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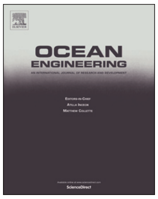

Numerical investigation of dynamic installation of torpedo anchors in clay

Y.H. Kim [1], M.S. Hossain *, D. Wang [2], M.F. Randolph [3]

Centre for Offshore Foundation Systems (COFS), The University of Western Australia, 35 Stirling highway, Crawley, WA 6009, Australia

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This paper reports the results from three-dimensional dynamic finite element analysis undertaken to provide insight into the behaviour of torpedo anchors during dynamic installation in non-homogeneous clay. The large deformation finite element (LDFE) analyses were carried out using the coupled Eulerian–Lagrangian approach, modifying the simple elastic-perfectly plastic Tresca soil model to allow strain softening, and incorporate strain-rate dependency of the shear strength using the Herschel–Bulkley model. The results were validated against field data and centrifuge test data prior to undertaking a detailed parametric study, exploring the relevant range of parameters in terms of anchor shaft length and diameter; number, width and length of fins; impact velocity and soil strength. The anchor velocity profile during penetration in clay showed that the dynamic installation process consisted of two stages: (a) in Stage 1, the soil resistance was less than the submerged weight of the anchor and hence the anchor accelerated; (b) in Stage 2, at greater penetration, frictional and end bearing resistance dominated and the anchor decelerated. The corresponding soil failure patterns revealed two interesting aspects including (a) mobilization of an end bearing mechanism at the base of the anchor shaft and fins and (b) formation of a cavity above the shaft of the installing anchor and subsequent soil backflow into the cavity depending on the soil undrained shear strength. To predict the embedment depth in the field, an improved rational analytical embedment model, based on strain rate dependent shearing resistance and fluid mechanics drag resistance, was proposed, with the LDFE data used to calibrate the model.

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1. Introduction

Dynamically installed anchors (DIAs) are increasingly considered for mooring floating facilities in deep waters. The most commonly used DIA geometry is rocket-shaped, referred to as a torpedo anchor, and may feature up to 4 fins at the trailing edge (see Fig. 1). The anchor is released from a specified height above the seabed. This allows the anchor to gain velocity as it falls freely through the water column before impacting the seafloor and embedding into the sediments.

One of the key challenges associated with torpedo anchors includes accurate prediction of the anchor embedment depth. This is complicated by the very high strain rates (exceeding 25 s^{-1}) at the soil anchor interface, resulting from the high penetration velocities; hydrodynamic aspects related to possible entrainment of water adjacent to the anchor and limited understanding of the soil failure mechanisms. The high strain rate leads to increase in undrained shear strength of the soil in the vicinity of the anchor while, in the absence of any better model, a simple limit equilibrium approach comprising frictional and bearing terms is used to estimate penetration resistance.

1.1. Previous work

Investigations on dynamic installation of anchors are very limited, and mostly through centrifuge modelling and field trials, with a summary given by Hossain et al. (2014). More recently the problem has been addressed through numerical modelling. Raie and Tassoulas (2009) carried out analysis using a computational fluid dynamics model, modelling the soil as a viscous fluid. Sturm et al. (2011) performed quasi-static simulation of the installation process of a torpedo anchor using an implicit finite element code. However, the installation process of a torpedo anchor is a dynamic soil-structure interaction problem involving extremely large deformations. Nazem et al. (2012) carried out dynamic large deformation finite element (LDFE) analysis of a free-falling cone

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* Corresponding author. Tel.: +61 8 6488 7358; fax: +61 8 6488 1044.
E-mail addresses: youngho.kim@uwa.edu.au (Y.H. Kim), muhammad.hossain@uwa.edu.au (M.S. Hossain), dong.wang@uwa.edu.au (D. Wang), mark.randolph@uwa.edu.au (M.F. Randolph).
[1] Tel.: +61 8 6488 7725; fax: +61 8 6488 1044.
[2] Tel.: +61 8 6488 3447; fax: +61 8 6488 1044.
[3] Tel.: +61 8 6488 3075; fax: +61 8 6488 1044.

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Nomenclature

A_A	anchor shaft cross-section area
A_{bF}	fins projected area
A_p	anchor shaft and fins projected area
A_s	total surface area of anchor
A_{sA}	embedded anchor shaft surface area
A_{sF}	embedded fin surface area
C_d	drag coefficient
D_A	anchor shaft diameter
D_p	equivalent diameter (including fins)
d_t	anchor tip penetration depth
$d_{e,t}$	installed anchor tip embedment depth
$d_{e,p}$	installed anchor padeye embedment depth
E_{total}	total energy during anchor penetration
F_b	end bearing resistance
$F_{b,bA}$	end bearing resistance at base of anchor shaft
$F_{b,bF}$	end bearing resistance at base of anchor fins
F_d	inertial drag resistance
F_f	frictional resistance
F_{fA}	frictional resistance along shaft
F_{fF}	frictional resistance along fins
F_γ	buoyant weight of soil displaced by anchor
h_d	anchor drop height
h_{min}	minimum element size
k	shear strength gradient with depth
L_A	anchor shaft length
L_F	fin length
L_T	anchor shaft tip length
m	anchor mass
m'	anchor effective mass
$N_{c,bA}$	bearing capacity factor at base of anchor shaft
$N_{c,bF}$	bearing capacity factor at base of anchor fins
n	factor relating operative shear strain rate to normalized velocity
R_f	factor related to effect of strain rate
R_{f1}	factor related to effect of strain rate for end bearing resistance
R_{f2}	factor related to effect of strain rate for frictional resistance
S_t	soil sensitivity
s_u	undrained shear strength
s_{um}	undisturbed soil strength at mudline
$s_{um,ref}$	reference undisturbed soil strength at mudline
$s_{u,bA}$	undrained shear strength at bottom of anchor shaft
$s_{u,bF}$	undrained shear strength at bottom of fins
$s_{u,sA}$	average undrained shear strength over embedded length of shaft
$s_{u,sF}$	average undrained shear strength over embedded length of fin
$s_{u,ref}$	reference undrained shear strength
$s_{u,tip}$	undrained shear strength at anchor tip level
t	incremental time
t_F	fin thickness
v	anchor penetrating velocity
v_i	anchor impact velocity
w_F	fin width
W_d	anchor dry weight
W_s	anchor submerged weight in water
z	depth below soil surface
α	interface friction ratio
β	shear-thinning index
β_{tip}	anchor tip angle
δ_{rem}	fully remoulded ratio
η	viscous property
λ	rate parameter for logarithmic expression
μ	rate parameter for power expression
μ_c	Coulomb friction coefficient
γ'	effective unit weight of soil
$\dot{\gamma}$	shear strain rate
$\dot{\gamma}_{ref}$	reference shear strain rate
θ_0	pullout angle at the mudline
θ_a	pullout angle at the padeye
ρ_s	submerged density of soil
τ_{max}	limiting shear strength at soil–anchor interface
ξ	cumulative plastic shear strain
ξ_{95}	cumulative shear strain required for 95% remoulding

penetrometer (similar to a finless anchor) using an arbitrary Lagrangian–Eulerian (ALE) approach, accounting for strain rate dependency, but considering uniform clay and assuming a frictionless cone–soil interface. As discussed later, frictional resistance along the surfaces of the anchor and the soil strength gradient have significant influences on the anchor embedment depth.

1.2. Theoretical prediction method for anchor embedment depth

1.2.1. Bearing resistance method

Due to the relative scarcity of investigations to assess installation depths of torpedo anchors, current practice relies on the limit equilibrium method proposed by True (1974), based on Newton's second law of motion and considering uniform clay. Several studies (Medeiros, 2002; de Araujo et al., 2004; Brandão et al., 2006; Richardson et al., 2009; O'Loughlin et al., 2009, 2013, Chow et al., 2014; Hossain et al., 2014) have adopted a similar approach, with variations on the inclusion and formulation of the various forces acting on the torpedo anchor. The equations of motion may be expressed as

$$\begin{aligned} m\frac{\mathrm{d}^2 z}{\mathrm{d}t^2} &= W_s - F_\gamma - R_{f1}F_b - R_{f2}F_f - F_d \\ &= W_s - F_\gamma - R_{f1}\left(F_{b,bA} + F_{b,bF}\right) - R_{f2}\left(F_{fA} + F_{fF}\right) - F_d \\ &= W_s - F_\gamma - R_{f1}\left(N_{c,bA}s_{u,bA}A_A + N_{c,bF}s_{u,bF}A_{bF}\right) \\ &\quad - \alpha R_{f2}\left(s_{u,sA}A_{sA} + s_{u,sF}A_{sF}\right) - \frac{1}{2}C_d\rho_s A_p v^2 \end{aligned} \qquad (1)$$

The terms used in the above expression are defined under nomenclature. R_{f1} and R_{f2} reflect the effects of shear strain rate for end bearing and frictional resistance, respectively. The frictional resistance term (F_f) comprises friction along the shaft (F_{fA}) and the fins (F_{fF}), while the bearing resistance term (F_b) includes end bearing at the base of the shaft ($F_{b,bA}$) and fins ($F_{b,bF}$). In addition, if soil backflow occurs above the installing anchor, reverse end bearing at the upper end of the shaft ($F_{b,tA}$) and fins ($F_{b,tF}$) must be accounted for. F_γ is the buoyant weight of the displaced soil and F_d is the inertial 'drag' resistance generally expressed in terms of a drag coefficient, C_d, as indicated (with ρ_s the submerged soil density and v the penetration velocity).

In practice, natural fine grained soils exhibit strain-rate dependency and also soften as they are sheared and remoulded. For dynamic installation of torpedo anchors, the rate dependency of

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