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Lateral response of piles subjected to a combination of spudcan penetration and pile head loads

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ABSTRACT

The effects of spudcan penetration on adjacent laterally-loaded piles mainly manifest themselves in the additional lateral shaft loads induced by large soil deformation. This paper presents a procedure to analyze lateral response of piles subjected to a combination of spudcan penetration and pile head loads. First, the Coupled Eulerian-Lagrangian technique (CEL) is post-processed and key model parameters are investigated to generate accurate soil displacement profiles during free-field spudcan penetration. Second, the effects of spudcan penetration on the adjacent piles loaded on the pile head are analyzed in two ways: the passive pile method and the offset p-y curve method. Results of an available centrifuge model test is firstly adopted to certify the effectiveness of the procedure in analyzing piles singly loaded by spudcan penetration. Then a combined-loading 1 g model test is conducted to calibrate the procedure. Agreement between the calculated and measured results is found especially with the combination of the CEL FE method and the passive pile method.

1. Introduction

Spudcans of jack-up drilling rigs deployed in offshore engineering often penetrate over 10 m in soft soils to provide enough bearing capacity for the upper structures, inevitably inducing large soil movements and in turn non-negligible soil loads on the adjacent piles (Mirza et al., 1988). Thus, it is necessary for the pile design to evaluate the effects of the additional loading caused by spudcan penetration, especially for a spudcan-pile clearance less than one spudcan diameter in the soil soils (SNAME, 2002), which is often met for deep-water operations. A direct analysis of the spudcan-pile interaction can be conducted in CEL analysis, which includes both the spudcan and the adjacent pile in a 3D model and the obtained pile shaft bending moments and soil flow contours prove to be convincing when compared with available centrifuge model tests (Arslan and Wong, 2014; Tho et al., 2013; Wang and Lan, 2016; Xie, 2009). However, the critical condition should be a combination of the spudcan penetration-induced loads and the environmental effects, which needs a series of analyzing parameters. The all-in model may also be time-consuming and not efficient when different working conditions are considered.

On the other hand, the decoupled analyzing method divides the spudcan penetration effects into two steps: the large soil displacements induced by spudcan penetration and in turn the pile response due to the soil loads. An accurate simulation of the soil displacement is thus a necessity in a decoupled spudcan-pile interaction analysis, but it is rarely seen in the literature to get a convincing soil displacement profile through numerical simulation. Although analytical soil displacement calculating methods such as the Cavity Expansion Method (CEM) can provide agreeable prediction of the pile driving-induced soil movements (Poulos, 1994), the irregular shape of the spudcan makes it hard for an accurate simulation of the penetration process, for the above two methods cannot describe the complicated soil flow mechanism near the spudcan. As for the traditional FE analysis using Lagrangian description of material movement, which was utilized to simulate the spudcan penetration process based on the wished-in-place assumption (Lyons and Wilson, 1985), an acceptable result of the penetration resistance may be obtained, but it cannot meet the demand for soil displacement calculation. Therefore, Large Deformation Finite Element (LDFE) methods should be considered to get an accurate soil displacement profile.

LDFE methods have been successfully applied to the simulation of the spudcan penetration process, and may be helpful in soil displacement calculation. Researchers have done extensive works based on the commercial FE software package ABAQUS by the CEL (Qiu and Grabe, 2012; Tho et al., 2013), mesh-to-mesh (Ragni et al., 2016; Tian et al., 2014) and

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ALE adaptive meshing (Li et al., 2015) techniques. Among the available numerical simulation of free-field spudcan penetration, attention has been mainly paid to the prediction of penetration resistance and the risk of punch-through. Only Li et al. (2015) adopted the ALE technique in ABAQUS to simulate the soil displacements in one of Xie's centrifuge model tests and the predicted results at the final penetration depth agree well with the test results. However, the ALE technique in ABAQUS does not change the topology of the mesh during the calculation, which makes it difficult to account for large deformation of the soils. In addition, only one large deformation material can be considered in the ALE analysis in ABAQUS, adding further restraints to its application.

The CEL technique may be an effective way to give more accurate and flexible simulation of soil deformation during spudcan penetration. It is characterized by the ability to simulate the deformation of layered soils, which gives more flexibility to the simulation. Tho et al. (2015) adopted the CEL method in the first step to calculate the soil displacement profiles when analyzing a centrifuge model test of perfectly-fixed head pile only subjected to spudcan penetration (Xie, 2009). However, the calculated soil displacement profiles seem to be diverging when compared with measured results and in turn lead to overestimated bending moments. The gap may be a result of unrealistic model settings. In this paper, the CEL method is improved for accurate soil displacement calculation, with firstly an additional python code to aid the analysis and then material parameters adjusted to be consistent with the next step.

As for the second step, there are two ways may be used to transform the soil displacements into the soil loads acting on the pile shaft: the offset p-y method and the passive-pile analyzing method. The former considers the soil loading effects by shifting the conventional soil springs according to the soil displacements and then adds the loads from the environment and the upper structure to the pile head (Mirza et al., 1988). The latter, however, predicts the pile response using the passive-pile analyzing method by which the response of piles, or retaining walls influenced by lateral soil movements have been extensively explored in the simulation of excavation, embankment, or pile driving with adjacent structures (Goh et al., 1997; Leung et al., 2013; Poulos, 1994). When the pile is subjected to a combination of spudcan penetration and pile head loads, it is a necessity to make clear how to determine the corresponding pile responses.

According to the above analyses, this paper is organized as follows. First, a procedure to analyze the lateral responses of piles subjected to a combination of spudcan penetration and pile head loads is presented. The post-processing of the CEL technique is discussed for the first stage of the procedure. Then compared with a centrifuge model test, key parameters in the numerical simulation are investigated to give accurate results of the induced soil displacements during spudcan penetration. Finally, a 1 g model test is conducted and analyzed by the procedure. In the second stage, the simulated results are considered in two ways and the corresponding bending moment profiles are compared with the model test, respectively, to prove the feasibility of the aforementioned process to consider the effects of spudcan penetration on the adjacent laterally-loaded piles.

2. Analysis procedure

The procedure is based on the conventional two-stage method proposed by Poulos and Chen (1997) to analyze passive piles, in which the soil displacement profile is firstly estimated or calculated, and then input into the equation of an elastic foundation beam in the second step. To facilitate the analysis of the combined-loaded piles considering both spudcan penetration and pile head loads, the two-stage procedure needs to be improved as followings: a LDFE method is first be utilized to yield accurate soil displacement profiles, and then a proper method to analyze the piles combining both active and passive behaviors is discussed to generate the corresponding responses of piles subjected to a combination of spudcan penetration and pile head loads.

2.1. Soil displacement calculation

Considering large soil deformation occurring during spudcan penetration, the LDFE methods may be adopted to simulate the process with adequate accuracy. Here the CEL method is selected because it has been extensively adopted in spudcan penetration simulation (Hossain et al., 2011; Qiu and Grabe, 2012). The CEL technique in ABAQUS lies within the ALE LDFE methods based on the operator split in computational mechanics with firstly an explicit Lagrangian phase and then an Eulerian convection phase (Wang et al., 2015). During calculation, the mesh is fixed with material flowing in it, by which mesh distortion can be avoided.

However, after a CEL calculation of spudcan penetration, a post-processing python code needs to be written to get the absolute soil displacement profiles for that the material and the mesh separate with each other at every incremental calculation. To track a certain material particle, its displacement during every incremental calculation needs to be extracted from the output database. And given that in the ABAQUS CEL calculation only the velocity is output, the displacement will be obtained by node velocity integration (Pucker and Grabe, 2012). In the paper, an appropriate output interval is set to 100 output data sets per step, with some incremental calculations neglected, but leading to efficiency and adequate accuracy.

For that the material particle may not locate itself exactly on the mesh node, the particle should first be spotted to find the element containing it throughout the whole analyzing domain, and then the velocity of the particle can be interpolated based on the spatial coordinates. In this paper, considering that spudcan penetration is an axisymmetrical problem where every material particle just moves within a certain plane of symmetry and for that the projected element face are all rectangles, the element containing the particle can be determined by Eq. (1).

$$a = \min\left\{ \left[(x - x_c)^2 + (y - y_c)^2 \right]^{1/2} \right\} \tag{1}$$

where (x, y) is the current coordinate of the target point, and (x_c, y_c) is the center of gravity of the element. After finding the element, the velocity of the particle can be obtained by the bilinear interpolation function Eq. (2).

$$v = A(v_j - v_i) + v_i + B\left[A(v_k - v_m - v_j + v_i) + v_m - v_i\right] \tag{2}$$

where *i, j, k, m* are the counter-clock numbering of a face of the Eulerian octahedral element, v_i, v_j, v_k, v_m are the corresponding node velocities of the *i, j, k, m* node, v is the velocity of the target point, $A = (x - x_i)/(x_j - x_i)$, and $B = (y - y_j)/(y_k - y_j)$. The interpolated velocity can be seen as the average velocity during the interval, and the displacement of the target point can be obtained by integration of time.

The corresponding flow chart of the python code is given in Fig. 1.

Combined with the flow chart, soil displacement profiles can be calculated as follows:

1. Establish the CEL free-field spudcan penetration model, and set the load and boundary conditions;
2. Set the model penetration rate and the output frequency, and submit the job in ABAQUS;
4. After ABAQUS calculation, run the script in Fig. 1 to calculate soil displacement profiles based on the output database file.

The CEL technique can include different materials in its large deformation area, and can provide better simulation compared with the mesh-to-mesh and the adaptive ALE technique in ABAQUS for its free simulation of deformation. The effectiveness of the CEL technique to obtain accurate soil displacement will be examined later by simulation of two model tests.