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Effect of strain rate and strain softening on embedment depth of a torpedo anchor in clay

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ABSTRACT

Torpedo anchors (of diameter ~1 m) are released from a height of 50–100 m from the seabed, achieving velocities up to 35 m/s at impacting the sediment. The strain rates induced in the surrounding soil by this dynamic installation is therefore significantly higher than those associated with installation of other offshore foundations and anchoring systems. The high strain rates enhance the mobilised undrained shear strength compared to that measured by in-situ penetrometer or laboratory tests. This paper reports the results from dynamic installation of a torpedo anchor in strain softening, rate dependent soft clays, quantifying the effects relative to results for ideal Tresca material. The three-dimensional dynamic large deformation finite element (LDFE) analyses were carried out using the coupled Eulerian–Lagrangian approach. The simple elastic-perfectly plastic Tresca soil model was modified to allow strain softening and strain rate dependency of the shear strength. Parametric analyses were undertaken varying the strain rate parameter, the sensitivity and ductility of the soil, and the soil undrained shear strength. Overall, embedment depth for rate dependent, strain softening clays lay below that for ideal Tresca material. Increased strain rate dependency of the soil led to marked reduction in embedment depth, only partly compensated by brittleness. Key results have been presented in the form of design charts, fitted by simple expressions to estimate the embedment depth of a torpedo anchor.

1. Introduction

Dynamically installed anchors (DIAs) are the most recent generation of anchoring systems for mooring floating facilities in deep waters. They have been identified as one of the most cost-effective and promising concepts for future oil and gas development in the emerging frontiers. The anchor is released from a designed height above the seabed. This allows the anchor to gain velocity as it falls freely through the water column before impacting and embedding within the sediments.

The most commonly used DIAs are rocket-shaped, referred to as torpedo anchors, typically 12–17 m long and 0.8–1.2 m in diameter, with a dry weight (W_d) of 230–1150 kN, and may feature up to 4 fins at the trailing edge (see Fig. 1; Brandão et al., 2006). They are released from a height of 50–100 m from the seabed, achieving velocities up to 35 m/s. Challenges associated with dynamically penetrating anchors include prediction of the anchor embedment depth and the subsequent capacity. The former is complicated by the very high strain rate (exceeding 25 s^{-1}) at the soil anchor interface, resulting from the high penetration velocities. There is general agreement that the undrained strength increases with increasing shear strain rate (e.g. Biscontin and Pestana, 2001; DeGroot et al., 2007; Lunne and Andersen, 2007; DeJong et al., 2012). Furthermore, natural soils also undergo softening as they are sheared and remoulded, with typical sensitivity values ranging from 2 to 5 for marine clays and 2 to 2.8 for reconstituted kaolin clay used widely in centrifuge tests (Kvalstad et al., 2001; Andersen and Jostad, 2004; Randolph, 2004; Menzies and Roper, 2008; Lunne et al., 2011; Gaudin et al., 2014).

The paper is a continuation of one that presents results from a parametric study: exploring the relevant range of parameters in terms of anchor length; diameter; tip angle; number, width and length of fins; impact velocity and soil undrained shear strength (Kim et al., 2015). In that paper, large deformation finite element (LDFE) analyses were carried out, accounting for the effect of strain rate and softening, but corresponding to a particular (kaolin) clay. In this study, the reverse was undertaken i.e. a typical torpedo anchor geometry and impact velocity were considered and parametric analyses were performed varying the soil sensitivity, brittleness and strain rate properties. The influence of these parameters on the proposed design expressions for anchor

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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	anchor projected area equivalent diameter (including fins)
$d_{e,t}$	installed anchor tip embedment depth
d_t	anchor tip penetration 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 (calculated using effective unit weight of soil)
g	earth's gravitational acceleration
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
$N_{c,bA}$	anchor tip bearing capacity factor
$N_{c,bF}$	fin bearing capacity factor
n	factor relating operative shear strain rate to normalised velocity
R_a	average strain rate coefficient for embedment prediction
R_b	average strain rate coefficient for energy method
R_{f1}	factor related to effect of strain rate and softening for end bearing resistance
R_{f2}	factor related to effect of strain rate and softening for frictional resistance
S_t	soil sensitivity
s_u	undrained shear strength
$s_{u,bA}$	undrained shear strength at bottom of anchor shaft
$s_{u,bF}$	undrained shear strength at bottom of fins
$s_{u,ref}$	reference undrained shear strength
$s_{u,sA}$	average undrained shear strength over embedded length of shaft
$s_{u,sF}$	average undrained shear strength over embedded length of fin
$s_{u,tip}$	undrained shear strength at anchor tip level
s_{um}	undisturbed soil strength at mudline
$s_{um,ref}$	reference undisturbed soil strength at mudline
t	time after anchor tip impacting seabed
t_F	fin thickness
v	anchor penetration 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
Δt	incremental time
$\Delta\varepsilon_1$	cumulative major principal strain
$\Delta\varepsilon_3$	cumulative minor principal strain
δ_{rem}	fully remoulded ratio
γ'	effective unit weight of soil
$\dot{\gamma}_{ref}$	reference shear strain rate
$\dot{\gamma}$	shear strain rate
η	viscous property
μ_c	Coulomb friction coefficient
θ_0	pullout angle at mudline
θ_a	pullout angle at padeye
ρ_s	submerged soil density
τ_{max}	limiting shear strength at soil-anchor interface
ξ	cumulative plastic shear strain
ξ_a	average cumulative plastic shear strain for embedment prediction
ξ_b	average cumulative plastic shear strain for energy method
ξ_{95}	cumulative plastic shear strain required for 95% remoulding

embedment depth was quantified. Analyses were also conducted simulating ideal Tresca, i.e. rate independent and non-softening, material for comparison.

Extensive background information to installation of torpedo anchors can be found in Hossain et al. (2014, 2015) and Kim et al. (2015), which are not repeated here. For convenience, Figs. 1 and 2 from Kim et al. (2015) are used here, showing a typical anchor geometry defining the nomenclature adopted for the problem and typical mesh details respectively.

2. Numerical analysis

2.1. Geometry and parameters

This study has considered a torpedo anchor, consisting of a circular shaft attached with 4 rectangular fins, penetrating dynamically into a soft non-homogeneous clay deposit as illustrated schematically in Fig. 1, where the mudline strength s_{um}, increases linearly with depth z, with a gradient k. The soil average effective unit weight is γ'. The anchor shaft diameter is D_A of 1.07 m, shaft length L_A of 17 m (including tip length, L_T), fin length L_F of 10 m ($=L_{F1}+L_{F2}+L_{F3}$) and fin width w_F of 0.9 m. Analyses were undertaken for anchors with a 30° conical tip ($\beta_{tip}=30°$). The shape was chosen similar to the T-98 anchor in the field, as illustrated by Medeiros (2002), de Araujo et al. (2004) and Brandão et al. (2006).

2.2. Analysis details

3D LDFE analyses were carried out using the coupled Eulerian–Lagrangian (CEL) approach in the commercial package ABAQUS/Explicit (Dassault Systemes, 2011). To reduce the computational effort, the anchor dynamic installation was modelled from the soil surface, with a given velocity v_i.

Considering the symmetry of the problem, only a quarter anchor and soil were modelled. The radius and height of the soil domain were $40D_A$ ($\sim 32D_p$ for 4-fin anchor) and $\sim 8L_A$, respectively, to ensure that the soil extensions are sufficiently large to