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Three-dimensional behavior of embedded anchor lines under out-of-plane loading

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ABSTRACT

As key components of the mooring system, anchor lines connect the anchors and the floating moored platform. When the platform suffers extreme environmental loadings, the mooring system may partially fail, such as breaking of one or more anchor lines within the spread. Hence, the orientation of the intact lines may change dramatically and the anchor may even present a three-dimensional motion in the seabed, attributed to the long-distance drift of the floater. In such a scenario, both the anchor and the anchor line will experience out-of-plane loading. To evaluate the anchor capacity and the anchor behavior under out-of-plane loading, the three-dimensional behavior of embedded anchor lines should be fully understood in advance. In the present work, a theoretical method is developed to analyze the three-dimensional behavior of embedded anchor lines, including the three-dimensional profile and tension transmitting properties of the line both in clay and in sand. A systematic comparative study is performed to examine the efficiency of the proposed method. Then, two examples of application are designed to analyze the three-dimensional profile and tension transmitting properties of the embedded line under out-of-plane loading. The first corresponds to the partial failure of mooring systems, where an offset of the platform occurs with the anchor fixed at the original penetration. The second corresponds to an engineering case, where the anchor is motivated by the drifting platform and dives in the seabed.

1. Introduction

As an effective, reliable and economical positioning technique, the mooring system, including the catenary, tension leg and taut-wire systems, guarantees the normal operation of floating platforms in a wide range of water depth (tens to thousands meters) [1]. For most anchors in the catenary and taut-wire mooring systems, such as anchor piles, drag anchors, suction anchors and OMNI-Max anchors [2], the attachment point (or padeye) is significantly below the mudline to maximize the holding capacity. Hence, a part of the anchor line will be embedded in the seabed. After the installation of anchors, the mooring lines will be attached to the floating platform, probably with a pre-loading of each anchor line in a vertical plane, such as for drag embedment plate anchors and gravity installed anchors. Then, the embedded line forms a reverse catenary shape attributed to soil resistance, interacting with the anchor at the padeye, as seen in Fig. 1a. The effect of the embedded line on the anchor performance can be approximately quantified by the magnitude and orientation of the load at the padeye.

When the platform suffers extreme environmental loadings (such as hurricane), the mooring system may partially fail, such as breaking of one or more anchor lines within the spread. In such a scenario, the orientation of the intact lines may change dramatically and the loading applied on the anchor no longer lies within the same plane, as illustrated in Fig. 1b. For plate anchors, the out-of-plane loading will reduce the effective bearing area of the anchor and hence the holding capacity of the anchor. The reduction of anchor capacity may result in the failure of the whole mooring system, with the remaining anchors being possibly pulled out. Investigation on the three-dimensional properties of the embedded line is beneficial to calculating the out-of-plane loading applied on the anchor and to evaluating the corresponding capacity that the anchor may provide.

Contrast to the pullout capacity, the anchor may dive into deeper soils to reach the required capacity and prevent the further drift of the platform. Being a gravity installed anchor recently developed, the OMNI-Max anchor was first put to the ultimate test during Hurricane Gustav [3]. An eight-leg mooring system was installed for a mobile offshore drilling unit (MODU) that operated in the Mississippi Canyon area. All eight anchors achieved 15.2 ~ 18.3 m of tip penetration after installation. After Hurricane Gustav passed, the MODU was found approximately 3700 m northwest of its original location attached to only

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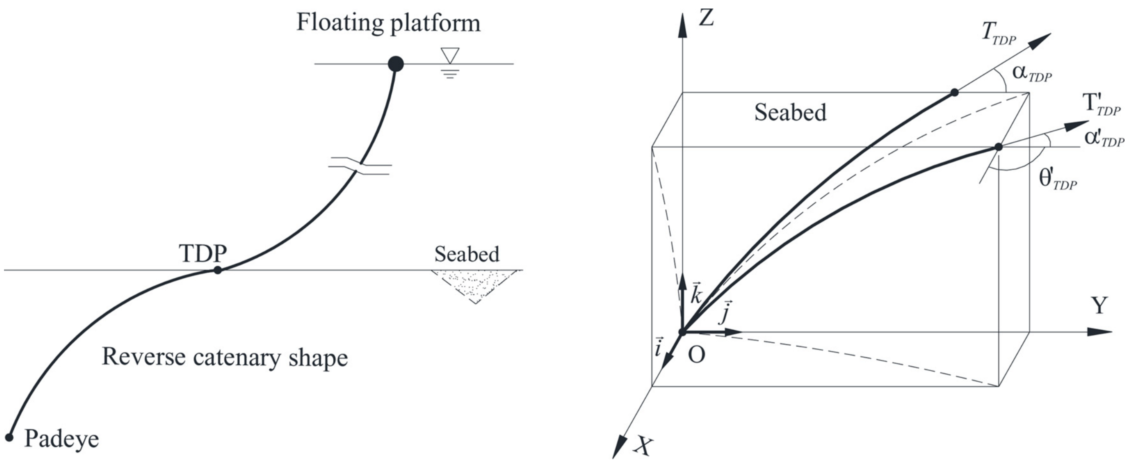
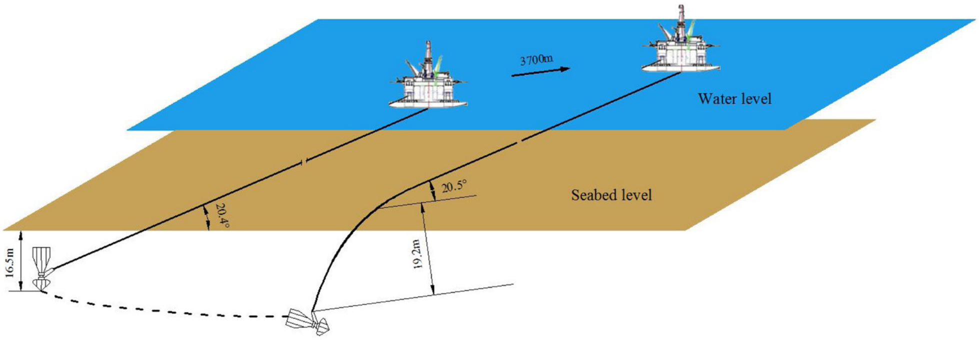


(a) The reverse catenary shape

(b) The embedded line under out-of-plane loading



(c) Three-dimensional motion of the OMNI-Max anchor

Fig. 1. General state of the embedded line in the seabed.

one OMNI-Max anchor (see Fig. 1c). The tip penetrations of the anchors increased to 19.2 ~ 36.6 m, which resulted from the keying and diving performance of the anchor. Unlike the conventional knowledge of the anchor failure, a large displacement or even long-distance movement of the anchor does not mean the failure of anchors, because the anchor still functions and exhibits a so-called non-catastrophic behavior. It should be noted that, the three-dimensional motion of the anchor is always accompanied with the three-dimensional deformation of the embedded line. To predict the comprehensive behavior of OMNI-Max anchors in the soil, which is still a challenging topic in offshore geotechnical engineering, the three-dimensional profile and tension transmitting properties of the embedded anchor line under out-of-plane loading should also be figured out.

1.1. Review of previous studies

There are plenty of theoretical and experimental studies on the reverse catenary properties of the embedded line, including the reverse catenary shape and the tension transmitting property. The theoretical methods can be categorized into two groups: the numerical incremental (NI) method [4–10] and the closed-form expression [11,12]. In the NI method, the reverse catenary properties are calculated via numerical integration of the governing differential equations, together with the iteration of the unknown boundary conditions to match the known boundary conditions. The NI method was first proposed by Reese [4], where the embedded line was discretized as circular elements and the tangential soil resistance and the self-weight of the line were both ignored. Based on the work of Reese [4], the NI method was improved by incorporating the effects of the tangential soil resistance and the self-weight of the embedded line [5–9]. In addition, Bang and Taylor [10] extended the mechanical governing equations to sandy soils. Although the NI method can reflect the effects of many factors and present high accuracy, the discretization and iteration of governing equations is an onerous work. By introducing the small-angle assumption, closed form expressions were proposed by Neubecker and Randolph [11] and Liu et al. [12] to evaluate succinctly the reverse catenary properties of the embedded line.

There are two main aspects concerned in the experimental investigation on the reverse catenary properties of the embedded line. One is to determine the soil resistance to the line, including the end bearing and the frictional resistance. The other is to measure the reverse catenary profile of the line. A series of model tests were carried out by Degenkamp and Dutta [7] to calibrate the effective widths of anchor chain, which was used to calculate the end bearing and the frictional resistance. Through model tests of drag anchor installation, Zhang et al. [13] proposed the range of values of several parameters to evaluate the soil resistance to the installation line in sand. To measure the reverse catenary profile of the embedded line, the static manual measurement approach was adopted by Bang et al. [14] and Heyerdahl and Eklund [15]. Recently, an automatic measurement technique was proposed by Liu et al. [16], where the real-time reverse catenary profile was captured during anchor penetration.

To date, the three-dimensional behavior of the embedded anchor line has received limited attention. Nie et al. [17] presented an analysis