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Supporting Capacity of Short Suction Anchor based on Numerical Modeling

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ABSTRACT

Foundations of offshore structures have been actively studied to provide design guides for oil platforms in the past. Presently, this asset from oil industry now finds its application in the design of the foundations for offshore wind turbines. The analytical solutions for the holding capacity of suction anchors have been developed based on limit equilibrium and limit analysis theorems and often compared to the results of novel approaches such as finite element (FE) analysis. However, some solutions show discrepancy with the FE analysis results under specific conditions, say under certain value of the ratio of length to diameter. The main scope of this paper is to analyze the hold capacity of suction caisson anchors, especially with slenderness ratio based on FE analysis. The results will provide a basis to enhance the existing plasticity solutions for anchor holding capacity.

1. INTRODUCTION

Foundations and anchors for offshore structures have actively been studied by oil industries, and under new demands for offshore wind energy the knowledge in offshore oil platforms finds its way in the development of foundations for offshore wind turbines. The vast majority of current foundations for offshore wind turbines are monopile fixed at the sea bed in shallow water, up to ~30 m. In deeper water, i.e. deeper than ~80 m, the floating wind turbines are thought to be most cost-effective. There recently were, therefore, researches initiated and conducted for this type of wind turbines including analytical works, model tests, and implementation of prototypes (Goupee et al., 2012; Cermelli et al., 2012).

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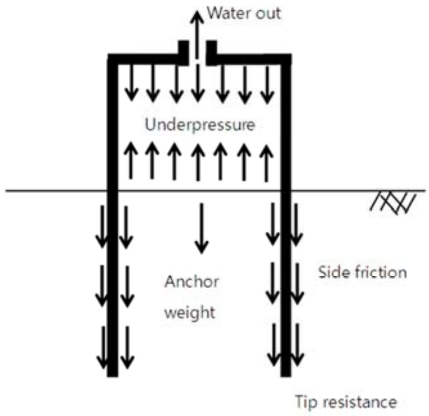


Fig. 1 Installation of suction caisson (after Supachawarote, 2006)

A principle interest of this study lies on the holding capacity of the suction caisson anchors of the floating wind turbines. During the installation process, the suction caisson anchor is first penetrated into the seabed by self-weight, and then the water is pumped out from inside the caisson causing the pressure inside to fall below that outside to achieve another round of penetration up to design embedment (Randolph and Gourvenec, 2011). It does not require pile driving systems making the suction caisson a viable option for anchoring system in deep water.

The concept of the suction caisson was reported by Goodman (1961), who conducted model tests on pull-out resistance of suction caisson anchors. Much effort has been invested, since then, to investigate the performance of the suction caisson anchors, such as physical modeling by 1-g model and centrifuge tests (Brown and Nacci, 1971; Fuglsang and Steensen., 1991; Andersen et al., 1993; Watson and Randolph, 1997; Watson et al., 2000; House and Randolph, 2001; Clukey et al., 1993; Kelly, 2006; Carol, 2009), analytical and numerical methods (Deng, 2001; Cao et al., 2002; Randolph and House, 2001; Aubeny, 2003; Cao et al, 2005a and 2005b; Zhan and Liu, 2010).

2. FINITE ELEMENT MODEL

A commercial software ABAQUS (Abaqus, 2011) was employed for the finite element analysis. The schematic in Fig. 2 is the system of interest in this study, and a relatively short anchor with L/D = 2 is considered. The dimensions of the finite element model are tabulated in Table 1, and a screen shot of the mesh in Fig. 3. Only half section of full three-dimensional model was used due to the symmetric nature of the problem.

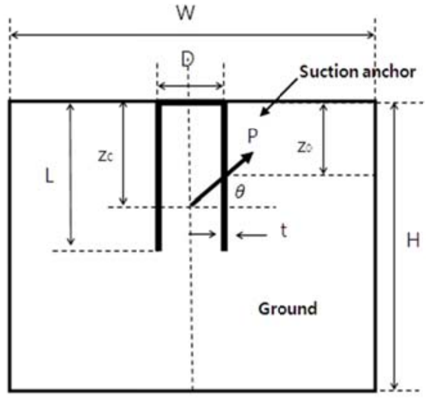


Fig. 2 Model definition (After Supachawarote, 2006)

Table 1 Variables for model definition

Sign	Contents
d	Diameter of Anchor (5m)
W	Diameter of Ground (30m)
D	Length of Ground (30m)
L	Length of Anchor (10m)
P	Load
θ	Angle of Load
t	Thickness of Anchor (0.5m)
z_c	Loaded depth of Center
z_0	Loaded depth of Padeye

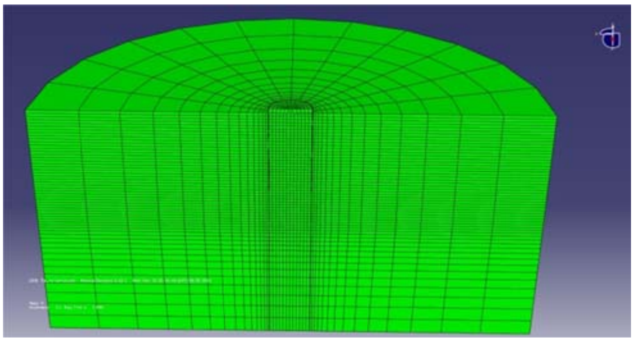


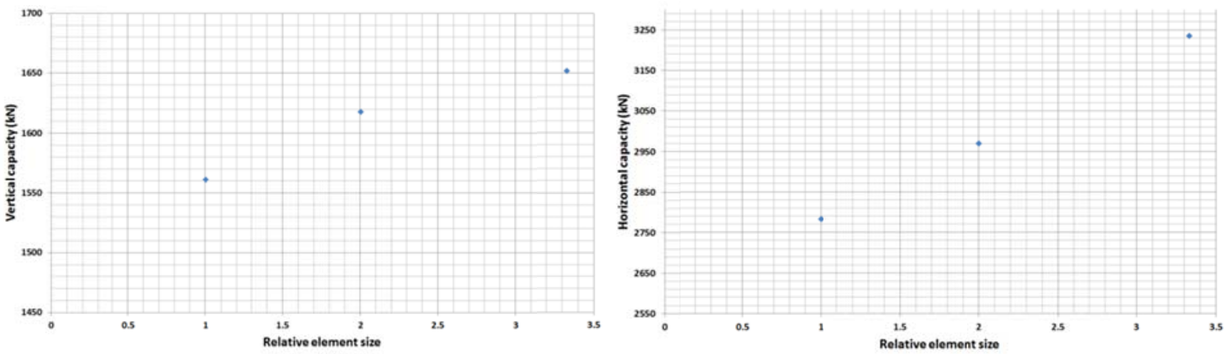
Fig. 3 Finite element mesh (L/D=2)

Both the suction caisson anchor and the soil are modeled by three-dimensional continuum element, and linear hybrid elements were used with reduced integration option available in ABAQUS database. As the soil is assumed to be under undrained condition, therefore incompressible, the use of hybrid elements is justified. For the soil material, von Mises yield criterion is used and corresponding material properties are presented in Table 2. It is noted that the relationship of the yield strength σ_y in von Mises criterion and the undrained shear strength s_u is $\sigma_y = \sqrt{3}s_u$. The caisson was model as linear elastic material and the modulus of elasticity was assumed to be much higher than that of the soil (10^8 times), so that the caisson results in a rigid behavior. The caisson and the soil are fully bonded, and no separation is considered in this study.

Table 2 Material of ground model

Young's Modulus	**Undrained shear strength**	**Poisson's ration**
5,000 kPa	10 kPa	0.49

Unless stated otherwise, the finite element mesh in Fig. 3 was used for the analyses through this article. However, to investigate the effect of element size on the holding capacity of the anchor, the element sizes were varied from the baseline size in Fig. 3 by 2 times and 3.3 times uniformly for the entire model. Then the caisson was pulled either vertically or horizontally restricting the rotation and the failing loads were evaluated under pure translation motion as shown in Fig. 4. As it can be seen in the figure, the larger element, the larger the estimated capacity as the stiffness of the system increases with rising element size. Assuming roughly a linear relationship between the capacity and the element size, when the element size is zero, the vertical and horizontal capacities are estimated to be 98% and 93% respectively of when the baseline element size was used. This correction ratio may be applied to the capacities estimated based on the baseline element size.



(a) Vertical capacity (b) Horizontal capacity

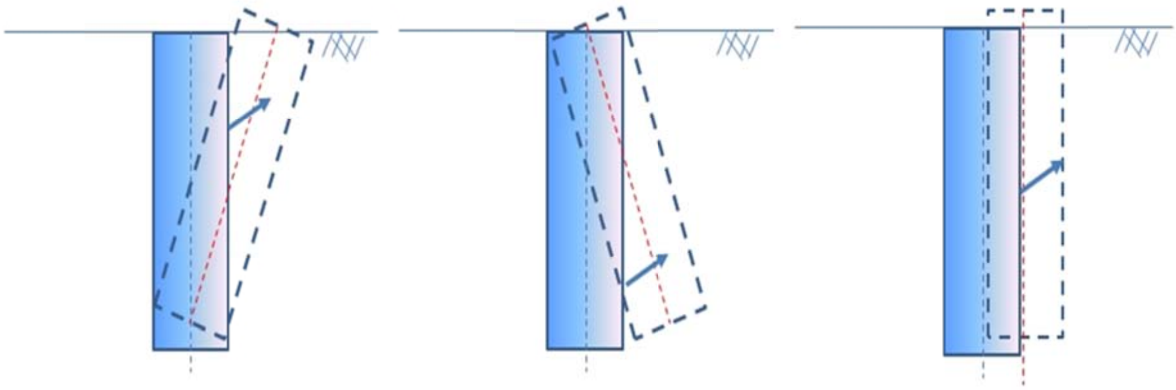
Fig. 4 Capacity estimated and element size

3. HOLDING CAPACITY

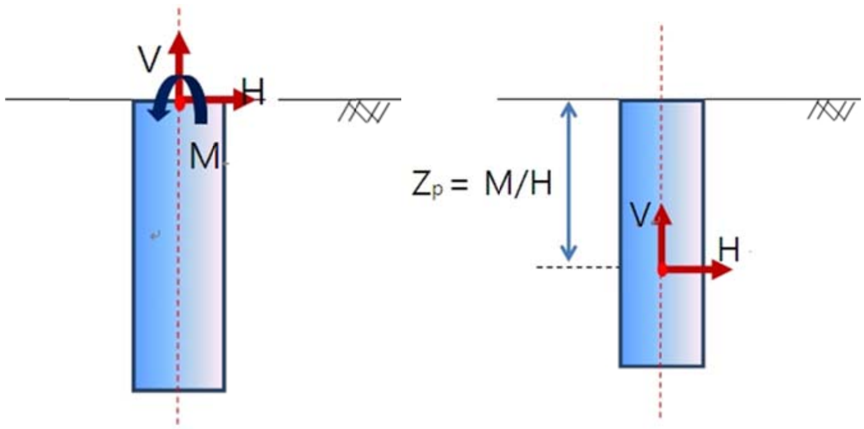
3.1. Optimal Loading Point

When the caisson is horizontally loaded at the padeye, depending on the location of the padeye the anchor may rotate forward, backward, or translate without rotation as shown in Fig. 5. The location of the padeye which makes the anchor purely rotate as in

Fig. 5(c) is called an optimal loading point, and the capacity is the largest when the caisson is pulled at this point (Supachawarote, 2006). For vertical loading, if the load is applied along the centerline of the cylindrical caisson, there would be no rotation anyway. Therefore, under inclined loads, combination of the vertical and horizontal loads, the same optimal loading point under horizontal load would role as an optimal loading point. When the caisson is loaded with rotation restricted, the reaction forces and moment can be read at a reference point, in this study given on the centerline of the caisson at mudline level as shown in Fig. 6. The location of optimal loading points can then be estimated from the two reactions, horizontal force and moment (Fig. 6(b)) (Supachawarote, 2006).



(a) Forward rotation (b) Backward rotation (c) Pure translation
Fig 5. Behavior of a caisson (after Supachawarote, 2006)



(a) Reactions at reference point (b) Optimal loading point
Fig. 6 Estimation of optimal loading point

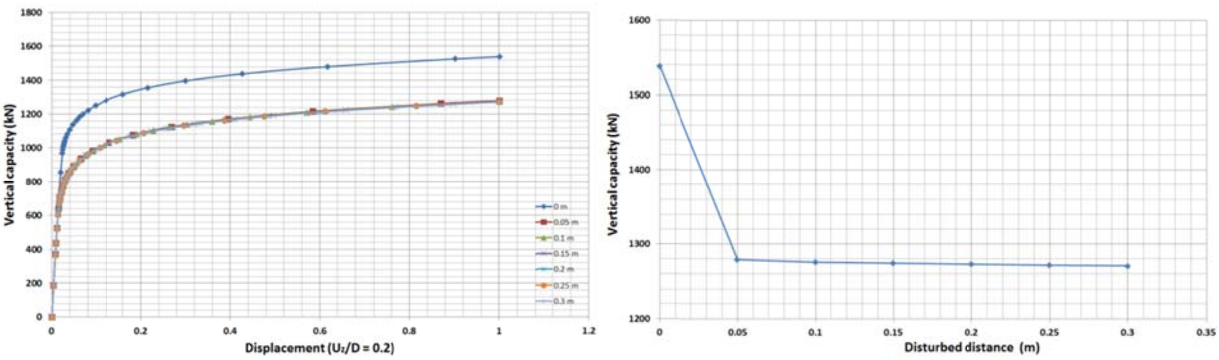
In order to estimate the location of the optimal loading point, the caisson was purely translated with translation angle of 0, 22.5, 30, 45, 60, 75, 90 degrees. It is noted that these angles are translation angles but not the angle of loads. In Table 3, the optimal loading points under different angles of translation and load are summarized. Whereas the location of optimal loading point should not vary in principle, they show about 1% scatter among them which is considered to be due to numerical artifacts.

Table 3 Optimal loading depth according to angle

Angle (θ)	Optimal loading depth(m)
0	5.69
22.5	5.78
30	5.68
45	5.70
60	5.76
75	5.73

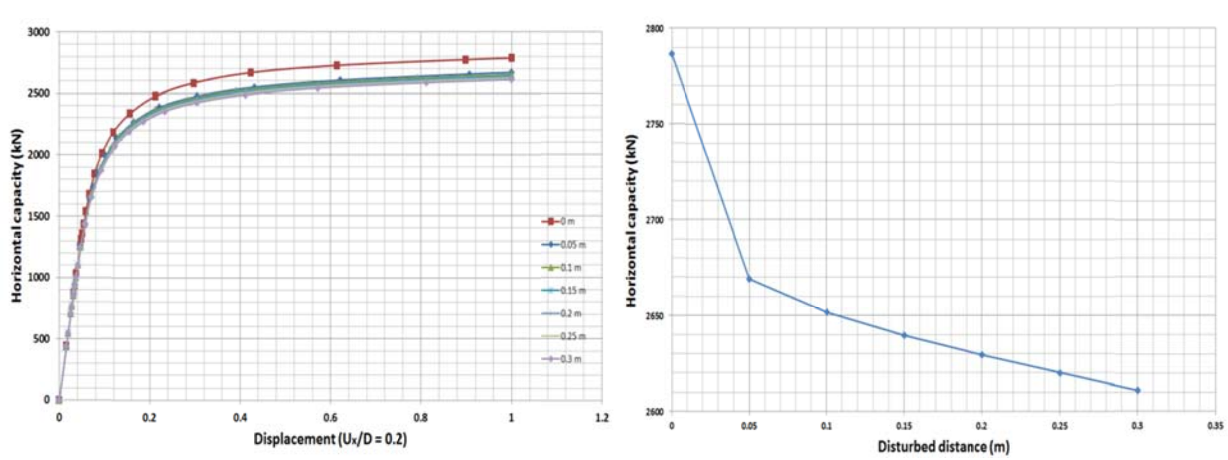
3.2. Effect of Soil Disturbance Width

During the installation procedure of the caisson, the soil surrounding the caisson may be disturbed and its strength may change. There may not be a single number to account for the reduction in strength but in this study the reduction is assumed to be 65% (Andersen and Jostad, 2002) and the effect of sine of disturbed zone on the capacity was investigated. A new finite element mesh was generated for this analysis making the disturbed width to vary from 0.05 m to 0.3 m by 0.05 m increment outside the caisson wall. A series of analyses were conducted under the exactly same mesh but only material property was modified up to the disturbed distance. The results were summarized in Figs 7 and 8, and it is noted that the width of disturbance does not affect significantly the horizontal capacity of the suction caisson anchor. In the following section, however, the disturbance is neglected for the capacity estimation as the scope of this paper is to provide a reference for the capacity under uniform and ideal soil condition.



(a) Capacity and displacement (b) Capacity and disturbed distance

Fig. 7 Vertical capacity and disturbed distance

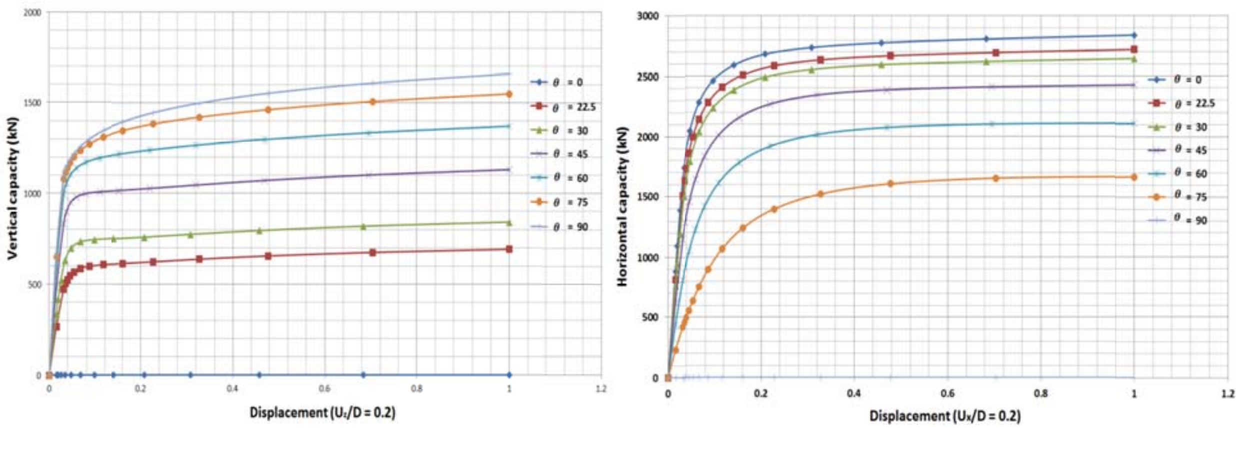


(a) Capacity and displacement (b) Capacity and disturbed distance

Fig. 8 Horizontal capacity and disturbed distance

3.3. Capacity under Inclined Load

In order to establish the full failure envelope in the vertical and horizontal loads space, the anchor was loaded in various angles. The caisson was translated with no rotation with translation angles of 0, 22.5, 30, 45, 60, 75, 90 degrees, and for each case the vertical and horizontal force reactions were investigated. Fig. 9 shows an example of vertical and horizontal reactions with respect to the translation of the caisson. The failure envelope is presented in Fig. 10 where the failure was defined either at convergence or the Padeye displacement of 20% the diameter. As analyzed in previous section, it is noted that the vertical and horizontal capacities may be few percent overestimated due to the effect of the element size.



(a) Vertical capacity (b) Horizontal capacity

Fig. 9 Capacity and padeye displacement

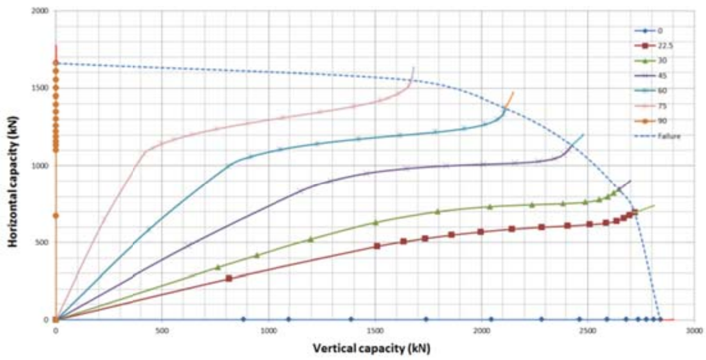


Fig. 10 Failure envelope

CONCLUSION

In attempt to establish a baseline for the estimation of the holding capacity of short suction caisson anchors, the caisson with a slenderness ratio of 2 was considered in finite element analysis. Under uniform profile of the soil undrained shear strength, and complete bonding of the caisson and soil, the optimal loading point was estimated to be about at 0.57 times the caisson length. When the reduction of soil strength is 65% due to installation disturbance, the difference in disturbance width does not significantly affect the horizontal capacity of the caisson. The anchor with 5-m diameter and 10-m length embedded in uniform clay that has 10-kPa undrained shear strength, when loaded optimally, has elliptical shaped failure envelope and its vertical and horizontal capacities were about 1660 kN and 2840 kN, respectively. It is further required to investigate the hold capacity of the caisson under other realistic soil profile.

ACKNOWLEDGEMENT

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