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Numerical simulation of pile installation in saturated sand using material point method

Vahid Galavi[a,]*, Lars Beuth[a], Bruno Zuada Coelho[a], Faraz S. Tehrani[a], Paul Hölscher[a], Frits Van Tol[a]

[a]*Geo-Engineering department, Deltares, Boussinesqweg 1, 2629 HV Delft, The Netherlands*

Abstract

In this study, numerical simulations of offshore monopile installation are performed using the Material Point Method (MPM) to capture the mechanical behavior of soil during the installation with impact and vibratory driven techniques. The MPM can be considered as an extension of the finite element method with the purpose of capturing large deformations without suffering from mesh distortion usually found with the finite element method. The aim of this study is to demonstrate the capability of the MPM to simulate pile installation with reference to field tests carried out in Cuxhaven, Germany.

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1. Introduction

Impact and vibratory driven piles are widely used in the construction of offshore structures, e.g. wind turbines. The pile installation leads to significant changes in soil structure and soil state (void ratio and stress state) in the vicinity of piles which affects their lateral and axial bearing capacity. A good understanding of the effect of pile installation on the bearing capacity is expected to reduce costs in the construction of wind parks and might allow installation of longer monopiles at greater sea depths. Furthermore, vibrated piles might stall during the installation

* Corresponding author.
*E-mail address:*vahid.galavi@deltares.nl

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process depending on soil conditions. A proper numerical tool for simulating pile installations would allow assessing installation time, pile refusal probability and material fatigue which are important factors in costs reduction.

The effect of pile installation is not considered in analysis with common numerical simulation methods (e.g. Finite Element Method) as it involves modeling of large deformations which is problematic. The Material Point Method (MPM) was introduced by Sulsky et al. [5] for solving problems in which large deformations are involved. The method can be considered as an extension of the Updated Lagrangian Finite Element Method (UL-FEM).
In this study, numerical simulations of pile installation are performed using an explicit MPM to capture the mechanical behavior of soil during the installation with impact and vibratory driven techniques. A dynamic two-phase formulation is utilized in order to consider generation and dissipation of excess pore water pressures during pile installation. For a description of the material point method, specifically the variant used in this study, the reader is referred to the PhD thesis of Al-Kafaji [1].

Monopiles have to maintain the vertical alignment of wind turbines over several decades under continuous lateral cyclic loading. It is unknown how the build-up of lateral system stiffness in the different soil conditions found in the North Sea is influenced by the vibration process. In order to assess the lateral bearing capacity of impact and vibratory driven piles, six monopiles were installed in Altenwalde near Cuxhaven in Germany in the frame of an extensive research program (VIBRO; e.g. [7]). The purpose was to investigate how sufficient lateral bearing capacity can be ensured with vibratory driving, to derive design approaches for guaranteeing sufficient lateral capacity. The monopiles have an outer diameter of 4.3 m, a wall thickness of 40 to 45 mm and a length of 21 m and were installed up to a depth of approximately 18.5 m. Three monopiles were installed with impact driving and the other three with vibratory driving. Each pile pair consists of one impact driven pile and one vibratory driven pile. Subsequently, the piles were subjected to lateral loads in order to compare the lateral bearing capacity of the installed piles. Several CPTs (Cone Penetration Tests) were carried out before and after the installation in order to estimate the effect of installation on soil properties. The test site consists of mostly dense and very dense sand layers. The water table is approximately at 4.0 m below the ground surface. A cohesive material with thickness of almost 1 m is present at a depth of 4.0 m. The numerical simulations of one pair of monopiles in the pile installation tests are presented in this study. The capability of the material point method to simulate pile installation using results of field tests is highlighted.

This paper covers numerical simulations of the pile installation starting at a depth of 16.5 m. Numerical modeling of the lateral load testing will be presented in another paper where results of the numerical simulations will be compared with the measurements.

2. Material model and parameter determination

The mechanical behavior of soils depends on the intrinsic properties and the state variables of the soil. The intrinsic properties are independent of the state of the soil. They define the type of particles, e.g. the mineralogy, size, shape and surface of soil particles while state variables describe how the particles are arranged together, e.g. relative density and stress state. It is assumed that the sand layers in this project have similar intrinsic properties. Then, by considering one set of intrinsic parameters, the only parameter which determines the mechanical behavior of the material will be the soil state.

The hypoplastic model developed by Von Wolffersdorff [6] has been chosen in this study to describe the mechanical behavior of the Cuxhaven sand layers. The model has been primarily developed for non-cohesive granular materials. The stiffness, strength and dilation are dependent on the soil state (void ratio). The basic model requires eight parameters: the critical state friction angle, φ_c, a hardness parameter, h_s, a compression law parameter, n, the reference minimum void ratio at zero mean effective stress, $e_{d0} \approx e_{min}$, the reference critical void ratio at zero mean effective stress, $e_{c0} \approx e_{max}$, the reference maximum void ratio at zero mean effective stress, $e_{i0} \approx 1.15e_{c0}$, a parameter to control the dependency of peak friction angle on relative density, α, and a parameter to control the dependency of soil stiffness on relative density, β.

The original hypoplastic model shows numerical difficulties when stresses vanish in a liquefied soil. The numerical issues, due to zero effective stress, are solved by modifying the hypoplastic model for low stresses. As a first solution, Mohr-Coulomb model with a tension cut-off is used as long as the stress state drops below a threshold (mean effective stress, p', smaller than 5 kPa).