

# Ultimate uplift resistance of circular plate anchors in undrained two-layer clays

Su Han Park<sup>a</sup> and Joon Kyu Lee<sup>\*</sup>

Department of Civil Engineering, University of Seoul, 163 Seoulsiripdae-ro, Dongdaemun-gu, Seoul, 02504, Republic of Korea

(Received May 20, 2021, Revised August 17, 2021, Accepted October 5, 2021)

**Abstract.** The vertical uplift resistance of circular plate anchors buried in undrained two-layered clays was studied by means of finite element method. Anchors with immediate breakaway (vented) and no breakaway (bonded) are taken into account. The numerical results are given in the form of the breakout factors accounting for the anchor embedment depth, top layer thickness, clay strength ratio, and clay overburden (clay self-weight), which are compared with existing empirical and analytical solutions. It is found that the breakout factors for strong-over-soft clays are greater than those for soft-over-strong clays. Also, the breakout factors of bonded anchors are identical to those of vented anchors with large overburden pressure. Failure patterns are examined for the cases of soft-over-strong clay and strong-over-soft clay, depending on anchor embedment depth and top layer thickness.

**Keywords:** clays; layered soil; numerical analysis; plate anchors; uplift resistance

## 1. Introduction

Many engineering structures require plate anchors to be used as foundation system. Such structures include transmission towers, sheet pile walls, and buried pipelines. It is also often the case that plate anchors are applied to moor offshore floating structures. Such structures induce to uplift forces and thus a good understanding of performance of the plate anchors is essential for geoenvironmental applications (Hoelher *et al.* 2008, Keskin 2015, Kim and Rosher 2019).

Although considerable attentions have been paid to the vertical uplift resistance of various shaped anchors in clay, only limited attention has been made to circular plate anchors in undrained clay. Approximate methods were proposed empirically from the results of 1g physical model tests. These studies can be found in the works of Ali (1966), Kupfeman (1971), Rao *et al.* (1993), Das *et al.* (1994), and Singh and Ramaswamy (2008). On the theoretical side, solutions were generated by means of the cavity expansion theory (Yu 2000), the finite element method (Rowe and Davis 1982), the large deformation finite element method (Wang *et al.* 2010), the lower bound limit analysis (Merifield *et al.* 2003), and the upper bound limit analysis (Zhao *et al.* 2015). The applications of the abovementioned studies focused on single uniform clay. However, natural soils are often deposited in discrete layers having different properties. The effect of soil layering for circular plate anchor is investigated by several researchers, notably Bouazza and Finlay (1990), Kumar 2003), Sakai and

Tanaka (2007), and Bhattacharya and Kumar (2016). These studies are limited only to two-layered sand, while the study of circular anchors in layered clays do not appear to exist.

The aim of this study is to present rigorous finite element solutions for the vertical uplift resistance of circular plate anchors embedded in two-layered clay under undrained condition. The obtained breakout factors for the anchors with immediate and no breakaways are provided for a wide range of geometrical and material combinations and verified against the results available in literature. Failure mechanisms are discussed for a few cases of circular anchor in two-layered clays. The effect of overburden pressure on the breakout factor is also highlighted.

## 2. Problem statement

The uplift resistance problem to be studied is shown in Fig. 1. A circular anchor of diameter  $D$  is buried horizontally at embedment depth  $H$  in a bottom layer of clay with undrained shear strength  $c_{ub}$ , unit weight  $\gamma_b$ , and infinite depth.

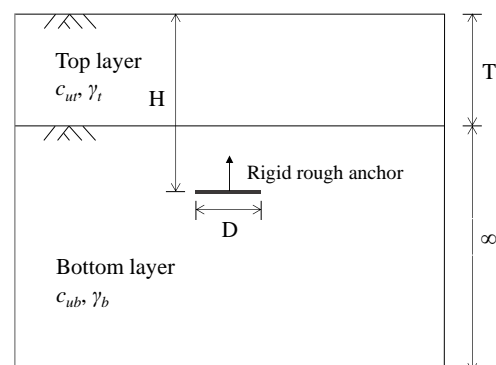


Fig. 1 Schematic of circular plate anchor to uplift force

\*Corresponding author, Associate Professor  
E-mail: jkleegeo@uos.ac.kr

<sup>a</sup>Graduate Student  
E-mail: qkrtngks99@uos.ac.kr

This is overlain by a clay layer of undrained shear strength  $c_{ub}$ , unit weight  $\gamma_u$ , and thickness  $T$ . As described in Merifield *et al.* (2003), the anchor is a thin and rigid plate with rough base, which is evenly moved in a vertical upward direction.

For analysis convenience, the uplift resistance of the circular anchor is quantified by the non-dimensional parameters, namely,  $H/D$ ,  $T/H$  and  $c_{ut}/c_{ub}$ . To cover most problems of practical interest, the following range of the parameters are considered:  $H/D = 0 - 8$ ,  $T/H = 0.2 - 0.95$ , and  $c_{ut}/c_{ub} = 0.2 - 5$ . Additionally, the single layer of uniform clay ( $T/H = 0$ ) is accounted for comparison purposes. It is noted that  $c_{ut}/c_{ub} < 1$  corresponds to the deposit of a soft clay layer over a strong clay layer, whereas  $c_{ut}/c_{ub} > 1$  corresponds to the reverse.

The undrained stability of vertical plate anchor is dependent on the bonding condition at the backface of the anchor. After Rowe and Davis (1982), the anchor analysis is concerned with two simplified categories: immediate breakaway (vented) where no tension is sustained at the anchor base, allowing the clay to separate between clay and anchor, or no breakaway (bonded) where suction is formed at the anchor base, ensuring the clay remain bonded to the back face of the anchor. Probably, the real uplift resistance of the circular anchor lies somewhere between the two extreme states.

The breakout factor  $F_{c0}$  of circular anchors in weightless two-layered clay can be derived from

$$F_{c0} = \frac{q_u}{c_{ub}} \quad (1)$$

where  $q_u$  is the ultimate uplift resistance of circular anchors. This approach is followed by current design code suggested by Det Norske Veritas (DNV, 2017). For two-layered clay with self-weight, the breakout factor  $F_{cy}$  of circular anchors in clays with self-weight is a function of overburden pressure, which can be expressed as

$$F_{cy} = F_{c0} + \frac{\gamma_m H}{c_{ub}} \quad (2)$$

where  $\gamma_m$  is the weight average unit weight of two-layer clay, defined as

$$\gamma_m = \frac{T\gamma_t + (H - T)\gamma_b}{H} \quad (3)$$

From the Eqs. (2) and (3), one may recognize that the value of  $\gamma_m$  is enough high, the plate anchor responses as a deep anchor even at shallow embedment depth and the breakout factor of whose situation is termed as  $F_{cyl}$ , representing the limit breakout factor in clay with self-weight.

### 3. Modelling details

Small-strain finite element (FE) analyses of circular plate anchors were performed using the commercial finite element program Plaxis (Brinkgreve *et al.* 2016). Due to the symmetry in geometry and loading conditions, only one half of the total domain was discretized. The soil was modeled with 15-node triangular elements and plate

elements were employed to model the anchor. The boundaries are set at a distance of 6D from the anchor so as not to affect the behavior of anchor and soil. A mesh refinement study was undertaken to ensure the best-estimate breakout factor was determined. The mesh refinement concentrated on gradual increasing the number of elements around the anchor where the collapse mode developed until further refinement did not improve the breakout factor (Grange *et al.* 2009).

The soil was modeled as an isotropic elasto-perfectly plastic material obeying a Tresca yield criterion. The undrained behavior was described by a Poisson ratio  $\nu = 0.495$  and Young's modulus  $E_u = 500c_{ub}$ , depending on whether the soil was soft and strong. It is noted that the undrained shear strength of the bottom layer  $c_{ub}$  was maintained as constant whereas that of the top layer  $c_{ut}$  was varied. Geostatic stress was generated using the coefficient of lateral earth pressure  $K_0 = 1$  and submerged unit weight  $\gamma_s' = 7 \text{ kN/m}^3$ , as adopted by Ardebili *et al.* (2016).

The anchor was represented as an elastic material with a Young's modulus of  $E_a = 1000E_u$ , considered as effectively rigid. The anchor was prescribed a unit weight of  $\gamma_f = 0$ , providing a conservative result. The anchor surface was assumed to be rough, given that the roughness of a soil-anchor interface has marginal effect on the breakout factor (Rowe and Davis 1982). Both the immediate and no breakaway conditions on the anchor base were taken into account. For the former, a very thin layer of zero tensile strength soil elements was modelled below the anchor, which were not allowed to sustain tension (Taiebat and Carter 2010). For the latter, tensile stresses were permitted to develop in soil that are in contact with the anchor (Yu *et al.* 2015). To obtain the failure load of the anchor, a uniform vertical load was applied to all nodes on the anchor. By observing a plastic plateau in load-displacement plot, overall failure of the anchor was clearly identified.

## 4. Results and comparisons

### 4.1 Anchors in weightless single uniform clay

Fig. 2 shows the breakout factors  $F_{c0}^I$  for anchors with immediate breakaway. At the ground surface ( $H/D = 0$ ), the value of  $F_{c0}^I$  is zero and increases as the anchor becomes deeper. For  $0 < H/D < 8$ , the  $F_{c0}^I$  value is described by

$$F_{c0}^I = 14.2 \left[ 1 - \exp\left(-0.35 \frac{H}{D}\right) \right] < 13.0 \quad (4)$$

The quality of the fit is presented in Fig. 2(a). It is noted that the maximum value of  $F_{c0,m}^I$  is 13.0, implying that a transition from shallow to deep anchor response occurs for a weightless clay. The critical embedment ratio  $(H/D)_{crit}$  corresponding to the maximum  $F_{c0}^I$  value is found to be 7, denoted by +. On the other hand, Fig. 2(a) provides the data from 1g model tests carried out by Ali (1966), Kupfeman (1971), Rao *et al.* (1993), Das *et al.* (1994), and Singh and Ramaswamy (2008). The model test results compare favorably well with the obtained FE results but underpredict the breakout factor for  $H/D$  greater than about 4. This discrepancy may be smaller, considering the assumption

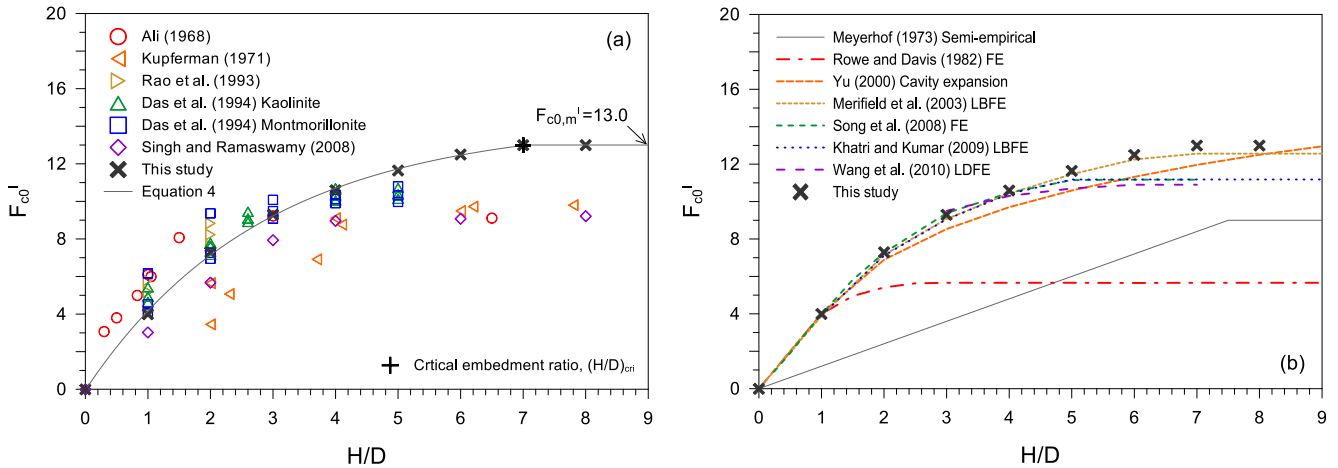


Fig. 2  $F_{c0}^I$  values for circular anchors with immediate breakaway in weightless uniform clay: comparison with (a) experimental data and (b) analytical solutions in literature

that the breakout factor from laboratory tests is insensitive to overburden pressure, particularly when tests are performed in soft clays. Fig. 2(b) compares the present FE values with the results by (1) Meyerhof (1973) using semi-empirical relationship, (2) Rowe and Davis (1982) using the FE method, (3) Yu (2000) using the cavity expansion theory, (4) Merifield *et al.* (2003) using the lower bound limit analysis, (5) Song *et al.* (2008) using the FE method, (6) Khatri and Kumar (2009) using the finite element limit analysis, and (7) Wang *et al.* (2010) using the large deformation FE method. For the anchors with  $H/D < 5$ , all solutions except for Meyerhof (1973) and Rowe and Davis (1982) fall in a very tight band but seem to be diverged for deeper  $H/D$ . The semi-empirical correlation of Meyerhof (1973) is clearly over-conservative, probably owing to a variety of uncertainty sources concerning model tests. The FE solution of Rowe and Davis (1982) is lower than the current FE solutions, particularly for  $H/D > 1$ . This is attributable to the truncation methodology selected by Rowe and Davis whereas the concept of ultimate uplift resistance was employed in this study, so they are not directly comparable.

Fig. 3 shows the breakout factors  $F_{c0}^N$  for anchors with no breakaway. At  $H/D = 0$ , the value of  $F_{c0}^N$  is 6.08, which is exactly identical to that from the stress characteristics method by Eason and Shield (1960). As was the results in Fig. 2 for immediate breakaway, the  $F_{c0}^N$  value increases monotonically before reaching a maximum value of  $F_{c0,m}^N = 13.3$  at the critical embedment ratio  $(H/D)_{cri} = 1$  (see symbol +). It thus follows, that the  $F_{c0}^N$  values exhibit a simple bi-linear curve with  $H/D$ , given by

$$F_{c0}^N = 7.2 \left( \frac{H}{D} \right) + 6.08 < 13.3 \quad (5)$$

A comparison of the obtained  $F_{c0}^N$  values with the existing solutions is also presented in Fig. 3. The model test data by Singh and Ramaswamy (2008), in which suction forces were permitted to develop between the clay and anchor, are grossly conservative. Also, the numerical solutions by Song *et al.* (2008) and Wang *et al.* (2010) stay close to the present FE result for anchors with  $H/D > 1$  but

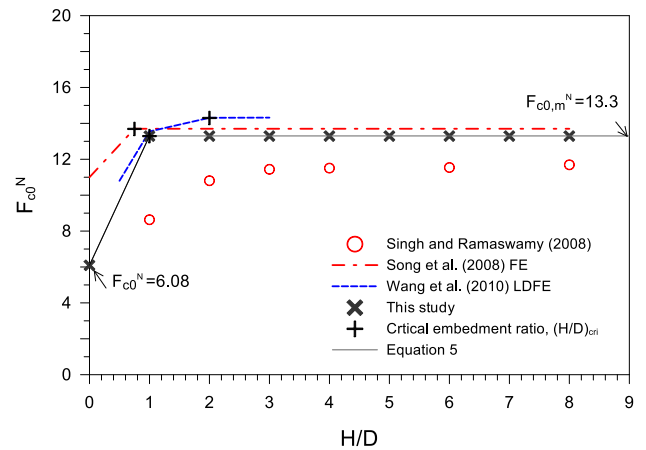


Fig. 3 Comparison of  $F_{c0}^N$  values for circular anchors with no breakaway in weightless uniform clay

Table 1 The values of  $F_{c0,m}^I$  and  $F_{c0,m}^N$  for circular anchors with immediate and no breakaways in weightless uniform clay

	MR	M	KK	W	Z	TS
$F_{c0,m}^I$	-	12.56	11.18	10.9	-	13.0
$F_{c0,m}^N$	13.11	-	-	13.75	13.31	13.3

Note: MR = Martin and Randolph (2001): exact solution; M = Merifield *et al.* (2003): lower bound limit analysis; KK = Khatri and Kumar (2009): finite element limit analysis; W = Wang *et al.* (2010): large deformation finite element analysis; Z = Zhao *et al.* (2015): upper bound limit analysis; TS = This study: finite element analysis.

are overestimated for anchors at small embedment ( $H/D < 1$ ). Table 1 summarizes the maximum breakout factors, i.e.,  $F_{c0,m}^I$  and  $F_{c0,m}^N$ , obtained from this study and literature. As expected, the  $F_{c0,m}^I$  values for anchors with immediate breakaway are always greater than the  $F_{c0,m}^N$  values. The current FE results for  $F_{c0,m}^I$  and  $F_{c0,m}^N$  show good agreement with the Merifield *et al.* (2003) using lower bound limit analysis and Zhao *et al.* (2015) using upper bound limit analysis, respectively.

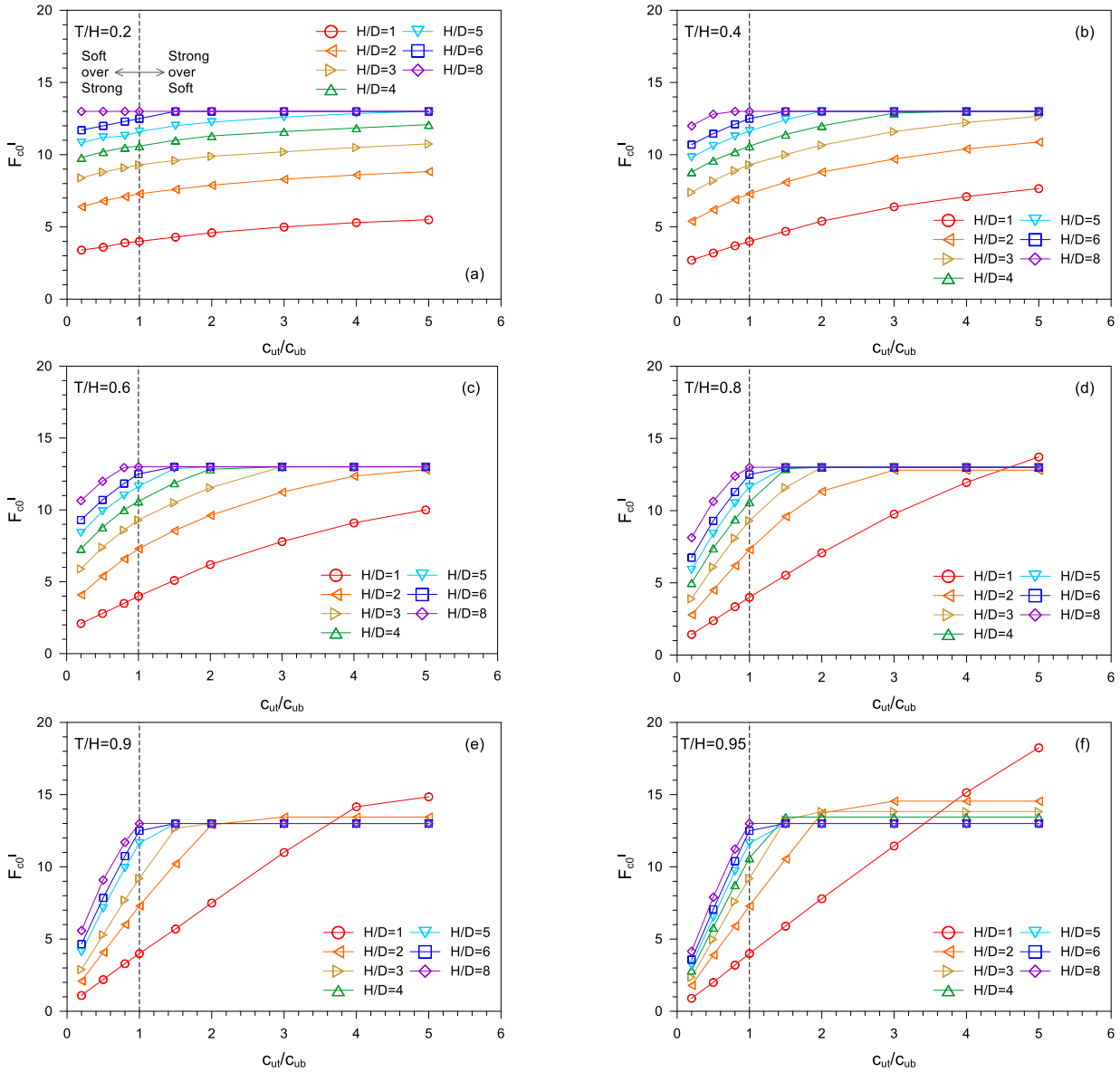


Fig. 4 Variation of  $F_{c0}^I$  values with  $c_{ul}/c_{ub}$  and  $H/D$  for circular anchors with immediate breakaway in weightless two-layered clay

4.2 Anchors with immediate breakaway in weightless two-layer clay

Fig. 4 shows the variation of  $F_{c0}^I$  values for different combinations of  $c_{ul}/c_{ub}$  and  $H/D$  is shown in for the cases of  $T/H = 0.2$  to  $0.95$ . The uplift resistance and failure mechanism of circular anchor in two-layered clay are demonstrated by two distinct cases, namely, soft-over-strong clay and strong-over-soft clay. For the soft layer overlying strong layer ( $c_{ul}/c_{ub} < 1$ ), the values of  $F_{c0}^I$  decrease in a non-linear tendency as the  $c_{ul}/c_{ub}$  decreases:  $F_{c0}^I$  values are lower than those for uniform clay ( $c_{ul}/c_{ub} = 1$ ). This result is attributed to the fact that the failure mechanism reaches the ground level but penetrates into the overlying soft layer, to some degree, which in turn causes the reduction of the anchor uplift resistance. This is supported by the displacement vector diagram illustrated in

Figs. 5(a) and 5(b) where punching shear through the bottom layer followed by the plastic yielding of the top layer. Especially for the anchors that are located near the overlying layer and shallowly embedded ( $T/H \geq 0.8$  and  $H/D \leq 2$ ), a vertical separation of the bottom strong layer acts as a rigid body of clay that pushes through to the top soft layer and thus significant yielding and large deformation occur in the overlying layer (Fig. 5(a)). As the anchor is moved away from the top layer and buried more deeply, the only a small vertical separation of the bottom layer is apparent, resulting in the lateral extent of plastic shearing above the anchor and little heaving at the ground (Fig. 5(c)). For the strong layer overlying soft layer ( $c_{ul}/c_{ub} > 1$ ), the values of  $F_{c0}^I$  values increase as the relative strength of the overlying layer rises, as shown in Fig. 4. This is due to the fact that as the bottom layer becomes increasingly softer compared with the top strong layer,

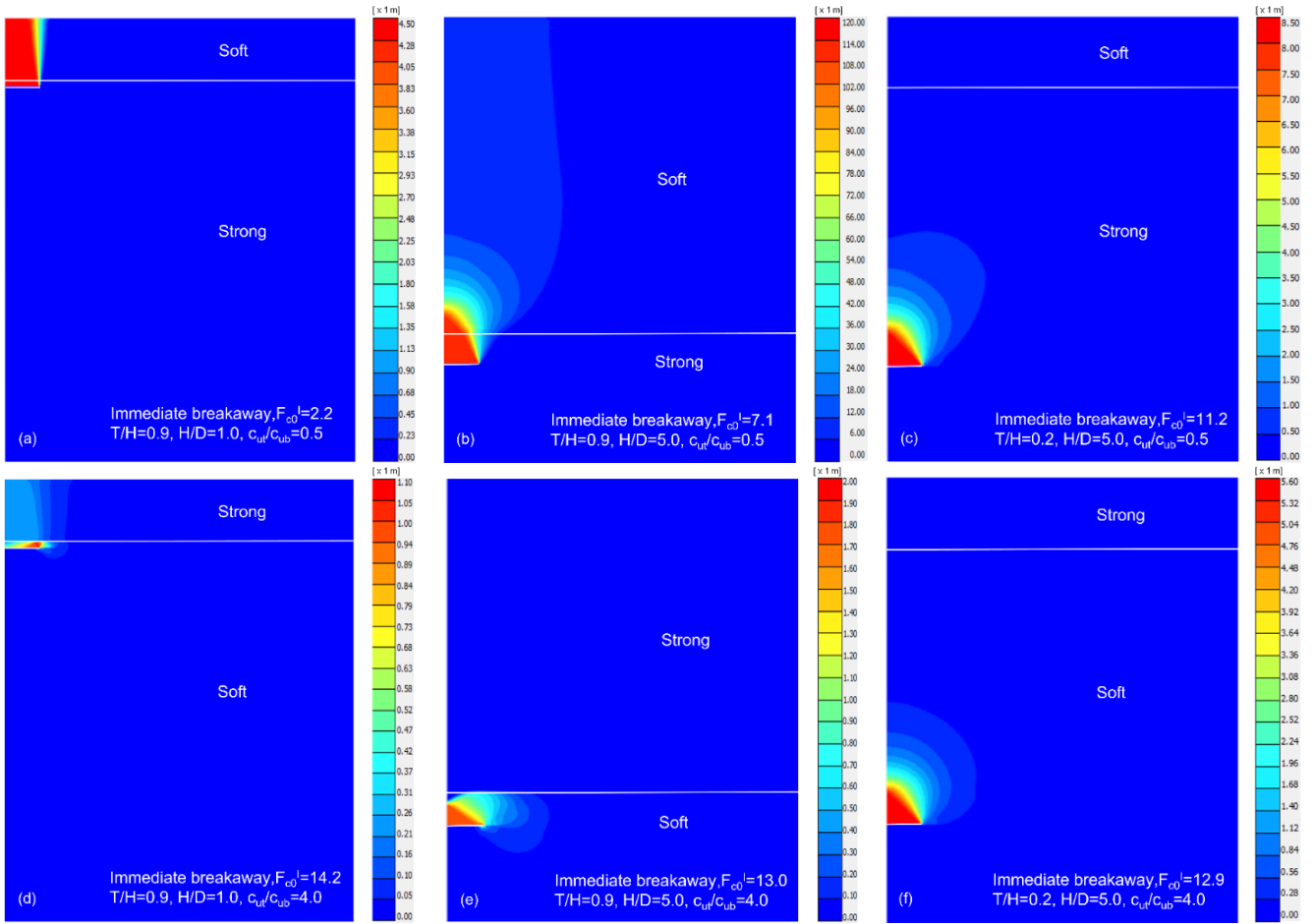


Fig. 5 Displacement contour diagram of circular anchors with immediate breakaway in weightless two-layered clay

the contribution of the overlying layer to the uplift resistance increases. Such failure mechanism is illustrated in Fig. 5(d) where although the much of yielding exists in the bottom soft layer, failure still occurs well into the top strong layer. Meanwhile, it is observed in Fig. 4 that for a certain value of  $T/H$  and  $H/D$ , there are a limiting ratio of  $c_{ul}/c_{ub}$  beyond which no further increase in  $F_{c0}^I$  is attained. This means that the anchor uplift resistance is insensitive to the strength of the overlying layer. As an example, at  $c_{ul}/c_{ub} = 4$ , the failure is mainly located within the bottom layer, as shown in Figs. 5(e) and 5(f) where the failure is induced by combining lateral squeezing and local shear at anchor edge.

#### 4.3 Anchors with no breakaway in weightless two-layer clay

Fig. 6 shows the variation of  $F_{c0}^N$  values for different combinations of  $c_{ul}/c_{ub}$  and  $H/D$  for the cases of  $T/H = 0.2$  to 0.95. Comparing to Fig. 4, it is seen that at an equivalent condition, the  $F_{c0}^N$  values for anchors with the no breakaway are always greater than the  $F_{c0}^I$  values for the immediate breakaway. It is also noticed that the trend of variation of  $F_{c0}^N$  with  $c_{ul}/c_{ub}$  is similar to that of  $F_{c0}^I$  illustrated in Fig. 4. For the case of no breakaway, no separation occurs between the clay and anchor and a localized clay flow around anchors becomes apparent.

However, its magnitude and shape are affected by  $c_{ul}/c_{ub}$  and  $T/H$ .

For the soft layer overlying strong layer ( $c_{ul}/c_{ub} < 1$ ), the values of  $F_{c0}^N$  decrease with a decrease in  $c_{ul}/c_{ub}$  and its trend is pronounced for greater  $T/H$ . For shallowly embedded anchor close to the overlying layer, the failure occurs as a result of shearing of the two-clay layers along lines directly above the anchor edge and shearing at the anchor in a form of bearing capacity failure as the soil flow formed at the anchor base (Fig. 7(a)). Meanwhile, when embedded deeper and located in the vicinity of the top soft layer, the anchor is controlled by the low strength of adjacent overlying layer, then the local soil flow around the anchor becomes significant and is prone to be extended such as that depicted in Fig. 7(b). When the anchor is deeply embedded and farther away from the overlying soft layer, the  $F_{c0}^N$  value reaches a maximum value, which corresponds to the onset of the self-contained failure mechanism, as shown in Fig. 7(c).

For the strong layer overlying soft layer ( $c_{ul}/c_{ub} > 1$ ), the value of  $F_{c0}^N$  is influenced by  $T/H$  and  $H/D$ . When the anchor is embedded shallowly and placed near the overlying layer and, a local soil flow is mobilized at the anchor edge, but its region is small (see Fig. 7(d)). As the top crust becomes thicker, a local shear zone with lateral squeezing at the anchor edge is developed for the anchor

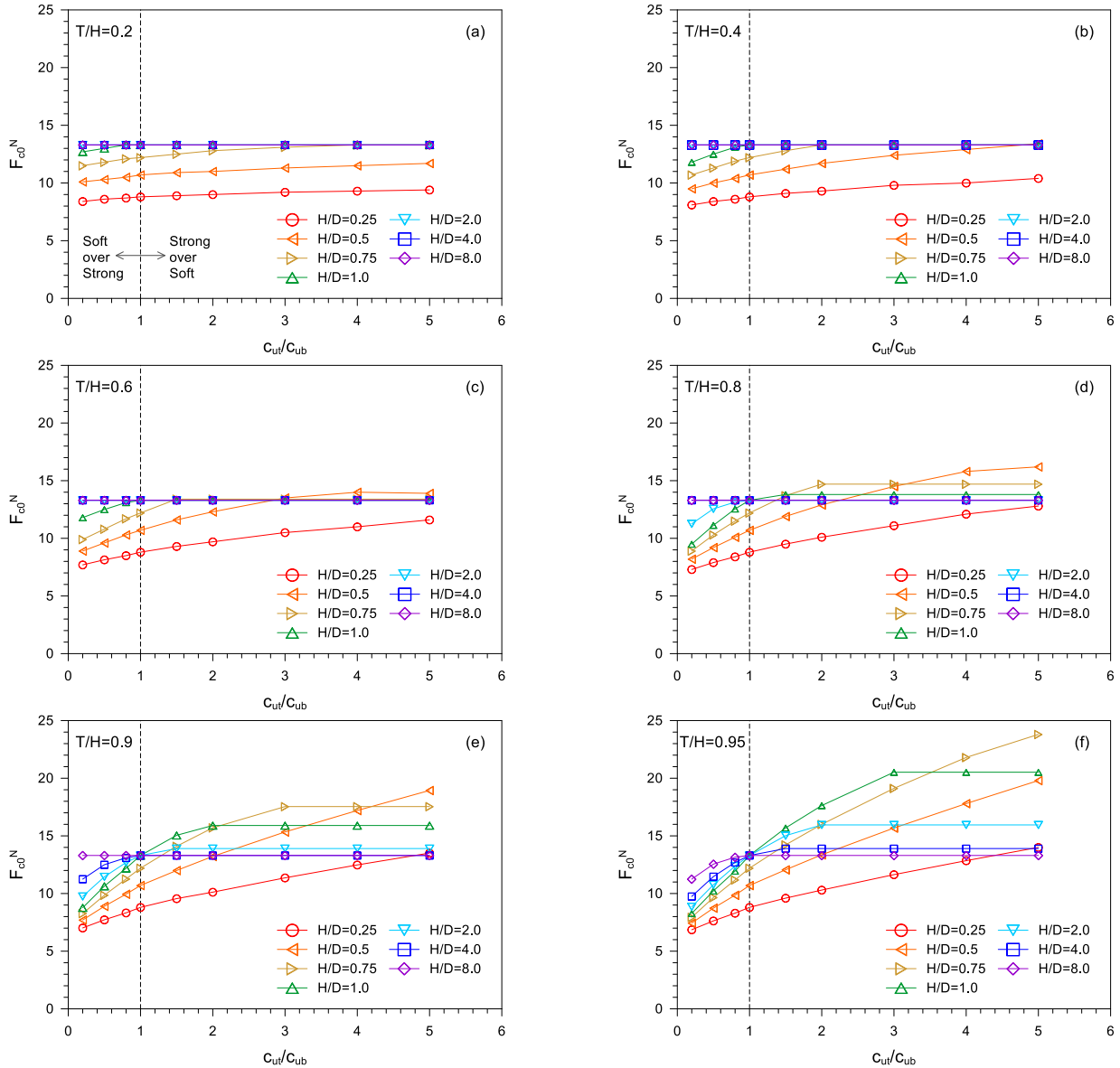


Fig. 6 Variation of  $F_{c0}^N$  values with  $c_{ut}/c_{ub}$  and  $H/D$  for circular anchors with no breakaway in weightless two-layered clay

adjacent to the overlying layer (Fig. 7(e)). For the anchors that are deeply embedded and far away from the overlying layer, a deep localized failure mechanism is clearly symmetric about the plane of anchor (Fig. 7(f)).

Fig. 8 shows the values of  $F_{c0}^I$  and  $F_{c0}^N$  with different combinations of  $T/H$  and  $c_{ut}/c_{ub}$ . The results demonstrates that the uplift resistance for strong-over-soft clay is greater than that for soft-over-strong clay. Also, the dependence of  $T/H$  on the uplift resistances of circular anchors is more prominent for immediate breakaway than for no breakaway.

#### 4.4 Anchors in two-layer clay with self-weight

Fig. 9 shows the obtained breakout factors  $F_{cy}^I$  of anchors with immediate breakaway for  $T/H = 0.9$  and  $H/D = 1$ . The value of  $F_{cy}^I$  increases linearly with overburden pressure until a limiting value, which is dependent on the clay strength ratio  $c_{ut}/c_{ub}$ . At this limiting value, the clay is

boned to the anchor base even though the immediate breakaway condition is imposed. Also, the overburden pressure delays the separation mechanism. For the high overburden ( $\gamma_m H/c_{ub}=10$ ), the clay does not separate from the anchor base immediately even at the shallow embedment ( $H/D = 1$ ). For zero overburden, in contrast, separation occurs. The critical overburden pressure  $(\gamma_m H/c_{ub})_{cri}$  at which no separation occurs is influenced by the value of  $c_{ut}/c_{ub}$ .

Comparing the  $F_{cy,l}^I$  presented in Fig. 9 with the value of  $F_{c0}^N$  in Fig. 6(e) for  $T/H = 0.9$  and  $H/D = 1$ , they are almost identical. This is due to the fact that the large overburden pressure induces the clay to remain attached to the underside of anchor. For the no breakaway case, the overburden has no effect on the uplift resistance of anchor because the clay weight does not influence the failure mechanism around the anchor. Therefore, the relationship between the breakout factors for the immediate and no breakaways are expressed as follows:

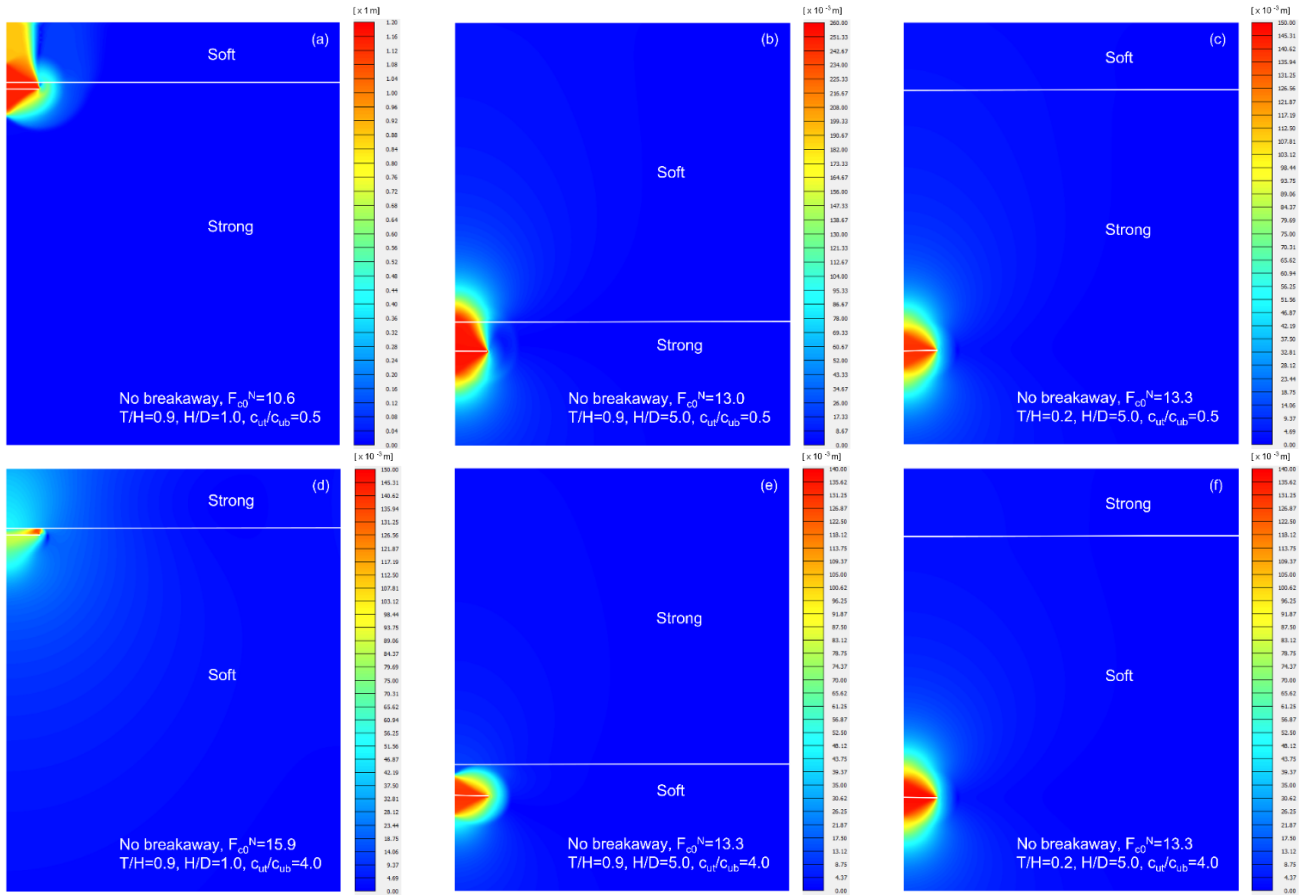
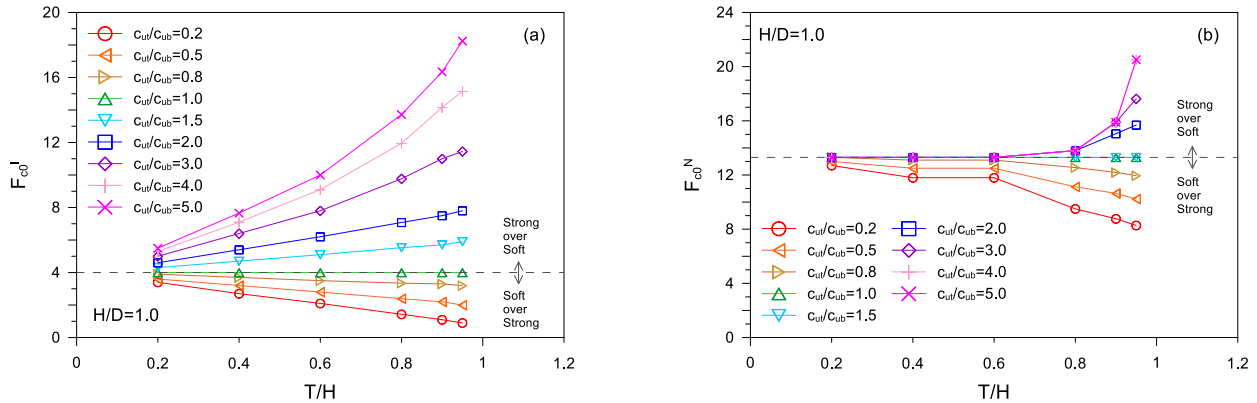


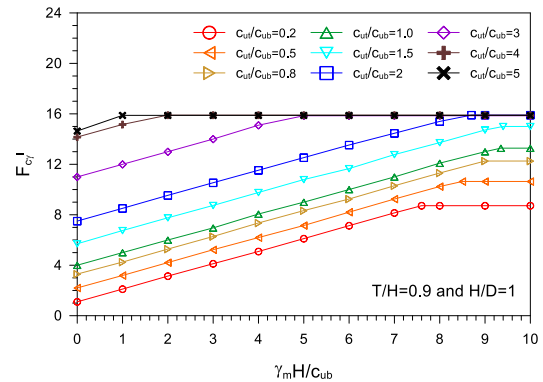
Fig. 7 Displacement contour diagram of for circular anchors with no breakaway in weightless two-layered clay


 Fig. 8 Variation of  $F_{c0}^I$  and  $F_{c0}^N$  with  $T/H$  and  $c_{u1}/c_{ub}$  for circular anchors in weightless two-layered clay

$$F_{cy,l}^I = F_{c0}^N = F_{cy}^N \quad (6)$$

where  $F_{cy}^N$  is the breakout factor of the anchors with no breakaway in clays with self-weight, which represents the ultimate breakout factor of the circular anchors embedded in undrained two-layered clays.

When compared to the FE results presented in Fig. 9, the values of  $F_{cy}^I$  determined from Eq. (2), they agree well with each other, only with a minimal difference of less than 1%. This indicates that by using the values of  $F_{c0}^I$  and  $F_{c0}^N (= F_{cy,l}^I)$  given in Figs. 4 and 6, together with the known values of  $\gamma_m$ ,  $c_{ub}$ , and  $H$ , the effective design of circular anchors in two-layered clay can be produced.


 Fig. 9  $F_{cy}^I$  values of circular anchors with immediate breakaway in two-layered clay with self-weight

## 5. Conclusions

The results presented in this study address the uniaxial vertical uplift resistance of circular plate anchors under undrained condition in two-layered clays. Best-estimate breakout factors for the anchors with immediate and no breakaway conditions are given. Key findings of this study are:

- The breakout factors obtained from the finite element analysis are in good agreement with those from laboratory model tests and analytical methods reported in literature. For weightless two-layer clays, the breakout factors for no breakaway are always greater than those for immediate breakaway.

- The breakout factors for strong-over-soft clays ( $c_{ul}/c_{ub} > 1$ ) are greater than those for soft-over-strong clays ( $c_{ul}/c_{ub} < 1$ ). For strong-over-soft clays, the breakout factors increase with an increase in  $T/H$  and  $c_{ul}/c_{ub}$ . For soft-over-strong clay, they decrease with increasing  $T/H$  and decreasing  $c_{ul}/c_{ub}$ .

- For immediate breakaway, the failure mechanism of anchors is significantly governed by the clay strength ratio  $c_{ul}/c_{ub}$ . For the strong-over-soft clays, clay experiences local squeezing failure in bottom soft layer, which is more notable for larger  $T/H$  and  $c_{ul}/c_{ub}$ . For the soft-over-strong clays, full or partial punching shear failure of bottom strong layer, which is predominant for smaller  $c_{ul}/c_{ub}$ . For no breakaway, no separation occurs between the clay and anchor and clay flow around the anchor becomes localized. However, as the values of  $T/H$  increases, i.e., the bottom layer is closer to the top layer, the modification of clay flow is produced.

- The breakout factors for no breakaway are the same as those for immediate breakaway with high overburden pressure (i.e. clay self-weight), which is the ultimate breakout factor of the anchors. For a given  $H/D$ , the critical overburden pressure ( $\gamma_m H/c_{ub}$ )<sub>cri</sub> corresponding to the ultimate breakout factors, reflecting a localized clay flow mechanism, varies severely with  $T/H$  and  $c_{ul}/c_{ub}$ .

As a final remark, recognizing that the breakout factors presented in this study are relevant only for the horizontal anchors subjected to vertical uplift load, further investigation may consider the plate anchor orientation (vertical or inclined anchors) with respect to loading direction, which affects the uplift resistance significantly.

## Acknowledgments

The authors acknowledge support in this research for the National Research Foundation of Korea (NRF) (Grant no. 2020R1C1C1005374).

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