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Installation and capacity of dynamically embedded plate anchors as assessed through centrifuge tests

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ABSTRACT

A dynamically embedded plate anchor (DEPLA) is a rocket or dart shaped anchor that comprises a removable central shaft and a set of four flukes. Similar to other dynamically installed anchors, the DEPLA penetrates to a target depth in soft seabed sediments by the kinetic energy obtained through free-fall in water and the self-weight of the anchor. In this paper DEPLA performance was assessed through a series of beam centrifuge tests conducted at 200 times earth's gravity. The results show that the DEPLA exhibits similar behaviour to other dynamically installed anchors during installation, with tip embedments of 1.6–2.8 times the anchor length. After anchor installation the central shaft of the DEPLA, termed a follower, is retrieved and reused for the next installation, leaving the DEPLA flukes vertically embedded in the soil. The load–displacement response during follower retrieval is of interest, with mobilisation of frictional and bearing resistance occurring at different rates. The load required to extract the DEPLA follower is typically less than three times its dry weight. The vertically embedded DEPLA flukes constitute the load bearing element as a circular or square plate. The keying and pullout response of this anchor plate is similar to other vertically embedded plate anchors, with an initial stiff response as the anchor begins to rotate, followed by a softer response as the rotation angle increases, and a final stiff response as the effective eccentricity of the padeye reduces and anchor capacity is fully mobilised. For the padeye eccentricity ratios considered (0.38–0.63 times the plate breadth or diameter), the loss in plate anchor embedment is between 0.50 and 0.66 times the corresponding plate breadth or diameter. Finally, the bearing capacity factors determined experimentally are typically in the range 14.2–15.8 and are higher than numerical solutions for flat circular and square plates. This is considered to be due to the cruciform fluke arrangement which ensures that the failure surface extends to the edge of the orthogonal flukes and mobilises more soil in the failure mechanism.

1. Introduction

Floating oil and gas installations in deep water require anchoring systems that can withstand high components of vertical load, whilst being economical to install. Deep water installations are typically moored using either (drag embedded) vertically loaded plate anchors or suction caissons, although a number of other anchoring systems such as suction embedded plate anchors (Zook and Keith, 2009) and dynamically installed anchors (Brandão et al., 2006; Zimmerman et al., 2009) have been used with effect in recent years. Predicting plate anchor capacity for a given embedment is generally straightforward as it is a function of the local undrained shear strength, the projected area of the plate and a dimensionless bearing capacity factor, which, for deeply embedded plates, is typically in the range 11.7–14.3 depending on plate geometry and roughness (Merifield et al., 2003; Song and Hu, 2005; Song et al., 2008). However, predicting the anchor installation trajectory and hence final embedment depth is more challenging and requires accurate shear strength data over a wide seabed footprint (Ehlers et al., 2004). Suction caissons are advantageous in this regard as embedment is monitored and controlled, although successful prediction of the ultimate holding capacity

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must account for a number of factors including the caisson geometry and padeye location, loading angle, time effects and the integrity of the internal seal provided by the soil plug (Randolph et al., 2011). Several disadvantages of these two anchor types have been mitigated by the suction embedded plate anchor (SEPLA) described by Wilde et al. (2001). The SEPLA employs a suction caisson to install a vertically oriented plate anchor. After installation the follower is removed (and reused) and the embedded plate is rotated or keyed so that it becomes normal or near normal to the load applied by the mooring chain.

Anchor installation operations become increasingly more complex, time-consuming and hence costly as water depth increases. However, this is not the case with dynamically installed anchors as no external energy source or mechanical operation is required during installation. Dynamically installed anchors are rocket or torpedo shaped and are designed so that, after release from a designated height above the seafloor, they will penetrate to a target depth in the seabed by the kinetic energy gained during free-fall. Centrifuge model tests indicate that in normally consolidated clay, expected penetration depths are 2–3 times the anchor length and expected anchoring capacities are 3–5 times the anchor dry weight (O'Loughlin et al., 2004). In contrast, expected anchoring capacities for vertically loaded plate anchors are typically 30–40 times the anchor dry weight in very soft clay.

A new anchoring system, termed the dynamically embedded plate anchor (DEPLA), combines the advantages of dynamically installed anchors and vertically loaded anchors in much the same way as the SEPLA combines the advantages of suction caissons with vertically loaded anchors. The DEPLA is a rocket or dart shaped anchor that comprises a removable central shaft or 'follower' that may be fully or partially solid and a set of four flukes (see Fig. 1). A stop cap at the upper end of the follower prevents it from falling through the DEPLA sleeve and a shear pin connects the flukes to the follower. As with other dynamically installed anchors, the DEPLA penetrates to a target depth in the seabed by the kinetic energy obtained through free-fall. After embedment the follower line is tensioned, which causes the shear pin to part allowing the follower to be retrieved for the next installation, whilst leaving the anchor flukes vertically embedded in the seabed. The embedded anchor flukes constitute the load bearing element as a plate anchor. A mooring line attached to the embedded flukes is then tensioned, causing the flukes to rotate or 'key' to an orientation that is normal or near normal to the direction of loading. In this way, the maximum projected area is presented to the direction of loading, ensuring that maximum anchor capacity is achievable through bearing resistance. The installation and keying processes are shown schematically in Fig. 2.

This paper provides DEPLA performance data through a series of centrifuge tests that were designed to quantify expected embedment depths and plate anchor capacities.

2. Centrifuge testing programme

The centrifuge tests were carried out at 200*g* using the fixed beam centrifuge at The University of Western Australia (UWA). The UWA beam centrifuge is a 1.8 m radius Acutronic centrifuge with a maximum payload of 200 kg at 200*g* (Randolph et al., 1991).

2.1. Model anchors and chain

The model DEPLAs used in the centrifuge tests comprised a set of DEPLA flukes (which form the plate anchor after the follower is retrieved), a DEPLA follower and anchor lines connected to the follower and plate anchor padeyes. An interchangeable modular design for the follower (ellipsoidal tip, shaft, padeye) allowed various steel and aluminium sections to be combined to form different overall follower lengths and masses, although the follower diameter and ellipsoidal tip length remained constant at D_f=6.0 mm and L_{tip}=11.4 mm (see Fig. 3). The overall length of the follower (and hence height of the anchor) used in the centrifuge tests was either 51.5 mm, 76.0 mm or 101.5 mm, which at 200*g* corresponds to equivalent prototype heights of 10.3 m, 15.2 m and 20.3 m respectively.

The flukes were fabricated from 0.8 mm thick steel and the sleeve from 0.75 mm thick copper (rather than steel) to permit soldering of the flukes to the sleeve without inducing high temperatures. The outer diameter of the sleeve is 7.8 mm, which, together with the sleeve wall thickness of 0.75 mm, gave a nominal clearance of 0.15 mm between the 6.0 mm diameter follower and the sleeve. The DEPLA flukes that formed the plate anchor element were either circular or square, with the latter oriented in a diamond shape on the DEPLA sleeve (see Fig. 3).

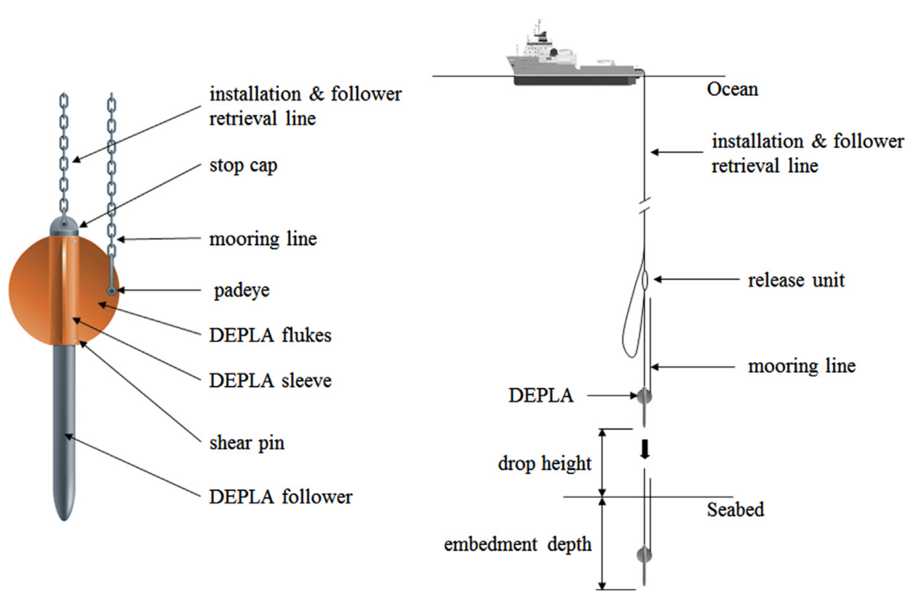

Fig. 1. Dynamically embedded plate anchor concept.