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Numerical Analysis of Inclined Uplift Capacity of Suction Caisson in Sand

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Three-dimensional finite element (FE) analyses are conducted to calculate the pullout capacity of a suction caisson subjected to oblique loadings. Two sets of FE analyses are performed using Abaqus FE software. In the first set, the sand around the caisson is modeled using the built-in Mohr–Coulomb (MC) model available in Abaqus where constant values of the angle of internal friction φ' and dilation ψ are defined. The effects of key variables, such as loading angle, mooring position, and aspect ratio, on pullout capacity and rotation of the caisson are examined. A comparison between FE and centrifuge test results is also shown. The second set of analyses are performed using a modified Mohr–Coulomb (MMC) model where the prepeak hardening, postpeak softening, and effects of density and confining pressure on stress-strain behavior of dense sand are implemented via a user subroutine by varying φ' and ψ as a function of plastic shear strain and confining pressure. By comparing the failure surface development in the soil with increase in loading for two different models (MC and MMC), it is shown that the mobilized φ' and ψ vary along the failure planes if the MMC model is used, although the capacity of the caisson could be obtained even if appropriate values of constant φ' and ψ are used in the MC model.

INTRODUCTION

Suction caissons (also known as suction anchors, suction piles, or suction buckets) are a unique form of foundation/mooring system that has several advantages over a traditional pile foundation and anchors. The main advantages include fast installation, elimination of the pile-driving process, a reduction in material costs, and reusability. A suction caisson is a large-diameter hollow cylinder, usually made of steel, having a closed top end and open bottom end, that is installed in soil by applying suction by pumping water out of the caisson interior. Suction caissons are now widely used in offshore industries for anchoring large offshore floating facilities to the seafloor. The pullout capacity of the caisson is one of the main concerns. The caissons are usually connected to the floating structures by a mooring line, which is attached to a pad eye on one side of the caisson.

The pullout behavior of suction caissons installed in both sand and clay is of great interest for the oil and gas development industry because of their advantages over other conventional foundation systems. Previous studies mainly focused on caissons in clay. For example, Aubeny et al. (2003) presented a theoretical method to estimate the inclined load capacity of suction caissons based on an upper-bound plasticity formulation for clay. Cao et al. (2002a, 2002b, 2003) conducted centrifuge tests and FE analyses for caissons in clay. Similarly, FE analyses have been performed using various soil-constitutive models, including Cam-Clay and MIT-E3 models, to understand the response of caissons in clay (e.g., Sukumaran et al., 1999; Handayanu et al., 2000; Zdravkovic et al., 2001).

Limited research is available in the literature to estimate the pullout capacity of suction caissons in sand. The mechanisms involved in the installation of a caisson in sand are different from those of in clay. In sand, the seepage due to applied suction plays a significant role. The installation issues of suction caissons in sand and sand/silt layers have been described by Houlsby and Byrne (2005a, 2005b) and Tran et al. (2007). Some centrifuge tests have been conducted in the past to increase the understanding of the pullout behavior of caissons in sand (e.g., Allersma et al., 2000; Lee et al., 2003; Kim et al., 2005; Jones et al., 2007; Kim et al., 2009; Kim et al., 2010; Bang et al., 2011; Jang and Kim, 2013). Bang et al. (2011) reported a series of centrifuge tests at 100 g on a model suction caisson in medium dense sand to evaluate the pullout capacities. More recently, Gao et al. (2013) conducted model tests to evaluate the pullout capacity of suction caissons in medium dense sand and reported the effects of load inclination angle, mooring position, and aspect ratio.

Numerical modeling of suction caissons in sand is very limited. Deng and Carter (2000) conducted FE analyses of suction caissons in sand assuming axisymmetric loading conditions using the AFENA FE software package and Mohr–Coulomb soil model. Iftekharuzzaman and Hawlader (2012) conducted three-dimensional FE analysis using Abaqus/Standard FE software, where they encountered some mesh distortion issues at large displacement.

In this study, three-dimensional FE modeling of suction caissons is performed to evaluate the pullout capacities at different load inclination angles and mooring positions in dense sand. In the first part of the paper, FE analyses are conducted using the built-in Mohr–Coulomb model available in Abaqus where φ' and ψ are constant. A total of 60 cases are analyzed to determine the pullout capacity of the caisson. A parametric study is also conducted to evaluate the effects of length/diameter ratio on pullout capacity. The FE results are compared with centrifuge test results available in the literature. In the second part, a set of FE analyses is presented using a modified Mohr–Coulomb model in which the stress–strain behavior of dense sand as observed in laboratory tests is incorporated.

PROBLEM DEFINITION

A suction caisson of length L and diameter D installed in dense sand is simulated in this study. During the installation, the soil in the vicinity of the suction caisson can be disturbed. However, the effects of disturbance on capacity are not considered in this study; instead, the simulations are performed for a wished-in-place suction caisson. The caisson is loaded at the five pad eye locations shown

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