Numerical Investigations on Vibratory Sheet Piling in Embankments using a Multi-Phase Material

Études numériques des effets de vibrofonçage sur les berges en utilisant une approche multi-phasique

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ABSTRACT: The influence of vibratory driving on the surrounding soil is difficult to predict due to complex mechanical processes in the soil. Effects like soil compaction, subsidence or a temporary reduction of the soil's shear strength can occur as a result of the dynamic loading. In case of water saturated soil additional effects like excess pore water pressure or soil liquefaction can occur. When driving piles in the area of embankments these effects can cause great deformations of the embankment and the driven pile. In this paper the lateral drift of a sheet pile wall due to the installation process in the area of an embankment is simulated by use of the finite element method using a coupled 2-phase approach to consider the development of excess pore water pressure and the resulting effects. The deformation mechanism and the mechanical processes in the soil are investigated. Further the calculated deformations of the sheet pile are compared to measurement data. A comparison of the results of a fully drained analysis and a coupled analysis considering the development of excess pore water pressure is done.

RÉSUMÉ : L'influence du vibrofonçage sur le sol environnant est difficile à prévoir en raison de phénomènes mécaniques complexes dans le sol. Les effets tels que la compaction du sol, l'affaissement ou la réduction temporaire de la résistance au cisaillement du sol peuvent se produire sous l'effet d'une charge dynamique. Dans le cas d'un sol saturé en eau, des effets supplémentaires tels que des surpressions interstitielles ou la liquéfaction des sols peuvent se produire. Lors de l'installation de pieux à proximité d'une berge, ces effets peuvent causer de grandes déformations de la berge et du pieu. Dans cette étude, le déplacement latéral d'une paroi de palplanches dû au processus d'installation à proximité d'une berge est déterminé en utilisant la méthode des éléments finis. Une approche biphasique est utilisée pour estimer le développement de la surpression interstitielle de l'eau et des effets qui en résultent. Le mécanisme de déformation et les phénomènes mécaniques dans le sol sont étudiés. Les déformations calculées pour la palplanche sont comparées aux résultats de mesure. Pour finir, la comparaison des résultats d'une analyse parfaitement drainée et d'une analyse biphasique est effectuée.

KEYWORDS: water saturated soil, soil liquefaction, two-phase approach, finite element method, installation process

1 INTRODUCTION

The influence of vibratory driving on the surrounding soil is difficult to predict due to complex mechanical processes in the soil. Effects like soil compaction, subsidence or a temporary reduction of the soil's shear strength can occur as a result of the dynamic loading. In case of water saturated soil additional effects like excess pore water pressure or soil liquefaction for water saturated loosely layered sands can occur. In particular, during driving of piles in embankments, such as railway embankments or shoreline stabilisations, these effects can influence the stability of the embankment and lead to a lateral drift of the driven pile or large deformations of the embankment. In practice, pile driving guides are usually used to prevent a drift of the pile during installation.

The finite element method provides a powerful tool for investigation of mechanical processes in soil during vibratory driving. Deformations of the embankment and the pile as well as the reaction forces can be predicted to design a pile driving guide.

In this paper, the lateral drift of a sheet pile wall of a quay wall, which has occurred due to the installation process, is simulated numerically. The soil is modeled by the use of a dynamic coupled 2-phase approach to investigate the mechanical processes in the soil and the development of excess pore water pressure during the vibratory driving. The deformation of the sheet pile and the soil as well as the reaction forces of a pile driving guide are investigated and compared with in-situ measured data. In previous three-dimensional calculations (Hamann and Grabe 2012a, Hamann and Grabe 2012b), in which the coupled approach was not yet available, fully drained conditions were assumed for simplification. In this paper simulations assuming coupled conditions with a predefined permeability and simulations assuming drained conditions are carried out and compared with each other to analyse the influence of excess pore water pressure on the deformations and reaction forces.

2 CONSIDERED CASE OF DAMAGE

As part of a power plant expansion a sheet pile wall acting as a new waterfront was built up in the area of an embankment consisting of sand. The sheet piles of type “AZ 41-700” were vibrated as double piles with a vibratory frequency of $f = 36$ Hz using an upper and lower pile driving guide as shown in Figure 1.

During the vibratory driving a lateral drift of the pile and the pile driving guide occurs. At the investigated cross section of the embankment horizontal deformations into the direction of the waterside of $u_h = 13$ cm at measuring point 1 and $u_h = 9$ cm at measuring point 2 were detected due to the installation process.

3 NUMERICAL MODELING

The described case of damage is simulated numerically by use of the finite elmente software Abaqus/Explicit (Dassault Systèmes 2009). A total stress analysis is carried out to consider the development of the pore water pressure for the area below the water level as presented in Pichler et al. (2012).

3.1 *Numerical Model*

As a current restriction of the dynamic coupled 2-phase approach two-dimensional plain strain analysis have to be carried out. The geometry and dimensions of the investigated cross section as well as the height of the water level are depicted in Figure 1. At the bottom and sideways surface of the soil body of the finite element model (see Figure 2) the displacement boundaries are fixed in vertical and horizontal direction and a hydrostatic pore water pressure is assumed. The sheet pile is modeled as a deformable body with a linear elastic material behavior. A Young's modulus of E = 210,000 MN/m² and a Poisson's ratio of $\nu = 0.3$ are assumed for the steel. Due to the elastic material behavior of the sheet pile a realistic wave propagation within the pile and lateral oscillations of the pile during the vibratory driving can be modeled. The sheet pile is modeled wished-in-place at its final penetration depth. The underlying assumption regarding the penetration process is, that the surrounding soil is mainly influenced by shaft friction. Toe resistance plays a minor role. The point of load application is at the head of the sheet pile.

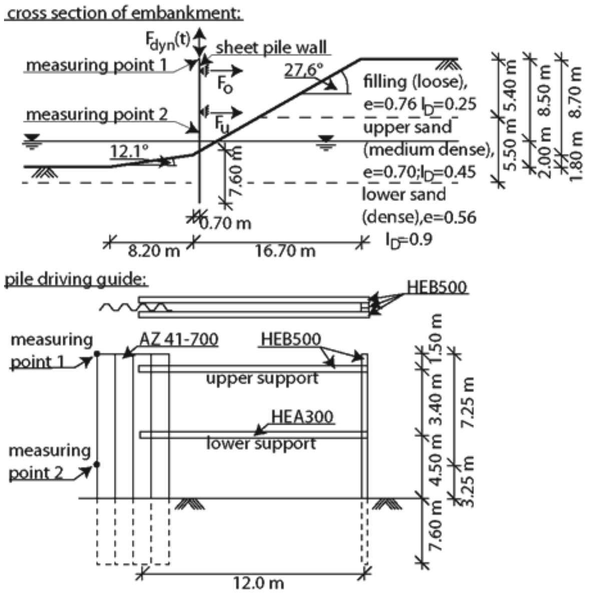

Figure 1. Top: cross section of the embankment; bottom: engaged pile driving guide.

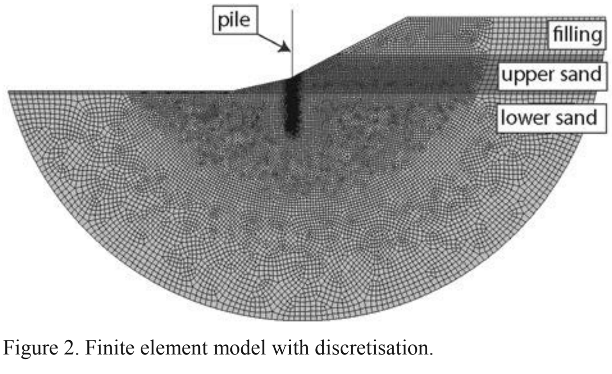

Figure 2. Finite element model with discretisation.

3.2 *Constitutive model of the sand*

A hypoplastic constitutive model is used to describe the non-linear and anelastic behavior and the dynamic compaction process of the sand being present in the embankment realistically. The hypoplastic model in the version of Gudehus (1996) and von Wolffersdorff (1996) in the formulation of von Wolffersdorff (1996) with the extension of intergranular strains by Niemunis and Herle (1996) is used. Modeling the sand by use of hypoplasticity, typical characteristics like dilatancy, contractancy, different stiffness for loading and unloading as well as the dependency of the stiffness from the void ratio and mean pressure can be considered. The sands, present in the embankment, are relativ inhomogeneous regarding their composition. Hypoplastic material parameters of the sands in situ are not available. For simplification the parameters of a so-called "Karlsruher Sand" are used for each soil layer, even though they comply with some layers insufficiently. A distinction between the three soil layers depicted in Figure 1 is done by specifying the bulk density in terms of an initial void ratio as depicted in Figure 1. The material parameters of Karlsruher Sand used in the analysis are given in Table 1.

In simulations considering coupled conditions for areas of the embankment consisting of water saturated sands the hypoplastic constitutive model of the solid skeleton is extended. A continuity equation for the water phase to describe the development of the pore water pressure is introduced (Pichler et al. 2012). The flow of the water through the sand is described by Darcy's law (Darcy 1856). The permeability was determined by soil tests and is assumed to k_f = 1.0·10^{-4} m/s for each soil layer.

Table 1. Hypoplastic material parameters of Karlsruher Sand.

Parameter	φ_c (°)	h_s (MPa)	n (-)	e_{d0} (-)	e_{c0} (-)	e_{i0} (-)	α (-)
Karlsruher Sand	30	5,800	0.28	0.53	0.84	1.00	0.13
Parameter	β (-)	m_T (-)	m_R (-)	R (-)	β_R (-)	χ (-)	
Karlsruher Sand	1.05	2	5	0.0001	0.5	6.0	

3.3 *Contact formulation*

The contact between pile and soil is modeled by use of a surface to surface contact algorithm (Dassault Systèmes 2009). An angle of wall friction of $\delta = 2/3\ \varphi'$ with a friction angle of φ' = 30° is assumed. An undrained soil behaviour is assumed at the contact surface between pile and soil.

3.4 *Discretisation*

The finite element model depicted in Figure 2 is discretised with approx. 15,000 four-node plain strain elements with reduced integration and hourglass control.

3.5 *Loading*

A geostatic stress state with a hydrostatic pore water pressure distribution is defined as initial condition. The vibratory driving of the sheet pile is simulated displacement-controlled to prevent a penetration of the sheet pile into the finite element mesh of the soil body as it happens in a force-controlled simulation. Therefore a harmonically oscillating vertical displacement is applied to the head of the sheet pile as an external loading for a period of 10 s. The magnitude of the oscillation is determined in a short foregoing force-controlled simulation with a dynamic vibrating force of F_{dyn} = 1500 kN. After the vibratory driving no external loading except gravity is applied to the model for a period of 10 s to investigate the behavior of consolidation in the model.

4 RESULTS

Considering an elastic pile driving guide as in reality was not possible in the numerical simulation due to numerical instabilities of the analysis caused by too many interactions in the model. For simplification the investigation of the presented case of damage is done by studying two limit cases:

1. Free-riding vibratory driving without a pile driving guide
2. Assumption of a rigid pile driving guide

The behavior of the real pile driving guide is to be expected between these two limit cases. Furthermore the deformations and reaction forces of the sheet pile obtained by an analysis with coupled conditions ($k_f = 1.0 \cdot 10^{-4}$ m/s) are compared to results obtained by assuming fully drained. The difference and the error done by assuming fully drained conditions can be shown.

4.1 *Deformation mechanism*

Due to the vibratory driving a cyclic shearing of the soil and a rearrangement of the soil particles with the result of soil compaction occurs in the near-field of the sheet pile. The deformation mechanism of the embankment shown in Figure 3 can be divided into two zones. In the first zone, in the near-field of the sheet pile, the soil is moving in approximately vertical direction due to soil compaction with the result of surface settlements. In a second zone at the surface of the embankment a layer of soil is sliding down the embankment into the compacted near-field and pushes against the installed sheet pile. This is the main reason of the observed horizontal deformations of the sheet pile wall. The presented deformation mechanism is in accordance to results of fully drained conditions of the soil (Hamann and Grabe 2012b).

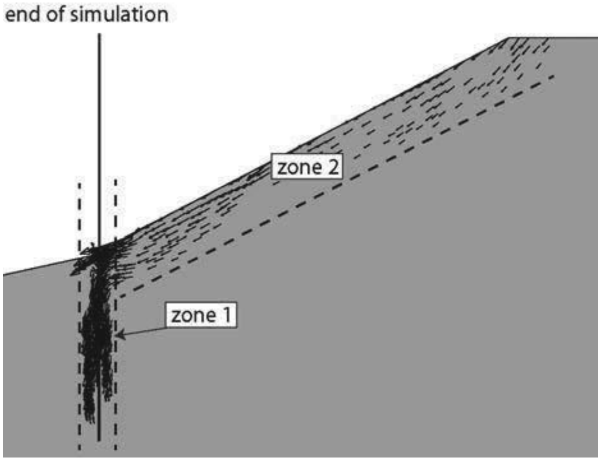

Figure 3. Deformation mechanism of the embankment for coupled conditions of the soil, free-riding vibratory driving.

4.2 *Horizontal deformation of the sheet pile*

The evolution of the deformation of the sheet pile with respect to time are shown in Figure 4 for the case of a free-riding vibratory driving with coupled and fully drained conditions. In case of a rigid pile driving guide the deformations are smaller than 5 mm and thus not illustrated. The great difference regarding deformations of coupled and fully drained conditions is caused by the velocity of soil compaction. In case of fully drained conditions no excess pore water pressure and thus no resistance against a reduction of the void volume can develop. Hence the whole deformation mechanism of the embankment caused by soil compaction, consisting of a layer of soil sliding down the embankment and pushing against the sheet pile, develops faster as for coupled conditions. Since no asymptotic behavior of the evolution of the deformation can be seen in both cases, a further increase of the deformations can be assumed in case of a longer simulation time. A possible limit of the deformation in case of a longer simulation time will be reached faster with a drained analysis.

In case of coupled conditions a very fast increase of the deformation after the beginning of the vibratory driving occurs due to soil liquefaction in the near-field of the pile. Afterwards the deformations are increasing slower, since the soil is compacted slower due to the development of excess pore water pressure. The movement of the layer of soil sliding down the embankment and thus the deformation of the sheet pile is slower. At the end of simulation horizontal deformations of u_{h1} = 11.5 cm at measuring point 1 and u_{h2} = 5.5 cm at measuring point 2 are calculated.

It has to be considered, that the deformations illustrated in Figure 4 are calculated for the case of a free-riding vibratory driving and that restrictions resulting of a two-dimensional analysis have to be observed. In reality the single double piles are installed one by another and the used pile driving guide which is fixed at the already installed piles can also drift laterally due to the installation process.

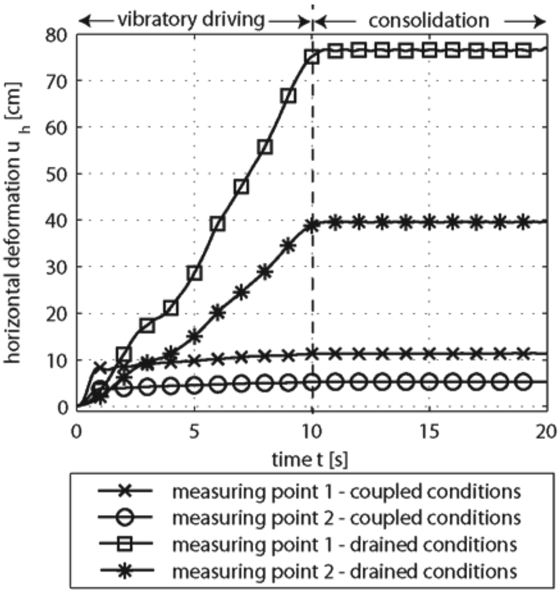

Figure 4. Evolution of horizontal deformation of measuring point 1 and 2, comparison of coupled ($k_f = 1.0 \cdot 10^{-4}$ m/s) and fully drained conditions of the soil, free-riding vibratory driving.

4.3 *Reaction forces of the pile driving guide*

The evolution of the horizontal reaction forces of a rigid pile driving guide with respect to time is given in Figure 5 for the case of coupled and fully drained conditions. The direction of action of the reaction forces is depicted in Figure 1. Due to the cyclic shearing of the soil caused by the vibratory driving a very fast decrease of the horizontal and vertical stress state in the near-field of the sheet pile occurs (Hamann and Grabe 2012b). Furthermore a layer of soil is sliding down the embankment and pushes against the sheet pile, which leads to a sided loading of the pile, see Figure 3. Thus a fast increase of the reaction forces occurs at the beginning of the vibratory driving in both cases.

In case of fully drained conditions a further increase of the reaction forces can be observed because the layer of soil sliding into the compacted near-field and thus the sided loading of the pile becomes bigger with progressing soil compaction.

In case of coupled conditions the reaction forces decrease after the initial increase. The evolution of the reaction forces is the result of a complex interaction of a sided increase of excess pore water pressure due to the layer of soil sliding into the near-field and pushing against the pile and a simultaneously occuring consolidation. Furthermore the horizontal effective stress state is reduced in the near-field up to a locally limited soil liquefaction arround the pile.

4.4 *Distribution of pore water pressure and effective stress*

The distribution of the pore water pressure and the effective stress in the area of the embankment is shown in Figure 6 after 10 s of vibratory driving. A distinct increase of the pore water pressure in an area of approx. 2.4 m arround the pile can be observed. Excess pore water pressure of approx. u_w = 20 kN/m² in the upper area of the near-field and u_w = 60 kN/m² at the pile toe arise.

Regarding the effective vertical stress state a reduction of the effective vertical stress state can be observed in the near-field. In a distance of 1.0 m around the pile a temporary soil liquefaction occurs. On the passive side of the pile the area becomes little larger at the surface area.

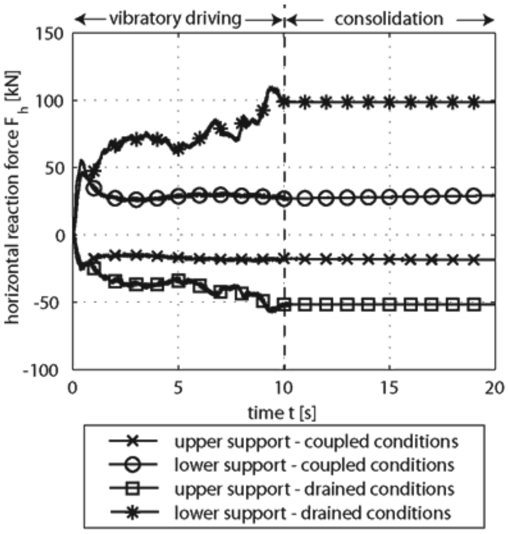

Figure 5. Evolution of horizontal reaction forces of the upper and lower support, comparison of coupled (k_f = 1.0·10^{-4} m/s) and fully drained conditions of the soil, rigid pile driving guide.

5 CONCLUSIONS

The numerical simulation of a case of damage, arised during the installation process of a sheet pile wall in the area of an embankment was presented. By use of the finite element method the mechanical processes in the soil during the vibratory driving can be explained e.g. a temporary and locally limited soil liquefaction. The calculated deformations of the installed sheet pile are in the range of the measurement data in case of a coupled analysis. Thus the deformation mechanism can be reproduced qualitatively correctly and in a quantitative acceptable way. The results of a fully drained analysis show great deviations to the measurement data. Regarding the calculated reaction forces of a pile driving guide a fully drained analysis provides also a different evolution of the reaction forces with respect to time compared to a coupled analysis.

In case of water saturated soil a consideration of the development of excess pore water pressure and the resulting effects seems to be of great importance for a numerical simulation or a prediction of geotechnical problems as presented.

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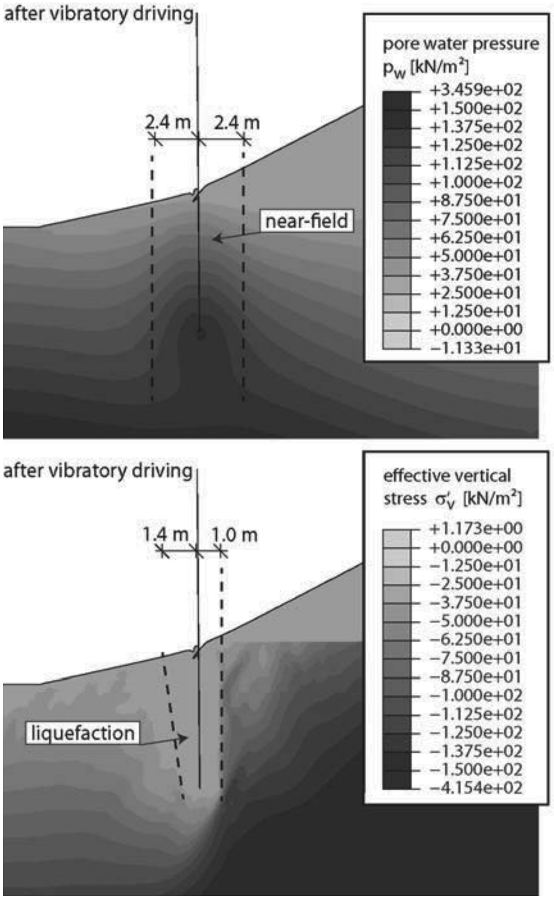

Figure 6. Distribution of pore water pressure and effective stresses in the area of the embankment after 10 s of vibratory driving.

7 REFERENCES

Darcy H. 1856. *Les fontaines publiques de la ville de Dijon*. Dalmont, Paris.

Dassault Systèmes 2009. Analysis User-Manual. Abaqus 6.9.

Gudehus, G. 1996. A comprehensive constitutive equation for granular materials. Soils and Foundations 36(1), 1-12.

Hamann T. and Grabe J. 2012a. Numerical investigations on vibratory sheet piling in embankments. Proceedings of Baltic Piling Days 2012 in Tallinn (Estonia), electronically published.

Hamann T. and Grabe J. 2012b. Numerische Untersuchungen zur Rammung von Profilen in Böschungen. Proceedings der 4. VDI-Fachtagung Baudynamik 2012, VDI-Berichte 2160, 625-640.

Niemunis, A. and Herle, I. 1996. Hypoplastic model for cohesionless soils with elastic strain range. Mechanics of cohesive-frictional materials 2(4), 279-299.

Pichler T., Pucker T., Hamann T., Henke S. and Qiu G. 2012. High-Performance Abaqus simulations in soil mechanics reloaded - chances and frontiers. Proc. of International Simulia Community Conference in Providense, Rhode Island/USA, pp. 237-266.

von Wolffersdorff, P.-A. 1996. A hypoplastic relation for granular material with a predefined limit state surface. Mechanics of cohesive-frictional materials 1, 251-271.