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Numerical investigation of novel dynamic installed fish anchors in clay and calcareous silt

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ABSTRACT

This paper reports the results from three-dimensional dynamic finite element analysis undertaken to provide insight into the behaviour of a novel dynamically installed anchor (DIA), termed as fish DIA, during dynamic installation and monotonic pullout in non-homogeneous clay and calcareous silt. The fish DIA has an elliptic-shaped shaft, which reduces hydrodynamic drag resistance. The shaft is shaped to be thicker near the head to lower the mass centroid, and increase its diving potential with a specialised padeye position. A series of large deformation finite element analyses have been carried out considering the relevant range of parameters in terms of soil undrained shear strength; impact velocity, padeye offset ratio and pullout angle. Considering the difference in soil undrained shear strength, and DIA dimensions and mass; overall anchor tip embedment depths of the fish DIA lied in the range of that of the OMNI-Max DIA. The tracked anchor trajectory confirmed that, compared to the OMNI-Max DIA, the fish DIA dove deeper and earlier for a wide range of padeye offset ratio. These are more critical and beneficial for calcareous silt where the achieved embedment depths are generally lower compared to those in clay.

1. Introduction

Dynamically installed anchors (DIAs) are the most recent generation of anchoring systems for mooring floating facilities for deep water oil and gas developments. During installation, the DIA is released from a specified height above the seabed. This allows the DIA to gain velocity as it falls freely through the water column before impacting the seafloor and embedding into the sediments.

In recent years, broadly two DIA geometries have evolved. The torpedo DIAs are rocket-shaped, typically consist of a long shaft, with the loading point (or padeye) attached at the top, and may feature up to 4 relatively small fins at the trailing edge (Brandão et al., 2006; Lieng et al., 2010). The OMNI-Max DIAs feature three large fins with intermittent discontinuity to accommodate an arm that transfers the loading point nearer to the head of the anchor (Zimmerman et al., 2009; Nie and Shelton, 2011). More than 1500 DIAs (until 2009) have been used for anchoring deep water flowlines and facilities at the Campos Basin, offshore Brazil and at the Gjøa field in the North Sea, off the Western coast of Norway and the Gulf of Mexico in water depths ranging from 200 m to 1400 m (Brandão et al., 2006; Lieng et al., 2010; Shelton et al., 2011).

The motivation of this study has emanated directly from the need identified by the offshore industry in an attempt to extend the application of DIAs in calcareous sediments e.g. in the Australia's North-West Shelf. Most previous field trials and installations were limited in clayey sediments, and no attempt was taken to install DIAs in calcareous soils. Centrifuge model tests have been carried out on existing DIAs (e.g. torpedo anchor) at the University of Western Australia (Hossain et al., 2014, 2015). The anchor embedment in calcareous silt, with shear strength 0–2.5 kPa at the mudline and gradient 2.9–3.3 kPa/m, was significantly lower (1–1.4L_A; where L_A is the anchor length) than that in clay (1.5 ~ 3L_A) under similar or even higher impact velocity. This was due to: (i) the stronger strain rate dependency in calcareous silt compared to clay (Boukpeti and White, 2011) and (ii) the dilative behaviour of calcareous silt compared to contractive behaviour of clay (Mao and Fahey, 2003; Miao and Airey, 2013).

Generally, the deeper embedment depths of DIAs guarantee higher pullout capacity due to the increase in shear strength (Richardson et al., 2009; O'Loughlin et al., 2009, 2013; Hossain et al., 2014, 2015; Kim and Hossain, 2016). In addition, several studies have demonstrated that the lowered padeye position may allow the anchor to embed further (through diving) during pullout (Tian et al., 2014; Liu et al., 2016b; Zhao et al., 2016; Kim and Hossain, 2017). The diving behaviour would distinctly increase anchor's pullout capacity and eliminate the risk of catastrophic failure (Zimmerman et al., 2009). It would be especially beneficial for calcareous sediments in which the embedment depth is

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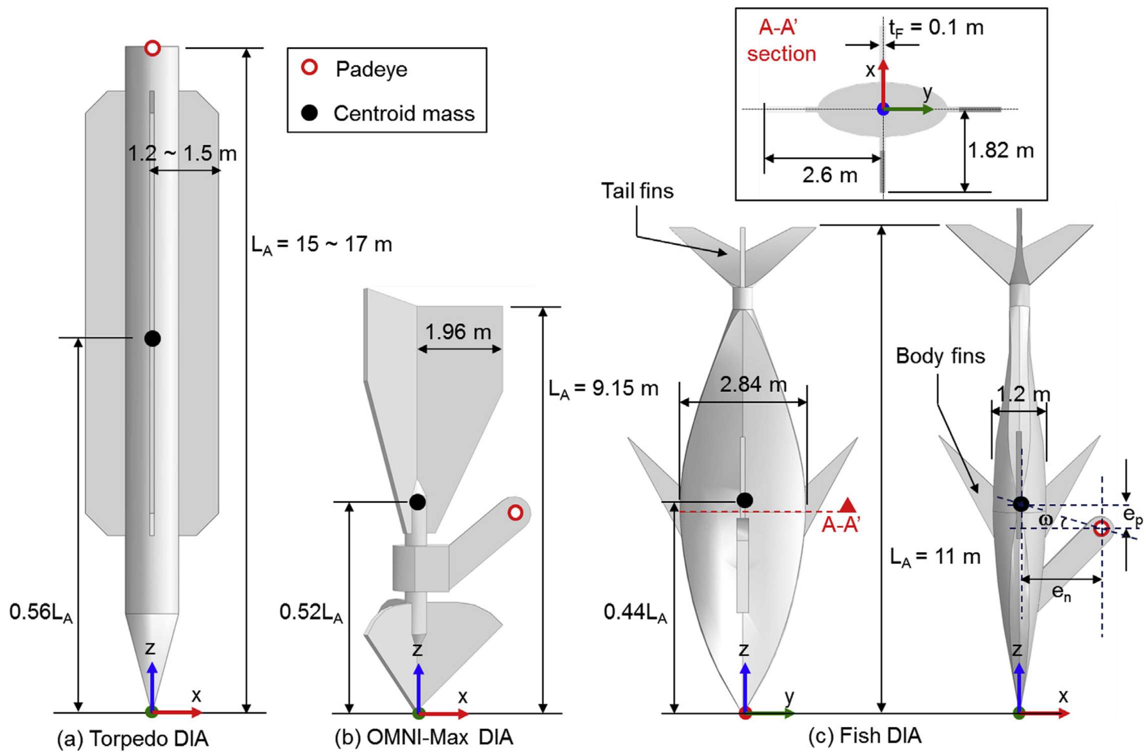

Fig. 1. Schematic geometries of existing DIAs and fish DIA: (a) Torpedo DIA; (b) OMNI-Max DIA; (c) Fish DIA.

relatively shallow and holding capacity is usually inadequate.

A new DIA shape, termed as fish DIA due to the geometric similarity, combines the advantages of streamline body for the deeper penetration depth and lowered padeye position for the higher pullout capacity. This is illustrated in Fig. 1 with comparisons of existing DIAs, and dimensions are given in Table 1. The fish DIA comprises a main elliptic cone-shaped shaft. Every cross section of the shaft is an ellipse and the widest part (A-A′ plane; see Fig. 1c) is in the middle with a constant major and minor axis ratio of 2.36. During the free fall through the water column, the elliptic-shaped shaft reduces hydrodynamic drag resistance, with the drag coefficient (C_d) being 0.04 (Young et al., 2010) compared to 0.22–0.42 for a torpedo DIA's cylindrical shaft (Richardson, 2008). To stabilise the trajectory during free fall in water, balancing the mass, two sets of four body and tail fins are attached to the middle and the tail of the shaft, respectively. The shaft is shaped to be thicker near the anchor head to lower the mass centroid to increase the diving potential upon pullout. The padeye is fitted perpendicularly to the wider part of the shaft (y-z plane; see Fig. 1c), so that the maximum resistance area can be mobilised under operational loading.

The main aim of this study is to investigate the performance of the fish DIA during installation and pullout through three-dimensional (3D) dynamic LDFE analyses. If the fish DIA leads eventually greater capacity, compared to torpedo and OMNI-Max DIAs, ensuring better diving potential, it can be recommended to be applicable the fields with calcareous sediments. A series of integrated dynamic installation-monotonic pullout analyses have been carried out accounting for strain softening and strain rate dependency of the undrained shear strength. An extensive parametric investigation was undertaken, varying the relevant range of various parameters related to the impact velocity, pullout inclination angle and padeye offset ratio. Improved rational approaches are then proposed for assessing the embedment depth and diving potential of DIAs.

Table 1
Fish DIA details.

Description	Symbol (unit)	F1	F2	F3	F4[a]	F5
Total anchor length	L_A (m)	11.0				
Fin thickness	t_F (m)	0.1				
Anchor frontal projected area equivalent diameter	D_p (m)	2.08				
DIA volume	V_A (m^3)	14.45				
DIA dry weight	W_d (kN)	850				
DIA submerged weight	W_s (kN)	702				
Padeye offset	e_p (m)	0.18	0.37	0.716	1.14	1.618
Padeye eccentricity	e_n (m)	1.796	1.796	1.799	1.801	1.804
Offset angle	ω (deg.)	5.7	11.6	21.7	32.3	41.9
Padeye offset ratio	η[b]	0.1	0.21	0.4	0.63	0.9

[a] Centrifuge testing model fish DIA (Chang et al., 2017).
[b] $\eta = \tan\omega = e_p/e_n$ (see Fig. 1).

2. Numerical analysis

3D LDFE analyses were carried out using the Coupled Eulerian-Lagrangian (CEL) approach in the commercial finite element package ABAQUS/Explicit (Version 6.12, Dassault Systèmes, 2012). Extensive background information about installation and pullout modelling of DIAs can be found in Kim et al. (2015a) and Kim and Hossain (2015, 2017), which are not repeated here.

Considering the symmetry of the problem, only a half anchor and soil domain were modelled. The lateral extension of the soil domain were $55D_p$ from the centre of the anchor (D_p is the anchor frontal projected area (A_p) equivalent diameter) on the pullout loading direction and $17D_p$ on the opposite respectively. A typical mesh is shown in Fig. 2. The Eulerian mesh comprised 8-noded linear brick elements (termed EC3D8R in ABAQUS) with reduced integration.

A very fine soil mesh was necessary to capture the anchor-soil contact accurately. Therefore, mesh convergence studies were first performed to ensure that the mesh was sufficiently fine to give accurate results. As shown in Fig. 3a, four different mesh densities were considered for a fish anchor installation (‘very fine mesh zone’ in Fig. 2) under an identical impact velocity of v_i = 19 m/s. The numerical results