Simulation of Suction Caisson Penetration in Seabed Using an Adaptive Mesh Technique

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Abstract

This paper reports results of a numerical investigation into the suction caissons penetration in sand. A 3D finite element model is used for this purpose. The water saturated soil domain is modelled as a two-phase medium, consisting of soil skeleton and pore-water phases. Nonlinear behavior of the solid phase is described by means of a bounding-surface plasticity model. The caisson itself is modelled by solid elements and non-porous linear elastic properties. The soil-soil and soil-caisson interactions along the penetration path are modelled with a master/slave contact algorithm using contact surfaces and a frictional contact interface. A re-meshing technique is also used to avoid excessive distortion of the finite elements along the caisson-soil penetration path. The model was first substantiated against laboratory test data. The numerical model was found to present acceptable agreements with the experimental measurements. The verified model was then used to study the influence of parameters such as soil internal friction, penetration speed and adaptive mesh schemes on the installation behavior of suction caissons in sands.

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1. Introduction

Suction caissons can be regarded as a comparatively new foundation system for offshore structures. A suction caisson has advantages over other foundation systems by virtue of its installation process. While, heavy duty equipments are necessary for the installation of offshore piles, relatively simple devices will be

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required to install the suction caisson foundations. Parts of the suction caisson behavior such as its installation design are still facing some degrees of uncertainty (Zeinoddini et al., 2006).

Suction caisson’s installation in different soils has been studied by means of analytical approaches (for example House et al, 1999), laboratory studies of small-scale model caissons at 1-g (ex: El-Gharbawy and Olson, 1998; Sanham, 2003), centrifuge studies (ex: House and Randolph, 2001; Andersen et al. 2005) and field trials using large-scale caissons (ex: Cho et al., 2003; Kelly et al., 2006).

Several researchers have also tried numerical approaches to study the suction caisson installation. Maniar and Tassoulas (2002) reported two dimensional (2D) axisymmetric finite elements modelling of a caisson installation. A pushing penetration scheme, instead of suction penetration, was used. The computational procedure included modelling of the soil as a porous media and the soil/caisson interface friction with Coulomb’s law. The installation was modelled both by re-meshing the finite element model and with no re-meshing. Results of the model with no re-meshing showed a higher resistance along the inner wall of the caisson.

Maniar (2004) reported 2D axisymmetric analysis of caissons installed in normally consolidated clay. Results from the weight plus forced penetration modelling showed that the soil resistance along the caisson inner wall was lower than that the outer wall. During deadweight insertion, the soil was observed to move from the inside of the caisson towards the outside, resulting in total downwards movement of the plug.

Andersen et al. (2004) simulated penetration of suction caissons with an aspect ratio of 4.2 using the commercial finite element code PLAXIS. The soil was modelled as an elastic- perfectly plastic material having isotropic initial stresses and shear strength.

Zhou and Randolph (2006) studies suction caisson penetration in clay using AFENA finite element software. Elements with large deformation formulations were used for modelling.

Zeinoddini et al. (2008-1/2/3) reported results from a series of numerical investigation into the suction caissons penetration in sand, in clay and for upright/tapered caissons. 2D axisymmetric models were used and effects from various soil/structure characteristics on the performance of the suction caissons during the installation phase were evaluated. They also examined the wall tapering effects on the installation performance of suction caissons.

The innovation of this paper is three dimensional (3D) simulation approach for the suction caissons penetration. Nonlinear behavior of the solid medium and its two-phase nature has been considered in these simulations. A re-meshing technique is also used to avoid excessive distortion of the finite elements along the caisson-soil penetration path. The model was used to study the influence of parameters such as soil internal friction, penetration speed and adaptive mesh schemes on the installation behavior of suction caissons in sands.

2. Finite Element Formulation

2.1. Type of analysis

In this study the general purpose finite element code ABAQUS 6.3 (SIMULIA, 2007) has been utilized for 3D modelling of suction caissons penetration. Eight- nodded hybrid brick element (C3D8H) has been considered for the soil body.

The caisson has been represented as a thin-walled rigid body and been modelled using conventional, 3-D, eight nodded elements. Taking advantage of symmetrical nature of the problem, only one-quarter (90 degrees) of the whole body has been modelled. The nodes at the plane of symmetry have been constrained in the normal direction of the plane.

The initial stress state in the modelling area has been generated in a geostatic step in which the gravity loads of the soil and caisson are introduced to the model. This is to obtain an initial converged stress
condition and ensure that the initial stress condition in any element within the soil body stays within the initial yield surface of the cap model.

Instead of a penetration under suction simulation, an under load penetration scheme has been used. Penetration load is applied slowly enough so that volume changes occur along with dissipation of the excess pore pressure due to the soil permeability. In the finite element model, the soil drained behavior is simulated using coupled analysis, where the pore water pressure is calculated for a given load increment in each soil element and then subtracted from the total stresses to estimate the effective stresses in the element.

2.2. Plasticity model of soil

The non-linear soil behavior has been taken into account using an elasto-plastic model based on the modified Drucker-Prager cap plasticity model which exhibits a pressure dependent yield criteria.

2.3. Soil-caisson interaction

The finite sliding between the caisson's wall interior and exterior skins is modelled using contact surfaces and a frictional contact interface. For the present problem, both interior and exterior surfaces on the caisson wall are defined as master surface, while the potential contact surfaces in outside soil and inside soil bodies are defined as the slave surface. The contact constraint is enforced with a Lagrangian multiplier, which represents the contact pressure in a mixed formulation. For this, a critical shear stress is defined, based on a Coulomb friction law $t_{\text{crit}} = p_n \mu$, where $\mu$ denotes the coefficient of friction on the caisson-soil interface.

2.4. The adaptive technique

To alleviate potential problems caused by element distortion, adaptive meshing has been used to reduce the distortions during the analysis. The Lagrangian-Eulerian adaptive mesh technique is a combination of the features of pure Lagrangian and Eulerian analysis. This type of adaptive meshing is often referred to as Arbitrary Lagrangian-Eulerian (ALE) analysis. ALE adaptive meshing is a tool that makes it possible to maintain a high-quality mesh throughout the analysis (Figure 1), even when large deformation or loss of material occurs, by allowing the mesh to move independently from the material (SIMULIA, 2007).

The ALE adaptive technique has been used to in the current study which has the advantage of being compatible with element types used for the soil models and with the 3D nature of the modelling.

![Figure 1: Effects from ALE adaptive technique for numerical modelling of cone penetration in clay (Hazell, 2008)](image-url)
3. Calibration and VALIDation of the Model

Experimental results from Kakasoltani et al. (2010) on the installation of suction caissons are used for FEM model calibration/validation. The caissons in their study are small scale with outer diameter of 8 cm and aspect ratios of 1, 2, 3 and 4. Caisson dimensions are summarized in Table 1. The caisson with an aspect ratio of 1 has been used for the calibration of the numerical model, while caissons with aspect ratios of 2, 3 and 4 have been used for the validation purpose. The friction coefficient on the contact surfaces ($\mu$) in the FE model has been chosen as the calibration parameter and the soil properties correspond to the loose sand (Table 2).

Table 1: Suction caissons geometrical parameters in Kakasoltani et al. (2010) experiments.

| Name | Outer diameter (cm) | Length (cm) | Thickness (mm) | Aspect ratio |
|------|---------------------|-------------|----------------|-------------|
| U8   | 8                   | 8           | 2.5            | 1           |
| U16  | 8                   | 16          | 2.5            | 2           |
| U24  | 8                   | 24          | 2.5            | 3           |
| U32  | 8                   | 32          | 2.5            | 4           |

Table 2: Mechanical soil properties in Kakasoltani et al. (2010) experiments.

| Density group | Test type    | Friction angle ($\phi$) (degree) | Cohesion (c) (kPa) |
|---------------|--------------|---------------------------------|--------------------|
| Loose sand (SI) | Direct shear | 31                              | 0                  |
|                | Triaxial (CD)| 29                              | 0                  |
|                | Triaxial (CU)| 26                              | 5                  |

Figure 2: Calibration of the numerical model (from current study) against experimental data (from Kakasoltani et al., 2010) for a suction caisson with an aspect ratio of 1.
The load-penetration result for models with friction coefficients ($\mu$) varying from 0.1 to 0.2 are shown in Figure 2. The ultimate penetration load seems to vary proportional to $\mu$. A friction coefficient of 0.18 provided an appropriate correlation so this value has been used in the validation tests and parametric studies. Figure 3 shows the results for the model validation for a caisson with an aspect ratio of 2. As it can be seen in Figure 3, the numerical predictions are in an acceptable agreement with the test data.

![Figure 3: results for the model validation for a caisson with an aspect ratio of 2](image)

![Figure 4: Penetration rate effects on the installation response of a numerical model of suction caisson in sand (D=8cm, L=8cm).](image)
Based on these calibration and verification attempts, it was concluded that the numerical models employed are able to reasonably well simulate the penetration of the suction caisson.

3.1. Penetration rate

Kakasoltani et al., (2010) used a penetration rate of 0.5cm/min in their experiments. Effects from variation in the penetration rates (0.1, 0.2, 0.5, 1 and 2cm/min) on the installation response have been examined. Figure 4 shows the load-penetration results along with that from the experiment. It can be noticed that by increase in the penetration rate, the soil grows stiffer against caisson penetration. This is most likely because during a rapid penetration, the pore water pressure does not find enough time for a quick dissipation.

![Figure 5: The pore pressure pattern in the soil body half way through the caisson penetration](image)

The pore pressure distribution in the soil body is shown in Figure 5. The pore pressure maintains its maximum at locations immediately bellow the caisson tip.

3.2. Internal friction angle of soil

In this study the caisson assumed to be installed in sand, therefore the internal friction angle of soil ($\varphi$) is expected to have a key role on the soil response. Using the numerical model, effects from variation in $\varphi$ values on the penetration resistance have been examined. A range of 25, 30, 35 and 40 degrees have been considered for the soil friction angle. Figure 6 shows the results along with the corresponding experimental data. It can be noticed that the soil internal friction angle presents an increasing effect on the installation force. The ultimate penetration load was found to be proportional to $(\tan\varphi)^{1.8}$. 
3.3. Adaptive technique effect

In the current study an ALE adaptive meshing technique has been used. Conditions with no adaptive mesh scheme, with a standard ALE adaptive mesh and ALE along with a mesh control algorithm have been examined.

The results are given in Figure 7 and show that different adaptive techniques had no significant impacts on the load-penetration results. In fact, contact surfaces have well been able to accommodate large surface
to surface sliding without imposing sizeable distortions into the soil and caisson elements even if they are very close to the soil caisson interfaces. It is emphasized that this is just true in this case where the penetration path coincides with the contact surfaces.

4. Conclusions

A three dimension non-linear coupled soil-structure finite element modelling has been used to simulate the installation of the suction caissons in sand. The model has been calibrated and verified against results from an experimental study. The model has been shown to be able of providing reasonable predictions for the load-penetration of the suction caissons. Effects of parameters such as soil internal friction, penetration speed and adaptive mesh schemes on the installation behavior of suction caissons have also been studied. It has been noticed that by increase of the penetration rate, the soil grew stiffer against caisson penetration. The soil internal friction angle was found to present an increasing effect on the installation force. The ultimate penetration load was found to be proportional to \((\tan \theta)^{1.8}\).

Penetration of suction caisson models with different adaptive algorithms and no adaptive scheme were examined. No significant differences on the load-penetration results were noticed. This seemed mostly due to the contact configuration considered for this numerical model. The contact surfaces in the current model were well able to accommodate large surface to surface sliding without imposing sizeable distortions into the soil and caisson elements. This judgment, however, is far from general and is just true in cases where the penetration path coincides with the contact surfaces.

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