Dynamic Installation of a Torpedo Anchor in Two-layered Clays

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ABSTRACT

The behavior of a torpedo anchor during dynamic installation in two-layered non-homogeneous clay sediments was investigated through large deformation finite-element (LDFE) analyses. Parametric analyses were undertaken varying the top layer thickness and strength ratio between two layers. The results showed that the location of the demarcation point between the acceleration and deceleration phases of the anchor in the soil relative to the layer interface is the key factor directing the anchor behavior in layered soils including the final embedment depth. Broadly, the anchor behavior in soft-over-stiff clay deposits is somewhat similar to that in single layer clay with strength increasing with depth. In stiff-over-soft clay deposits, the anchor penetrates deeper where the anchor deceleration phase (or the demarcation point) falls within the soft layer. Where the demarcation point lies within the top stiff layer, the anchor penetration depth decreases with increasing strength ratio, and the anchor penetration is terminated between the two layers for strength ratio $\geq 15$. For assessing the anchor embedment depth in two-layered fine-grained ocean sediments in the field, an extended total energy based method, along with a design expression, is proposed.

KEYWORDS: dynamically installed anchors; two-layered clays; dynamic installation; embedment depth; numerical modelling; offshore engineering
NOMENCLATURE

As  total surface area of anchor
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
E_{bottom} potential energy for bottom layer
E_{top} sum of kinetic and potential energy for top layer
E_{total} total energy during anchor penetration
F_d  inertial drag resistance
F_b  end bearing resistance
F_f  frictional resistance
F_y  buoyant weight of soil displaced by anchor
g  Earth’s gravitational acceleration
H  top layer thickness
k_1  shear strength gradient for top layer
k_2  shear strength gradient for bottom layer
k_{eff1} effective shear strength gradient for top layer
k_{eff2} effective shear strength gradient for bottom layer
L_A  anchor shaft length
L_F  fin length
L_T  anchor shaft tip length
m  anchor mass
m'_b  anchor effective mass for bottom layer
m'_t  anchor effective mass for top layer
62 \( N_{bar} \) T-bar factor
63 \( N_{kt} \) cone factor
64 \( p, q \) exponents and coefficient of energy models
65 \( R_{f1} \) factor related to effect of strain rate for end bearing resistance
66 \( R_{f2} \) factor related to effect of strain rate for frictional resistance
67 \( S_t \) soil sensitivity
68 \( s_u \) undrained shear strength
69 \( s_{ub} \) soil strength at mudline
70 \( s_{ut} \) soil strength at top-bottom layer interface
71 \( s_{u,ref} \) reference undisturbed soil strength
72 \( s_{ub,ref} \) reference undisturbed soil strength at interface between top and bottom layers
73 \( s_{ut,ave} \) average reference soil strength for top layer
74 \( s_{ut,ref} \) reference undisturbed soil strength at mudline
75 \( t \) time after anchor tip impacting seabed
76 \( v \) anchor penetrating velocity
77 \( v_i \) anchor impact velocity
78 \( v_{max} \) maximum anchor velocity
79 \( w_F \) fin width
80 \( W_d \) anchor dry weight
81 \( W_s \) anchor submerged weight in water
82 \( z \) depth below soil surface
83 \( \beta \) shear-thinning index
84 \( \beta_{tip} \) anchor tip angle
85 \( \delta_{rem} \) fully remoulded ratio
86 \( \eta \) viscous property
87 $\dot{\gamma}$ shear strain rate

88 $\dot{\gamma}_{\text{ref}}$ reference shear strain rate

89 $\xi$ cumulative plastic shear strain

90 $\xi_{95}$ cumulative plastic shear strain required for 95% remoulding
INTRODUCTION

Dynamically installed anchors (DIAs) are the most recent type of anchoring solution providing a cost-effective alternative for mooring floating facilities in deep water clayey sediments. They are also being increasingly considered in shallow waters for temporary mooring of floating facilities and for mooring floating wind turbines. Seabed sediments generally comprise discrete layers of different thicknesses and properties. A distinguished strong or crust layer (either at the surface or underlaid by a soft mud layer) is prevalent in both shallow and deep ocean in the West coast of Africa, the Sunda Shelf, offshore Malaysia, Australia’s Bass Strait and North-West Shelf (Castleberry II & Prebaharan, 1985; Ehlers et al., 2005; Erbrich, 2005; Colliat et al., 2011; Kuo & Bolton, 2013; Hossain et al., 2014a). Layered deposits are also encountered at the Campos Basin, offshore Brazil and the Troll field in the North Sea, offshore Norway (Argiolas & Rosas, 2003; Brandão et al., 2006; Zimmerman et al., 2009; Lieng et al., 2010). Figure 1 shows examples of layered seabed with a surface and embedded strong layer.

For dynamic installation of DIAs in a single layer clay, a number of investigations have been carried out (e.g. Richardson et al., 2009; Nazem et al., 2012; O’Loughlin et al., 2013; Hossain et al., 2014b, 2015; Kim et al., 2015a, 2015b; Kim & Hossain, 2015). This paper focuses on two layer clays with the aim at resolving the questions (i) what is the effect of soil layering on the anchor embedment depth; (ii) if the anchor will penetrate through the top crust layer; (iii) if the expressions developed for single layer clay is applicable for assessing anchor embedment depth in two-layered deposits.
NUMERICAL ANALYSIS

Geometry and parameters

In recent years, broadly three DIA geometries have evolved including (a) dynamically penetrating anchor (Lieng et al., 1999, 2000, 2010), (b) torpedo anchor (de Araujo et al., 2004; Brandão et al., 2006), (c) OMNI-max anchor (Zimmerman et al., 2009; Shelton et al., 2011). This study has considered a torpedo anchor with 4 fins. The shape was selected similar to the T-98 (W_d = 98 tonnes; L_A = 17 m; D_A = 1.07 m; L_F = 10 m; w_F = 0.9 m) anchor installed in the Campos Basin, offshore Brazil (de Araujo et al., 2004; Brandão et al., 2006).

Figure 2 shows a schematic diagram of an anchor of length L_A installed in a layered clay deposit. The top clay layer of thickness H with uniform undrained shear strength \( s_{u,\text{ref}} = s_{u,\text{ref}} \) or non-uniform undrained shear strength \( s_{u,\text{ref}} = s_{u,\text{ref}} + k_1 z \) is underlain by a clay layer of (nominally) infinite depth of non-uniform undrained shear strength \( s_{u,\text{ref}} = s_{u,\text{ref}} + k_2 (z-H) \). The strength difference between the two distinct layers is characterized by the ratio of the top layer average strength to the bottom layer surface strength \( s_{u,\text{ave}}/s_{u,\text{ref}} \). The strength ratio \( s_{u,\text{ave}}/s_{u,\text{ref}} < 1 \) corresponds to soft-over-stiff clay deposits and \( s_{u,\text{ave}}/s_{u,\text{ref}} > 1 \) the reverse. The relative thickness of the top layer defined as \( H/L_A \).

Analysis details

3D large deformation finite-element (LDFE) analyses were carried out using the coupled Eulerian-Lagrangian (CEL) approach in the commercial package ABAQUS/Explicit (Dassault Systèmes, 2012). For simulating torpedo anchor installation, LDFE analysis is essential to avoid severe mesh distortion. There are three approaches for carrying out LDFE analysis: (a) remeshing and interpolation technique by small strain, (b) efficient arbitrary Lagrangian–Eulerian, (c) CEL, with the latter is more appropriate for simulating dynamic installation of relatively complex shaped torpedo anchors. Considering the symmetry of the
problem, only a quarter anchor and soil domain were modelled. A typical mesh is shown in Figure 3. The Eulerian mesh comprised 8-noded linear brick elements (termed EC3D8R in ABAQUS) with reduced integration. As obtained from preliminary convergence studies (e.g. Kim et al., 2014, 2015a, 2015b), the radius and height of the soil domain were 40Dₜ (~32Dₚ for 4-fin anchor) and ~7Lₜ, respectively, and the typical soil element size along the trajectory of the anchor (‘very fine mesh zone’ in Figure 3a, with the plan view given in Figure 3b) was adopted as 0.019Dₜ. The anchor dynamic installation was modelled from the soil surface, with a given impact velocity vᵢ.

The installation of torpedo anchors is completed under undrained conditions. The soil was thus modelled as an elasto-perfectly plastic material obeying a Tresca yield criterion, but extended to capture strain-rate and strain-softening effects, following the models of Herschel-Bulkley (Herschel & Bulkley, 1926) and Einav-Randolph (Einav & Randolph, 2005) respectively (see Equation 1).

The definitions are given under notation list. The first bracketed term of Equation 1 augments the strength according to the operative shear strain rate, \( \dot{\gamma} \), relative to a reference value, \( \dot{\gamma}_{\text{ref}} \), which is typically around \( 10^{-5} \text{ s}^{-1} \) for laboratory element tests and up to \( \sim 0.5 \text{ s}^{-1} \) for field penetrometer testing. The second part of Equation 1 models the degradation of strength according to an exponential function of cumulative plastic shear strain, \( \xi \), from the intact condition to a fully remoulded ratio, \( \delta_{\text{rem}} \) (the inverse of the sensitivity, \( S_t \)). The relative ductility is controlled by the parameter, \( \xi_{95} \), which represents the cumulative plastic shear strain required for 95% remoulding. Further details can be found in Zhu & Randolph (2011), Boukpeti et al. (2012) and Kim et al. (2015a, 2015b). The elastic behaviour was defined by a
Poisson’s ratio of 0.49 and Young’s modulus of 500 $s_u$ throughout the soil profile. A uniform submerged unit weight of 6 kN/m$^3$ was adopted over the soil depth. The soil-anchor interface was modelled as frictional contact, using a general contact algorithm. Typical computation times on a high performance workstation with 12 CPU cores were about 40 hours for an anchor dynamic installation.

**BEHAVIOR OF TORPEDO ANCHOR IN TWO-LAYERED CLAYS**

An extensive parametric study was carried out varying (a) relative thickness of the top layer ($H/L_A = 0.125$ to 1); (b) strength ratio of two layers ($s_{ut,ave}/s_{ub,ref} = 0.264$ to 13.3); and considering (c) a very strong homogeneous top crust layer ($s_{ut,ref}/s_{ub,ref} = 5$ to 50, $H/L_A = 0.125$ and 0.25), as assembled in Table 1. Parameters in terms of rate dependency and strain-softening were taken as $\eta = 1.0$, $\beta = 0.1$, $\dot{\gamma}_{ref} = 0.1$ s$^{-1}$, $\delta_{rem} = 1/3$, and $\xi_{95} = 20$; as they typically provided excellent match with the field and centrifuge tests data (Kim et al., 2015a). A typical impact velocity achieved by the torpedo anchors of $v_i = 20$ m/s was selected.

**Anchor penetration profiles and soil failure mechanisms**

The anchor velocity profiles and corresponding soil failure mechanisms during penetration of the anchor with different soil strength ratios of $s_{ut,ave}/s_{ub,ref} = 0.88$, 0.285 and 8.8, 2.85 (in Group I, Table 1) are shown in Figure 4a and Figure 4b, respectively. Top layer soil strength was fixed at $s_{ut,ref} = 5$ kPa and $k_1 = 2$ kPa/m, but thickness H was varied as $0.125L_A$ and $1.0L_A$. The anchor velocity profile can be divided into two stages: (a) acceleration stage at shallow penetration depths: the anchor penetration resistance is less than the submerged weight of the anchor; (b) deceleration stage at greater penetration depths: frictional and end bearing resistance dominate the anchor performance. The demarcation point between these two stages corresponds to the maximum anchor velocity, $v_{max}$ (see Figure 4). In soft-over-stiff clays (e.g. $s_{ut,ave}/s_{ub,ref} < 1.0$; Figure 4a), the earlier appearing of the demarcation point leads to lower
maximum velocity and hence shallower embedment depth. This trend is somewhat consistent to that in single layer clay with strength increasing with depth. In stiff-over-soft clays (e.g. \( \frac{s_{ut,ave}}{s_{ut,ref}} > 1.0 \); Figure 4b), the demarcation point appears in the bottom soft layer for \( H = 0.125L_A \) and in the top stiff layer for \( H = 1.0L_A \). Interestingly, if the soft bottom soil layer locates below the demarcation point (e.g. for \( H = 1.0L_A \)), the deceleration rate of the anchor reduces in the bottom soft layer, and hence the anchor penetrates deeper. As such, the relationship between the location of the layer interface and the depth of the demarcation point is critical for anchor penetration in stiff-over-soft clays.

Effect of soil strength ratio (\( \frac{s_{ut,ave}}{s_{ut,ref}} \)) and thickness ratio (\( H/L_A \)): influence of soil layering on anchor embedment depth

The effect of the soil strength ratio (\( \frac{s_{ut,ave}}{s_{ut,ref}} \)) was investigated, varying the soil strength combinations in two-layered soils (Groups I ~ III, Table 1). Overall, the tip embedment depth (\( d_e,t \)) increases with increasing soil strength ratio (see Figure 5). This increasing rate reduces, and becomes somewhat constant when \( \frac{s_{ut,ave}}{s_{ut,ref}} \) exceeds 2. It confirms that, at shallow penetration (e.g. acceleration stage), the soil strength (and hence the end bearing and frictional resistance) has a limited influence. Therefore, the bottom stiff layer (e.g. \( \frac{s_{ut,ave}}{s_{ut,ref}} < 1.0 \)) has significant influence on reducing \( d_{e,t}/L_A \).

To examine the effect of \( H/L_A \), \( d_{e,t}/L_A \) values for various \( H/L_A \) of 0.125, 0.5 and 1.0 are plotted in Figure 6 for soft-over-stiff clays (\( \frac{s_{ut,ave}}{s_{ut,ref}} < 1.0 \)) and stiff-over-soft clays (\( \frac{s_{ut,ave}}{s_{ut,ref}} > 1.0 \)), with \( s_{ut,ref} = 5 \text{ kPa} (k_1 \text{ and } k_2 = 2 \text{ kPa/m}) \) and 10 kPa (\( k_1 \text{ and } k_2 = 3 \text{ kPa/m} \)) (Groups I & II, Table 1). As \( H/L_A \) increases, \( d_{e,t}/L_A \) becomes greater, which is more profound for soft-over-stiff clays. For instance, for soft-over-stiff clays (\( \frac{s_{ut,ave}}{s_{ut,ref}} = 0.264 \sim 0.88 \)), \( d_{e,t}/L_A \) increases by 32 \sim 45.4\% as \( H/L_A \) increases from 0.125 to 1.0, but that difference reduces to 16.3 \sim 16.9\% for stiff-over-soft clays (\( \frac{s_{ut,ave}}{s_{ut,ref}} = 2.638 \sim 8.8 \)).
Effect of crust layer: if the anchor will penetrate through the crust?

This section specifically focuses on the surface crust layer with uniform strength ($k_1 = 0$; $s_{ut,ref} = s_{ut,ave}$) to resolve the common concern that if the anchor will penetrate through the crust layer, and if not, where it will be rested. In order to examine the effect of high strength crust soil on the penetration depth, a series of analyses were carried out with very high strength ratios ($s_{ut,ave}/s_{ub,ref} = 5 \text{ to } 22.3$) and relatively thin top layer thickness ($H/L_A = 0.125$ and $0.25$) overlaid by a NC clay strength profile (Group IV, Table 1). Figure 7 plots typical anchor velocity profiles and corresponding soil failure mechanisms. The result for the single layer NC clay is also included from Kim et al. (2015a) for comparison.

As expected, the final embedment depth of the anchor reduces as the crust soil strength increases. Interestingly, however, for the thin top layer thickness with $H/L_A = 0.125$, the reduction rate is relatively small ($d_{e,t} = 32.16$ vs $27.28$ m i.e. $< 15\%$), although the crust soil strength is over 20 times higher than the NC clay strength profile (see Figure 7). This is chiefly because the demarcation point lies below the layer interface and (hence) the anchor accelerates in the thin crust layer. The anchor therefore passes through the top thin crust layer quickly, and the bottom soil becomes dominant for the anchor penetration resistance. On the contrary, for $H/L_A = 0.25$ with the demarcation point lies in the crust layer, the reduction rate increases dramatically up to 62.5% compared to the single NC clay soil ($d_{e,t} = 32.16$ m vs $12.06$ m). The final embedment depth, $d_{e,t}$, is lower than the anchor length ($L_A$), where $s_{ut,ref}/s_{ub,ref}$ is over 15, as shown in Figure 8. With these conditions, the anchor penetrating energy has dissipated quickly at shallow depth and penetration terminated between the two layers (see Figure 7). It should be noted that the crust layer’s effective thickness and strength ratio are only valid for the anchor geometry and impact velocity considered in this paper.
EXTENDED MODIFIED ENERGY METHOD FOR ASSESSING ANCHOR EMBEDMENT IN TWO-LAYERED CLAYS

Recently, O’Loughlin et al. (2013), Kim et al. (2015a, 2015b), Hossain et al. (2015) and Kim & Hossain (2015) proposed a simple expression using the total energy concept to predict the penetration depth for DIAs in single clay or silt deposit. To apply this concept in two-layered clays, the total energy ($E_{\text{total}}$) is divided into 2 parts according to

$$E_{\text{total}} = E_{\text{top}} + E_{\text{bottom}} = \left[ \frac{1}{2} m'_{t} v_{t}^2 + m'_{t} g H \right] + \left[ m'_{b} g (d_{e,t} - H) \right]$$

(2)

The first bracketed term of Equation 2 is the sum of kinetic energy from the free-fall dropping and potential energy dissipation for the top layer ($E_{\text{top}}$). The second part is the energy dissipation for the bottom layer ($E_{\text{bottom}}$). In Equation 2, somewhat equivalent effective masses, $m'_{t}$ and $m'_{b}$, are used for the potential energy dissipation terms because $m'_{t} g$ and $m'_{b} g$ (where $g$ is Earth’s gravitational acceleration = 9.81 m/s$^2$) represent the submerged weight of the anchor in the top and bottom layer soils, respectively. From the parametric study encompassing a range of relevant values of two-layered clays (see Table 1), Equation 2 may be re-written as

$$\frac{d_{e,t}}{D_p} = p \left[ \frac{E_{\text{top}}}{k_{\text{eff1}} A_s D_p^2} + \frac{E_{\text{bottom}}}{k_{\text{eff2}} A_s D_p^2} \right]^q = p \left[ \frac{1/2 m'_{t} v_{t}^2 + m'_{t} g H}{k_{\text{eff1}} A_s D_p^2} + \frac{m'_{b} g (d_{e,t} - H)}{k_{\text{eff2}} A_s D_p^2} \right]^q$$

(3)

where $k_{\text{eff1}}$ and $k_{\text{eff2}}$ are the effective soil strength gradients for the top layer and bottom layer, respectively (see Figure 2). As demonstrated by Figure 9, $p = 4.0$ and $q = 0.43$ provide a good harmony to all the LDFE results (Group I ~ IV, Table 1). The performance of Equation 3 with $p = 4.0$ and $q = 0.43$ has not been evaluated for other DIA geometries although the same principle can be applied.
The embedment depth was also calculated using a conventional shear resistance model according to (as also adopted by several studies e.g. True, 1974; O’Loughlin et al., 2013; Chow et al., 2014; Hossain et al., 2015; Kim et al., 2015a, 2015b)

\[ m \frac{d^2 z}{dt^2} = W_s - F_f - R_{r1} F_b - R_{r2} F_f - F_d \]  

The terms used in this expression are defined under nomenclature, with the extensive background information along with selected values for bearing capacity factors and coefficient of friction given by Hossain et al. (2015) and Kim et al. (2015a, 2015b). As shown in Figure 10, both methods provide reasonable estimates in regards to anchor final embedment depth with the error falling in \( \pm 10\% \) (‘+ve’ means overestimation) band except for the cases with a curst layer (Group IV, Table 1), in which the overestimation by using the conventional shear resistance model becomes as high as 40%.

**CONCLUDING REMARKS**

Dynamic installation of a torpedo anchor in two-layered clay deposits has been explored through 3D large deformation finite element analyses, accounting for strain softening and strain rate dependency of the undrained shear strength. The following key conclusions can be drawn from the results presented in the paper.

1. The demarcation point between the acceleration and deceleration phases of the anchor in the soil is the key factor directing the anchor behavior in layered soils including the final embedment depth.

2. In soft-over-stiff clays \( (s_{sat,ave}/s_{sub,ref} < 1) \), for a given impact velocity, the penetration profiles are somewhat consistent to those in single layer clay with strength increasing with depth. The earlier appearing of the demarcation point led to lower maximum velocity and hence shallower embedment depth.
3. In stiff-over-soft clays with a more stronger crust ($s_{ut,ave}/s_{ub,ref} \geq 5$), the anchor embedment depth reduced somewhat linearly with increasing $s_{ut,ave}/s_{ub,ref}$. For $H/L_A = 0.125$ with the demarcation point below the crust layer, the anchor accelerated and passed through the crust quickly, and the effect of $s_{ut,ave}/s_{ub,ref}$ was relatively lower. For $H/L_A = 0.25$ with the demarcation point within the crust layer, the influence of $s_{ut,ave}/s_{ub,ref}$ was much stronger, and the anchor penetration was terminated between the two layers where the strength ratio was over 15.

4. For assessing anchor embedment depth in two-layered clay deposits, an extended total energy based expression was proposed calibrating against computed results. The performance was justified comparing with a conventional shear resistance model.

Sensitivity analyses in terms of strain rate and strain softening parameters and soil strength sensitivity have not been carried out in this paper. However, relevant guidelines for torpedo anchor installation in single layer clay were reported in Kim et al. (2015b).

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REFERENCES


Figure Caption (no. of Figures: 10)

Figure 1. Typical layered seabed with strong layer: (a) Surface crust layer: Offshore West Africa (Ehlers et al., 2005); (b) Interbedded strong layer: Australia’s Bass Strait (Erbrich, 2005)

Figure 2. Schematic diagram of installed torpedo anchor in layered clay

Figure 3. Typical mesh used in CEL analysis: (a) Side view; (b) Plan view

Figure 4. Soil failure mechanisms and anchor velocity profile (in Group I, Table 1): (a) Soft-over-stiff clays ($s_{ut,ave}/s_{ub,ref} < 1.0$); (b) Stiff-over-soft clays ($s_{ut,ave}/s_{ub,ref} > 1.0$)

Figure 5. Effect of strength ratio on anchor embedment depth (Groups I~III, Table 1): (a) $H/L_A = 0.125$; (b) $H/L_A = 1.0$

Figure 6. Effect of top layer thickness ratio on anchor embedment depth (Groups I ~ III, Table 1)

Figure 7. Effect of very stiff crust layer on anchor velocity profile and embedment depth (Group IV, Table 1)

Figure 8. Effect of very strong crust layer on anchor embedment depth (Groups I and IV, Table 1)

Figure 9. Extended total energy-based method for two layer clays (Groups I ~ IV, Table 1)

Figure 10. Comparison results for anchor embedment depth (Groups I ~ IV, Table 1)
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(b) Interbedded strong layer: Australia’s Bass Strait (Erbrich, 2005)
Figure 2. Schematic diagram of installed torpedo anchor in layered clay
Figure 3. Typical mesh used in CEL analysis
(a) Soft-over-stiff clays ($s_{utave}/s_{ub,ref} < 1.0$)

(b) Stiff-over-soft clays ($s_{utave}/s_{ub,ref} > 1.0$)

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(Group IV, Table 1)
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Figure 10. Comparison results for anchor embedment depth (Groups I ~ IV, Table 1)
Table 1. Summary of 3D LDFE analyses performed

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<th>Group</th>
<th>H (m)</th>
<th>H/LA (m)</th>
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<th>Bottom layer</th>
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