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Reliability assessment of drag embedment anchors in clay for catenary mooring systems

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ABSTRACT

Drag embedment anchors are attractive anchoring solutions, which are widely used for temporary and permanent station keeping of floating structures. The number of floating facility incidents related to mooring system failure continues to raise concerns in the industry in general. This necessitates the reliability assessment of mooring components and their contribution to system integrity. The reliability of drag embedment anchors as a key component of popular mooring systems has never been explored before due to the high complexity of anchor-soil interaction and extensive inherent uncertainties. In this paper, the reliability of drag anchors for catenary mooring lines was investigated with attention to the seabed condition and environmental loads. The probabilistic modelling of anchor capacity was conducted using plastic yield loci to characterize the fluke-soil interaction and failure states. The embedded profile and the frictional capacity of the anchor chain at the seabed were also considered in the calculation of ultimate holding capacity. The uncertainties of the environmental loads, metocean variables, and consequently the stress distribution throughout the catenary lines were accounted for using the response surface method. First order reliability method (FORM) was used through an iterative procedure to obtain the probabilistic failures. The results show an acceptable level of reliability for these anchor families and reveal its sensitivity to key components of anchor geometry.

1. Introduction

Drag embedment anchors are one of the most popular elements in station keeping of floating facilities. These anchors provide the required holding capacity to maintain the floating system in-place under environmental loads. Mooring lines transfer the load generated by vessel motions to the padeye located at the end of the anchor shank, which transfer the load to the fluke and surrounding seabed soil (Fig. 1). Drag embedment anchors are usually the simplest to install and the most challenging to analyse. Catenary mooring lines ending with drag embedment anchors are usually used when large horizontal offsets of the floating system are expected under environmental loads.

Besides excellent achievements in design and application of mooring line components, the number of mooring system related incidents involving floating facilities (on an average of more than two incidents per year [1]) continue to raise concerns in the industry in general. The large uncertainties in seabed parameters and environmental loads combined with the inaccessibility for monitoring, inspection, and maintenance mandates the reliability assessment of mooring components.

Anchors are critical components of mooring system and their reliability assessment can have a significant contribution to the

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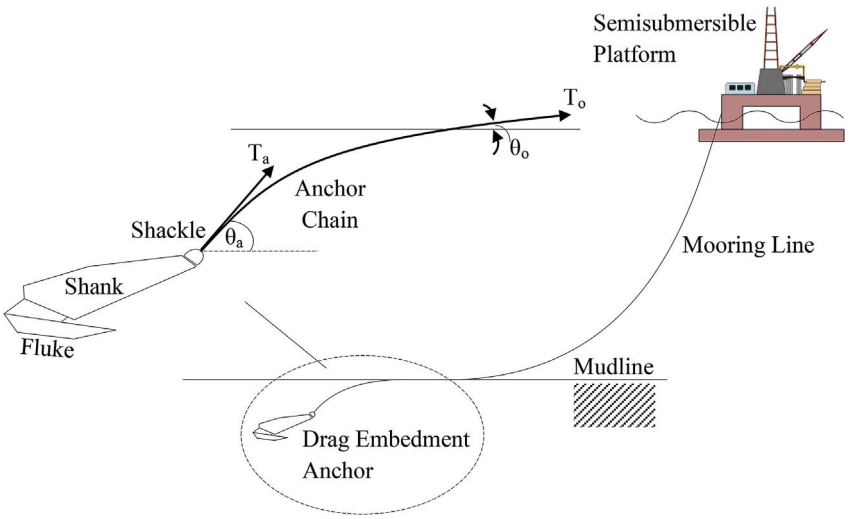

Fig. 1. Catenary mooring system and soil interaction with drag embedment anchor.

reliability of the whole system. A critical review of the literature shows that the reliability of deepwater anchors implementing the complex anchor-seabed interaction is less explored. Only a few studies have been published within recent years, most of them focusing on reliability assessment of suction caissons. There is almost no study on reliability assessment of drag embedment anchors that are the most common anchoring solution in offshore industries. These anchors are widely used in a range of water depths and geographical locations, and this was the motivation of the current study.

1.1. Review of reliability studies for suction anchors

Despite drag anchors, there are several studies conducted on reliability assessment of suction anchors. Considering a relatively close concept of the overall reliability assessment methodologies for these anchor families and the absence of any published works in reliability of drag embedment anchors, it is worth shortly reviewing some of the key studies conducted on suction anchors. This can provide a basis on how to develop a reliability assessment methodology for drag embedment anchors as well.

Clukey et al. [2] studied the reliability of suction caissons. They used linear response surface and defined the lateral holding capacity as a function of soil shear strength and mooring line tension. The authors considered a limit state function for lateral and axial failures to model the catenary and taut-leg mooring and assessed the reliability. Choi [3] conducted a reliability assessment of suction caissons estimating the caisson capacity at padeye using the upper bound plastic limit formulation proposed by Aubeny et al. [4]. They used the Neubecker and Randolph [5] formulations at mudline to account for soil-chain interactions. The biases and variation factor of caisson capacity were calculated using the analytical methods and validated against the test results. In terms of environmental load, authors simulated the hurricane and loop current sea states in the Gulf of Mexico. The dynamic mooring line tensions were assumed Gaussian and the reliability assessment was conducted in terms of median safety factors, and biases and coefficients of variation for loads and capacity. Valle-Molina et al. [6] modelled the mean and expected maximum dynamic tensions as functions of the extreme environment using response surfaces obtained from catenary mooring lines of a Floating, Production, Storage and Offloading System (FPSO). The authors fitted Weibull distributions to few selected total line tensions, which in turn were obtained from simulating the environmental variables and response surfaces. Valle-Molina et al. [6] used Monte Carlo simulation to evaluate the reliability, estimating the caisson capacity based on plastic limit equations proposed by Aubeny et al. [4,7,8]. Silva-Gonzalez et al. [9] assessed the reliability of suction caissons through probabilistic modelling of caisson capacities based on simulations using a plastic limit model. The authors applied first order reliability method (FORM) and established linear relationships between caisson height and failure probability calibrating partial safety factors for line tensions and caisson capacity. Review of the published works shows that proper characterization of anchor capacity is a significant aspect in reliability assessment, particularly considering the significant differences in terms of loading and capacity that is highly affected by anchor-seabed interaction.

1.2. Methodology

In this study, the reliability of drag embedment anchors was assessed based on the calculation of the anchor capacity and mooring line tension at mudline. A limit equilibrium model (LEM) originally proposed by Neubecker and Randolph [17] and a yield envelope approach proposed by O'Neill et al. [10] was developed in an Excel spreadsheet VBA Macro (Visual Basic Application) to estimate the anchor capacity taking into account the soil-chain interaction effects. The LEM model was used to produce the probability densities of anchor capacities. A generic semisubmersible platform was modelled in the Caspian Sea using the Orcaflex software package. 3D coupled finite element analyses were conducted to obtain the characteristic mean and maximum dynamic line tensions for 100 years return period sea states, as well as the design line tension and corresponding line angle at mudline. Samples of drag anchor capacity