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Toward a quick evaluation of the performance of gravity installed anchors in clay: Penetration and keying

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ABSTRACT

Gravity installed anchors (GIAs) are the most recent generation of anchoring solutions to moor floating facilities for deepwater oil and gas developments. Challenges associated with GIAs include predicting the initial embedment depth and evaluating the keying performance of the anchor. The former involves high soil strain rate due to large anchor penetration velocity, while the later influences the subsequent behavior and pullout capacity of the anchor. With the coupled Eulerian–Lagrangian method, three-dimensional large deformation finite element models are established to investigate the penetration and keying of GIAs in non-homogeneous clay. In the penetration model, a modified Tresca soil model is adopted to allow the effects of soil strain rate and strain softening, and user-defined hydrodynamic drag force and frictional resistance are introduced via concentrated forces. In the keying model, the anchor line effects are incorporated through a chain equation, and the keying, diving and pulling out behaviors of the anchor can all be replicated. Parametric studies are undertaken at first to quantify the effects of various factors on the performance of GIAs, especially on the penetration and keying behaviors. Based on the results of parametric studies, fitted formulae are proposed to give a quick evaluation of the anchor embedment depth after the installation, and the shackle horizontal displacement, shackle embedment loss and anchor inclination at the end of the keying. Comparative studies are also performed to verify the effectiveness of the fitted formulae.

1. Introduction

Gravity installed anchors (GIAs) are the most efficient and economical deepwater anchors in terms of the installation, with high pullout capacity. GIAs can hold predominantly vertical loads, resulting in that they are increasingly used in the taut and semi-taut moorings [1,2]. The existing GIAs include deep penetration anchors (DPAs) [3], torpedo anchors [4] and OMNI-Max anchors [5], which are released from a height of 30–150 m above the seabed, achieving velocities up to 19–35 m/s and tip embedment depths of 1.0–2.4 times the anchor length [6]. The installation of GIAs is illustrated in Fig. 1(a), which are divided into three stages: Stage 1 corresponds to the anchor dropping in the water; Stage 2 corresponds to the anchor partly penetrating into the soil; and Stage 3 corresponds to the anchor totally penetrating into the soil. The capacity of GIAs is a function of its initial embedment depth. To evaluate the capacity of GIAs, the anchor embedment depth should be firstly determined. However, the prediction of anchor embedment depth is a very difficult problem, due to high soil strain rate (up to 25 s^{-1}) resulting from large anchor penetration velocity, and hydrodynamic aspects related to hydrodynamic drag and possible entrainment of a boundary layer of water adjacent to the anchor [1]. The hydrodynamic drag affects the anchor motion in the water and eventually determines the impact velocity v_i of the anchor in Stage 1. When the anchor partly penetrating into the soil (Stage 2 in Fig. 1(a)), the hydrodynamic drag still exists for the anchor body in the water.

The penetration of GIAs involves large deformations of the soil, so the preferred analysis tool is the large deformation finite element (LDFE) method, such as the remeshing and interpolation technique by small strain (RITSS) [7], the arbitrary Lagrangian–Eulerian (ALE), the coupled Eulerian–Lagrangian (CEL) and the sequential limit analysis (SLA) methods [8]. The ALE analysis of a finless torpedo anchor was carried out by Sabetamal et al. [9], where an effective stress analysis was performed and the soil setup after the installation could also be simulated. Recently, the RITSS method was used by Chang et al. [10] to perform an effective stress analysis

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Nomenclature

A_A	Contact area of the shaft
A_F	Frontal projected area of the anchor
A_p	Anchor projected area perpendicular to the plane of the anchor arm
A_s	Anchor surface area
A_{sF}	Contact area of fins
$A_{s,unit}$	Contact area per unit length of the anchor
C_f	$N_{cl}E_nd$
C_{dw}	Drag coefficient in the water
D_A	Anchor shaft diameter
d	Diameter of the anchor line
E	Young's modulus
E_n	Multiplier to give the effective width in the normal direction to the anchor line
E_{total}	Total energy of the anchor
e_s	Padeye eccentricity
e_n	Padeye offset
k	Soil strength gradient
k_{eff}	Effective soil strength gradient
L_A	Anchor length
L_w	Length of the anchor in the water
m	Mass of the anchor
m′	Effective mass (submerged in the soil) of the anchor
N_{cl}	Bearing capacity factor for the anchor line
N_{cs}	Pullout capacity factor = $T_a/s_{u,c}A_p$
$N_{cs,m}$	Maximum pullout capacity factor
q, r	Non-dimensional coefficients of the total energy method
R^2	Coefficient of determination
R_{f1}	Factor related to the effect of strain rate and strain softening for end bearing resistance
R_{f2}	Factor related to the effect of strain rate and strain softening for frictional resistance
r_d	$(z_{t,i} - z_{t,base})/z_{t,base}$
S_t	Soil sensitivity
s_u	Undrained shear strength
s_{um}	Undrained shear strength at the mudline
$s_{u,c}$	Undrained shear strength at the anchor centroid
$s_{u,ref}$	Reference undrained shear strength
$s_{u,sA}$	Undrained shear strength averaged over the contact area of the shaft
$s_{u,sF}$	Undrained shear strength averaged over the contact area of fins
T_a	Shackle load
t_c	Time interval
v	Current anchor velocity
v_c	Control velocity
v_i	Impact velocity of the anchor
$\overline{v_s}$	Average horizontal velocity of the shackle
x_a	Horizontal coordinate of the shackle
z_a	Shackle depth
$z_{a,i}$	Initial embedment depth of the shackle
$z_{t,base}$	Tip embedment depth of the base case
$z_{t,i}$	Initial tip embedment depth
α	Adhesion factor
β	Shear-thinning index
β_k	Anchor inclination at $\Delta z_{a,k}$
$\dot{\gamma}$	Strain rate
$\dot{\gamma}_{ref}$	Reference strain rate
ΔT	Load increment
Δt	Time increment
$\Delta x_{a,k}$	Horizontal displacement of the shackle at $\Delta z_{a,k}$
$\Delta x_{a,m}$	Horizontal displacement of the shackle at $N_{cs,m}$
$\Delta x_{rp,k}$	Horizontal displacement under the maximum embedment loss of the anchor reference point
$\Delta z_{a,k}$	Maximum embedment loss of the shackle
$\Delta z_{rp,k}$	Vertical displacement under the maximum embedment loss of the anchor reference point
$\Delta\varepsilon_1$	Cumulative major principle strain
$\Delta\varepsilon_3$	Cumulative minor principle strain
δ_{rem}	Ratio of remoulded to in situ shear strength
η	Viscous property index
θ	Angle formed by the anchor line to the horizontal
θ_a	Loading angle to the anchor shaft
$\theta_{a,k}$	Loading angle at the shackle to the anchor shaft at $\Delta z_{a,k}$
$\theta_{a,m}$	Loading angle at the shackle to the anchor shaft at $N_{cs,m}$.
θ_{ah}	Loading angle at the shackle to the horizontal
$\theta_{ah,k}$	Loading angle at the shackle to the horizontal at $\Delta z_{a,k}$
θ_e	Loading angle at the mudline
θ_{pe}	Arctan(e_s/e_n)
μ	Frictional coefficient between the anchor line and the soil
μ_c	Coulomb frictional coefficient
ξ	Cumulative plastic shear strain
ξ_{95}	Cumulative plastic shear strain for 95% remoulding
ρ_w	Water density
σ	Normal contact pressure
τ	Shear strength at soil-anchor interface
τ_{max}	Limited shear strength at soil-anchor interface

of torpedo anchors dynamically penetrating in the soil. In the RITSS method, the effective stress analysis was achieved by total stress analysis, with the soil skeleton's effective stress-strain matrix and the pore water stiffness being defined respectively. However, the ALE and RITSS analyses were under a two-dimensional (axisymmetric) condition. For anchors with more complicated geometry, such as 4-fin torpedo anchors and OMNI-max anchors, it is difficult for the ALE and RITSS methods to complete the simulation. With the CEL method, Kim and Hossain [11], Kim et al. [12,13] and Liu et al. [6] investigated the penetration of torpedo anchors and OMNI-Max anchors, in which the effects of soil strain rate and strain softening were considered. Being different from the RITSS, ALE and SLA methods with strict formulations to simulate the soil-anchor interface [7–9], the interaction between the anchor and the soil should be carefully solved for the CEL method. In the analysis of Kim et al. [12,13], a permanent shear stress τ_{max} was adopted to govern the shear failure at the soil-anchor interface during the whole penetration process. In the analysis of Liu et al. [6], a user-defined frictional resistance was introduced to govern the shear failure, where the effects of soil strength, strain rate and strain softening were reflected. In addition, the hydrodynamic drag in Stage 2 was also considered.

In the theoretical prediction of the embedment depth of GIAs, bearing resistance method and total energy method were proposed by True [14] and O'Loughlin et al. [15], respectively. The bearing resistance method, based on the Newton's second law of motion, was broadly adopted and developed [6,11–13,15–17]. Although the total energy method was also developed by Hossain et al. [17], Kim and Hossain [11] and Kim et al. [12,13], the effect of adhesion factor on the anchor embedment depth is not reflected. The frictional resistance acted on the anchor increases linearly with the adhe-