The 2014 World Congress on
Advances in Civil, Environmental, and Materials Research (ACEM14)
Busan, Korea, August 24-28, 2014

Effect of interaction characteristics on the holding capacity of suction caisson anchors

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ABSTRACT

Suction caissons are one of the most widely used options for the anchoring system of floating platforms used in oil exploration and production, and, recently, offshore wind power generation. It is required to understand the interaction of the caisson and soil to reasonably evaluate the holding capacity of the anchors as well as material properties of soils, and failure mechanism; however, not much has been done in investigation of interaction of the caisson and soil. In this study, the finite element method is applied to investigate and quantify the effect of interaction formulation between the anchor and soil on the holding capacity and behavior of anchors. It was observed that a rough interaction significantly has no effect on the vertical capacity of the anchor but may overestimate the anchor's horizontal capacity when compared to a penalty friction formulation whether a separation or no separation after contact is defined under various load inclinations.

1. INTRODUCTION

As more exploration and development are carried out in deep waters, foundations of floating platforms have been intensively studied by oil industries, leading to the development of design guidelines for foundations of offshore wind turbines. Recently, suction caissons have become the preferred mooring system for those offshore structures since they have several advantages over other mooring systems. They are considered as particularly reliable and cost effective alternatives to more conventional mooring systems, such as driven pile foundations, especially for deep water platforms. Suction caissons are easier to install than impact driven piles and can be used in water depths well beyond where pile driving becomes infeasible. Suction caissons have higher load capacities than drag embedment anchors and can be inserted reliably at preselected locations and depths with minimum disturbance to the seafloor environment and adjacent facilities (Sparrevik 2001).

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Fig. 1 A suction caisson anchor (after Eltaher et al. 2003)

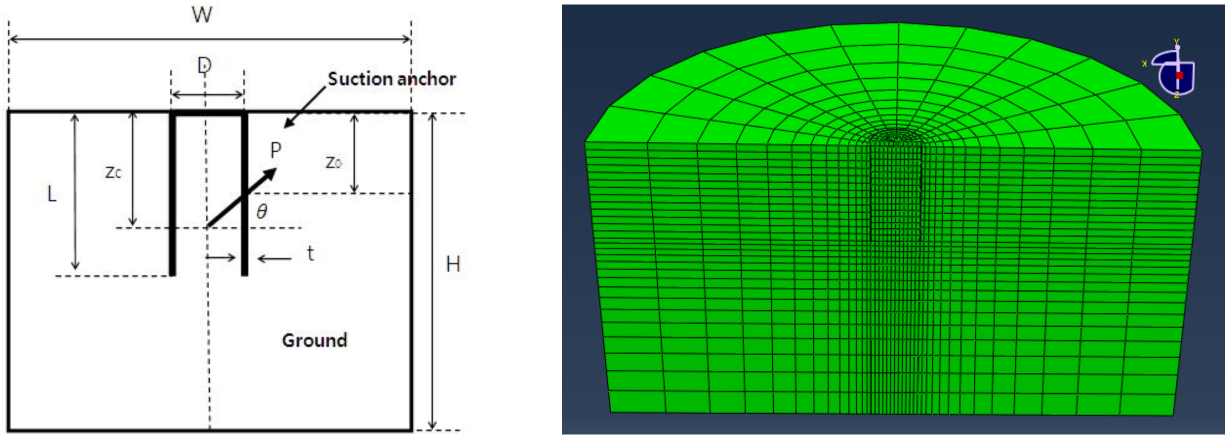
A suction caisson is a hollow steel cylinder which is open at bottom but capped on the top. It is allowed to penetrate the seafloor under its own weight and then pushed to the required depth with differential pressure applied by pumping water out of the caisson interior. Mooring loads are applied by an anchor line usually attached to the side of the caisson exterior as reflected in Fig. 1 (Andersen et al. 2005). It has typically a large diameter and a wide range of length-to-diameter ratio, thereby providing relatively large horizontal and vertical capacities. The optimal holding capacity is obtained when the chain is attached at a depth where the anchor failure mode exhibits large translational displacements with minimal rotation.

Suction caisson is comparatively a new foundation system for offshore structures as compared to piled foundations, which benefit from more than a century of experimental, analytical and computational investigation of their behavior. Reliable rules for describing the behavior of suction caissons are yet subject to development and investigation. The effects from different parameters such as the caisson geometry, soil characteristics, and soil-caisson interaction nature on the load bearing capacities of suction caissons still need further study. The current numerical study mainly deals with effects of interface modeling on the responses of the suction caisson subjected to various loading conditions.

2. FINITE ELEMENT FORMULATION

2.1 Finite element mesh and boundaries

Finite element analyses were carried out using a general purpose finite element code ABAQUS. Undrained conditions imply an incompressible material for which mean stress cannot be determined from displacements. Hybrid displacement-pressure elements provide an effective means for numerical modeling of this condition. The ABAQUS element library offers a number of hybrid elements. A three-dimensional 8-node hybrid brick element with reduced integration (C3D8HR) was selected for the FEM simulations. The dimensions of the suction caisson anchor with an aspect ratio of 2.0 are presented in Fig. 2a, and are tabulated in Table 1.



(a) (b)

Fig. 2 (a) Model definition (after Supachawarote 2006), and
(b) Finite element mesh (L/D = 2)

Table 1 Variables for model definition

Variable	**Definition**	**Value**
D	Diameter of anchor (m)	5
W	Diameter of ground (m)	60
H	Length of ground (m)	30
L	Length of anchor (m)	10
t	Thickness of anchor (m)	0.5
P	Load (kN)	-
θ	Load inclination (degrees)	-
z_c	Loaded depth of center (m)	-
z_0	Loaded depth of padeye (m)	-

Taking advantage of symmetry about the plane in which the load is applied, only one-half (180 degrees) of the problem had to be modeled as depicted in Fig. 2b. The displacement at the outer boundary and at the base of the mesh were assumed to be zero. All the nodes at these boundaries were constrained by imposing zero displacements. The nodes at the plane of symmetry were constrained in the normal direction of the plane.

2.2 Soil constitutive model

In this study, the behavior of suction caissons embedded in an isotropic cohesive soil was investigated. The soil supporting the caisson is represented by the von Mises strength model, which is a pressure independent criterion appropriate for undrained total stress analysis. Table 2 presents the physical parameters used to model the soil. ABAQUS characterizes the von Mises yield surface in terms of the yield strength, σ_y.

This is related to the undrained shear strength used in this study to characterize soil shearing resistance by the following relationship, $\sigma_y = \sqrt{3}s_u$. The suction caisson was modeled as a rigid body. A rigid body is a group of nodes or elements whose motion is governed by the motion of a single node also called the rigid body reference node. Displacement-controlled analyses was enforced on the rigid body reference node.

Table 2 Material of ground model

Young's modulus	**Undrained shear strength**	**Poisson's ratio**
5,000 kPa	10 kPa	0.49

2.3 Soil-caisson interaction

The exterior soil-caisson interface is modeled with a contact algorithm based on a slide-line formulation (Hallquist et al. 1985), which allows for large relative displacements between the caisson and the soil. The slide-line formulation involves nodes on the soil side (slave surface) of the interface and surface elements (master surface) on the caisson side. Moreover, tie constraints are used to tie other potential contact surfaces for the duration of the simulation. 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, $\tau_{crict} = \mu p$, where μ is a user-defined friction coefficient and p is the normal contact pressure between the two surfaces. Figure 3 summarizes the behavior of the Coulomb friction model.

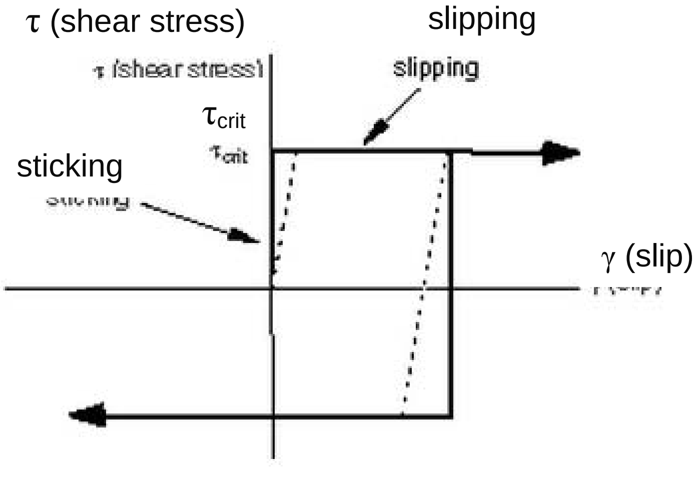


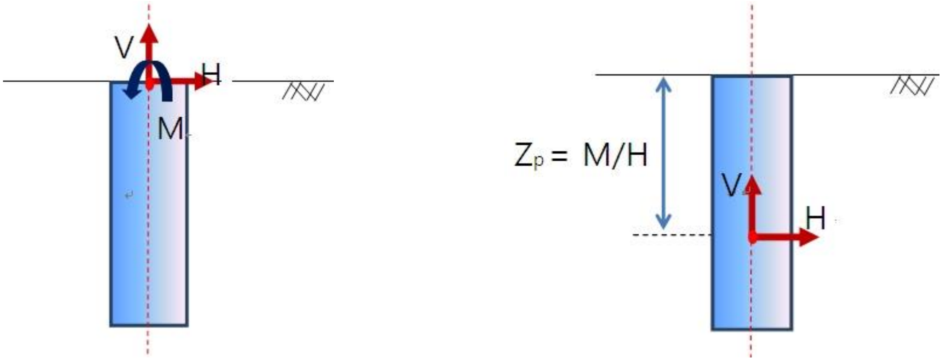
Fig. 3 Coulomb friction model (after Abaqus 2011)

Simulating ideal friction behavior can be very difficult; therefore, by default in most cases, ABAQUS uses a penalty friction formulation with an allowable “elastic slip”, shown by the dotted line in Fig. 3. The “elastic slip” is the small amount of relative motion between the surfaces that occurs when the surfaces should be sticking. ABAQUS automatically chooses the penalty stiffness (the slope of the dotted line) so that this allowable "elastic slip" is a very small fraction of the characteristic element length (Abaqus 2011).

3. HOLDING CAPACITY OF SUCTION CAISSON ANCHOR

3.1. Optimal loading point

If the load is attached at its optimal location, the caisson will experience pure translation with no rotation. This corresponds to a condition in which the maximum pullout resistance of the caisson is mobilized. This case was simulated in ABAQUS by purely translating the caisson with translation angles ranging from zero degrees with respect to the horizontal to ninety degrees at an arbitrary reference point as shown in Figure 4 (a). Through this procedure, the FEM analyses calculate an ultimate load as well as the magnitude of the moment required to restrain the caisson against rotation. With the ultimate horizontal force and restraining moment known, the distance of the optimal loading point from the reference point is computed simply by dividing the restraining moment by the horizontal force as depicted in Figure 4 (b). The reference point used in these simulations was on the centerline at the top of the caisson. Table 3 summarizes the restraining moments, horizontal forces, and optimal loading points under various translation angles.



(a) Reactions at reference point (b) Optimal loading point

Fig. 4 Estimation of optimal loading point (after Ahn et al. 2014)

Table 3 Optimal loading depth according to translation angles

Angle (θ)	Restraining moment (kN-m)	Horizontal force (kN)	Optimal loading depth (m)
0	16,410.50	2,874.30	5.71
22.5	15,662.80	2,759.10	5.68
30	15,221.00	2,681.90	5.67
45	14,072.30	2,473.84	5.69
60	12,547.80	2,175.67	5.77
75	10,198.50	1,760.87	5.79

The variation of optimal attachment point with different translation angles is shown in Figure 5. These values reflected the optimal loading depth determined in the work of Ahn and Lee (2012). It can be observed that the reaction forces were identical to that computed for the case in which the caisson was restrained against rotation.

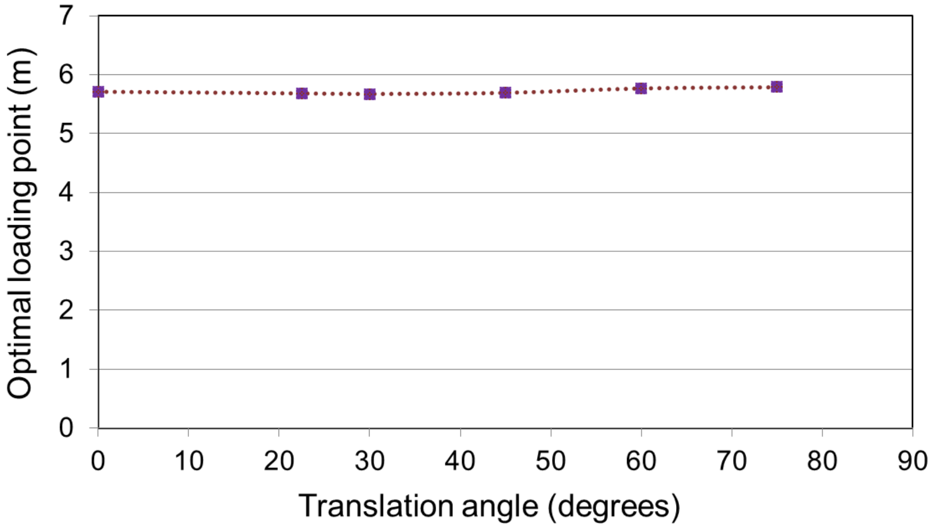


Fig. 5 Variation of optimal attachment point with translation angles

3.3. Holding capacities under inclined loading

In order to investigate the effect of interface modeling on the holding capacity of suction caisson anchors, the following FEM analysis cases, as summarized in Table 4, were performed for a uniform soil profile under inclined loading. All cases followed the FE formulation discussed in sections 2.1 and 2.2. They only differed in the exterior soil-caisson interface formulation.

Table 4 FEM analysis cases

Case	**Exterior soil-caisson interface formulation**
1	Tie constraints method
2	Rough interaction method
3-1	Penalty interaction method (do not allow separation)
3-2	Penalty interaction method (allow separation)

Under case 3, two conditions in characterizing the normal behavior of the exterior soil-caisson interface were defined namely allow separation and do not allow separation after contact. However, it was noticed that the two conditions gave identical total resultant forces for different translation angles. In addition, cases 1 and 2 also yielded almost the same total reaction forces. These observations are presented in Figure 6.

Examples of force-displacement curves for various translation angles for the case of no rotation are shown in Figure 7. The horizontal-vertical force interaction diagrams are presented in Figure 8 where the failure was defined either at convergence or the padeye displacement which is 20% of the anchor diameter. It should be regarded that the vertical and horizontal reaction forces may be few percent overestimated due to the effect of the element size (mesh discretization).

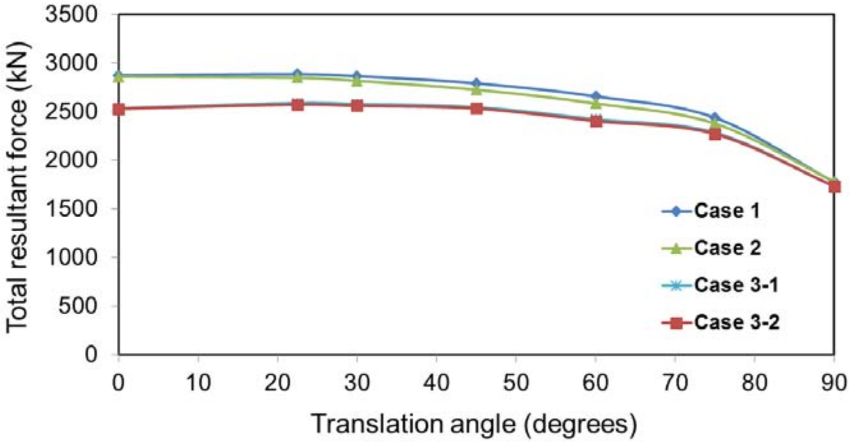
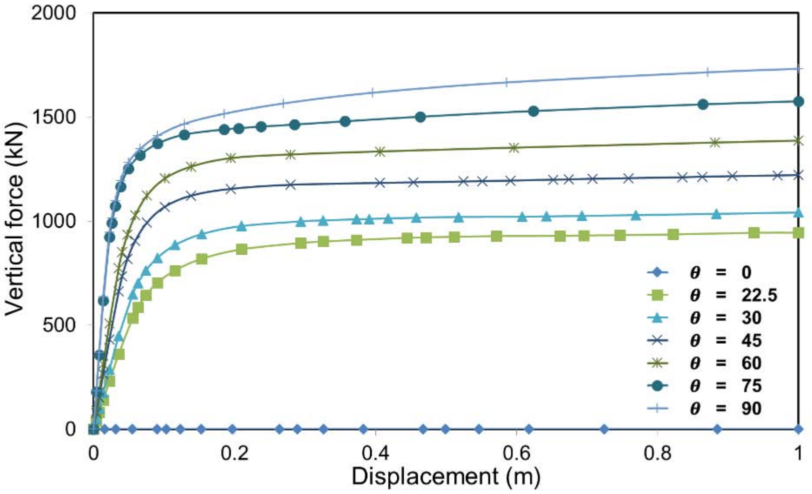
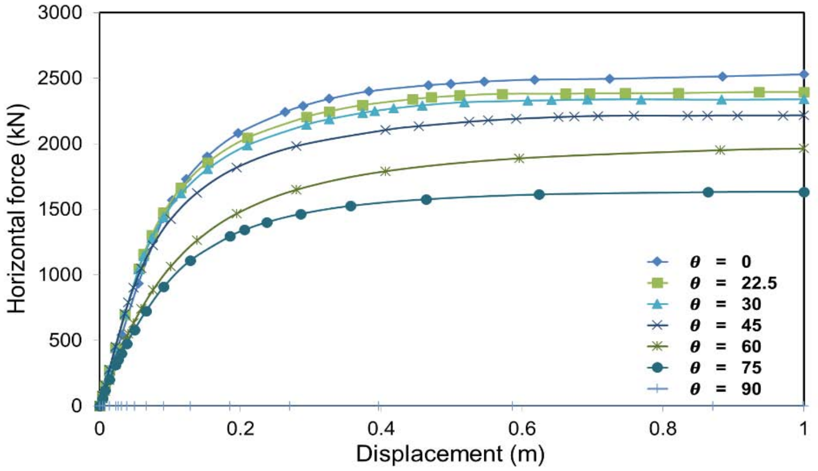


Fig. 6 Variation of total resultant force with translation angles

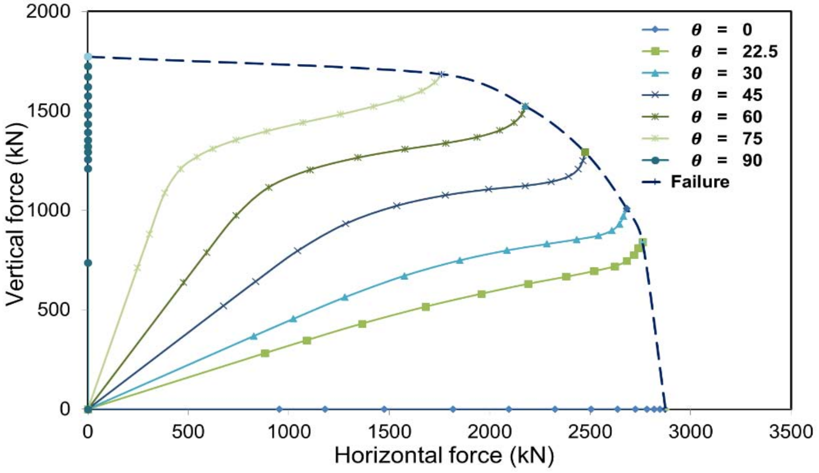


(a) Vertical reaction force

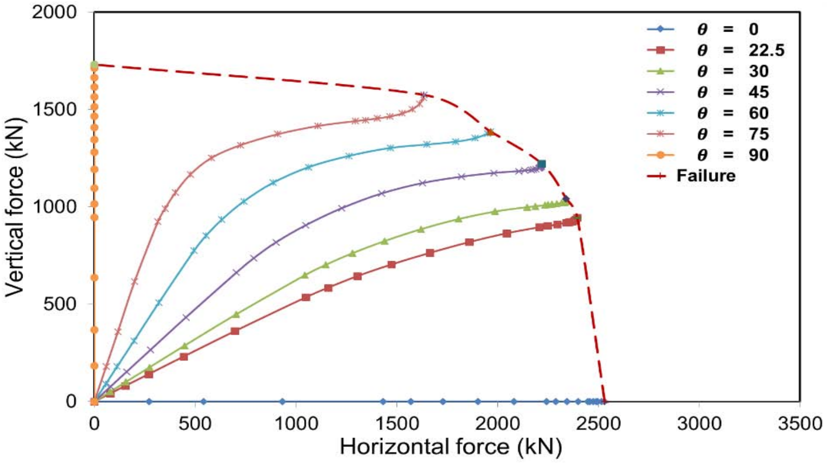


(b) Horizontal reaction force

Fig.7 Force-displacement curves for penalty interaction



(a) Rough interaction



(b) Penalty interaction

Fig. 8 Failure envelopes

4. CONCLUSION

A three-dimensional soil-structure finite element model has been used to estimate the holding capacity of a suction caisson anchor, with an aspect ratio of 2.0, under various translation angles. The caisson was assumed to be embedded in a homogeneous soil which deforms under undrained conditions. The responses of the caisson under different translation angles and the interaction of forces in the form of failure envelopes in vertical-horizontal loading planes were presented. The optimal load attachment depth was estimated such that the resultant load intersects the centerline at very close to 0.57 times the caisson length. The effects of interface modeling on the computed capacities are demonstrated. Contact surface elements were used to model the behavior of the soil-caisson interaction. A finite element model that assumes a rough interface contact significantly has no effect on the vertical capacity of the anchor but may overestimate the anchor's horizontal capacity when compared to a penalty friction formulation whether a separation or no separation is defined under various load inclinations. Penalty friction formulation led to capacities reduced by approximately 12% for horizontally translating caissons when compared to rough, no separation interface. It is further required to investigate the interface effect for different aspect ratios and more realistic soil profile.

ACKNOWLEDGEMENT

This work was supported under the New & Renewable Energy Program (No. 20113020020010-11-1-000) of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Mid-Career Researcher Program (No. 2011-0029426) of the National Research Foundation (NRF) of Korea, both of which are funded by the Korea government.

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