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Uplift Capacity of a Plate Anchor Considering Suction Effects

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KEY WORDS: Plate anchor, Uplift capacity, Suction force, Clays, Failure modes, Breakout factor, Finite element method

ABSTRACT: *Anchors have been commonly used to as foundation systems of the structures that require the uplift resistance. Recently anchors have been used in ocean sediment for mooring systems to stabilizeoffshore structures. In the saturated clayey soil however, suction developed between the soil and anchor and affects the uplift capacity of anchor. To estimate the uplift capacity of the anchor accurately, the failure mechanisms of the anchor by the uplift force should also be correctly assumed. The uplift capacity is usually expressed in terms of breakout factors with respect to embedment ratio. In this paper, a two-dimensional plane strain numerical investigation into the vertical uplift capacity of a plate anchor in a clayey soil is described. The breakout factor against their corresponding values of embedment ratio was calculated and plotted along a single curve. The modes of failure mechanism at shallow and deep anchors are also presented.*

1. Introduction

Soil anchors are usually used as foundation systems, such as transmission towers or earth retaining structures to resist the uplift forces. Recently, anchors have been used in ocean sediment for mooring systems to provide stability of offshore structures. For the last 30 years, a number of research works, both experimental and theoretical, have been carried out to estimate the uplift capacity of anchors. A comprehensive overview of those works can be found in Das (2001), Merifield et al. (2001; 2005) and Merifield and Sloan (2006). In their results, the uplift capacity of anchor is usually expressed in terms of a breakout factor, which is a function of the anchor shape, embedment depth, overburden pressure and the soil properties. In the domestic research works related to the uplift capacity of the anchor, Bang et al. (2003) performed laboratory test considering the relative density of the sand and the embedment ratio. Park and Lee (2005) investigated the effects of interference between the anchors in group screw anchors using the laboratory and numerical methods. Bae et al. (2008) also performed laboratory test to estimate the pullout behavior of pipe type anchor with surface roughness, embedment ratio and diameter in sand condition.

In contrast to the many experimental and theoretical works, very few numerical analyses have been carried out to estimate the uplift capacity of anchors in saturated clayey soil condition. For the numerical analysis research works related to the clayey soil condition, Merifield et al. (2001; 2005) presented the breakout factor for the range of embedment depth and material properties along with the effects of anchor roughness and overburden pressure. However, they assumed that there is no the suction effects between the soil and anchor.

When the uplift force is applied to the anchor in saturated clay, the soil above the anchor is compressed while the soil below is relieved from the stress. Hence there will be an increase the pore water pressure above the anchor while a decrease pore water pressure below the anchor. Figure 1 shows a typical numerical analyses result showing the porewater pressure distribution when the uplift forces is applied to the anchor in saturated clay soil condition. The difference of the pressure results in a suction force.

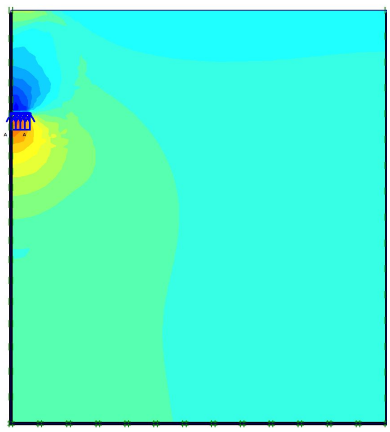

Fig. 1 Porewater distribution around the anchor

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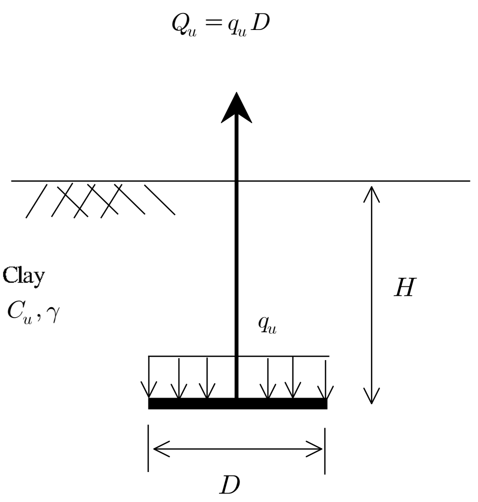


Fig. 2 General layout of the problem

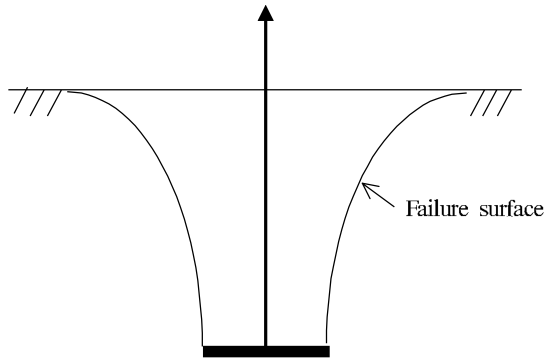
This suction force developed between the soil and anchor is likely to be the function of several variables including the embedment depth, soil permeability, undrained shear strength and loading rate. However, the suction forces could be calculated numerically by treating two different soil systems which are undrained and drained soil conditions. The uplift force developed in the undrained soil condition partially contains the suction force. However, the uplift force could not be effected by suction force if the anchor is embeded in drained soil condition. The suction force could be numerically estimated from the difference of those two previously mentioned uplift forces.

The present paper provides the two dimensional plane strain numerical analyses results for the uplift capacity of a plate anchor considering the suction force effects. Additionally, the displacement failure modes for the deep and shallow anchor in clayey soil are presented.

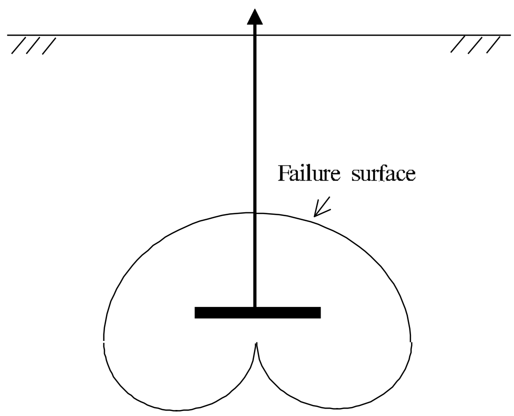
2. The Ultimate Anchor Capacity

Figure 2 shows the general layout of the anchor embedded in clayey soil which has undrained shear strength C_u, unit wight $\gamma = 16$ kN/m^3 and permeability $k = 1.0e^{-4}$. m/day The anchor has width D and the embedment depth is H from the ground surface.

According to the failure modes which are depended on the embedment ratio (H/D), the anchor can be divided into shallow or deep anchors (Das, 2001). If the failure mode extends to the ground surface, it is referred to as a hallow anchor. On the other hand, the soil failure mode takes place around the anchor, it is called a deep anchor. Figure 3 shows the general shape of the failure modes.



(a) Shallow anchor (Small H/D ratio)



(b) Deep anchor (Large H/D ratio)

Fig. 3 Failure modes for the anchor

The gross ultimate uplift capacity Q_u per unit length of stripe anchor in $c-\phi$ is written as (Das, 2001)

$$\begin{aligned} Q_u &= Q_n + W_a + F_s \\ &= C_u F_c D + q F_q D + W_a + F_s \end{aligned} \quad (1)$$

where D is width of the anchor plate; W_a is self weight the anchor plate; F_s is the suction force; q is the overburden pressure; F_c, F_q are the uplift capacity factors corresponding to cohesion and surcharge respectively.

The net ultimate uplift capacity Q_n of the anchor for the undrained condition ($\phi = 0, c = C_u$ thus $F_q = 1$) can be reduced as

$$Q_n = C_u F_c D + qD \quad (2)$$

According to the Das (2001), the breakout factor for the square or circular anchors increases with H/D up to the 9 and remains constant thereafter. The embedment ratio H/D at which F_c reaches the maximum value $F_{c-\max}$ called to as the critical embedment ratio, $(H/D)_{cr}$ as shown in Fig. 4.

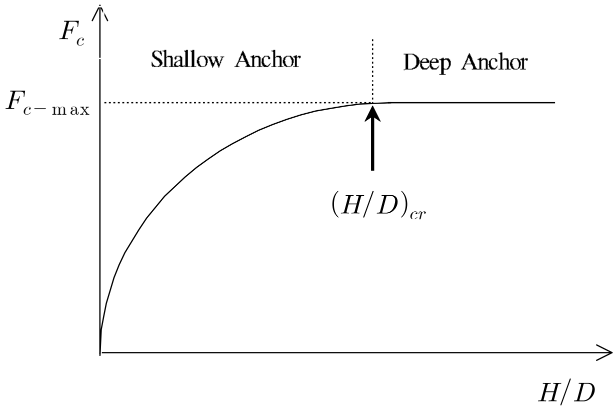


Fig. 4 Variation of breakout factor with embedment ratio

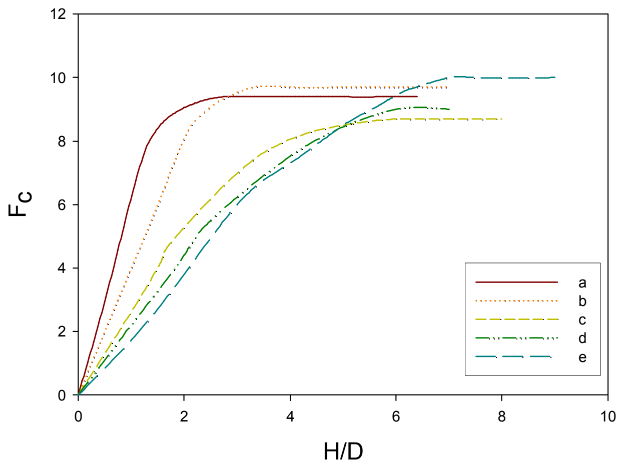


Fig. 5 Variation of breakout factor

Table 1 Details for the curves shown in Fig. 5

Curve No.	Reference	Year	C_u (kN/m^2)
a	Ali	1968	5.18
b	Kupferman	1971	6.9
c	Adams and Hayes	1967	10.35-11.8
d	Bhatnagar	1969	53.17
e	Adams and Hayes	1967	96.6-172.5

When the embedment ratio is less than $(H/D)_{cr}$, the anchor is referred to shallow anchor, otherwise deep anchor.

Das (1978) complied a number of laboratory model test results on circular anchors embedded in saturated clay with the various undrained cohesions. Figure 5 shows the average plots of F_c obtained form those results. The details relating to curves a, b, c, d and e shown in Fig. 5 are given in Table 1.

Das (1978) also reported some model test results conducted with square and rectangular anchors in clay. Based on those model test results, the following relationship was proposed

$$(H/D)_{cr} \approx 0.107\,C_u + 2.5 \leq 7 \tag{3}$$

He also proposed the following empirical relationship of the critical embedment ratio ($F_{c-\max}$) for a given anchor

$$F_{c-\max} = 7.56 + 1.44(\frac{D}{B}) \tag{4}$$

It can be seen from the equation (4) that for square and circular anchors $F_{c-\max}$ is equal to 9.

However the suction force developed in undrained condition can influenced the gross ultimate uplift capacity and uplift capacity factor with the H/D ratio.

3. Finite Element Method

The use of finite element method is now widespread among the researchers, but it has not been frequently used when estimating the uplift capacity of the anchor. Considering the behavior of the anchor in clayey soil condition, the finite element computer program called PLAXIS (Verneer and Brinkgtrve, 1995) was chosen as a computer tool to analyze the problem. This geotechnical finite element program distinguishes between drained and undrained soil conditions which correspond to the problem.

As using the finite element program, the following assumption is included

1. The anchor plate is prefectly rigid.
2. The anchor load has no influence on the failure load.
3. The soil at failure follows a Mohr-Coulomb failure criterion.
4. The soil profile is homogeneous.
5. The water lever is at the ground all the times.
6. The problem is two dimensional plane-strain problem.

Since the problem is symmetrical, only one half is modeled. As for the element type, six node triangular elements were used. Figure 6 shows a typical numerical model which consists 12m high and 10m width of the clayey soil. Tests were preformed with three different undrained shear strength ($C_u = 5$, 8 and 11 kN/m^2). The anchor which has 1 m width is modeled as a plate element with very high rigidity. The interface between the soil and anchor interface did not considered to sustain adequate tension to ensure the anchor remains in contact with the soil.

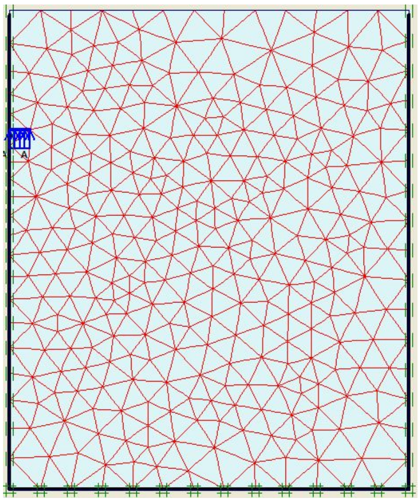


Fig. 6 Typical finite element mesh

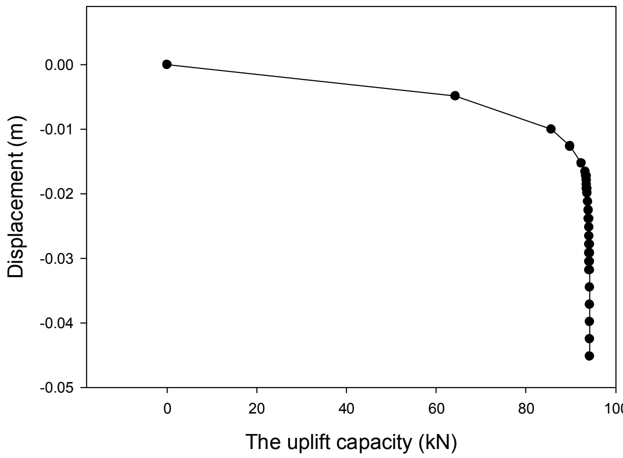


Fig. 7 Load-displacement curve

The soil system was treated in drained condition for the calculation of the net ultimated uplift capacity. However the gross ultimated uplift capacity was obtained by considering the undrained soil behavior. The uplift capacity was calculated by using the load-displacement curve in the middle of the anchor. Figure 7 shows the typical plot of the load-displacement relationship.

4. Results and Discussions

Finite element analyses were performed to obtain the uplift capacity of the plate anchor in saturated clayey soil condition. In the results, all the curves of the graphs are obtained from the regression by using exponential function of the given data.

The net ultimate uplift capacity of the anchor with three different undrained shear strength is shown graphically in Fig. 8 for embedment ratio of 1-6.

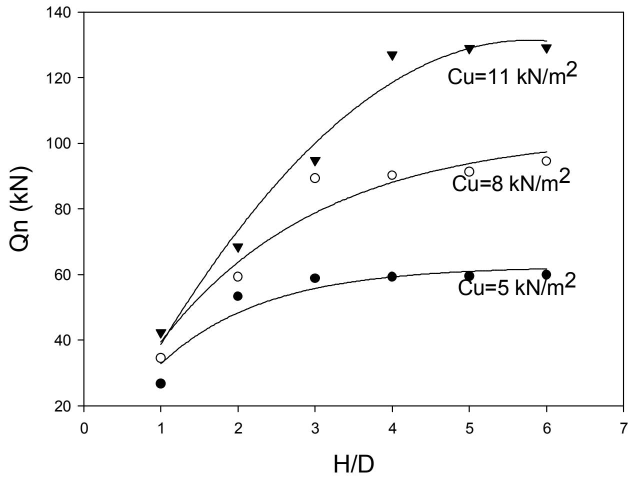


Fig. 8 Variation of Q_n with H/D

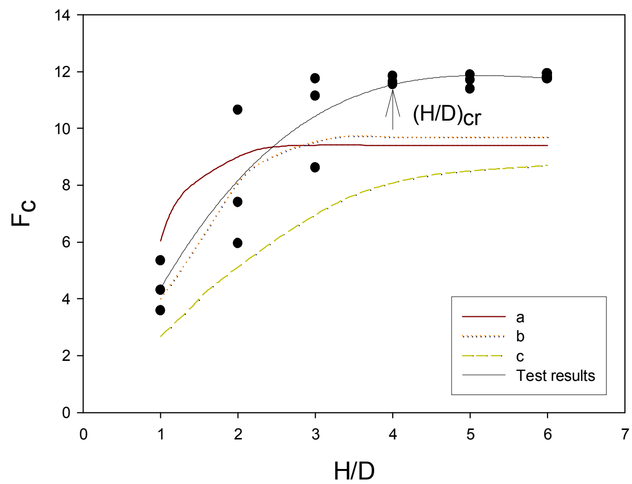


Fig. 9 Variation of F_c with H/D

It was found that for a given embedment ratio, the uplift capacity increases with an increase in the soil of undrained shear strength. Also, for any given clay, the magnitude of Q_n increased with the increase in the embedment ratio. By using the numerically calculated results and Eq. (2), the average magnitude of breakout factor F_c were calculated and plotted in a single curve against their corresponding values of H/D in Fig. 9.

The critical embedment ratio $(H/D)_{cr}$ is about 4 and the maximum value of F_c is about 11.5. Compare to the laboratory results in Table 1 (a, b, c), it shows breakout factor reaches a maximum limiting value but gives slightly higher value of $(H/D)_{cr}$ and F_c. in plate anchor. Another comparison to the Das's suggested relationship in equation (3) and (4), it also gives slightly higher values. The reason might to be that the anchor types used in the laboratory tests were limited to circular, square or rectangular anchors. and the

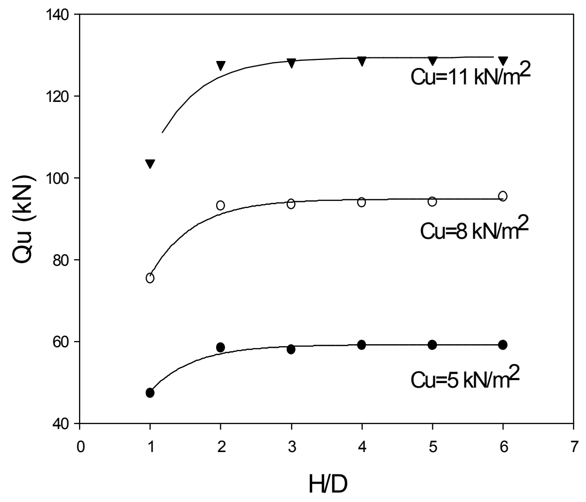


Fig. 10 Variation of Q_u with H/D

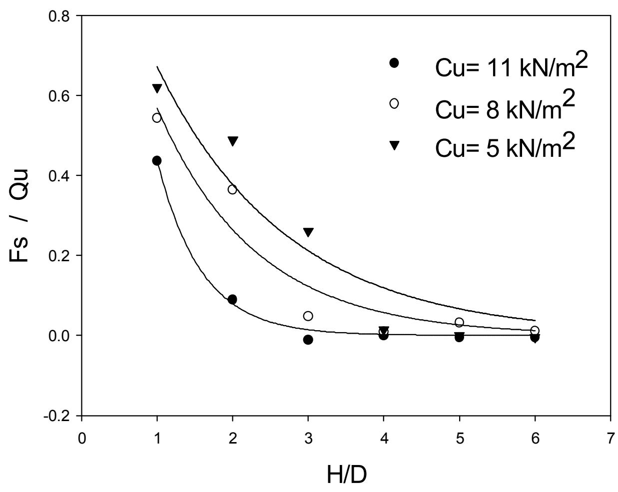


Fig. 12 Variation of F_s / Q_u with H/D

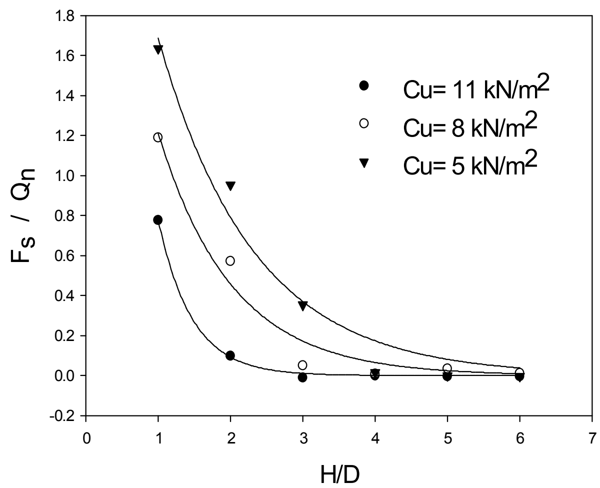


Fig. 11 Variation of F_s / Q_n with H/D

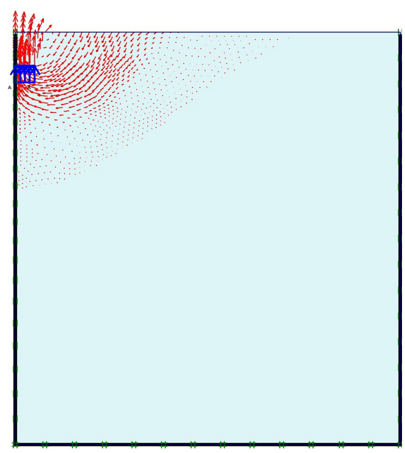


Fig. 13 Failure mode at shallow anchor $(H/D=2)$

assumption in current study also leads to the overestimation of the anchor capacity. However, it should be noted that the breakout factor continued to increase and reaches a limiting values which checks the transition between the shallow and deep anchor.

Figure 10 shows the value of the ultimate uplift capacity Q_u obtained from the undrained tests. This Q_u value reaches to limiting values similarly in all given clay.

This result tells that the suction force effects are not much related to the strength of the soil but it is much more related to the embedment ratio in certain depth. In this case, H/D is between 2 and 3.

Using the test values shown in Fig. 9 and Fig. 10, the variation of suction force $(Q_u - Q_n)$ for three given different clays with respect to H/D can be calculated.

The effects of suction force with respect to the net ultimate uplift capacity and the ultimate uplift capacity were plotted in Fig. 11 and Fig. 12. When the embedment ratio increases, the suction effects decreases in all values of undrained shear strength. Based on the F_s / Q_n and F_s / Q_u curves, as the embedment ratio approaches to the critical embedment ratio $(H/D)_{cr} \approx 4$, the suction force decreases very fast in all clayey soils. This tells that the suction effects are not the necessary function of the undrained shear strength, but the mainly function of the embedment ratio.

The modes of failure at shallow anchor condition is shown in Fig. 13. In general, for the shallow anchor, the vertical deformation extends to the ground surface and lateral deformation extending out from the anchor.

The modes of failure at deep anchor condition is shown in Fig. 14. For relatively deep anchor, a localized zone of compression and lateral deformation forms above the anchor.

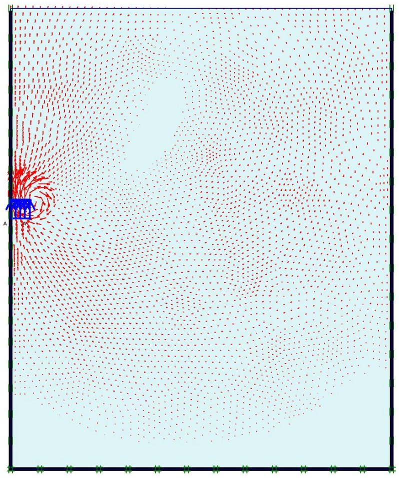


Fig. 14 Failure mode at deep anchor ($H/D=6$)

Although the critical embedment depth is a complex function, the failure mechanism beyond this depth essentially remains unaltered.

5. Conclusions

Two dimensional plane strain numerical analyses of a plate anchor for the uplift capacity embedded in saturated clayey soil condition has been presented. the suction force developed between the soil and anchor was numerically estimated in the first time, with using the drained and undrained soil conditions. However, it needs further experimental research to be confirm the suggested results.

The following main conclusions can be drawn from the numerical results;

(1) For a given embedment ratio, the uplift capacity increases with an increase in the soil of undrained shear strength. Also, for any given clay, the magnitude of Q_n increased with the increase in the embedment ratio.

(2) When the embedment ratio increases, the suction effects decreases in all values of undrained shear strength.

(3) The decreasing ratio of suction forces to the uplift force are significant in the weak soil (smaller undrained shear strength) as the embedment ratio decreases.

(4) The failure modes are generally agrees with the suggested modes.

(5) In general, it was found that the failure mode for the shallow anchor consists of the immediate upward movement above the anchor, accompanied by the lateral movements which extends to the surface of the ground.

(6) For the relatively deep anchor, a localized zone of compression and lateral deformation forms above the anchor.

References

Adams, J.I. and Hayes, D.C. (1967). "The Uplift Capacity of Shallow Foundations", Ontario Hydro. Res. Qtrly., Vol 19, No 1, pp 1-13.

Ali, M. (1968). Pullout Resistance of Anchor Plates in Soft Bentonite Clay, M.S. Thesis, Duke University, Durham, N.C., USA.

Bae, W., Lee, B., Kwon, Y. and Lee, J. (2008). "Study of Pullout Behavior of Pipe Anchor", J. of Korean Geo-Environ. Society, Vol 9, No 1, pp 5-10.

Bang, S.T., Kim, Y.J., Kim, J.M., Kim, J.G. (2003). "The Method Estimating Group Effects with Small Pullout Tests of Screw Anchors", Conference paper 2003, Korean Geo-Environ. Society, pp 219-225.

Bhatnagar, R.S. (1969). Pullout Resistance of Anchors in Silty Clay, M.S. Thesis, Duke University, Durham, N.C., USA.

Das, B.M. (1978). "Model Tests for Uplift Capacity of Foundations in Clay", Soils and Found. Japan, Vol 18, No 3, pp 17-24.

Das, B.M. (2001). Earth Anchors, J. Ross Publishing, Fort Lauderdale.

Kuferman, M. (1971). The Vertical Holding Capacity of Marine Anchors in Clay Subjected to Static and Cyclic Loading, M.S. Thesis, University of Massachusetts, Amherst, USA.

Merifield, R.S., Lyamin, A.V. and Sloan, S.W. (2005). "Stability of Inclined Strip Anchors in Purely Cohesive Soil", J. of Geotech. and Geoenviron. Engrg., Vol 131, No 6, pp 792-799.

Merifield, R.S. and Sloan, S.W. (2006). "The Ultimate Pullout Capacity of Anchors in Frictional Soils", Canadian Geotechnical Journal, Vol 43, No 8, pp 852-868.

Merifield, R.S., Sloan, S.W. and Yu, H.S. (2001). "Stability of Plate Anchors in Undrained Clay", Geotechnique. Vol 51, No 2, pp 141-153.

Park, S.S. and Lee, H.K. (2005). "The Pullout Behavior of Pipe Anchor in Sandy Soil" J. of Korean Geotechnical Society, Vol 21, No 10, pp 123-131.

Vermeer, P.A. and Brinkgreve, R.B.J. (1995). PLAXIS User Manual Version 6.1, Balkema, Rotterdam.

2008년 11월 4일 원고 접수
2008년 12월 8일 최종 수정본 채택