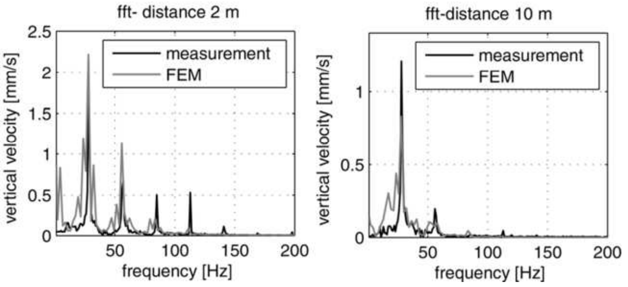

Fig. 4. Fast-fourier transformation of the ground vibration velocities of measurement data and numerical data

Regarding the results it can be stated that there is a very good accordance between numerical analysis and test data. Even the first harmonic of the vertical velocites can be simulated using Finite-Element-Method. For further information regarding the in-situ measurements at CT4 Bremerhaven refer to Henke (2008).

4 PARAMETRIC STUDY – ADDITIONAL STRESSES ON ADJACENT STRUCTURES

4.1 *Investigated system for the parametric study*

The main scope of this paper is to show the influence of pile driving on adjacent structures and to investigate the main parameters which mainly influence the additional loading due to pile installation. For this reason, a parametric study is carried out. Piles of different cross-section (see Tab. 1) are installed next to an existing wall which is modeled as a rigid boundary and is located in different distances from the penetrating pile. As a result of this parametric study the additional horizontal stress on the wall due to pile installation is calculated and compared, see Fig. 5.

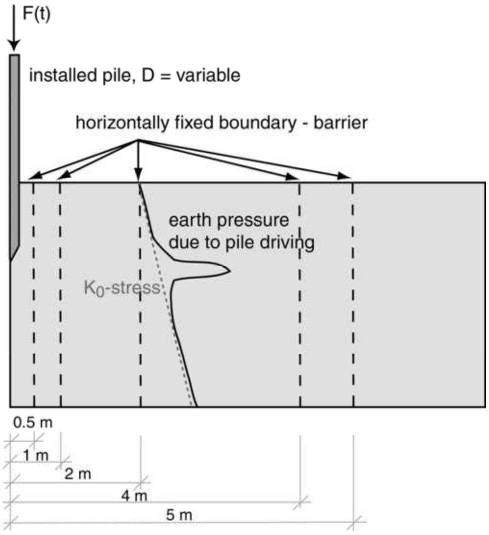

Fig. 5. Investigated system for the parameteric study concerning earth pressure increase due to pile installation

Furthermore, the parameters soil density and installation method (pile jacking, vibratory pile driving) are varied throughout the parametric study.

4.2 *Influence of distance*

In Fig. 6 the normalized horizontal stress $\sigma_{11}/\sigma_{11,0}$ against the distance of the wall towards the installed pile regarding pile jacking into medium dense *Karlsruher Sand* is shown.

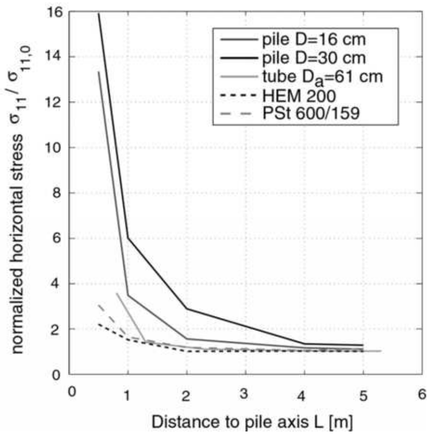

Fig. 6. Normalized horizontal stress against distance to axis of penetration for different cross-sections – pile jacking in medium dense sand

It can be seen that for every investigated cross-section the influence on the horizontal stresses acting on the wall decreases with increasing distance to the axis of penetration. For example, the installation of a pile with a diameter D = 30 cm leads to an increase in horizontal stress that is 16 times higher than the K_0-stress in a distance of 0.5 m from the penetrating pile. It can be stated that in a distance of 2 m from the newly driven pile only this pile has a significant influence on the earth-pressure distribution on the wall.

In Fig. 7 the results for vibratory pile driving in medium dense *Karlsruher sand* are depicted.

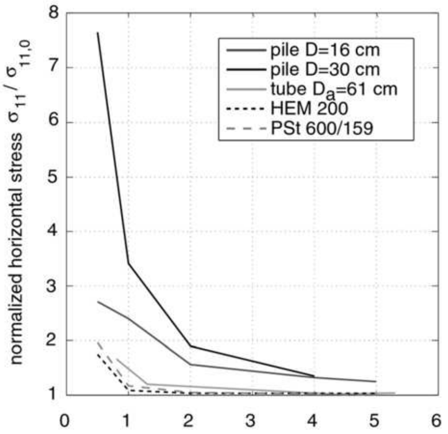

Fig. 7. Normalized horizontal stress against distance to axis of penetration for different cross-sections – vibratory pile driving in medium dense sand

Regarding these results, it becomes clear that the curves show the same characteristics compared to pile jacking. The influence on the adjacent wall decreases with increasing distance to the penetration axis and in a distance of about 2 m there is hardly any influence remarkable.

4.3 *Influence of installation method*

By comparison of Fig. 6 and Fig. 7 it can be found out that pile jacking induces much higher horizontal stresses acting on the neighboring wall compared to vibratory pile driving. Regarding the results of the displacement pile with diameter D = 30 cm the influence is about two times higher if the pile is jacked into the ground as if it is installed by vibratory pile driving.

4.4 *Influence of cross-section*

The cross-section has a main influence on the additional loading. Regarding the numerical results in Fig. 6 and 7 it becomes clear that the profiles with a high pile toe area A_S have a bigger influence on the increase in horizontal stress than those piles with a smaller pile toe area. On the one hand, the displacement pile with diameter D = 30 cm has the biggest pile toe area. Therefore, it leads to the highest increase in horizontal stress. On the other hand, the HEM 200 is the smallest investigated profile so that the effect on the adjacent wall is much smaller compared to all investigated profiles.

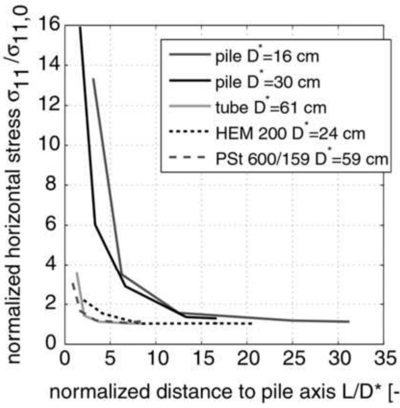

Fig. 8. Normalized horizontal stress against normalized distance to axis of penetration for different cross sections – pile jacking medium dense sand

Another interesting phenomenon can be seen in Fig. 8. In this figure the distance to the pile axis is normalized on the equivalent diameter D^*. D^* denotes the equivalent diameter of a circular pile with an equivalent area A_S. Regarding Fig. 8, it becomes clear that the ratio $\xi = A_S/A_u$ has a significant influence on the additional loading due to pile driving. Looking at Tab. 1 and Fig. 8 it can be found out that the profiles with similar ratio ξ have similar effects on the adjacent structure. For example, the displacement piles with $\xi = 1.0$ or the tube and the PSt 600/159 with ξ about 0.07 nearly become congruent.

4.5 *Influence of soil density*

At last, the parametric study leads to the result that higher soil density leads to a significant increase in the additional stress on the adjacent structure. This result cannot be fully described in the framework of this paper. For further information about the influence of soil density on the horizontal stresses refer to Henke (2008).

5 CONCLUSION

In this paper numerical models to simulate the pile driving process with three-dimensional Finite-Element analyses are presented. These models are well suited to simulate the penetration of piles with different cross-section into the subsoil using different installation methods.

The numerical models are validated by comparison of numerical results with measurement data. The measurements were carried out during the construction of the newly build container terminal CT4 in Bremerhaven.

Concluding, a parameteric study has been fulfilled to show the influence of pile driving on adjacent structures. With the help of this study it can be shown that the distance between newly driven pile and existing structure, the installation method, the cross-section of the installed pile and the soil density are the main factors which influence the additional loading on the adjacent structure. The main result of this parametric study are several diagrams which are a helpful tool for the practicing engineer to estimate the additional loading on existing structures due to pile driving.

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