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# Numerical Investigation of Installation Effects on the Cyclic Behaviour of Monopile Foundation Under Horizontal Loading

Viet Hung Le(✉), Fabian Remspecher, and Frank Rackwitz

Soil Mechanics and Geotechnical Engineering Division,
Technical University of Berlin, Gustav-Meyer-Allee 25, 13355 Berlin, Germany
hung.le@grundbau.tu-berlin.de
https://www.grundbau.tu-berlin.de

**Abstract.** This paper presents results of the numerical investigation of cyclic behaviour of monopile foundations for offshore wind power turbine considering effects of the vibratory driven installation process. The dimensions and properties of the soil in the direct vicinity of the pile shaft are based on the experimental investigation. The sophisticated High Cyclic Accumulation model (HCA-model) is used for the simulation of the cyclic lateral loading. This novel approach of refining the numerical soil model for the lateral loading simulation highlights the significance of induced changes in the soil structure due to the installation process. The parameter study shows that a narrow loosening zone directly around the pile shaft increases the lateral deflection of the pile head significantly compared to a homogeneous soil distribution. A wider zone of compacted soil further away from the pile on the other hand only has a negligible influence on the deflection behaviour.

**Keywords:** Vibratory driven installation · Offshore foundations
High cycle accumulation model · Monopile foundation · FEM

## 1 Introduction

To reduce the installation time and costs for offshore pile foundations, the method of vibratory installation is aimed to be established as an alternative approach in recent years. Although the technique of vibratory installation has been used for decades for the installation of temporary and permanent sheet pile or soldier pile walls, the application for offshore foundations demands new design methods and loading scenarios. This paper will present the numerical investigations of the monopile foundation under cyclic lateral loading. Based on the results of the model tests presented in the separate paper "*Vibratory driven installation of monopoles – an experimental investigation of the soil-pile interaction*" [1], the influence of the installation process will be considered in the numerical models.


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## 2 Numerical Simulation of the Cyclic Horizontal Behaviour

### 2.1 Explicit Calculation Concept

For the FE calculations of boundary value problems with cyclic loading there are two fundamentally different ways of calculation: the *implicit* and *explicit* method (*implicit* and *explicit* are here not to be confused with the integration algorithm). In an implicit procedure the cyclic loading at each cycle is calculated based upon the relationship of the stress-strain rate at many increments. The accumulated strain results from the not completely closed stress-strain hysteresis due to the plastic strain at the re- and unloading cycle. Because of this systematic error of the material model and the numerical error of the integration routine this method is confined to a very limited number of loading cycles (N < 50 according to Niemunis [2]). In order to investigate high cyclic problems the explicit calculation method delivers a more accurate result. The plastic strain in this approach is explicitly calculated with an empirical approximation. The accumulation under cyclic loading is analogue to the creep of a viscous material. Instead of using the time $t$ as the reference the number of cycles $N$ is being referred to. This explicit method greatly reduces the calculation effort (calculation time) and the systematic error.

In the numerical investigation of this study, the HCA model (**H**igh-**C**ycle-**A**ccumulation model [3]) will be used. For the FE calculation with the HCA model a conventional constitutive law is necessary in addition to the explicit accumulation model. With this constitutive law the monotonous loading up to the average stress and the first two cycles are implicitly calculated (see Fig. 1). In the second cycle the strain paths at each integration point will be recorded. These results in turn are required to determine the strain amplitude $\varepsilon^{ampl}$. The algorithm for the calculation of $\varepsilon^{ampl}$ is described by Le [4] in detail. The strain amplitude $\varepsilon^{ampl}$ is an important input parameter for further calculation steps. The calculation of subsequent cycles is done explicitly with the accumulation model (HCA model). Here, the plastic strain of each integration point is calculated depending upon the increment of the cycle number. The increment $\Delta N$ can be small at the beginning of the calculation and larger with an increasing number of cycles (at the beginning $\Delta N = 0.1$ and at the 100,000$^{th}$ cycle $\Delta N = 1,000$). During the explicit calculation the strain amplitude $\varepsilon^{ampl}$ is assumed to be constant. For the implicit calculations, the hypoplatic model with intergranular strain (HYPiD) according to Niemunis and Herle [5] is used. The explicit calculations done with the HCA model have been used successfully in several FE-calculations [4, 6].

### 2.2 FE-Model and Boundary Condition

In this study, the numerical investigation focuses on the deformation behaviour of the pile under lateral cyclic loading considering the installation effects. The results from the model test shown in Fig. 4 indicate that the installation process has a significant impact on the density of the sand around the pile shaft. This change in the soil properties will be considered in the following FE-simulation.

By the FE-calculation in this study, the HCA-Model and additional material model were implemented in the FEM-Program ANSYS® 17.0 under the subroutine

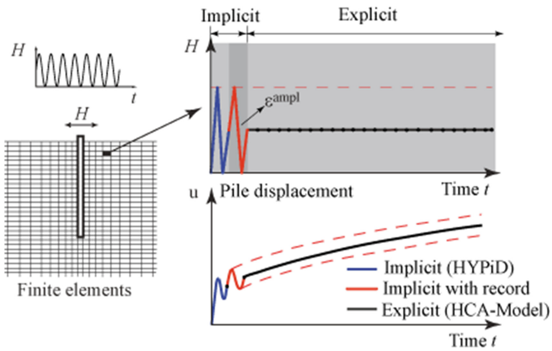


**Fig. 1.** Schematic view of the calculation with HCA model

"USERMAT". For the discretization, the 8-Node element SOLID185 was used with linear shape function and full integration for the 3D simulation. The parameters of the HCA-Model for the test sand are shown in Table 1. These were calibrated based on result of eleven cyclic triaxial tests. In the Table 2, the parameter for Hypoplastic with intergranular strain are listed. The detailed calibration procedure and the results of the laboratory tests can be taken in the research work by Le [4]. In all the calculation, the steel pile was simulated with linear elastic material model with a Young's modulus $E = 2.1 \cdot 10^5 MN/m$, Poisson's ratio $v = 0.3$ and a bulk density of $\rho = 7850\,\mathrm{kg/m^3}$. The interaction between pile and soil was modelled with a contact pair using Mohr-Coulomb-contact with a friction coefficient of $\mu = 0.5$. The sand is fully saturated. The boundary condition for all calculations was chosen in the way that the nodes on the bottom of the system are fixed (displacements in all directions are blocked). The nodes on the side surface could only move vertically (displacements in horizontal direction are blocked).

**Table 1.** Parameter of HCA-Model for Berlin sand

| $C_{\mathrm{ampl}}$ | $C_{\mathrm{N1}}$ | $C_{\mathrm{N2}}$ | $C_{\mathrm{N3}}$ | $C_p$ | $C_{\mathrm{Y}}$ | $C_e$ | $C_{\pi 1}$ | $C_{\pi 2}$ |
|---|---|---|---|---|---|---|---|---|
| 2.05 | 0.002 | 0.022 | $8.5 \cdot 10^{-5}$ | 0.55 | 1.96 | 0.325 | 56 | $1.25 \cdot 10^{-3}$ |

**Table 2.** Parameter of Hypoplastic with intergranular strain for Berlin sand

| $\varphi_c$ [°] | $h_s$ [MPa] | $n$ | $e_{d0}$ | $e_{c0}$ | $e_{i0}$ | $\alpha$ | $\beta$ |
|---|---|---|---|---|---|---|---|
| 31.5 | 2300 | 0.30 | 0.391 | 0.688 | 0.791 | 0.13 | 1.0 |

| $m_R$ | $m_T$ | $R$ | $\chi$ | $\beta_r$ |
|---|---|---|---|---|
| 4.4 | 2.2 | $10^{-4}$ | 6.0 | 0.2 |

Based on the results of the model tests, presented in the separate paper "*Vibratory driven installation of monopoles—an experimental investigation of the soil-pile interaction*" [1], the condition of the soil after pile installation is simulated with a loosening zone directly at the pile shaft and a compaction zone around (Fig. 2, left).

The outer diameter of the pile is $d = 0.2$ m, wall thickness $t = 4$ mm. The loosening zone directly at the pile is 4.0 mm wide and the compaction zone is 40 mm wide.The initial density of the model is donated $I_0$, the density of the compaction zone $I_{com}$ and density of the loosening zone $I_{loo}$.

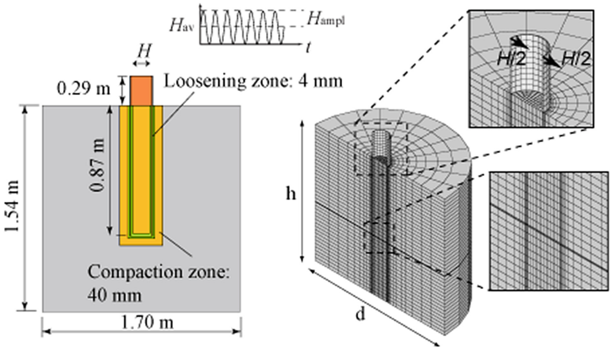


**Fig. 2.** Schematic view of the model (left) and FE-discretization with elements SOLID185 (right)

For all simulations of this study the elements within the top 3.0 cm of the pile head were modelled with a larger stiffness than $E = 10^{10}$ kPa. The horizontal force on the model pile was distributed at two opposite nodes located at the outer perimeter of the pile head (Fig. 2, right). The soil has a lateral earth pressure of $K_0 = 1 - sin\varphi = 0.478$ at the beginning of the simulation. The horizontal loading was defined with the middle values at $H_{av} = 0.25$ kN and an amplitude of $H_{ampl} = 0.20$ kN.

### 2.3 Result of the Simulation

For the experimental part with the DIC method the development of the different density zones around the pile were found. In the next part, the influence of the density changes in loosening zone $I_{loo}$ and in compaction zone $I_{com}$ on the pile head are investigated.

In Fig. 3 the typical distribution of the horizontal displacement (left) and the void ratio (right) of the soil under lateral loading are presented. In the right illustration the distribution of the density change around the pile during the cyclic loading can be observed. The cyclic loading causes an increase of the soil density in the upper area of the loading direction and directly on the pile shaft in the opposite direction. A rotation of the pile during the test was also observed.

In another test series the density of the loosening zone directly around at the pile shaft $I_{loo}$ is varied while the initial density $I_0 = 76\%$ and the compaction zone $I_{com} = 80\%$ remain the same in all tests. Figure 4 shows the displacement of the pile head depending on the number of cycles (left) and on the density $I_{loo}$ (right). The curves in the left hand diagram show that the smaller the densities become, the larger the deformation will be. The deformation of the pile after a certain number of cycles decreases linearly with density $I_{loo}$ (right).

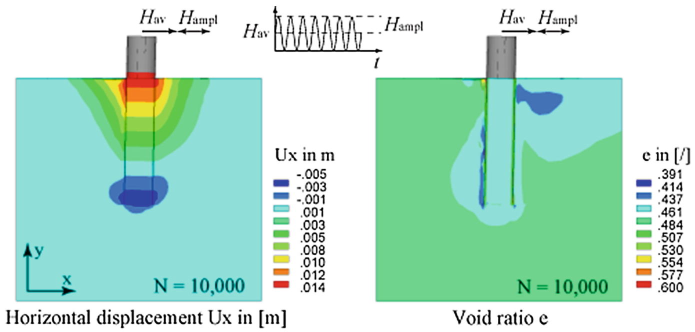


**Fig. 3.** Horizontal displacement and distribution of the void ratio after 10,000 cycles in the test with $I_0 = 76\%$, $I_{loo} = 55\%$ and $I_{com} = 80\%$

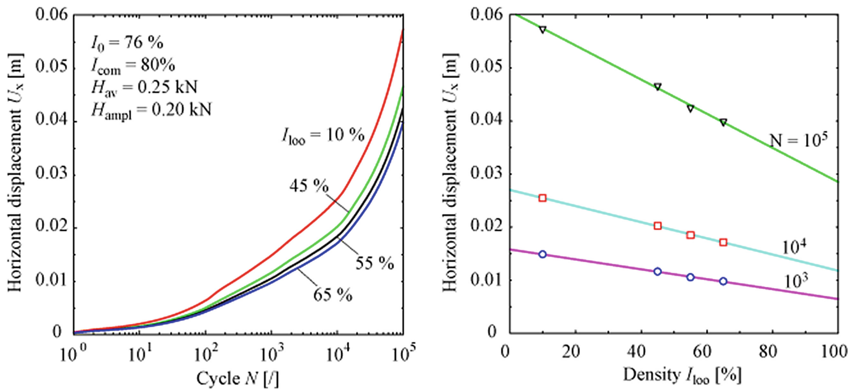


**Fig. 4.** Horizontal displacement at the top of the pile depending on the density $I_{loo}$ of the loosening zone

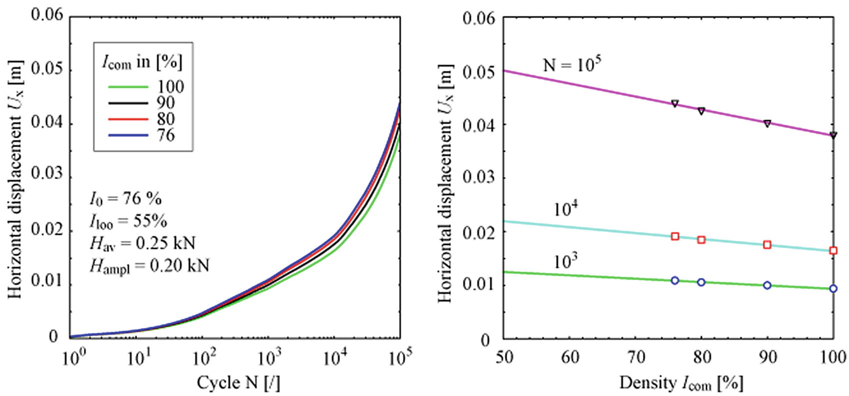


**Fig. 5.** Horizontal displacement of the pile head depending on the density $I_{com}$ of the compaction zone

In the next series, the influence of increasing the density around the pile is investigated. In four simulations, the density of the compaction zone is varied from $I_{com} = 76\%$ to 100% while the initial density remained at $I_0 = 76\%$ and in the loosening zone at $I_{loo} = 55\%$. The results show a light difference in the displacement of the pile head during the cyclic loading (Fig. 5, left). This can be seen as a negligible deflection compared to the total deflection of the pile head.

## 3 Conclusion

The results of this study show a promising approach for the determination of the cyclic lateral loading behaviour of vibratory driven piles. Changes in the soil structure induced by the installation process also have to be considered in the subsequently following loading analysis. The HCA-model has proven to be a reliable tool for simulating the lateral bearing behaviour of a pile over 100,000 cycles. Results show that the narrow loosening zone directly at the pile shaft has a notable impact on the lateral loading resistance of the pile. Compared to a homogeneous soil set up, the consideration of the loosening zone increased the pile head defection significantly. This means, in terms of the lateral loading resistance, that a simulation with a homogeneous soil distribution would underestimate the pile head deflection for a given cyclic load.

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