Investigation of the Long-Term Cyclic Behaviour of Monopile Foundation by Impact and Vibratory Installation

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Abstract. This paper presents the results of the numerical investigation of the cyclic behaviour of the monopile which has been installed by impact and vibratory driving. By the numerical investigation, two different phases were considered: installation process (phase 1) and lateral cyclic loading (phase 2). In the first phase, a model with MMALE formulation for the simulation of large deformation of soil due to penetration was used. Hereby the impact and vibratory driving were modelled. In the second phase, a model with Lagrangian formulation was used. In this model, an explicit accumulation model (HCA-Model) for the simulation of the long-term cyclic loading was applied. The influences of the installation were considered in the second model in form of the initial condition of the void ratio and stress states after the penetration of the pile which were adapted from the first model. The investigation showed a significant effect of the installation on the behaviour of the pile. In the small scale models, the vibratory pile indicated a stiffer behaviour on the lateral cyclic loading in comparison to the impact driven pile.

Keywords: Installation effects · Vibratory driving · Impact driving · Long-term cyclic loading · Accumulation deformation · Explicit accumulation model · MMALE formulation

1 Introduction

In geotechnics, the penetration of a pile in the ground is one of the most complicated processes with different complex mechanical phenomenon. Furthermore, for different soil types and different boundary conditions, various installation methods can be used (e.g.: jacking, drilling, impact or vibratory driving etc.). Therefore, it is still a big challenge for engineers to predict the installation and to consider the influence of this process in the design phase.

During the penetration of a pile in sand, the initial stress condition and void ratio of the sand is changed significantly. This can have a crucial influence on the bearing capacity and deformation behaviour of the installed pile. However, in many analytical

D. V. K. Huynh et al. (Eds.): VSOE 2021, LNCE 208, pp. 140–147, 2022.
https://doi.org/10.1007/978-981-16-7735-9_13

and numerical design approaches this process is usually ignored (calculation with K_0-stress condition and constant void ratio) or strongly simplified. In the present study, the behaviour of the monopile which has been installed by impact and vibratory driving was investigated using different numerical models. With the aim to validate the simulation results, small scale model tests were conducted.

2 Numerical Calculation Concept

Due to the fundamental difference of the mechanical phenomenon and the behaviour of soil due to the installation and the loading of a monopile, different numerical formulations and calculation methods were required for the simulation of these processes. Therefore, in the present study, a concept with two separate simulations were carried out for the installation and loading process (Fig. 1).

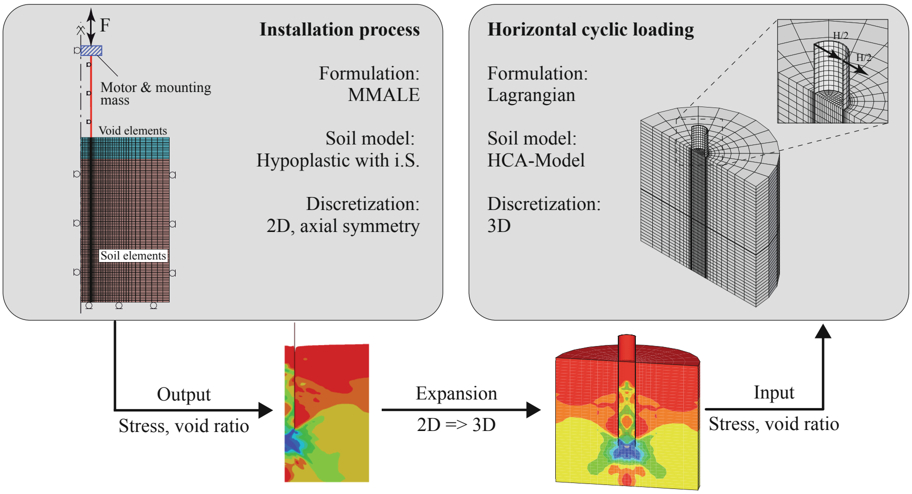

Fig. 1. Schematic view of the calculation concept with models for installation process (left) and for horizontal cyclic loading (right)

In the first simulation, a model with MMALE formulation [1] was used to simulate the large deformation by the penetration of the pile in sand. Hereby two installation methods (impact and vibratory driving) were considered. In the second phase, a model with Lagrangian formulation (small strain) was used. The influences of the installation process were considered in the second model in form of the initial condition (void ratio and stress states) which is based on the condition of soil after the penetration of the pile in the ground. The state variables of all integration points at the end of the first model (2D axis symmetric model) simulation were extrapolated in to a 3D model. Afterward, these variables were applied in the second model for the long-term cyclic loading. While in the first model, the Hypoplasticity with Intergranular Strain (Niemunis & Herle [2]) was used to describe the behaviour of sand, in the second model, the explicit calculation method with HCA-Model was applied [3]. This calculation method is a combination of different material models which enables to simulate the boundary condition with a large number of load cycles effectively. Details of the calculation steps with the explicit accumulation model were presented by Le & Rackwitz [4] and Le et al. [5]. All calculations in this study were conducted under fully drained condition.

3 Soil Conditions After the Installation Process

In the first part of this study, the modelling of the pile penetration process using vibratory and impact pile driving was conducted. The theoretical backgrounds and details regarding numerical algorithms and procedures by using the MMALE technique were published in previous works of the research group at TU Berlin. The results used in the following sections and several investigations were presented by Daryaei et al. [6] in detail. For further information about the calculations, the authors would like to refer to this paper.

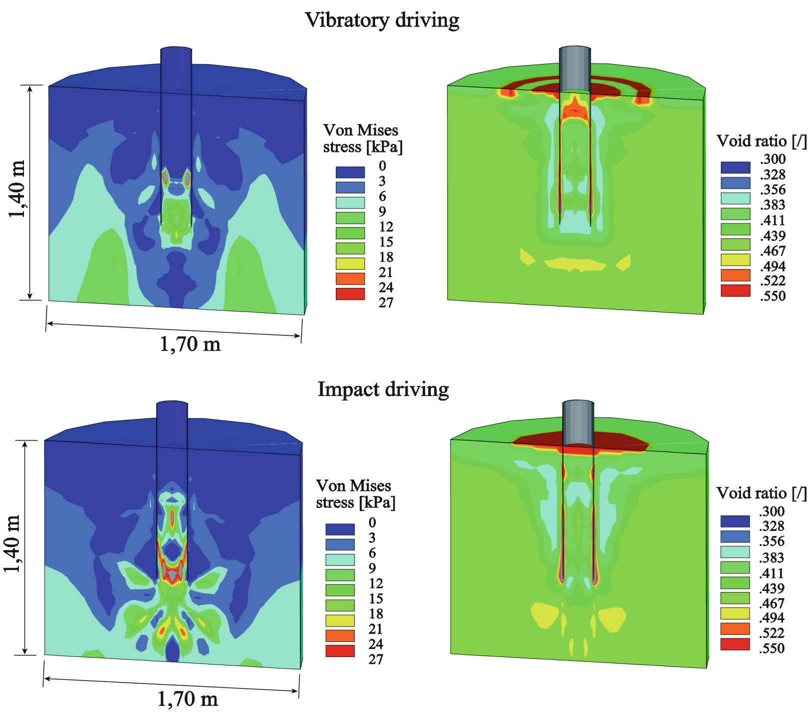

Fig. 2. Distribution of the Von Mises stress and void ratio before the horizontal loading (after the installation process)

As an output of these simulations, the soil conditions after the installation including the distribution of the void ratio and stress are delivered. Figure 2 shows the initial condition of the soil before the cyclic loading in the second model adapted from the results of the installation simulations. The presented stress condition is von Mises stress, which is defined with $\boldsymbol{q}(\sigma) = \sqrt{3/2} \cdot \|\boldsymbol{\sigma}_{dev}\|$. It can be observed that there are significant differences in stress as well as in void ratio between vibratory and impact driving. In comparison to the condition of the soil before the pile installation, stress condition and void ratio distribution are changed. By impact driving, it can be seen that the stress values under the pile tip were significantly higher compared to vibratory driving. This can be explained with the well-known plugging effect that can occur during impact penetration. This effects were also observed in the conducted small scale model tests. The disturbed zone around the pile by the void ratio which is developed during the installation seems to be larger for the pile with impact driving. In both simulations, a thin loosening zone arose directly at the pile shaft.

4 Simulation of the Cyclic Loading

4.1 Numerical Model and Load Program

In this study, for the modelling of the loading phase with a large number of load cycles, the explicit accumulation model (HCA-Model) was used. The discretisation of the model is shown in Fig. 1 (right) as well as presented by Le et al. [7] in detail. Figure 3 presents the schematic view of the load program, which is identical in both calculations for impact and vibratory driving. The horizontal force was applied in two outer points of the pile head and 30 cm over the sand surface. At the beginning of the test a static preloading of 450 N was applied. Afterwards two load packages with 1,000 cycles each followed. The first package had a force amplitude of $F^{ampl} = 225\,N$ with an average force $F^{avg} = 122{,}5\,N$. In the second package the force amplitude was $F^{ampl} = 450\,N$ and the average force $F^{avg} = 225\,N$.

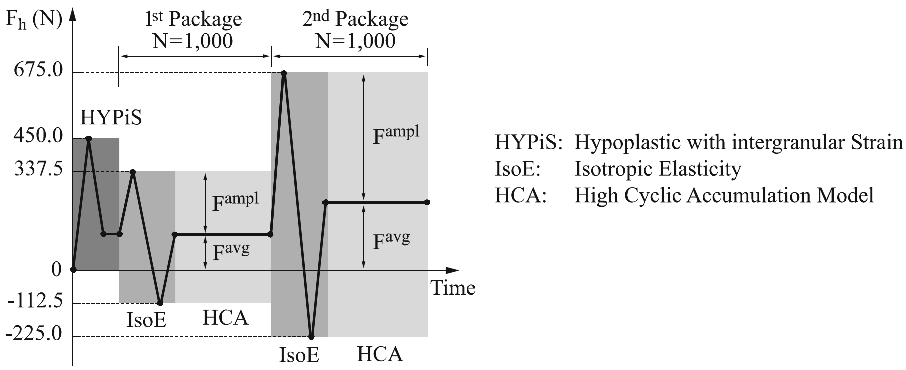

Fig. 3. Horizontal loading schema for numerical simulation

In the calculation concept with the HCA-Model used in this study, the first cycle of each package is simulated with the isotropic elasticity (IsoE) [8]. The preloading was calculated with Hypoplasticity with Intergranular Strain (HYPiS). The HYPiS has already demonstrated its ability to represent soil behaviour under monotonic loads down to a few loading cycles. Due to the "ratchetting" problem by un- and reloading, according to Wichtmann [9], the simulation with HYPiS in the second cycle can lead to unrealistic deformation predictions. Therefore, for the second cycle and the update cycles performed during explicit calculation, the Isotropic Elasticity (IsoE) was preferred.

4.2 Material and Parameters for the Constitutive Models

For this study, Berlin Sand was used for the investigations. This is a medium to coarse sand with a uniformity coefficient $C_u = 3.3$ and an average grain diameter $d_{50} = 0.55$ mm. The minimum and maximum density was determined according to the German standard DIN 18126 with $\rho_{d,max} = 1.906\,\mathrm{g/cm^3}$ ($e_{min} = 0.391$) and $\rho_{d,min} = 1.570\,\mathrm{g/cm^3}$ ($e_{max} = 0.688$). The parameter of this material for the HYPiS and HCA-Model are presented in Le et al. [7]. In comparison to [7], the record cycle was calculated in this study with the IsoE (the implicit cycle for the evaluation of ε^{ampl}). The parameters of this material model for Berlin Sand are listed in Table 1. These parameters were calibrated using results of the cyclic triaxial tests. The material used for the pile was steel. In the numerical simulation it was modelled with the linear elastic material model.

Table 1. Parameter of Berlin Sand for isotropic elasticity

C_{1c}	C_3	C_4	C_5
725	1.70	0.50	0.40

4.3 Validation of the Numerical Results

For validation of the numerical model the results of the small scale model tests were used. In a test setup at the TU Berlin, cyclic tests on the pile with impact and vibratory driving were carried out. The test set up consisted of a steel container with inner base dimensions of 1.70 m by 0.90 m and a height of 1.15 m plus an additional 0.25 m of drainage layer at the bottom of the container. This dimensions and boundary conditions were considered in the numerical simulations presented above. After preparation using dry pluviation technique, the sand placed in the container was saturated from the bottom through the drainage layer. The steel pile has an outer diameter of 200 mm, a wall thickness of 4 mm and achieved a penetration depth of 0.87 m. A system of guide rollers above the container ensured vertical penetration of the pile along the glass panel and restricted any tilt. Technical data of the test setup and results of the experimental investigation were presented in [10] and [11] in detail.

Figure 4 shows the results of the FEM simulations in comparison with those of the experimental model. These diagrams show the displacements of the pile at the ground level. By the FEM-results, the values from the explicit calculation present the average displacement of each cycle, while the results from the experimental model test include the complete movement of the pile (with oscillation due to un- and reloading). In both installation methods the FEM results were in good accordance with the conducted model tests. At the end of the second package the difference in displacement at the ground level was less than 5%. The results of the FEM calculation as well as of the experimental model tests indicate a stiffer behaviour of the vibratory driving pile in case of cyclic lateral loading.

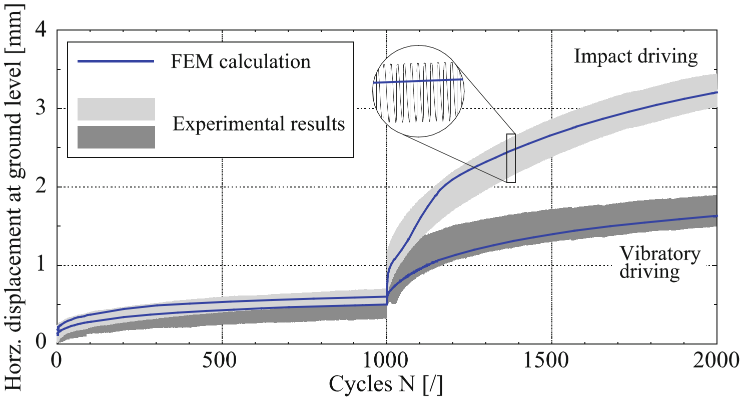

Fig. 4. Validation of the FEM calculation using results of the small scale model tests for impact and vibratory driving

5 Parameter Study

In this part of the study, the influence of the separate state parameters from the results of the installation simulation are investigated. Figure 5 presents results of a test series with different initial conditions. In the first simulation the installation effects were not taken into account (black curves). The initial condition of the soil was assumed in these investigations with a constant density and homogeneous stress distribution under K_0-conditions. At the beginning of the cyclic loading in this calculation, a condition of the soil with the relative density $I_{D0} = 75\%$ and $K_0 = 0.5$ was applied (the same density at the beginning of the pile penetration). In the second simulation the stress condition was transferred from the first model of pile penetration while the void ratio remained constant (magenta dashed curves). Here, only the influence of the change in stress was considered. In the next calculation, only the effect of the change in density was considered. The distribution of the stress condition here was homogeneous (according to K_0-condition) while the void ratio was adapted from the penetration model (orange pointed curves). For the last model, both variations of stress and density parameters were considered (blue curves, same simulation as in Fig. 4).

The development of the pile deformation in Fig. 5 showed the difference when installation effects were considered. In the literature, the installation effects are usually not considered, i.e. the so called “wished in place” technique is used. Obviously, the installation process had a significant effect on the pile deformation. In both cases of vibratory and impact driving, the penetration of the pile led to stiffer soil behaviour. The same trend was observed by the numerical study from Staubach et al. [12]. It can be seen for both installation methods that the change in density resulted in a larger reduction of horizontal pile head displacement compared to the change in stress. Especially in the first loading package the effects of the installation process were mainly dominated from the change in void ratio.

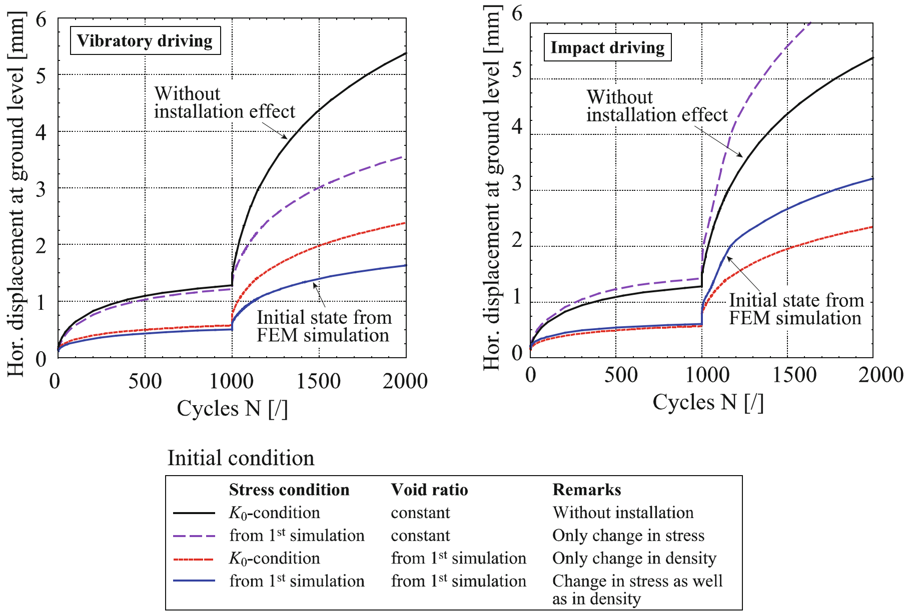

Fig. 5. Parameter study for the influence of the installation effects

6 Conclusions

In this study a numerical methodology with two separate models was carried out to consider the influence of the installation process on the cyclic behaviour of the monopile. The effects of the impact and vibratory driving were investigated. The comparison between numerical and experimental results showed good agreement for vibratory as well as for impact driving. In comparison with impact driving, vibratory driven piles had smaller deformations under the same cyclic load (stiffer behaviour). In total, the calculation without installation effect (using “wished in place” technique) resulted in larger deformations of the pile and was more conservative.

Acknowledgement. The investigation presented was partly supported by INNOGY SE as part of the research project “Cyclic and Near Field Effects of Vibratory Driving in Sand - CAFE”, which is gratefully acknowledged here.

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