UPLIFT RESISTANCE OF STRIP AND CIRCULAR ANCHORS IN A TWO LAYERED SAND

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ABSTRACT

The vertical uplift resistance of shallow strip and circular plate anchors buried horizontally in a two layered sand has been determined by using the upper bound theorem of limit analysis. Uplift factors \( f_s \) and \( f_c \) due to the effects of soil unit weight and surcharge pressure, respectively, have been established. For a given thickness of the two layers, the uplift factor \( f_s \) is found to be comparatively greater when the anchor is embedded in dense sand underlying a loose sandy layer. However, the factor \( f_c \) remains unaffected by the layers' relative positions. As compared to available experimental results, the theory provides a slight overestimation of the uplift resistance especially for greater embedment ratios.

Key words: anchors, limit analysis, numerical modeling, plasticity, sands (IGC: E4)

INTRODUCTION

The vertical uplift capacity of anchors buried horizontally in homogeneous ground has earlier been computed by various researchers using different methods (Sutherland, 1988) such as limit equilibrium (Meyerhof and Adams, 1968; Vermeer and Sutjiadi, 1985), upper bound limit analysis (Murray and Geddes, 1987; Kumar, 1997, 1999, 2001), the method of characteristics (Subba Rao and Kumar, 1994), the finite element method (Rowe and Davis, 1982; Tagaya et al., 1988), and centrifuge experiments (Dicken, 1988). However, for anchors embedded in a layered soil medium, up until recently only a few small scale experiments have been performed by Stewart (1985) and Bouazza and Finlay (1990). Stewart (1985) determined the vertical uplift capacity of circular anchors embedded in a fully cohesive medium with the overlay of a sandy layer. Bouazza and Finlay (1990) conducted model tests on circular anchors embedded in two layered sands. In the present article, the vertical uplift capacity of shallow strip and circular horizontal plate anchors buried in a two layered sand has been evaluated by using the upper bound theorem of limit analysis, with consideration of straight rupture lines. Comparison of the results has been made with the available experimental data and the existing theories.

DEFINITION

To determine the vertical uplift resistance of strip and circular anchor plate anchor, having width/diameter \( b \), placed in a two layered sand at a depth \( d \) from ground surface. The upper and lower layers are referred to with the subscripts 1 and 2, respectively. The depth of the upper layer is \( d_1 \), and the soil in this layer has friction angle \( \phi_1 \) and unit weight \( \gamma_1 \). The anchor is embedded in layer 2 at a depth \( d_2 \) below the interface of the two layers. Layer 2 is defined by the soil parameters \( \phi_2 \) and \( \gamma_2 \). The ground surface is loaded with a surcharge pressure of magnitude \( q \).

ASSUMPTIONS

1. The upper surface of the anchor is assumed to be fully bonded with the overlying soil mass, and no relative movement occurs between the plate and adjoining soil mass. The lower surface of the anchor on the other hand has been assumed not to offer any resistance to pullout. It should be noted that the assumption of no relative movement between plate and adjoining soil mass will be valid only for perfectly rough anchors; however, for smooth anchor surfaces a slip can always take place along the anchor-soil interface.

2. Along the interface of two layers, the angle \( (\phi_m) \) of the shearing resistance of the soil is assumed to be an average value of the two layers, that is, \( \phi_m = (\phi_1 + \phi_2)/2 \). It will be demonstrated later that this assumption does not affect the results at all; it has been found that for the critical collapse mechanism, no energy dissipates along the interface of the two layers.

3. The principle of superposition remains applicable and the total pullout resistance of the anchor can be obtained with the separate consideration of sur-
charge and unit weight components.
4. The soil medium follows Mohr-Coulomb's failure criterion and an associated flow rule.

COLLAPSE MECHANISM AND VELOCITY HODROGRAPHS

The collapse mechanism was assumed to be a combination of different rigid blocks bounded by linear rupture/velocity discontinuity lines. On account of the symmetry about the axis of the anchor, only half of the collapse mechanism as shown in Fig. 1, was used for carrying out analysis. The mechanism was assumed to be comprised of a central block OADC and two side blocks, AGE and EFGD. The central block was assumed to be fully bonded with the upper surface of the plate and to move with the velocity $V_0$, the same as that of the velocity of the anchor. The relative velocities of the blocks AGE and EFGD with respect to the central block are $V_{20}$ and $V_{10}$. The relative velocity of the block EFGD with respect to the underlying block AGE is $V_{12}$. At failure, the blocks AGE and EFGD will move outward relative to each other. Consequently, the direction of the vertical component of the velocity vector $V_{12}$ should always point upward. However, on the other hand, the horizontal direction of $V_{12}$ could be either way. Therefore, both the horizontal directions of $V_{12}$, as shown in Figs. 1(a) and 1(c), were analyzed for finding the minimum pullout load. Since the material is assumed to follow an associated flow rule, all the velocity vectors should incline at an appropriate angle $\phi$ with the corresponding rupture line. The velocity hodographs have been drawn in Figs. 1(b) and 1(d). For a collapse mechanism to be kinematically admissible, the horizontal component of the velocity vector $V_{12}$ should point from (i) right to left for $\phi_2 > \phi_1$, and (ii) left to right for $\phi_2 < \phi_1$. For given values of $b$, $d_1$, and $d_2$, in order to define the collapse mechanism and the associated velocity hodographs, the values of only two independent variables are needed. The two chosen variables were angles $\beta$ and $\alpha_1$, where $\beta = \angle OAD$ and $\alpha_2 = \angle EGA$. Using the velocity hodographs as shown in Figs. 1(b) and 1(d), all the velocity terms and the angle $\alpha_1$ can be written in terms of $V_0$, $\alpha_2$, and $\beta$, where $\alpha_1 = \angle DFG$. The expressions for $V_{20}$, $V_2$, $V_{12}$, $V_{10}$, $V_1$, and $\alpha_1$, are given below for two different cases:

**Case 1:** $\phi_2 > \phi_1$

The corresponding admissible velocity hodographs are shown in Fig. 1(b). Using the geometry of the velocity hodographs triangles, it can be shown that:

$$
\frac{V_2}{V_0} = \frac{\sin (\pi/2 - \beta + \phi_2)}{\sin (\alpha_2 + \beta)}; \quad \frac{V_{20}}{V_0} = \frac{\sin (\pi/2 - \alpha_2 - \phi_2)}{\sin (\alpha_1 + \beta)};
$$

$$
\frac{V_{12}}{V_{20}} = \frac{\sin (\phi_2 - \phi_1)}{\sin (\beta + \phi_1 + \phi_m)};
$$

$$(1a)$$

$$
V_1 = \sqrt{V_2^2 + V_{12}^2 - 2V_2V_{12}\cos(\alpha_2 + \phi_2 + \phi_m)} \quad (1b)
$$

where $\alpha_1 = \phi_2 + \alpha_2 - \phi_1 - \cos^{-1}\left(\frac{V_2^2 + V_{12}^2 - 2V_2V_{12}\cos(\alpha_2 + \phi_2 + \phi_m)}{2V_2V_1}\right)$

**Case 2:** $\phi_2 < \phi_1$

The velocity hodographs in this case are shown in Fig. 1(d). It can be shown that:

$$
\frac{V_2}{V_0} = \frac{\sin (\pi/2 - \beta + \phi_2)}{\sin (\alpha_2 + \beta)}; \quad \frac{V_{20}}{V_0} = \frac{\sin (\pi/2 - \alpha_2 - \phi_2)}{\sin (\alpha_1 + \beta)};
$$

$$
\frac{V_{12}}{V_{20}} = \frac{\sin (\phi_1 - \phi_2)}{\sin (\beta - \phi_1 + \phi_m)};
$$

$$(2a)$$

$$
V_1 = \sqrt{V_2^2 + V_{12}^2 - 2V_2V_{12}\cos(\alpha_2 + \phi_2 + \phi_m)} \quad (2b)
$$

where $\alpha_1 = \phi_2 + \alpha_2 - \phi_1 - \cos^{-1}\left(\frac{V_2^2 + V_{12}^2 - 2V_2V_{12}\cos(\alpha_2 + \phi_2 + \phi_m)}{2V_2V_1}\right)$

PULLOUT RESISTANCE

The ultimate pullout capacity of the anchor plate can be determined by equating the rate of the total work done by the external and body forces to the rate of dissipation of the total internal energy; the later term becomes equal...
to zero for cohesionless soil media with an associated flow rule (Chen, 1975; Chen and Liu, 1990). On this basis, the following expressions for finding the uplift resistance for strip and circular anchors were obtained:

**Strip Anchors**

\[
P_u = \frac{2[(W_{1l} + W_{2l} + Q_{CD})V_0 + (W_{1r} + Q_{DF})V_1 \sin(\alpha_1 + \phi_1) + W_{2r}V_2 \sin(\alpha_2 + \phi_2)]}{V_0}
\]

where \(P_u\) = total vertical uplift resistance per unit length of the strip anchor plate; \(W_{1l}\) = weight of the block BDEC, \(W_{1l} = 0.5\gamma d_1L_{BE} + L_{CD};\) \(W_{2l}\) = weight of the block OAB, \(W_{1r} = 0.5\gamma d_2L_{OA};\) \(W_{1r}\) = weight of the block EGFD, \(W_{1r} = 0.5\gamma d_1L_{EG} + L_{DF};\) \(W_{2r}\) = weight of the block AGE, \(W_{2r} = 0.5\gamma d_2L_{EG};\) \(Q_{CD} = qL_{CD};\) and \(Q_{DF} = qL_{DF}.\) The subscripts to \(L\) denote the lengths of the corresponding lines.

**Circular Anchors**

\[
P_u = \frac{[(W_{1l} + W_{2l} + Q_{CD})V_0 + (W_{1r} + Q_{DF})V_1 \sin(\alpha_1 + \phi_1) + W_{2r}V_2 \sin(\alpha_2 + \phi_2)]}{V_0}
\]

where \(P_u\) = total vertical uplift resistance of the circular anchor plate;

\[
W_{1l} = \frac{\pi\gamma d_1}{3} (L_{CD} + L_{BE} + L_{CD}L_{BE});
\]

\[
W_{2l} = \frac{\pi\gamma d_1}{3} (L_{OA} + L_{BE} + L_{OA}L_{BE});
\]

\[
W_{1r} = \frac{\pi\gamma d_1}{3} (L_{CF} + L_{DF} + L_{CF}L_{DF}) - W_{1l};
\]

\[
W_{2r} = \frac{\pi\gamma d_2}{3} (L_{OA} + L_{BE} + L_{OA}L_{BE}) - W_{2l};
\]

\[
Q_{CD} = \pi L_{CD}q;\) and \(Q_{DF} = \pi L_{DF}q - Q_{CD}.\)

For chosen values of \(\alpha_2\) and \(\beta,\) the magnitude of the \(P_u\) can be determined on the basis of Eqs. (3) and (4) for strip and circular anchor plates, respectively. The magnitude of the \(P_u\) can then be minimized with respect to independent variations of parameters \(\alpha_1\) and \(\beta.\) The value of \(\alpha_2\) was varied in between 0 to \(\pi/2 - \phi_2\) and, for a chosen value of \(\alpha_2,\) the value of \(\beta\) was varied in between \(\tan^{-1}[2(d_1 + d_2)/b]\) and \(\pi - \alpha_2;\) if the point \(D\) lay on the right side of the point \(F,\) the mechanism was simply omitted from the analysis. A computer program was written in FORTRAN so as to search for the minimum value of \(P_u.\) The values of the angles \(\alpha_2\) and \(\beta\) were independently varied within two do-loops by dividing the corresponding admissible range of the angles \(\alpha_2\) and \(\beta\) into 1000 equal divisions. For chosen values of \(\alpha_2\) and \(\beta,\) the mechanism was said to be kinematically admissible if all the velocity terms (in terms of \(V_0\)) remain greater than or at least equal to zero.

**RESULTS**

For both strip and circular anchors, the computations have invariably revealed that the magnitude of the pullout resistance becomes minimum when no relative movement occurs among the various blocks; that is, for the critical collapse mechanism, the magnitudes of the relative velocities, \(V_{1a}, V_{2b}\) and \(V_{1c},\) become simultaneously equal to zero. This finding is similar to that observed earlier by Murray and Geddes (1987) and Kumar (1997, 2001) for obtaining the pullout resistance of anchors placed in homogeneous soil. The critical collapse mechanism is separately shown in Fig 2. For the critical collapse mechanism the magnitude of the \(P_u\) can be written as, \(P_u = P_{uq} + P_{us},\) where \(P_{uq}\) and \(P_{us}\) are the corresponding surcharge and unit weight components of the pullout resistance. The expressions for finding \(P_{uq}\) and \(P_{us}\) are given below:

**For Strip Anchors**

\[
P_{uq} = q(b + 2d_1 \tan \phi_1 + 2d_2 \tan \phi_2)
\]

\[
P_{us} = \gamma d_1(b + 2d_2 \tan \phi_2 + d_1 \tan \phi_1) + \gamma d_2(b + d_2 \tan \phi_2)
\]
For Circular Anchors

\[ P_{\text{eq}} = \frac{\pi}{4} q(b + 2d_1 \tan \phi_1 + 2d_2 \tan \phi_2)^2 \]  
\[ P_{\text{uw}} = \frac{\pi}{12} \gamma_1 d_1 ((b + 2d_2 \tan \phi_1) - d_1 \tan \phi_1)^2 
+ (b + 2d_2 \tan \phi_1)(b + 2d_2 \tan \phi_2) 
+ \frac{\pi}{12} \gamma_2 d_2 (b^2 + (b + 2d_2 \tan \phi_2)^2 
+ b(b + 2d_2 \tan \phi_2)) \]  
\[ (6a) \quad (6b) \]

UPLIFT EQUATION

The pullout resistance was expressed in the form given below:

\[ p_u = qf_u + f_r \]  
\[ \text{where} \quad p_u = \frac{P_u}{b} \quad \text{for strip anchors} \]
\[ \frac{4P_u}{(\pi b^2)} \quad \text{for circular anchors} \]
\[ \gamma_m = \frac{\gamma_1 d_1 + \gamma_2 d_2}{d_1 + d_2} \]

and \( f_u \) and \( f_r \) are the non-dimensional uplift factors, due to the components of surcharge and unit weight, respectively, the values of which are defined below:

For Strip Anchors

\[ f_u = (1 + 2\lambda_1 \tan \phi_1 + 2\lambda_2 \tan \phi_2) \]
\[ f_r = \frac{\gamma_1 \lambda_1}{\gamma_m} (1 + 2\lambda_2 \tan \phi_2 + \lambda_1 \tan \phi_1) \]
\[ + \frac{\gamma_2 \lambda_2}{\gamma_m} (1 + \lambda_2 \tan \phi_1) \]  
\[ (8a) \quad (8b) \]

For Circular Anchors

\[ f_u = (1 + 2\lambda_1 \tan \phi_1 + 2\lambda_2 \tan \phi_2)^2 \]
\[ f_r = \frac{\gamma_1 \lambda_1}{\gamma_m} ((1 + 2\lambda_2 \tan \phi_2 + 2\lambda_1 \tan \phi_1)^2 + (1 + 2\lambda_2 \tan \phi_2)^2 
+ (1 + 2\lambda_2 \tan \phi_2)(1 + 2\lambda_2 \tan \phi_2)) 
+ \frac{\gamma_2 \lambda_2}{\gamma_m} (1 + (1 + 2\lambda_2 \tan \phi_2)^2 + (1 + 2\lambda_2 \tan \phi_2)) \]  
\[ (9a) \quad (9b) \]

in the above expressions, \( \lambda_1 = \frac{d_1}{b} \) and \( \lambda_2 = \frac{d_2}{b} \).

EFFECT OF LAYERS' RELATIVE POSITIONS ON PULLOUT RESISTANCE

Let \( d_{\text{dense}} \) and \( d_{\text{loose}} \) represent the thickness of dense and loose sand layers, respectively; and \( d = d_{\text{dense}} + d_{\text{loose}} \). In the following section, by keeping the same values of \( d_{\text{dense}} \) and \( d_{\text{loose}} \), the comparison of the pullout resistance is made for the two different relative positions of the loose and dense sand layers, that is, (i) \( d_1 = d_{\text{dense}}, \ d_2 = d_{\text{loose}} \); (ii) \( d_1 = d_{\text{loose}}, \ d_2 = d_{\text{dense}} \); \( d_2 = d_{\text{dense}} \). To study the effect of the relative positions of the two layers on the magnitude of the uplift factors \( f_u \) and \( f_r \), two soil layers having same unit weight (\( \gamma_1 = \gamma_2 \)) and with \( \phi \) equal to 30° (loose sand) and 45° (dense sand) were selected. The variation of the factor \( f_r \) for two different relative positions of the two layers with changes in the ratio \( d_{\text{dense}} / d \), for different values of \( \lambda \), is demonstrated in Figs. 3(a) and 3(b) for strip and circular anchors, respectively; \( d_{\text{dense}} = d_1 \) with the upper dense layer, and \( d_{\text{dense}} = d_2 \) with the lower dense layer. For given values of \( d \) and \( d_{\text{dense}} \), it can be seen that the magnitude of \( f_r \) becomes invariably higher when the loose sand layer is placed over dense sand. The difference between the two cases becomes higher with an increasing value of \( \lambda \); the difference is found to be maximum when the two layers have almost the same thickness (\( d_1 = d_2 \)). The variation of the factor \( f_u \) with the ratio \( d_{\text{dense}} / d \) for strip and circular anchors has been indicated in Figs. 4(a) and 4(b). Unlike the factor \( f_r \), for given values of \( d \) and \( d_{\text{dense}} \), the magnitude of the pullout factor \( f_u \) remains unaffected by the layers’ relative position; it can be seen from Eqs. (8a) and (8b) that the value of \( f_u \) remains unchanged, both for strip and circular anchors, when \( \lambda_1 \) and \( \phi_1 \) are replaced simultaneously with \( \lambda_2 \) and \( \phi_2 \) and vice-versa. For values of the \( d_{\text{dense}} / d \) equal to 0 and 1, the magnitudes of both the pullout factors...
become simply that of the homogeneous ground with $\phi = 30^\circ$ and $45^\circ$, respectively. The magnitudes of the $f_a$ and $f_u$ have been found to increase with increases in the values of $d_{	ext{dense}}/d$ and $\lambda$. It should be noted that the pullout factors for circular anchors have been found to be much higher than for the strip anchors.

**COMPARISONS**

Bouazza and Finlay (1990) have conducted model uplift tests on circular plate anchors (diameter = 37.5 mm) in a two layered dry sand. The sand used in these tests exhibits following properties: specific gravity = 2.65, minimum porosity = 33.2% and maximum porosity = 44.2%. Three different relative densities of the sand were employed for testing: (i) loose sand: relative density = 29%, $\gamma = 15.23$ kN/m$^3$, $\phi_{\text{trial}} = 33.8^\circ$; (ii) medium sand: relative density = 59%, $\gamma = 16.07$ kN/m$^3$, $\phi_{\text{trial}} = 39.0^\circ$; and (iii) dense sand: relative density = 59%, $\gamma = 16.87$ kN/m$^3$, $\phi_{\text{trial}} = 43.7^\circ$. The anchor plate was buried under a dense sand layer with the overlay of either a loose or medium sand layer. No surcharge pressure was used in their tests. The comparison of the present theory with the experimental results of Bouazza and Finlay (1990) for circular anchors has been shown in Figs. 5(a) and 5(b). In Fig. 5(a) the overlying layer is loose sand, whereas Fig. 5(b) refers to overlay of the medium dense sand layer. The comparison of the results is given with respect to the variation in embedment ratio $\lambda$ and for different values of $\lambda_1$. It can be seen that the pullout capacity increases (i) with a decrease in the value of $\lambda_1$; (ii) with an increase in the value of $\lambda$; and (iii) with a change in the overlying soil layer from loose to medium dense sand. The theoretical pullout resistance was found to be a little higher as compared to the reported experimental test results. Up to $\lambda = 3$, the theory compares quite well with the experimental data. However, for higher values of $\lambda$, the difference between theoretical and experimental data increases. However, it should be noted that an almost equal difference exists between the two even with $\lambda_1$ equal to 0 and 1, that is, even for the anchors buried in a single layer homogeneous soil medium. In any case, the theory is able to provide a reasonable estimation of the vertical uplift resistance of anchors in a two layer sandy medium.

For a single layer homogeneous ground, Table 1 provides the comparisons of the results for strip anchors with the available theories of Meyerhof and Adams (1968),
Table 1. Comparison of the uplift factors $f_u$ and $f_a$ for strip anchors in homogeneous ground with $\lambda = 3.0$

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Rowe and Davis (1982), Murray and Geddes (1987), and Subba Rao and Kumar (1994). It can be seen that theory provides exactly the same results as given by Murray and Geddes (1987) and Kumar (1997, 2001); this is due to the fact that for the single layer homogeneous ground, the present theory is exactly the same as earlier given by Murray and Geddes (1987) and Kumar (1997, 2001). The theory compares reasonably well with the widely used analysis of Meyerhof and Adams (1968). The finite element theory of Rowe and Davis (1982) for an associated flow rule material provides the maximum pullout resistance in all the cases. On the other hand, the method of characteristics approach of Subba Rao and Kumar (1994) provides the minimum answer, which signifies that the true uplift capacity will be still lower than the solution provided in this paper.

DISCUSSIONS
1. Although along the interface of the two layers, the magnitude of the friction angle ($\phi_{oa}$) has been assumed to be an average $\phi$ of the two layers; however, in the final solution, this assumption does not affect the results. It is due to the fact that for the critical collapse mechanism, no relative motion occurs among the various rigid blocks, and consequently, no energy dissipation takes place along the interface of the two layers.
2. The shape of all rupture lines have been assumed to be linear in nature. However, it is known that curved rupture lines result in lower uplift resistance than that based on linear rupture lines (Meyerhof and Adams, 1968; Subba Rao and Kumar, 1994). The true uplift resistance will be lower than the solution provided in this article.
3. The soil has been assumed to follow an associated flow rule. For non-associated flow rule material, the uplift resistance will be lower than that presented in this article (Drescher and Detournay, 1993).
4. The paper discusses only the estimation of the ultimate resistance. It does not provide any information to find the amount of the anchor deformation required to fully mobilize the ultimate uplift resistance. However, it is known that strain levels in the dense sand required to attain the peak shear resistance are often smaller than that prevail for loose sands. Therefore, if the anchor is buried in a dense sand layer with an overlay of loose sandy material, it is expected that the magnitude of the anchor deformation under the working load will remain comparatively smaller. Therefore, in order to achieve not only a higher ultimate uplift resistance but also to restrict the anchor movements under working load conditions, it will be advantageous to compact the sufficient fill material just above the anchor before adding the remaining soil overburden. If the anchor is buried in a dense sand layer, then the nature of the failure will be most likely progressive (not sudden) since dense sand, after attaining the peak shear resistance, generally gradually softens (during drained test) at large strain levels.
5. Since the rupture surfaces have been assumed to reach the ground surface, the theory will be applicable only for shallow anchors, whereas for deep anchors, the theory will provide an overestimation of the uplift resistance.
6. The principle of superposition has been assumed to be valid. Computations have revealed that the geometry of the critical collapse mechanism remains unchanged even if the solution is directly determined with $q \neq 0, \gamma \neq 0$ rather than obtaining independently for two cases with (a) $q = 0, \gamma \neq 0$, and (b) $q \neq 0$ and $\gamma = 0$. Consequently, the principle of superposition has been found to result in no error at all.

CONCLUSIONS
The vertical uplift resistance of shallow strip and circular plate anchors placed horizontally in a two layered sand has been determined. For the critical collapse mechanism, the entire soil wedge lying above the anchor has been found to move as a single rigid block with the same velocity as that of the anchor itself. The component of the uplift resistance due to soil unit weight for anchors embedded in dense sand underlying loose sandy layer has been found to be more than that for the anchors in loose sand underlying dense sandy strata; the difference is quite significant especially for the case when the two layers have almost equal thickness. However, the surcharge component has been found to remain unaffected by the relative positions of the layers. Uplift factors for circular anchors have been found to be much higher than for strip anchors. As compared to the existing experimental results, the theory has been found to provide a little overestimation of the uplift resistance, especially for higher embedment ratios.

REFERENCES