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Numerical analysis of suction embedded plate anchors in structured clay

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ABSTRACT

As offshore energy developments move towards deeper water, moored floating production facilities are increasingly preferred to fixed structures. Anchoring systems are therefore of great interest to engineers working on deep water developments. Suction embedded plate anchors (SEPLAs) are rapidly becoming a popular solution, possessing a more accurate and predictable installation process compared to traditional alternatives. In this paper, finite element analysis has been conducted to evaluate the ultimate pullout capacity of SEPLAs in a range of post-keying configurations. Previous numerical studies of anchor pullout capacity have generally treated the soil as an elastic-perfectly plastic medium. However, the mechanical behaviour of natural clays is affected by inter-particle bonding, or structure, which cannot be accounted for using simple elasto-plastic models. Here, an advanced constitutive model formulated within the kinematic hardening framework is used to accurately predict the degradation of structure as an anchor embedded in a natural soft clay deposit is loaded to its pullout capacity. In comparison with an idealised, non-softening clay, the degradation of clay structure due to plastic strains in the soil mass results in a lower pullout capacity factor, a quantity commonly used in design, and a more complex load–displacement relationship. It can be concluded that clay structure has an important effect on the pullout behaviour of plate anchors.

1. Introduction

In recent decades the global demand for energy has increased rapidly and this trend is predicted to continue into the future [1]. Offshore oil and gas reserves have been a mainstay of energy production around the world. However, as the most accessible resources in shallow coastal waters are depleted, the attention of energy producers is moving further offshore [2]. Energy resources requiring installations in water depths of over 2000 m are becoming economically viable and the engineering challenges of deep water developments are therefore of great importance.

As water depths increase rigid structures that are fixed to the seabed, such as jackup units, jacket platforms and gravity platforms, become impractical. Instead, moored floating facilities are preferred. An anchoring system tethers the structure to the seabed, with the amount of free movement of the facility being controlled by the mooring arrangement. The primary goal of the anchor is to resist the combined vertical and horizontal pullout loads that the floating facility is subjected to in the offshore environment.

Suction embedded plate anchors (SEPLAs) are designed to overcome certain limitations of drag embedded anchors, which operate according to the same principles as a ship's anchor. The soil mass in front of the anchor gives resistance to pullout loads. An accurate prediction of holding capacity is difficult as embedment depth of drag-in anchors is hard to predict. SEPLAs are installed into the seabed by a suction caisson, the plate anchor being inserted into a slot at the base of the caisson during penetration. The depth and location of the installed anchor are consequently known to a high degree of accuracy. Using the plate anchor rather than the suction caisson itself for anchoring is significantly less expensive [3]. Following installation, the plate anchor is keyed into the soil through loading of the anchor chain and rotates from a vertical orientation to a direction normal to the applied load if the anchor is symmetrically loaded.

The problem of anchor pullout capacity in undrained clay has been studied by various researchers. For horizontal anchors, Vesic [4] proposed an analytical solution for pullout capacity based on cavity expansion theory in a rigid-plastic material; this approach provides reasonable results for shallow anchors in soft clays. Das [5]

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presented a more versatile approach for the estimation of pullout capacity of shallow and deep horizontal anchors, with an empirical expression derived from model tests.

Rowe and Davis [6] undertook both an experimental and numerical investigation of horizontal and vertical plate anchor capacity in clay. Finite element analysis was used to predict pullout factor values for a range of anchor configurations and soil types, and results were found to agree well with model tests. The study considered an idealised clay which deforms according to the Tresca criterion. A practical definition of failure was adopted, with the failure load being taken as the load causing a displacement four times that of an elastic analysis. This was due to the extent of plastic deformation observed before a well-defined collapse load could be obtained. Merifield et al. [7] used a finite element formulation of upper and lower bound theorems from limit analysis to analyse a similar problem. Results provide a bracket for the true collapse load, and were shown to compare favourably with previous laboratory work.

For SEPLAs, the keying process undertaken after insertion of the anchor by suction caisson leads to rotation and loss of embedment. This was observed in field tests reported by Wilde et al. [3] and has been a recent topic of research (e.g. [8,9]). The capacity of plate anchors at a range of inclination angles is therefore of interest. Limited empirical research has been undertaken, for example the study by Das and Puri [10] tested a model square anchor at several inclination angles to obtain an empirical expression for pullout capacity. Meyerhof [11] also presented a closed-form expression for inclined strip and square anchors in frictional soils. Merifield et al. [12] undertook a numerical investigation of inclined strip anchor capacity where upper and lower bound solutions for pullout factors from limit analysis were compared with finite element results. The finite element analysis, using a Tresca material, was found to be very close to the upper bound solution. Only results for the vented or immediate breakaway case were reported.

Recently, a range of further studies applying finite element analysis have been carried out. Yu et al. [13] conducted a thorough investigation of the pullout capacity of plate anchors at a range of inclination angles and considered a variety of soil conditions. The effect of an inhomogeneous strength profile on the pullout capacity of a square anchor was extensively analysed by Tho et al. [14] using a three-dimensional large deformation finite element formulation. Other examples of finite element studies include Wang et al. [15] and Fahmy et al. [16].

In these cases, the soil was described as a simple elastic-perfectly plastic material. This assumption may be unsuitable for describing natural clays, which often show inter-particle bonding, or structure, that can significantly affect mechanical behaviour [17]. Load–displacement curves show rapid post-peak softening as structure degrades with increasing soil deformation. As an extreme example, the highly sensitive quick clays of Scandinavia [18] demonstrate the impact of the loss of natural structure during soil deformation. In this paper, an advanced soil constitutive model will be used in a finite element analysis of the ultimate pullout capacity of a SEPLA in an undrained structured clay. Plate anchor capacity will be evaluated in a range of post-keying inclinations. This will allow an assessment of the effect of soil structure on pullout capacity, and the subsequent implications for design. In addition, the localised degradation of structure in the soil mass during the deformation process may be observed and related to the failure mechanism.

2. Plate anchor capacity

2.1. Problem outline

This study considers a strip anchor and the layout and notation are shown in Fig. 1. A SEPLA, in its post-keying state, may be rotated at any angle depending on the direction of the applied load and the configuration of the plate anchor, including factors such as offset of the padeye from a central position. Here, the pullout load is considered to act at the midpoint and in a direction perpendicular to the longitudinal axis of the anchor. The inclination angle, β, is measured from the horizontal. The embedment depth (H) of the anchor is non-dimensionalised by considering the H/B ratio, where B is the anchor width.

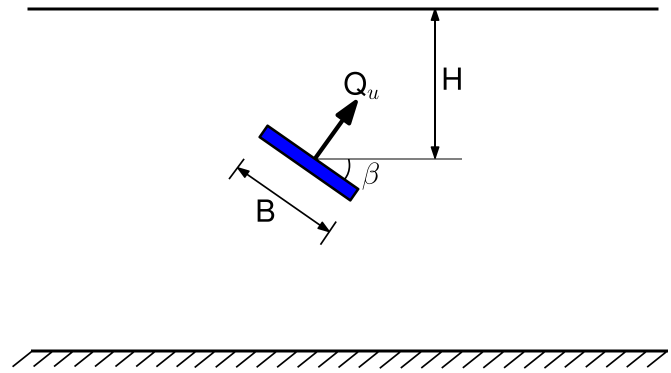

Fig. 1. Schematic of plate anchor pullout scenario and sign convention.

Pullout behaviour of an anchor is affected by the strength of the interface between the anchor and surrounding soil. Physically, suction may develop behind the anchor as it is subjected to a pullout load. As originally suggested by Rowe and Davis [6] the limiting cases are the immediate breakaway 'vented' condition, where no suction or bond exists between anchor and soil, and the no breakaway 'attached' condition where separation is not permitted. These cases form a lower and upper bound, respectively, for the true pullout capacity, as the developed suction or bond between anchor and plate must lie between the two extremes. A distinction is also made between shallow and deep anchors [7]. For a shallow anchor, the failure mechanism involves a block of soil being lifted upwards with the shear planes extending to the ground surface. However, at a certain critical embedment depth the shear zone becomes localised around the anchor. This flow-around mechanism no longer reaches the surface and the anchor is classified as deep.

2.2. Pullout capacity factor

In an undrained clay, the primary design concern is the ultimate pullout capacity of the plate anchor. This is generally expressed as a pullout capacity factor:

$$N_c = \frac{Q_u}{As_u} \tag{1}$$

where Q_u is the ultimate pullout load, A is the plate area and s_u the undrained shear strength. This approach is followed by current design codes (e.g. [19]) for capacity assessment. If the anchor is installed in a soil with an undrained shear strength that increases with depth, the pullout capacity factor may be obtained as:

$$N_c = \frac{Q_u}{As_{u,m}} \tag{2}$$

where $s_{u,m}$ is the undrained shear strength at the midpoint of the anchor. The pullout capacity factor may be further broken down to explicitly analyse the effect of soil weight and an inhomogeneous shear strength profile. It has been shown that this is a reasonable assumption [7]. In this study, a practical scenario is simulated and hence a lumped pullout capacity factor N_c will be calculated with soil weight and inhomogeneous shear strength considered simultaneously.