RESPONSE OF ANCHOR IN TWO-PHASE MATERIAL UNDER UPLIFT

K. Ilamparuthi  
Professor and Head, Division of Soil Mechanics and Foundation Engineering, Anna University, Chennai–25, India.  
E-mail: kannilam@gmail.com

V. Shreni  
P.G. Student, Division of Soil Mechanics and Foundation Engineering, Anna University, Chennai–25, India.  
E-mail: shrenishreedhar@gmail.com

ABSTRACT: Anchors are foundation systems used to withstand uplift forces acting on to the foundations of structures constructed both in land and offshore. Numerous methods were developed to design anchors embedded in varieties of deposits. In most of the existing methods, the two-phase response of soil is not represented adequately. Moreover, contribution to anchor capacity through suction and influence of upward seepage flow are not quantified particularly for anchors embedded in submerged sand. In order to bring out the effect of two-phase material on load-displacement response and ultimate pullout capacity, an attempt is made in this research to analyse the anchor using the finite element code PLAXIS. Depth of embedment, relative compactness of sand and seepage velocity are the variables considered in the study. Finite element analyses showed distinctly two different responses namely shallow and deep anchor behaviour. Load-displacement curves are interpreted to arrive at the ultimate pullout load and thus the breakout factors which are in good agreement with the experimental results reported in literature. Suction contribution is marginal in sand, being equal to 5% in dense sand and 12% in loose sand at H/D = 1. Upward seepage is found to reduce the ultimate pullout capacity.

1. INTRODUCTION

Structures are subjected to uplift forces originating from sources such as wind load or wave action. A common method to obtain the required stabilizing force is to bury an anchor in soil that is fixed to the structure through a tie rod. Installation of these buried anchors normally involves excavation and backfilling. The anchors transmit uplift forces directly from the anchored structure to the soil, through mobilization of uplift resistance provided by the soil cover. Types of structures in which anchors are used include transmission towers and earth retaining structures which are supported directly by soil anchors. More recently, anchors are being used to provide simple and economical mooring system for offshore floating oil and gas facilities which are subjected to large magnitudes of tensile forces coupled with fluctuating loads which become significant during storms. A wide variety of anchor systems have been developed in order to satisfy the increase in demand for foundations to resist pullout loads. Due to their wide applications, evaluation of uplift capacity of anchors has become increasingly significant over the years. Many researchers have worked on the anchor uplift problem in the past years. Experimental, numerical and studies involving both experimental and numerical analyses were done. Rowe & Davis (1982) studied the uplift behaviour of anchors in clay and sand with an elasto-plastic finite element analysis using soil structure interaction theory. Tagaya et al. (1983) analysed the pullout resistance of a buried anchor using a finite element analysis program based on Lade’s constitutive equation. Merifield et al. (2006) applied three dimensional numerical limit analysis and axisymmetrical displacement finite element analysis to evaluate the effect of anchor shape on the pullout capacity of horizontal anchors in sand. More recently, Dickin & Laman (2007) carried out finite element analysis of the anchor uplift problem using the commercially available finite element code PLAXIS wherein strip anchors embedded in dry loose and dense sand beds were analysed using the Hardening Soil Model.

In this paper, response of a circular anchor under uplift in a two-phase soil is done using the PLAXIS finite element code. Circular anchor of 100 mm diameter embedded in sand of loose, medium dense and dense states is analysed for dry as well as submerged condition. Density of sand bed, depth of embedment, upward seepage velocities etc. are the parameters considered in this study.

2. NUMERICAL ANALYSIS

Soils tend to behave in a highly nonlinear way under load and their behaviour can be modelled at several levels of sophistication. In this study, the well known Mohr-Coulomb model is selected to represent the soil behaviour. This model involves five basic parameters namely, Young’s modulus E, Poisson’s ratio vs. friction angle φ, dilatancy angle ψ and cohesion c. The input parameters used in the analysis are shown in Table 1.
Table 1: Input Parameters for Analysis in Sand

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Loose sand</th>
<th>Medium dense sand</th>
<th>Dense sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$ (kN/m²)</td>
<td>12000</td>
<td>36000</td>
<td>45000</td>
</tr>
<tr>
<td>$\nu$</td>
<td>0.35</td>
<td>0.35</td>
<td>0.35</td>
</tr>
<tr>
<td>$\phi$</td>
<td>33.5°</td>
<td>38.5°</td>
<td>43°</td>
</tr>
<tr>
<td>$\psi$</td>
<td>1°</td>
<td>8°</td>
<td>13°</td>
</tr>
<tr>
<td>$\gamma$ (kN/m³)</td>
<td>15.5</td>
<td>16.5</td>
<td>17</td>
</tr>
</tbody>
</table>

The anchor is modelled as a plate element. Plates in the 2D finite element model are comprised of beam elements with three degrees of freedom per node, two translational degrees of freedom and one rotational degree of freedom. In all the analyses done, the boundary conditions are simulated by the standard fixities option available in PLAXIS. On selecting this option, PLAXIS automatically imposes a set of boundary conditions to the geometry model. Vertical geometry lines for which the $x$ coordinate is equal to the lowest or highest $x$-coordinate in the model obtain a horizontal fixity ($u_x = 0$). Horizontal geometry lines for which the $y$-coordinate is equal to the lowest $y$-coordinate in the model obtain a full fixity ($u_x = u_y = 0$). Typical numerical model adopted in the study with meshing of the continuum is shown in Figure 1. The vertical extent of mesh refinement given above the anchor equals the diameter of the anchor. For problems with upward seepage flow, a totally fine mesh is used since flow in every soil element is significant.

Mechanisms of failure for different cases, load-displacement relationship and effect of submergence, effect of suction pressure and effect of upward seepage flow on uplift capacity are described in the following sections.

2.1 Mechanisms of Failure

PLAXIS finite element analysis on anchors in sand showed distinctly two different responses which are functions of the depth of embedment for a given density. In case of shallow embedded anchor, the failure mechanism reached the soil surface whereas in case of anchor embedded at deeper depth, the rupture zone is confined within the deposit and around the anchor. Typical displacement contours for a shallow anchor ($H/D = 3$) and a deep anchor ($H/D = 9$) are shown in Figures 2 and 3 respectively in loose sand. From Figure 2, it can be seen that the failure mechanism is extending to the surface in case of a shallow anchor ($H/D = 3$). Distance from the centre of the anchor to the farthest point where the failure pattern touches the soil surface is equal to 1.3 times the anchor diameter for the embedment ratio of 3 in loose sand.

In case of an anchor embedded (Fig. 3) at an embedment ratio of 9 in sand, it can be seen that the failure mechanism is confined around the anchor and within the deposit. It extends to a height equal to 2.6 times the diameter of the anchor above the anchor. This observation is the same irrespective of the soil density. Only difference will be in the critical embedment ratio where the anchor changes its behaviour from shallow to deep. These responses are in conformity with the findings of earlier researchers (Ghaly et al., 1991; Ilamparuthi & Muthukrishnaiah, 1999 etc.).
2.2 Load-Displacement Behaviour

Typical load-displacement behaviour for anchors in sand is shown in Figure 4. The shape of the load-displacement curves show that the load increases gradually with displacement. The rate of increase of load decreases with displacement irrespective of the depth of embedment. In general, the shape of the load-displacement curve is the same irrespective of the depth of embedment and density of sand. Since the load-displacement curve does not indicate any clear peak, the ultimate pullout load and the corresponding displacement were obtained by the method of tangent intersection.

![Figure 4: Typical Load-displacement Behaviour of Anchors in Dense Sand ($\phi = 43^\circ$)](image)

The ultimate pullout load and thus the breakout factor increased with increase in depth of embedment and soil density. The rate of increase in ultimate pullout load increases with embedment ratio. For a given depth of embedment, ultimate pullout load is the highest for dense sand. The effect of density on ultimate pullout load is less significant at shallow embedments and it becomes pronounced at higher depths of embedment (Fig. 5).

![Figure 5: Variation of Peak Pullout Load with Embedment Ratio in Dry Sand](image)

2.3 Effect of Submergence

Effect of submergence was studied by making the sand bed submerged under a 300 mm water column above the surface of sand bed. For any given depth of embedment and soil density, ultimate pullout load in submerged sand is less than that in dry sand. Effect of submergence on ultimate pullout load is shown in Figure 6 for loose sand. It is noted from the figure that the effect of submergence becomes pronounced only after an embedment ratio of 3. The difference in pullout load between dry and submerged cases is low for shallow embedded anchors. This may be attributed to the suction effect in sand at shallow embedments. The difference is larger at deeper depths of embedment, which is mainly due to the difference in unit weights between dry and submerged sands.

![Figure 6: Effect of Submergence on Ultimate Pullout Load for Loose Sand ($\phi = 33.5^\circ$)](image)

2.4 Effect of Suction

To understand the suction contribution to uplift capacity, analysis of anchor in submerged sand was carried out by selecting the undrained analysis option in PLAXIS. Once it is selected, the capacity including suction contribution is obtained. Elimination of suction was done by venting the anchor base. Suction force is defined as the difference in capacities between the cases in which the anchor base is not vented and vented. Suction contribution is found to be marginal in sand. However its contribution to anchor capacity is higher in loose sand when compared to dense sand. Suction force is represented as a non-dimensional parameter called force ratio. It is the ratio of the suction force to the ultimate pullout load. Variation of force ratio with embedment ratio is shown in Figure 7 for loose and dense sands. In loose sand, suction contribution is 12% whereas in dense sand, it is 5% at $H/D = 1$.

![Figure 7: Variation of Force Ratio with Embedment Ratio](image)

2.5 Effect of Upward Seepage

Upward seepage flow reduces the ultimate pullout capacity of anchor irrespective of the depth of embedment and density of soil. The percentage reduction in uplift capacity increases with increase in seepage velocity. The maximum reduction in ultimate pullout load was 23% for a velocity of $15.4 \times 10^{-3}$ m/s. The variation in ultimate pullout load with seepage velocity for a circular anchor embedded in dense sand is shown in Figure 8.

![Figure 8: Variation of Ultimate Pullout Load with Seepage Velocity](image)
2.6 Comparison with Experimental Results

Results of uplift response of circular anchor in sand are validated against experimental results from Ilamparuthi (1991). A comparison of breakout factors obtained from PLAXIS analyses as well as experimental study for a circular anchor embedded in loose sand in dry condition is shown in Figure 9. The comparison reveals good agreement between experimental and PLAXIS breakout factors for all depths of embedment.

3. CONCLUSIONS

PLAXIS analyses clearly demarcates between shallow and deep anchor behaviour. In case of shallow anchor, the failure mechanism reaches the surface whereas in case of deep anchor, it is confined around the anchor as reported by Ilamparuthi & Muthukrishnaiah (1999) and Ghaly et al. (1991) through their experimental investigation.

In case of submerged sand, shapes of the load-displacement curve as well as the mechanisms of failure are the same as dry sand. For a given depth of embedment and density, ultimate pullout load is lower in case of submerged sand than that of dry sand. Suction contribution to uplift capacity is marginal in sand. In case of loose sand, the suction contribution is 12% at H/D = 1, whereas for dense sand it is 5% for the same embedment ratio.

In submerged sand, upward seepage reduced the pullout load of anchor. The reduction in pullout load is proportional to the velocity of flow and the maximum reduction is 23% for velocity of $15.4 \times 10^{-5}$ m/s.

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REFERENCES


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