Eulerian Finite Element Analysis for Uplift Capacity of Circular Plate Anchors in Normally Consolidated Clay

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ABSTRACT: Anchors are often used to provide uplift resistance for mooring of boats and floating decks as well as anchoring of pipelines offshore. Anchor is often idealized as a circular plate in the analysis of its uplift resistance. The uplift capacity of circular plate anchor in uniform soil is well documented in the literature. However, the pullout behavior of circular anchor in nonhomogeneous soil is less well studied and forms the motivation of this paper. In order to circumvent computational difficulties associated with severe mesh distortion during the pullout process, the Eulerian large strain, large deformation finite element approach is adopted in this study to investigate the pullout behavior of circular plate in normally consolidated clay. The applicability of the Eulerian numerical model is validated by comparing the numerical results with analytical solutions from lower bound limit analysis for a uniform soil as well as data for a centrifuge test conducted in normally consolidated Kaolin clay. Conventionally, it is generally accepted that the uplift behavior of a plate anchor in a normally consolidated soil can be inferred from that in a uniform soil by adopting the strength at the initial plate position as the reference strength. However, it is observed from the numerical results that the failure mechanisms corresponding to plate anchors in uniform clay and normally consolidated clay are different for the same set of reference undrained shear strength and geometric parameters. This implies that the conventional approach is not always applicable. A direct design method for obtaining the uplift capacity of a circular plate anchor embedded in a linearly increasing soil shear strength profile is then proposed.

KEYWORDS: Eulerian finite element, circular plate anchor, normally consolidated clay

1. INTRODUCTION

As the worldwide demand for oil and gas increases, the oil and gas exploration and production activities move steadily from shallow to deep water. Plate anchors are being used increasingly to moor large floating structures in deep and ultra deep waters to withstand uplift load. An anchor is often idealized as a circular plate in the analysis of uplift resistance (Merifield 2011). The uplift capacity of circular plate anchor in uniform soil has been investigated by many researchers (for example Vesic (1971); Das (1980); Rowe (1978); Rowe and Davis (1982); Das and Singh (1994); Yu (2000); Martin and Randolph (2001); Merifield et al. (2001; 2003); Song et al. (2008); Wang et al. (2010)) by means of model tests, analytical solutions, finite element simulations and plasticity limit analyses.

Small scale 1g model tests have been carried out by Das (1978; 1980) for circular plate by inserting a hollow tube at the base of the anchor to eliminate the suction effect and concluded that the uplift capacity in a real soil with self-weight can be computed as the sum of the soil overburden pressure and the corresponding capacity in a weightless soil. Rowe and Davis (1982) were among the early researchers employing numerical technique using conventional two-dimensional small displacement small strain finite element analysis to determine the uplift capacity of circular anchors. The deformation due to contained plastic flow before collapse was so large that the capacity factor had to be determined by taking the anchor capacity at a given displacement. The failure load was arbitrarily defined as the load mobilized at a displacement four times that predicted by an elastic analysis. With the advancement of numerical technique recently, both two-dimensional and three-dimensional Remeshing and Interpolation Technique with Small Strain (RITSS) approach were applied by Song et al. (2008) and Wang et al. (2010) to investigate the behavior of circular plate anchors.

Yu (2000) derived an expression for the breakout factor for strip, square and circular anchor based on cavity expansion theory in cohesive soil. The same formulation was used to compute the pullout capacity of square and circular plate anchors and no distinction was made between the failure mechanisms for shallow and deep embedment anchors. The uplift capacity for plate anchor is solely a function of anchor embedment ratio (anchor embedment depth/anchor width or diameter). Lower bound limit analysis was applied by Merifield et al. (2001; 2003) to investigate the capacity of circular plate anchor in uniform clay.

Majority of existing studies stated above focused on the behaviour of circular plate in uniform clay. However, the strength profile in most offshore seabeds is rarely uniform. Many seabeds have shear strength varying linearly with depth represented by

$$s_u = s_{u,0} + kz \tag{1}$$

where $s_{u,0}$ is the soil undrained shear strength at the mudline and k is the gradient of increase in s_u with depth z. The soil is considered normally consolidated if $s_{u,0} = 0$. This paper compares the different behaviour of circular plate anchor embedded in uniform clay and clay with linearly increasing shear strength profile. A chart is provided as a proposed design method to obtain the uplift capacity of a circular plate embedded in clay with linearly increasing shear strength profile.

2. VERIFICATION

In this section, the predictions of circular plate anchor uplift capacity from three-dimensional Eulerian finite element analyses are verified with those from existing limit equilibrium analyses, RITSS method as well as centrifuge model tests. Recently, Eulerian finite element method is extensively adopted to analyze geotechnical problems involving large deformation (Chen et al. 2013; Qiu et al. 2011; Tho et al. 2012; Tho et al. 2013) such as those encountered during the continuous pull-out of a plate anchor. In an Eulerian analysis, the spatial position of the nodes is fixed and the finite element mesh undergoes zero distortion during the analysis. Instead, materials are allowed to flow through the mesh during the analysis. Consequently, mesh distortion does not occur despite the material undergoing large deformation.

Owing to symmetry, only 1/8 of the circular plate anchor and soil are considered in this study as shown in Figure 1. The plate is modeled as a discrete rigid solid part and meshed with 8-noded Lagrangian brick elements. The soil domain consists of 8-noded Eulerian brick elements. In the Eulerian domain, a void layer is defined above the mudline with a "void" material of zero strength and stiffness. The purpose of the void layer is to allow the soil to heave and flow into the empty Eulerian elements at the subsequent stage of the analysis. The Tresca material model with an associated flow rule is adopted to model the clay. In order to simulate undrained condition, the Poisson's ratio is set to 0.495. A consistent E/s_u ratio (E is the Young's modulus of soil) of 500 is adopted for all analyses. The selection of domain size, mesh density and pullout rate follow that of the earlier work by Chen et al. (2013).

The suction force between the anchor and the soil can be divided into two categories: "immediate breakaway" and "no breakaway" (Rowe and Davis 1982). For the "immediate breakaway" case, it is assumed that no adhesion or suction between soil and anchor is allowed. Once the anchor is no longer in contact with the underlying soil, the vertical stress below the anchor reduces to zero. For the "no breakaway" case, it is assumed that the soil anchor interface can sustain infinite tension to ensure that the anchor remains in full contact with soil at all times during pullout. In reality, it is likely that the true breakaway state of an anchor will fall somewhere in between these two idealized extremities. Owing to uncertainty of the suction force underneath the plate anchor, the "immediate breakaway" is applied for the normal direction and smooth condition is applied for the tangent direction to obtain a conservative estimate of the uplift resistance.

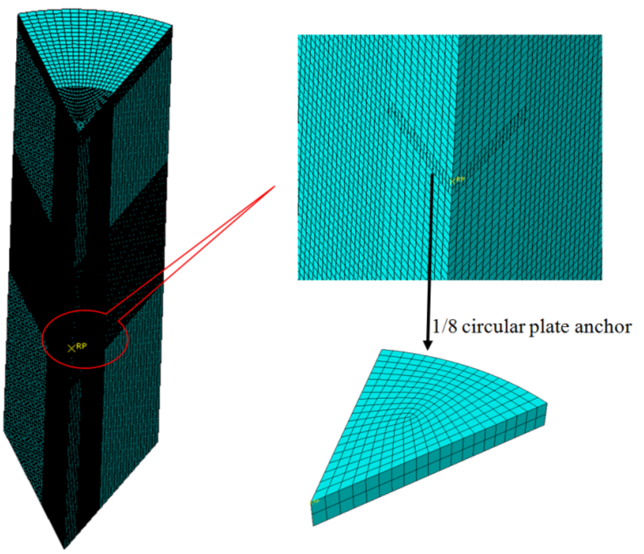

Figure 1 Eulerian finite element model

2.1 Circular plate anchor in uniform weightless clay

The uplift capacity factor of circular plate anchor N_c, which is defined as ultimate resistance divided by the area of the plate and the soil undrained shear strength, at different embedment ratios in uniform weightless clay is verified with the limit analysis and RITSS method in Figure 2. In order to facilitate direct comparison with the results by previous researchers (Merifield et al. 2001; Wang et al. 2010), the geometry of the circular plate anchor and the soil properties are the same as their reported values. The circular plate anchor with diameter of 0.5m and thickness of 1/20*D* is modeled in ABAQUS/Explicit and cylindrical coordinate system is applied.

The results from the current Eulerian large deformation FE agree well with those presented by Wang et al. (2010) obtained using the RITSS technique. Both large deformation finite element analyses predict a lower capacity factor than that by the lower bound limit analysis of Merifield et al. (2010) and the cavity expansion theory by Yu (2000). As illustrated by Chen et al. (2013), the soil rigidity index plays an important role in predicting the capacity factor for plate anchor embedded in weightless soil. As the inherent assumption that the soil is a rigid plastic material with an infinite elastic modulus in the lower bound limit analysis, the Type C failure mechanism (Chen et al. 2013) is not able to be captured and resulting a higher capacity factor for the deep embedded cases. The Type C failure mechanism is a localized mechanism but the full flow is not mobilized due to insufficient driving force from the soil overburden pressure. A gap is observed between the soil and plate.

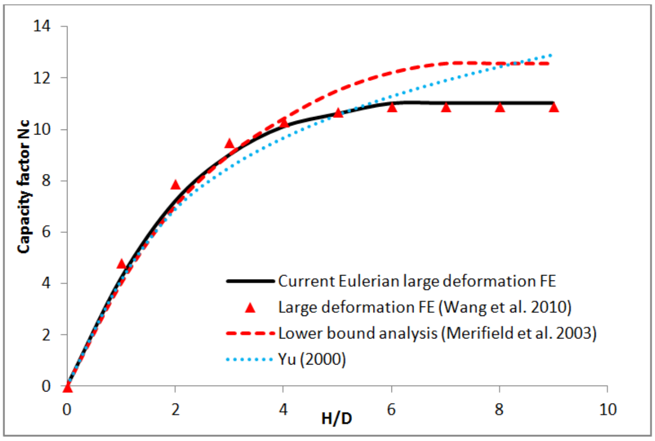

Figure 2 Uplift capacity factors obtained from different methods for circular plate anchor with different embedment ratios in weightless soil

A comparison of capacity factor between circular plate and square plate is shown in Figure 3. The capacity factor of a circular plate is slightly higher than that of a square plate. This finding is consistent with the conclusion by Merifield et al. (2001) and Wang et al. (2010).

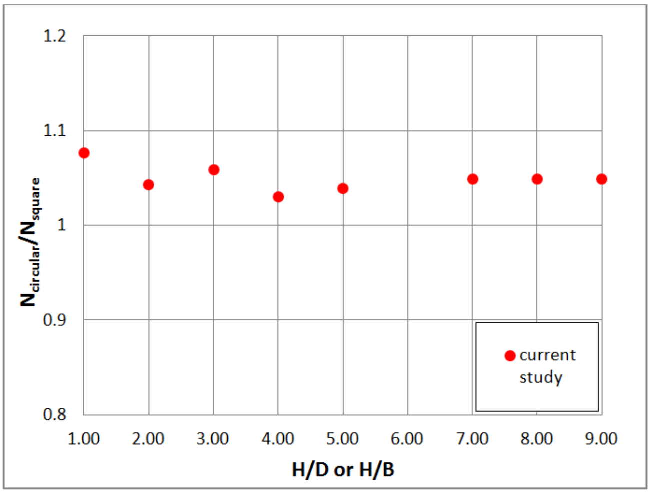

Figure 3 Comparison of anchor capacity factors for circular and square plates

2.2 Circular plate anchor in normally consolidated clay with overburden pressure

As the Eulerian finite element method is capable of modeling the continuous pullout process of a circular plate, the load-displacement curve is verified with the centrifuge test for circular plate anchor embedded in normally consolidated Kaolin Clay in this section. A hollow vertical shaft is designed at the anchor base to eliminate the suction force in the centrifuge test. This is the same as the "immediate breakaway" condition in the Eulerian finite element model. The plate has a diameter of 3m embedded in Kaolin clay with soil strength profile of $s_u = 1.3z$ at an initial embedment ratio *H/D*=5. The normalized load q/s_u (q is the pullout pressure and s_u is the soil shear strength at the current anchor depth) and anchor current embedment depth is plotted together with the centrifuge model tests (Song et al. 2008) in Figure 4. The numerical result agrees fairly well with the centrifuge test result. It should be noted that in Song et al. (2008) centrifuge test, their initial anchor embedment changes from 5 at initial sample preparation to 4.6 at the start of the pull out process. This is probably due to the process of soil reconsolidation after the installing the plate anchor.

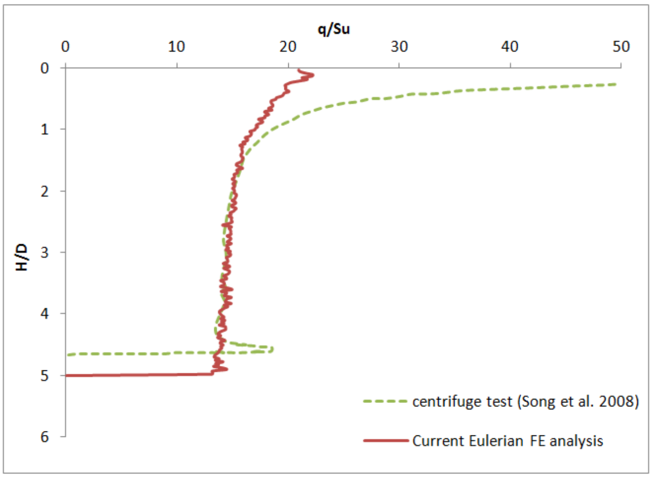

Figure 4 Pullout response of a circular plate anchor in NC clay

3. COMPARISON OF CIRCULAR PLATE ANCHOR IN UNIFORM AND NC CLAY

As the circular plate embedded in nonhomogeneous clay has not been extensively studied, the behavior of circular plate embedded in uniform clay and clay with linearly increasing shear strength are compared in this section. The dimensionless group $kD/s_{u,0}$ represents the soil nohomogeneity, which has been adopted by several researchers (Hossain and Randolph 2009; Merifield et al. 2001; Tho et al. 2014). According to the recent study by Tho et al. (2014), $kD/s_{u,0} = \infty$ corresponds to a normally consolidated clay and provide a conservative solution for square plate embedded in nonhomogeneous clay. Hence the value of $kD/s_{u,0} = \infty$ is adopted for the present analysis.

3.1 Shallow embedment depth (*H/D*=2)

The normalized uplift resistance versus anchor elevation during the continuous pullout for both uniform clay and normally consolidated clay with the same undrained shear strength at the anchor initial position is plotted in Figure 5. The ultimate anchor capacity in uniform soil is much higher than that of normally consolidated soil. The soil flow mechanisms are shown in Figures 6(a) and 6(b) for uniform clay and nonhomogeneous clay, respectively. The general failure mechanism is operative for both cases but with different influence zones. For normally consolidated clay, the inclination of the shear plane is sharper and the heave of the mudline surface is narrower. This can be attributed to the phenomenon that the failure plane tends to pass through a path with the least resistance.

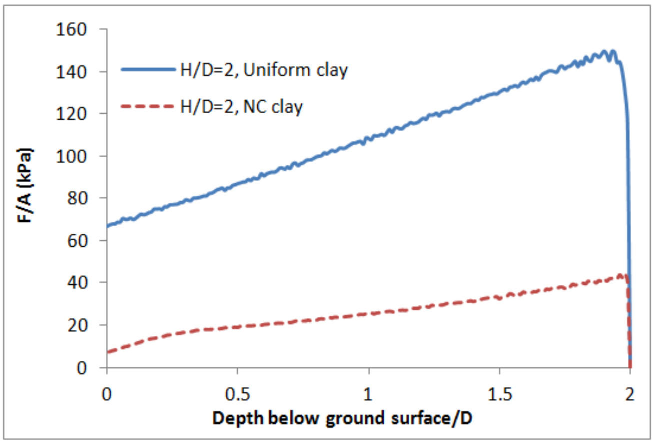

Figure 5Normalized load-anchor displacement plots for *H/D*=2

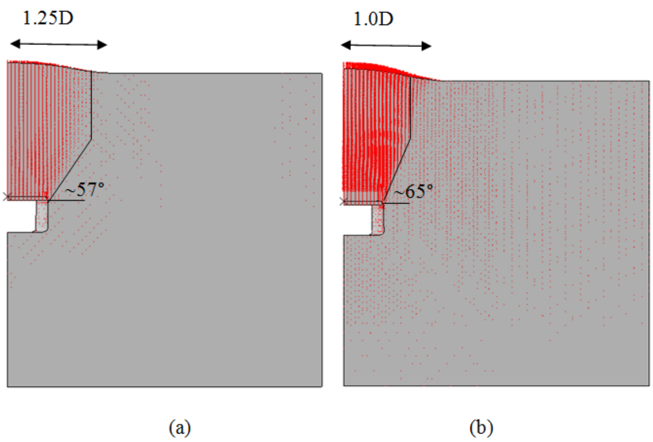

Figure 6 Comparison of failure mechanisms for *H/D*=2 at pullout distance *w/D*=0.2 ((a) for uniform clay, (b) for normally consolidated clay)

3.2 Deep embedment depth (*H/D*=7)

The normalized load and anchor elevation for two cases corresponding to deep embedment depth is shown in Figure 7. Similar to the case of shallow embedment depth (*H/D*=2), the circular plate resistance for uniform clay is much higher than nonhomogeneous clay even with the same undrained shear strength at initial embedment depth of the circular plate. A plateau is observed after the maximum resistance is reached for a uniform soil while the pullout resistance for the nonhomogeneous soil decreases immediately after mobilizing the maximum anchor. It is also noted that the displacement required to mobilize the maximum resistance is larger for a uniform soil as compared to a nonhomogeneous soil. The displacement required to mobilize the maximum anchor resistance in a uniform soil is about 1.0*D* while that for a nonhomogeneous soil is 0.3*D*.

The instantaneous velocity vector plots, which provide indications of soil flow mechanisms, for a deep embedment anchor (*H/D*=7) in uniform and nonhomogeneous soil are shown in Figures 8(a) and 8(b), respectively. For the case of a uniform soil, a localized failure mechanism with partial soil backflow is observed. This mechanism is denoted as Type C failure mechanism in Chen et al. (2013). On the other hand, for the nonhomogeneous soil with $kD/s_{u,0} = \infty$, the soil flow is directed upwards and no backflow is observed as illustrated in Figure 8(b). This pattern resembles a general failure mechanism, which is denoted as Type A failure mechanism in Chen et al. (2013).

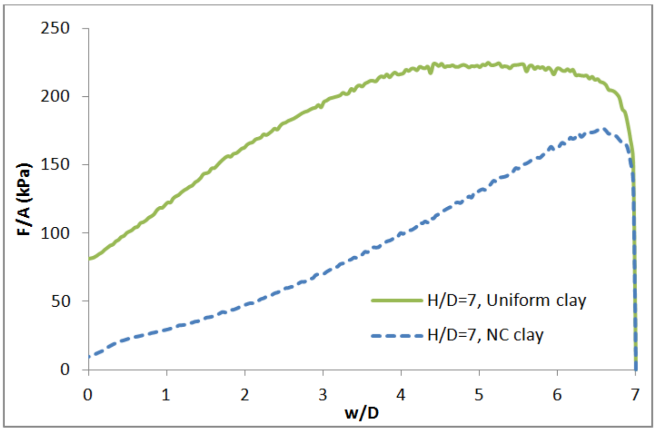

Figure 7 Normalized load-anchor displacement plots for *H/D*=7

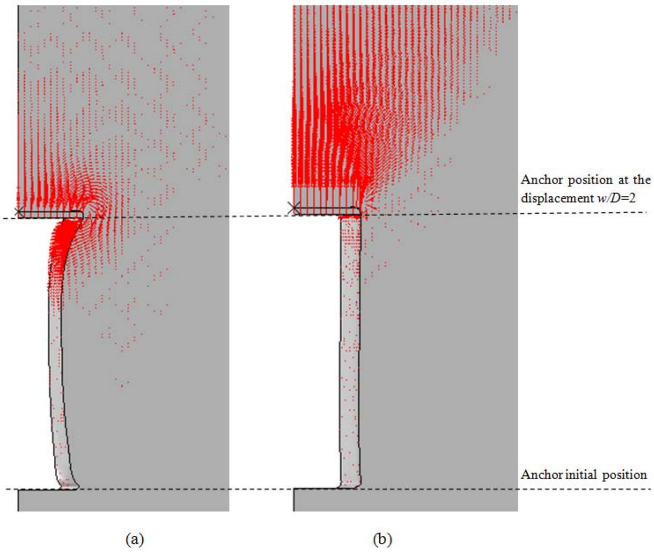

Figure 8 Comparison of failure mechanisms for *H/D*=7 at pullout distance *w/D*=2 ((a) for uniform clay, (b) for normally consolidated clay)

4. PROPOSED DESIGN METHOD FOR CIRCULAR PLATE ANCHOR EMBEDDED IN CLAY WITH LINEARLY INCREASING SHEAR STRENGTH PROFILE

As reported by Tho et al. (2014), the plate anchor capacity is a function of anchor embedment depth *H/D*, soil nonhomogeneity $kD/s_{u,0}$ as well as the soil overburden pressure. The overburden pressure is represented as a non-dimensional factor $\gamma H/(s_{u,0}+kH)$ (where γ is the saturated unit weight of the soil, H is the circular plate embedment depth). In order to provide a direct conservative design method to obtain the ultimate capacity of circular plate anchor in nonhomogeneous clay, parametric studies are carried out for the non-homogeneous factor ($kD/s_{u,0}=\infty$) under different overburden pressure. Figure 9 shows the capacity factor increases with overburden pressure up to a limiting value of 14.2, which is 8% higher than the value for square plate anchor.

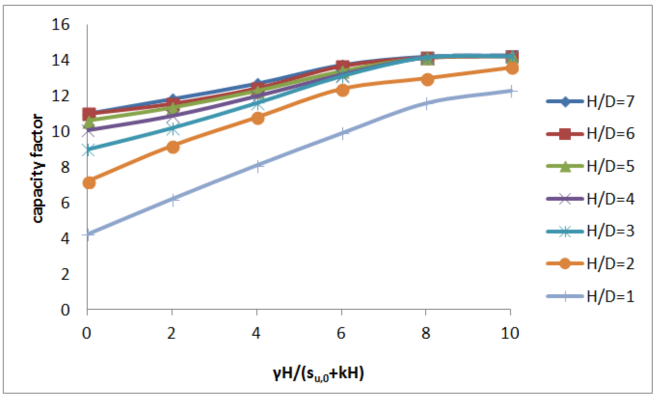

Figure 9 Design chart for circular plate anchor embedded in nonhomogeneous clay

With the results from Figure 9, a simple procedure to predict the capacity factor for a circular plate in nonhomogeneous clay is proposed:

1. Compute *H/D* and $\gamma H/(s_{u,0}+kH)$ based on the anchor geometry, embedment depth and soil property.
2. For a soil with linearly increasing strength profile, obtain the N_c factor directly from Figure 9.

5. CONCLUSION

The continuous pullout process of circular plate anchor embedded in a soil with linearly increasing shear strength profile is simulated using Eulerian large strain, large deformation finite element technique. In an idealized weightless soil, distinct differences in pullout behaviour are observed when compared to the corresponding case in a soil with uniform strength. For the same undrained shear strength at the initial embedment depth, the uplift resistance of a plate anchor is much lower in a soil with linear increasing shear strength profile soil as compared to that in a uniform soil. This can be attributed to the differences in soil flow mechanisms in uniform soil and nonhomogeneous soil.

When the effect of soil self-weight is taken into account, the limiting capacity factor for a circular plate anchor in a soil with linearly increasing shear strength profile is 14.2. This occurs when the overburden ratio is large enough to force the soil to mobilize the full flow mechanism. A method to predict the uplift capacity factor for a circular plate anchor under different combinations of H/B, $kB/s_{u,0}$ and $\gamma H/(s_{u,0}+kH)$ is proposed in this study. With this approach, the effect of soil nonhomogeneity and self-weight are directly taken into account without the need for further simplifying assumptions.

6. REFERENCES

Chen, Z., K. K. Tho, C. F. Leung and Y. K. Chow. (2013) "Influence of overburden pressure and soil rigidity on uplift behavior of square plate anchor in uniform clay". Computers and Geotechnics, 52, pp71-81.

Das, B. M. (1978) "Model tests for uplift capacity of foundations in clay". Soils and Foundations, 18, Issue 2, pp17-24.

Das, B. M. (1980) "A procedure for estimation of ultimate uplift capacity of foundations in clay". Soils and Foundations, 20, Issue 1, pp77-82.

Das, B. M. and G. Singh, (1994) "Uplift capacity of plate anchors in clay", Proceedings of 4th international offshore and polar engineering conference, Golden, Colo.

Hossain, M. S. and M. F. Randolph. (2009) "New mechanism-based design approach for spudcan foundations on single layer clay". Journal of Geotechnical and Geoenvironmental Engineering, 135, Issue 9, pp1264-1274.

Martin, C. M. and M. F. Randolph, (2001) "Application of the lower and upper bound theorems of plasticity to collapse of circular foundations", Proceeding of 10th International Conference of the International Association for Computer Methods and Advances in Geomechanics, Balkema, Rotterdam.

Merifield, R. (2011) "Ultimate Uplift Capacity of Multiplate Helical Type Anchors in Clay". Journal of Geotechnical and Geoenvironmental Engineering, 137, Issue 7, pp704-716.

Merifield, R. S., A. V. Lyamin, S. W. Sloan and H. S. Yu. (2003) "Three-dimensional lower bound solutions for stability of plate anchors in clay". Journal of Geotechnical and Geoenvironmental Engineering, 129, Issue 3, pp243-253.

Merifield, R. S., S. W. Sloan and H. S. Yu (2001), "Stability of plate anchors in undrained clay." Geotechnique, Vol.51(2), 141-153.

Qiu, G., S. Henke and J. Grabe. (2011) "Application of a Coupled Eulerian–Lagrangian approach on geomechanical problems involving large deformations". Computers and Geotechnics, 38, Issue 1, pp30-39.

Rowe, R. K. (1978) "Soil structure interaction analysis and its application to the prediction of anchor behavior". PhD thesis, University of Sydney, Australia.

Rowe, R. K. and E. H. Davis. (1982) "The behaviour of anchor plates in clay". Geotechnique, 32, Issue 1, pp9-23.

Song, Z., Y. Hu and M. F. Randolph. (2008) "Numerical Simulation of Vertical Pullout of Plate Anchors in Clay". Journal of Geotechnical and Geoenvironmental Engineering, 134, Issue 6, pp866-875.

Tho, K. K., Z. Chen, C. F. Leung and Y. K. Chow. (2014) "Pullout behaviour of plate anchor in clay with linearly increasing strength". Canadian Geotechnical Journal, 51, Issue 1, pp92-102.

Tho, K. K., C. F. Leung, Y. K. Chow and A. C. Palmer. (2012) "Deep cavity flow mechanism of pipe penetration in clay". Canadian Geotechnical Journal, 49, Issue 1, pp59-69.

Tho, K. K., C. F. Leung, Y. K. Chow and S. Swaddiwudhipong. (2013) "Eulerian finite element simulation of spudcan–pile interaction". Canadian Geotechnical Journal, 50, Issue 6, pp595-608.

Vesic, A. S. (1971) "Breakout resistance of objects embedded in ocean bottom". Journal of the Soil Mechanics and Foundations Division, 97, Issue 9, pp1183-1205.

Wang, D., Y. Hu and M. F. Randolph. (2010) "Three-Dimensional Large Deformation Finite-Element Analysis of Plate Anchors in Uniform Clay". Journal of Geotechnical and Geoenvironmental Engineering, 136, Issue 2, pp355-365.

Yu, H. S. (2000) Cavity Expansion Methods in Geomechanics, Kluwer Academic Publishers.