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Research Paper

Numerical investigation of pile installation effects in sand using material point method

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ABSTRACT

The installation of displacement piles in sand leads to severe changes in the stress state, density and soil properties around the pile tip and shaft, and therefore has a significant influence on the pile bearing capacity. Most current numerical methods predicting pile capacity do not take installation effects into account, as large deformations can lead to mesh distortion and non-converging solutions. In this study, the material point method (MPM) is applied to simulate the pile installation process and subsequent static pile loading tests. MPM is an extension of the finite element method (FEM), which is capable of modelling large deformations and soil-structure interactions. This study utilizes the moving mesh algorithm where a redefined computational mesh is applied in the convective phase. This allows a fine mesh to be maintained around the pile tip during the installation process and improves the accuracy of the numerical scheme, especially for contact formulation. For the analyses a hypoplastic constitutive model for sand is used, which takes into account density and stress dependent behaviour. The model performs well in situations with significant stress level changes because it accounts for very high stresses at the pile tip. Numerical results agree with centrifuge experiments at a gravitational level of 40 g. This analysis confirms the importance of pile installation effects in numerical simulations, as well as the proposed numerical approach's ability to simulate installation and static load tests of jacked displacement piles.

1. Introduction

During installation, jacked displacement piles are pushed into the ground causing severe distortion of the surrounding soil. As a result, large shear strains and significant increase of stresses surrounding the pile tip are observed (e.g. [1]). This complex installation process will influence the bearing capacity of the pile foundation substantially.

In engineering practice, installation effects are usually accounted for using empirical methods (e.g. [2]). These methods estimate the pile bearing capacity of simple foundation structures whilst they do not take into account the underlying physical mechanisms. For more complex geotechnical problems where a reliable prediction of the load settlement behaviour is required, such as where pile group installation or in case of a strong interaction with neighbouring structures, empirical prediction methods are limited in use. In these cases, the finite element method (FEM) is more suited. Griffiths, Sloan and Randolph [3,4], amongst others, have assessed the ultimate bearing capacity of foundations using FEM simulations, and De Borst and Vermeer [5] simulated cone penetration in FEM assuming small strain analysis. Although both models provided good basic techniques to determine the pile capacity, the influence of large deformation during the installation process was not taken into account. Later, Baligh, Broere and Van Tol [6,7] tried to simulate the installation effects by applying prescribed stress or strain to the soil along the pile, but did not model the installation process itself, due to the fact that classical FEM suffers from severe mesh distortion when dealing with large deformations. To overcome this problem, Engin et al. [8] presented a simplified FEM technique to model a jacking pile, the so-called 'Press-Replace' technique. The main advantage of this technique is that it does not suffer from mesh distortion. However, the continuous flow mechanism of soil being pushed under the pile tip towards the shaft is not properly captured. Therefore, current FEM practices for determining pile capacity do not take into account the change of soil state and properties due to installation, or do so in a simplified manner only. Consequently, the accuracy in predicting the pile capacity by FEM is rather limited.

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Notations

c	is the cohesion of soil
D	is the pile diameter
d_{50}	is the mean grain size diameter
E	is the stiffness of soil
e_0	is the initial void ratio of soil
e_{c0}, e_{d0}, e_{i0}	are the critical, minimum and maximum void ratios at zero pressure in the hypoplastic model respectively. They are reference void ratios specifying positions of limiting void ratio curves
$\mathbf{F}^{ext}$, $\mathbf{F}^{int}$	are the vectors of external and internal nodal forces respectively
h_s, n	control the shape of limiting void ratio curves in the hypoplastic model
I_R, Q, R	are relative dilatancy indices according to Bolton (1986)
$\mathbf{M}$	is the (lumped) mass matrix
r	radial distance from the centre of the pile
R_D	is the relative density of soil
p'	is the mean effective stress level
$\mathbf{u}$	is the vector of nodal displacement
α	is a constant in the hypoplastic model controlling the dependency of peak friction angle on relative density
β	is a constant in the hypoplastic model controlling the dependency of soil stiffness on relative density
ε_{vol}, ε_{vert}	is the volumetric and vertical strain, respectively
φ'_{max}, φ'_{crit}	are the maximum and critical friction angle respectively
ψ	is the dilation angle of soil
μ	is the coefficient of friction between pile and soil
ν	is the Poisson ratio of soil

In contrast with the purely Lagrangian and updated Lagrangian methods used in FEM, the Eulerian and Arbitrary Lagrangian–Eulerian (ALE) schemes (e.g. [9,10]) allow for uncoupling of mesh and material and permit independent movement of the material with respect to the mesh. One of the most effective ALE methods in modelling penetration problems is the Coupled Eulerian–Lagrangian (CEL) method. In CEL, the soil is discretized by an Eulerian mesh, while the pile is discretized by a Lagrangian mesh [11,12]. This helps to overcome mesh distortion. In the case of remeshing, however, the mapping of state variables allocated to the material introduces additional inaccuracies into the calculation [25,26,42]. This has led to the development of meshless methods, such as the smoothed particle hydrodynamics (SPH) method (e.g. [13]), and mesh-based particle methods such as the material point method (MPM). Originally developed as the Particle-In-Cell method, MPM was initially applied to fluid dynamic problems [14] and later adapted to solid mechanics by Sulsky et al. [15]. Więckowski et al. [16] applied the method to simulate the problem of silo discharge, which showed the potential of MPM for simulating flow of granular material. Following this, several MPM analyses to model large deformations in geotechnical problems, including pile installation, were performed by Więckowski [17,18]. Coetzee et al. [19] used MPM for studying the problem of anchor pull out. The application of MPM was then extended to include coupled two-phase behaviour to simulate large deformations in fully saturated soil [20] and partly saturated soil with groundwater table and groundwater flow [21].

For this paper the joint MPM code of the MPM Research Community is used, which is being developed by the University of Cambridge, UPC Barcelona, Technical University Hamburg-Harburg, University of Padova, Delft University of Technology and Deltares. This implementation is based on an explicit time integration scheme as introduced in Section 2.

Choosing a suitable constitutive model for the soil plays a crucial role in geotechnical numerical modelling. In this study, the hypoplastic constitutive model in the formulation of Von Wolffersdorff [33] is used. This model is able to incorporate dilation, contraction and the dependence of stiffness on stress and density. Centrifuge test [22,23] which are used for validation of the results showed that very high stresses occur at the pile tip during the installation process. The range of stress may increase up to 100 times the initial value. Such a large increase of stress in the soil leads to dilation and a significant reduction of strength of the soil [24]. These effects are addressed by adapting the hypoplastic model parameters accordingly in order to successfully simulate a centrifuge test as presented in this work.

In this paper, numerical simulations are presented for modelling the installation process of jacked displacement piles in sand using the aforementioned MPM Software and the hypoplastic model of Von Wolffersdorff [33]. Two different initial densities of sand are investigated, namely loose ($R_D = 36\%$, $e_0 = 0.75$) and medium-dense sand ($R_D = 54\%$, $e_0 = 0.68$). Afterwards simulations of a static load test following the pile installation process are carried out. Numerical simulation results are compared with results of pile installation and static load test experiments in the centrifuge. It should be noted that a shortcoming of the centrifuge test is that it captures the size effect due to stress level but not due to the mean grain size in the case of shear localization. However, choosing a pile with large dimensions relative to the grain size can minimize the error of the grain size effect [43]. Moreover, centrifuge tests are preferred to field tests because of the well-defined testing and material conditions compared to the complex characteristics of sand in natural condition.

2. Material Point Method (MPM)

MPM can be referred to as FEM formulated in an ALE description of motion. It uses two kinds of space discretization: first, the computational background mesh, and second, the collection of material points, which move through the fixed background mesh. The advantage of MPM is that the state variables are assigned to the material points and are carried independently of the computational mesh. Therefore, MPM is well suited for modelling large deformation. This section briefly presents the basic concept of the material point method used in the simulations of this study and introduces several aspects related to penetration problems modelled in MPM, i.e. dynamic contact algorithm and moving mesh concept.

2.1. Basic concept of dynamic explicit MPM

The governing equation of dynamic MPM which is based on an explicit time integration scheme is given in Eq. (1), and is identical to an explicit formulation in FEM,

$$\mathbf{M}\ddot{\mathbf{u}} = \mathbf{F}^{ext} - \mathbf{F}^{int}, \tag{1}$$

where $\mathbf{M}$ is the (lumped) mass matrix, $\mathbf{u}$ is the vector of nodal displacements, and $\mathbf{F}^{ext}$ and $\mathbf{F}^{int}$ are the vectors of external and internal nodal forces, respectively.

The solution algorithm can be divided into three basic steps: the initialization phase, the Lagrangian phase and the convective phase