INFLUENCE OF PHREATIC SURFACE ON THE ULTIMATE PULLOUT RESISTANCE OF VERTICAL ANCHOR PLATE BY FEM

S. Sakib¹ and M. S. Islam²

ABSTRACT

Vertical anchors embedded in soil are structural components used for stabilization of various foundation systems. Due to the complex behavior of surrounding soil, the design of such anchors becomes an arduous task. The fluctuation of phreatic surface adds to the complexity of the design process. In this paper the influence of rising phreatic surface on the pullout resistance of anchor plate was analyzed using finite element method (FEM) in PLAXIS 3D. From the analysis it was observed that when the phreatic level lies just beneath the anchor plate it has no influence on the pullout resistance. However, as the phreatic level rises upwards, ultimate pullout resistance is reduced and when phreatic surface merges with the ground surface ultimate pullout resistance is reduced by almost 50%. This reduction is similar for cohesionless soils with different frictional angles. Such behavior is different from effect of phreatic level on bearing capacity of isolated footing, where the effect is observed when phreatic level lies within a depth equal to twice the width of the foundation beneath the foundation. Sudden reduction of pullout capacity may lead to catastrophic failures such as failure of retaining walls and result in collapse of adjoining structures. While designing vertical anchor plates for those regions, phreatic level must be taken into consideration along with other governing factors.

Introduction

In a riverine country like Bangladesh the fluctuation of the phreatic surface pose a huge threat to the stability of riverside structures. Besides due to unplanned urbanization and pressure of overpopulation numerous structures are built on reclaimed lands. During monsoon heavy rainfall and frequent flooding causes the phreatic level to rise, reducing the soil strength and undermining the foundations of different structures. Earth anchor is one such foundation system, which gives stability to civil engineering structures by resisting pullout forces. Compared to other foundation systems, earth anchors provide an efficient and economic design solution. These earth anchors such as vertical plate anchors are typically attached with the retaining structures and embedded in the soil to sufficient depth so that they resist pullout forces with safety. They derive their resisting force from the passive pressure of the surrounding soil mass. The ultimate pullout resistance of vertical anchor plate depends on few factors including but not limited to anchor embedment depth (H) to anchor height (B) ratio or embedment depth ratio (H/B), anchor length (L) to height (B) ratio or aspect ratio, (L/B), shear strength parameters of the soil (soil friction angle, φ and cohesion, c) and angle of friction at the anchor-soil interface, δ. These terms are illustrated in Figure 1. Study of the existing literature shows that researchers have focused on determining the capacity of vertical anchors especially for anchor plate. (Hueckel 1957; Ovesen and Stromann, 1972; Neely et al., 1973; Akinmusuru, 1978; Ghaly, 1997; Shahriar, 2018). Furthermore, the works by Bowles (1997), Naser (2006), and Jadid et al. (2018) focused on block anchors. Past researchers favored analytical models to practical models for designing of anchors. The huge cost and labor required for field testing made those unpopular. Numerical analysis was a far better alternative and in the field of anchor design it was found to be pioneered by Rowe and Davis (1982). They assumed the sand to have a Mohr-Coulomb failure criterion and assessed the initial stress state, anchor plate roughness, effect of anchor plate embedment, friction angle and dilatancy for vertical anchor plates. Koutsabeloulis and Griffiths (1989) investigated the trap door problem by the initial stress finite element method. Both plane strain and axisymmetric works were conducted. Upper and lower bound limit analysis techniques have been used by Murray and Geddes (1987, 1989) and Basudhar and Singh (1994) to estimate the capacity of vertical strip anchor plates. Merifield et al. (2006) presented the results of a rigorous numerical work to estimate the ultimate capacity load for vertical anchor plate in cohesionless material. Rigorous bounds have been obtained using two numerical procedures that are based on finite element method of the upper and lower bound of limit analysis.

Although there are much study on the pullout capacity of various anchors in dry soil, the same cannot be

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found for anchors in saturated soils. For designing earth anchors fluctuating phreatic level must be taken into consideration. Ganesh and Sahoo (2017) investigated the vertical pullout capacity of plate anchors with fluctuating ground water conditions. They employed an analytical model and presented the results in the form of non-dimensional uplift capacity factor $F_{\gamma w}$. They showed that for various embedment depth ratio ($H/B$) and soil friction angle ($\phi$) values, as the depth of phreatic surface ($H_w$) rises uplift capacity factor $F_{\gamma w}$ decreases. The phreatic surface has no influence on the anchor capacity when it is just beneath the anchor bottom or lower. No further literature is found on the influence of fluctuating phreatic surface on vertical plate anchors. In the current research a finite element analysis was carried out to verify the impact of phreatic surface on the pullout capacity of horizontally loaded vertical anchor plates. The plate anchors are assumed to be embedded in cohesionless soil. The phreatic surface will be placed at different positions beneath the ground surface to observe its effect. The adoption of finite element analysis provides us with the opportunity to study a wide range of circumstances and reinforce our design concept.

**Methodology**

In this paper, the finite element analysis was done by using PLAXIS 3D. A vertical anchor plate which was modelled with 6 nodded plate element was placed inside a cohesionless soil bed at a certain depth. The boundaries of the soil bed were placed far away from the anchor, so that it does not affect anchor’s resistance. The phreatic surface was varied by changing the head in the design borehole. Respective mechanical properties were assigned to the elements of the model. Refer to Table 1 for soil and anchor properties adopted during finite element (FE) modeling. The soil was assumed to follow Mohr - Coulomb failure criterion. To replicate the effect of pullout load, a horizontal point load was applied at the centre of mass of the anchor plate. The process was repeated for a number of embedment depth ratios and phreatic levels ($H_w$) and the corresponding load vs. displacement data was recorded. The point of anchor plate failure was determined with the instructions provided by Neely et. al (1973).

![Figure 1. Problem definition; (H - embedment depth; H_w - position of phreatic surface; B - height of the anchor plate; L - length of the anchor plate; P_u = ultimate pullout load)](image)

<table>
<thead>
<tr>
<th>Properties of Soil</th>
<th>Properties of Anchor Plate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unsaturated Unit Wt. ($\gamma$)</td>
<td>16 kN/m$^3$</td>
</tr>
<tr>
<td>Saturated Unit Wt. ($\gamma_{sat}$)</td>
<td>18 kN/m$^3$</td>
</tr>
<tr>
<td>Poisson’s ratio ($\nu$)</td>
<td>0.2</td>
</tr>
<tr>
<td>Interface reduction factor ($R_{int}$)</td>
<td>0.5</td>
</tr>
<tr>
<td>Frictional angle ($\phi$)</td>
<td>35°</td>
</tr>
<tr>
<td>Dilatancy angle ($\psi$)</td>
<td>5°</td>
</tr>
<tr>
<td>Cohesion ($c$)</td>
<td>0.01 kN/m$^2$</td>
</tr>
<tr>
<td>Length ($L$)</td>
<td>0.5 m</td>
</tr>
<tr>
<td>Height ($B$)</td>
<td>0.5 m</td>
</tr>
<tr>
<td>Thickness ($t$)</td>
<td>0.05 m</td>
</tr>
<tr>
<td>Poisson’s ratio ($\nu_p$)</td>
<td>0.3</td>
</tr>
<tr>
<td>Unit weight ($\gamma_p$)</td>
<td>78.5 kN/m$^3$</td>
</tr>
</tbody>
</table>

*Though the soil bed is formed of cohesionless soil, the cohesion is not 0 practically.*

**Table 1. Properties of soil and anchor plate used for the FE analysis.**
Results and Discussions

Validation of the Finite Element Model

Few researches have worked with FE modelling and employed it to solve geotechnical problems. Out of the few numerical studies, the study by Merifield and Sloan (2006) is the most comprehensive one. The result was presented with of dimensionless anchor breakout factor, \( N_\gamma = P_u / \gamma BH \). Their analysis showed that this factor increases with the increase of embedment depth ratio (\( H/B \)) of the anchor plate i.e. the pullout capacity of the anchor increases with the depth of embedment of the anchor from the ground surface. To validate the use of PLAXIS 3D for the analysis of anchor plate similar approach was taken. The results obtained from the current analysis is presented in dimensionless form and compared with Merifield and Sloan (2016) in Figure 3. Data from both sources are in close agreement for \( H/B \leq 8 \) which implies that PLAXIS 3D provides acceptable estimation within this range. The discrepancy at higher embedment depth may be caused by variation of roughness parameter used for the models. Sakib and Islam (2018) also showed the credibility of FE modelling comparing with experimental findings by Choudhary and Dash (2014).

Figure 2. Finite element model as viewed in PLAXIS 3D.

(a) Element contour of the soil bed, plate anchor (yellow) and phreatic surface (blue plane)  
(b) Section through the soil bed and anchor plate

Figure 3. Comparison of current analysis with previous numerical analysis.

Influence of fluctuating phreatic surface

To observe the influence of phreatic surface on the ultimate pullout capacity of vertical anchor plate, the phreatic surface was kept at different depths as shown in Figure 4 and anchor plate was loaded until failure. The process was repeated for several embedment depths. The analysis showed that the depth of the phreatic surface did not have any effect on the ultimate pullout capacity while it was kept below the bottom of the anchor plate for any embedment depth. The value was identical to the one obtained for phreatic surface at great depths. Since the soil mass just in front of the anchor was not saturated, it did not affect the ultimate
pullout capacity. The vertical anchor plate derives its resistance from the passive soil surface in front of it. Again when the phreatic surface was gradually raised, the ultimate pullout resistance started to decline for all embedment depths. As the unit weight of the soil is diminished by the influence of water, the soil surrounding the anchor loses its resisting capacity resulting in lower ultimate pullout resistance. When the phreatic surface reaches the ground surface the ultimate pullout resistance is almost 50% of the value obtained when the soil was dry. Using soil having different friction angle ($\phi$) values same analysis was carried out and the obtained results were identical. So it can be implied that the influence of the phreatic surface is not dependent on the friction angle ($\phi$) of the soil. At high embedment depths, a logarithmic spiral or a rotational failure mechanism is a more common occurrence (Neely et al. 1973) and as such some soil existing below the bottom of the anchor plate provides some passive resistance. The current analysis shows that its influence on ultimate pullout capacity is negligible.

**Use of correction factor for design purposes**

To account for this reduction, while designing vertical plate anchors a correction factor as presented in Figure. 5 can be utilized. The correction factor, $C_p$ can be found from the dimensionless normalized phreatic surface depth ($H_w/H$), which has to be multiplied with the ultimate pullout capacity of the anchor when the soil is in dry condition. The use of the correction factor is illustrated in a simple mathematical problem.

![Figure 4](https://example.com/fig4.png)

**Figure 4.** Different depths of phreatic surface (navy blue line) used for numerical analysis and relative displacements of surrounding soil mass at anchor plate (yellow rectangle) failure.

**Mathematical Example.** A vertical anchor plate of height 750 mm placed at a depth of 5 m fails at a pullout load of 1500 kN when the phreatic surface is at a great depth. What ultimate pullout capacity if the phreatic surface rises to a depth of 1.25 m?

**Solution.** Given, $H = 1$ m; $P_{u,dry} = 1500$ kN; $B = 750$ mm = 0.75 m; $H_w = 1.25$ m.

For $H_w/H = 1.25/5 = 0.25$, from Figure. 5 we get, $C_p = 0.74$.

Therefore, if the phreatic surface rises ultimate pullout capacity = $0.74 \times 1500 = 1110$ kN.

**Comparison with effect of phreatic surface on bearing capacity**

While designing an isolated footing the phreatic level is taken into consideration in two cases as shown in Figure. 6. For the case of vertical anchor plates a correction factor similar to $R_{w1}$ was used and its value was between 0.5 and 1 similar to the isolated footing foundation. However, no factor like $R_{w2}$ was required. From this it is revealed that, the pullout of the vertical anchor plates are not influenced by the phreatic surface in the same manner as shallow isolated footing. Though the failure surface of the vertical plate anchor and isolated footing has much similarity, the design principle for one cannot be match to other.
Figure 5. Correction factor for depth of phreatic surface.

(i) When the phreatic surface is below the base of the foundation at a distance ‘b’ the correction $R_{w_2}$

$$R_{w_2} = 0.5 + 0.5 \times (\frac{b}{B_f}) \leq 1$$

(ii) When the phreatic surface further rises above the base of the foundation the correction $R_{w_1}$

$$R_{w_1} = 1 - 0.5 \times (\frac{a}{D_f}) \leq 1$$

Figure 6. Influence of phreatic surface on the bearing capacity of isolated footing foundation. ( $D_f$ - depth of foundation; $B_f$ - width of the footing; $a$, $b$ - positions of phreatic surface from the bottom of footing )

Conclusions

In this paper to predict the effect of phreatic surface on the ultimate pullout resistance of vertical anchor plate finite element analysis was used. The model was checked with existing numerical results. From the analysis it was seen that the phreatic surface has profound effect on the ultimate pullout resistance when it lies above the bottom of the anchor and causes a maximum resistance reduction of 50% which is independent of the internal angle of friction of the soil. For designing anchors having possibility of going under the phreatic surface a correction factor was proposed. If the phreatic surface is beneath the anchor plate it has no effect on it and gives maximum ultimate pullout resistance. The research outcomes can be utilized for designing economic foundations for areas having problems with fluctuating phreatic levels and ensure safety from sudden catastrophic collapse.

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References


