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Behavior of drag anchor under uni-directional loading and combined loading

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ABSTRACT

Drag anchor is an economical foundation option for offshore floating structures. Although there are studies on ultimate pullout capacity of drag anchors, the drag-in installation process is still not fully understood. The approach using yield envelopes for drag anchor under combined loading for the installation behavior prediction is promising. However, more needs to be done to understand anchor bearing behavior during the installation process. The current study focuses on the capacity of drag anchor under uni-directional vertical, horizontal and moment loading in uniform clay and the behavior of anchor fluke under combined loading. Finite element analyses are conducted for "wished-in-place" anchor fluke. The effect of anchor embedment depth and soil overburden pressure is investigated. The horizontal and rotational capacity factors for different embedment ratios and overburden pressure ratios, which have not been covered in the existing studies on anchor capacity, are provided here. The effect of anchor/soil interface breakaway condition on the capacity under the three uni-directional loading is also studied. Based on the understanding of drag anchor capacity under uni-directional loading, its behavior under combined loading is characterized by the yield envelopes for both shallow and deep anchor behavior. The current study provides a good understanding for the capacity of drag anchors. The yield envelopes can be used for the prediction of anchor trajectory with consideration of both shallow and deep anchor behavior.

1. Introduction

Offshore deep water oil and gas industry develops at a fast pace due to the increasing demand of energy. The resulted increase for offshore floating structures increases the need for different offshore anchors for mooring systems. Drag anchor is a commonly used economical anchor type due to its simple, low cost of installation and high holding capacity relative to the low anchor weight in soft clay (Kim, 2005).

Although drag anchor has been widely used, the uncertainty of the anchor position during and after the installation is still a major problem for anchor design as the final anchor position determines the anchor holding capacity. Therefore, it is necessary and important to understand the anchor behavior during installation. The method using yield envelopes to characterize the anchor behavior under combined loading for installation prediction is promising. This method has been used for the installation behavior prediction of the drag embedment anchor (DEA) and vertical loaded anchor (Bransby and O'Neill, 1999; O'Neill et al., 2003; Elkhatib and Randolph, 2005; Elkihatib, 2006), the prediction of keying process of suction embedded plate anchor (SEPLA) and OMNI-MAX anchor (Yang et al., 2011; Cassidy et al., 2012; Wei et al., 2014; Wei et al., 2015; Liu et al., 2016). However, this method still needs to be improved considering the lack of understanding of the anchor bearing behavior in the installation process from shallow embedment to deep embedment.

Due to the complex geometry of practical drag anchors, studies on drag anchors usually start from anchor plate with simplified geometry, which is similar to plate anchor. The majority of the earlier studies have focused on the plate anchor uplift capacity, which is based on analytical solutions or experimental data (O'Neill et al., 2003). Numerical studies have been conducted by Rowe and Davis (1982), Merifield et al. (2001, 2003), Song and Hu (2005), Song et al. (2008) and Wang et al. (2010). However, these studies only focused on the anchor uplift capacity. The anchor plate is subjected to combined vertical, horizontal and moment loading during the drag-in installation. In order to understand the anchor behavior under combined loading and predict the anchor trajectory, it is necessary to understand the anchor behavior under uni-directional vertical, horizontal and moment loading. The limiting values of anchor capacity under the three uni-directional loadings with deep localized failure were studied by Bransby and O'Neill (1999), O'Neill et al. (2003), Elkhatib and Randolph (2005), Elkihatib (2006),

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Yang et al. (2011) and Wei et al.(2015) . However, few studies have been conducted on anchor horizontal and rotational capacity at shallow embedment depths, which is necessary for understanding the anchor behavior during installation.

Based on the review above, most of existing studies have been for vertical pullout capacity and focus on plate anchor with a small anchor plate thickness. For the understanding of installation behavior of drag anchor, further investigations are still required in the following areas: (1) the pullout behavior of drag anchor, which has a larger anchor plate thickness. (2) the horizontal and rotational performance of drag anchor at different installation depths; and (3) the drag anchor behavior under combined loading for both shallow and deep anchor behavior, which is important for anchor trajectory prediction .

For the anchor trajectory prediction using anchor yield envelope and plasticity theory, previous prediction applied the yield envelopes from deep anchor behavior for the whole anchor drag-in from shallow depth to deep depth (Bransby and O'Neill, 1999; O'Neill et al., 2003; Elkhatib and Randolph, 2005; Elkihatib, 2006), whereas the anchor shallow behavior was not considered. Therefore, the current analysis also aims to investigate the yield envelopes for shallow and deep anchor behavior. As the soil/anchor interface friction condition is uncertain, two limiting interface friction (smooth and rough interface) conditions are considered in the current study.

In order to solve the above problems, the current study focuses on the drag anchor capacity under vertical, horizontal and moment loading. The effects of anchor embedment depth, soil weight and breakaway conditions are investigated. The trajectory prediction using yield envelopes in previous studies assumed deep anchor behavior for the whole drag process by using yield envelope for deep anchor behavior. It is thus necessary to integrate the shallow anchor behavior and deep anchor behavior for the prediction of anchor trajectory. Therefore, the current study also focuses on the anchor yield envelope for shallow anchor behavior.

2. Finite element modeling

The commercial computer program ABAQUS is used to conduct plane strain analysis. Displacement-controlled small strain finite element analyses were conducted for "wished-in-place" anchor fluke to investigate the anchor capacity under three uni-directional loading conditions. Practical drag anchors have a wedge-shape cross section. The ratio of anchor width (B) to thickness (t) of the larger side of wedge is about 7 for Stevpris MK5 and 20 for the Stevmanta VLA (Vryhof Anchors, 2015). In the current analysis, the anchor plate is simplified as a rectangular plate with anchor width-thickness ratio B/t = 7, which is similar to that adopted by other researchers (Bransby and O'Neill, 1999; Elkhatib and Randolph, 2005) and is simplified from a Vryhof Stevpris fluke. The plate geometry is shown in Fig. 1, with a width (B) of 0.35 m and a thickness (t) of 0.05 m. The vertical, horizontal and moment loading is shown as V, H and M, respectively. The plate is modeled as a rigid body.

The clay is modeled as a uniform, elastic-plastic Tresca material with rigidity E/S_u=10,000, where E is Young's modulus and S_u is the soil undrained shear strength. This large artificial soil rigidity is applied in this study after the study of the influence of soil rigidity. It is found that the soil rigidity does not influence the maximum capacity and smaller displacement is required to mobilize the maximum capacity. The effect of anchor soil rigidity on the capacity of strip anchors is also confirmed by Wang et al. (2010). The soil Poisson's ratio is 0.495 for modeling the undrained condition of clay and 6-node plane strain triangular elements are used. The finest mesh size is 0.005 m. The schematic and meshes of the finite element model are shown in Fig. 2. H_D is the anchor embedment depth (H_D/B = 10 in Fig. 2). The domain size is 16B in horizontal direction and 20B in vertical direction for all cases with different embedment depth ratio H_D/B (embedment depth/ anchor width) after a domain study for H_D/B = 10. 6-node plane strain triangular element is chosen after a series of element type studies by comparing of available vertical bearing capacity factors with results from others (Merifield et al., 2001).

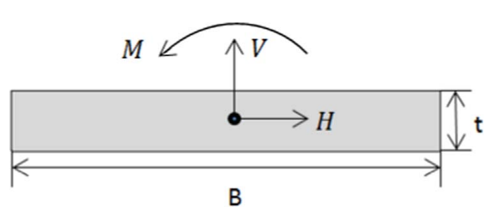

Fig. 1. Anchor fluke geometry.

At the anchor/soil interface, behavior in both normal and tangential direction should be considered. The normal behavior is the interface breakaway condition while the tangential behavior is the friction condition. From Rowe and Davis (1982), the interface breakaway condition was defined for the numerical study of anchor pullout capacity. The "immediate breakaway/no breakaway" condition they used first in the analysis has since been widely applied. For the "immediate breakaway" condition, it is assumed that the soil/anchor interface cannot sustain tension and vertical stresses below the anchor plate reduce to zero as soon as load is applied and the anchor is no longer in contact with the soil, which means that there is no adhesion or suction between the anchor and the soil. For the "no breakaway" condition, there is no breakaway of soil/anchor interface, which is also called the fully bonded condition (Rowe and Davis, 1982). This situation would happen if the interface can sustain tension due to suction or adhesion or if the initial stresses are sufficiently large to ensure that the stresses behind the anchor are compressive for all anchor loads up to and including the failure load. The practical breakaway condition may fall in between these two limiting conditions. For the current study on uni-directional capacity, both the "immediate breakaway" and "no breakaway" conditions are applied to study the influence. For the study on yield envelopes, "no breakaway" interface are assumed in which all the interfaces are attached together. More details are given in the corresponding sections.

For the tangential behavior of the interface in the capacity study, the influence of interface roughness has been studied by many researchers. Merifield et al. (2001) and Wang et al. (2010) conclude that anchor roughness has minor influence on the anchor vertical bearing capacity factors, especially when soil overburden is considered. Elkhatib and Randolph (2005) studied the influence of anchor roughness on the limiting bearing capacity factors in three uni-directional loading directions (vertical, horizontal and rotational). Although the influence of anchor roughness on vertical and rotational bearing capacity is small, the difference between the horizontal bearing capacity factors for smooth and rough condition is about 88% for anchor with B/t=7, which is not unexpected . As anchor plate with lower friction coefficient is more efficient during installation due to lower resistance, the current study focuses on a smooth anchor /soil interface for capacity study while both smooth and rough interfaces are considered for the anchor yield envelopes study.

For the capacity under uni-directional loading, displacement in the corresponding direction is prescribed until the maximum capacity is reached. For the yield envelopes study, two-dimensional loading and multi-directional loading cases are also required. The load at failure is normalized by anchor soil top interface contact area A (which is equal to anchor width B for strip anchor) and soil shear strength (S_u), while the moment is normalized by the contact area, soil shear strength and anchor width to obtain the capacity factors N_{cv} ,N_{ch}, N_{cm}. The subscript "0" is added to denote the capacity in weightless soil. For the yield envelopes study, the maximum capacity factor corresponding to the uni-directional loading are given as V_{max}/AS_u,H_{max}/AS_u and M_{max}/ABS_u to be consistent with other researchers for comparison.