ABSTRACT: Soil anchors are required to withstand uplift or lateral forces acting on the foundations of structures constructed both in land and offshore sites. Plate anchoring system is being increasingly used to moor floating structures for the exploration and development of oil and gas fields. In this study, various experimental, theoretical and numerical approaches for estimation of pullout capacity of horizontal and inclined plate anchors in clayey soils are reviewed. A comparative analysis of the ultimate capacity is then carried out for plate anchors embedded in clayey soils by varying embedment ratio for horizontal anchors and by varying inclination angle for inclined plate anchors.

Keywords: Plate anchors; vertical loading; inclined loading; pullout capacity.

1. Introduction

Several structures such as transmission towers, suspension bridges, submerged pipelines and floating offshore platforms involve generation of uplift forces. Earth-retaining walls and waterfront structures are subjected to horizontal forces. Conventional foundations are unable to take this type of loading, and soil anchoring systems are required to resist the pullout forces. They can be plate anchors, helical anchors, pile anchors, grouted anchors and drilled shafts. For the design of these anchoring systems, it is necessary to estimate the ultimate pullout capacity. Plate anchors are now widely used as a simple and economical mooring system for offshore floating facilities. The loading applied on plate anchors can be vertical, inclined or horizontal depending on the anchor orientation. They can be circular, square or strip in shape, and are usually made of steel plates or concrete slabs. As the range of applications for plate anchors increases, a greater understanding of the response to loading is essential. If the failure mechanism is not clear, both model and field tests are needed for the formulation of design procedures.

In the last four decades, a number of researchers have proposed different approaches to estimate the pullout load-deformation response of plate anchors of various shapes in clayey soils. They are based on model tests, on limit equilibrium analysis, or on rigorous numerical analysis. The capacity of plate anchors against pullout is obtained from a combination of soil weight above and shear resistance mobilized within a failure surface or a defined boundary in the soil mass. The effects of anchor shape, embedment depth, inclination, soil unit weight, and soil shear strength non-homogeneity on the pullout capacity have been investigated. The design of these anchors in clays is usually for undrained conditions. In this study, they are summarized in terms of the procedures and relationships for determining pullout capacity. The static ultimate pullout capacity for both horizontal and inclined plate anchors embedded in clayey soils is worked out by using the various approaches, and the computed results are presented and compared.
2. Pullout Capacity of Horizontal Plate Anchors

Meyerhof & Adams (1968) noticed that there is lack of agreement on uplift-capacity theories of foundations based on slip surface mainly due to the difficulty of predicting the geometry of the failure zone. Based on model tests, they proposed a semi-theoretical relationship for strip, circular & rectangular footings in sand and clay soils. They observed very distinct failure pattern in sandy soils, whereas the failure pattern was complicated in clayey soils due to the formation of tensile cracks. The theory is derived for a strip footing and is then modified for circular and rectangular footings and for group action. The same theory can be applied to plate anchors. The proposed relationship for ultimate pullout capacity of strip footings is:

\[ Q_u = 2cH + \gamma H^2 k_p \tan \delta + W \]  

where \( \delta = 0/2 \) to \( 20/3 \), \( k_p \) = coefficient of passive earth pressure, and \( W \) = weight of soil above the footing.

Vesic (1971) proposed an analytical approach for determining the pullout capacity of horizontal plate anchors based on the solutions for the problem of an expanding cavity close to the surface of a semi-infinite rigid plastic solid. These solutions gave the ultimate radial pressure needed for the breakout of a cylindrical or a spherical cavity embedded at a depth below the surface of the solid. The pullout capacities for strip and circular anchors were then assessed by assuming that the pullout load was equivalent to the ultimate cylindrical or spherical cavity pressure, plus the weight of soil acting directly above the anchors. The ultimate pullout capacity is given by:

\[ Q_u = A(\gamma H F_q + c F_c) \]

For circular and square anchors,

\[ F_c = 1.2 \left( \frac{H}{b} \right) \leq 9 \]

For strip anchors,

\[ F_c = 0.6 \left( \frac{H}{b} \right) \leq 8 \]

Das (1978) compiled a number of laboratory model test results on circular anchors embedded in saturated clay with undrained cohesion \( C_u \), varying from 5.18 kN/m² to 172.5 kN/m². He also reported some model test results conducted with square and rectangular anchors. Based on all the model test results, Das (1980) proposed an empirical procedure to obtain breakout factors for shallow and deep anchors. The expressions for ultimate pullout capacity are:

For deep anchors,

\[ Q_u = A \left( 7.56 + 1.44 \left( \frac{H}{b} \right) C_u + \gamma H \right) \]

For shallow anchors,

\[ Q_u = A \beta' \left( 7.56 + 1.44 \left( \frac{H}{b} \right) C_u + \gamma H \right) \]

where \( \beta' \) is a non-dimensional factor.

Rowe & Davis (1982) carried out an elasto-plastic finite element analysis of the undrained behaviour of anchor plates in homogeneous, isotropic saturated clay, so as to predict the behaviour of strip anchor plates buried to various depths, with both vertical and horizontal loading. Consideration was also given to the effect of anchor thickness and shape. The numerical solutions were obtained using a soil-structure interaction theory with the following considerations: plastic failure within the soil, anchor breakaway from the soil behind the anchor, and shear failure at a frictional dilatant soil-structure interface without the introduction of special joint or interface elements. The results were compared with the authors’ model tests and other available experimental data. The results were presented in the form of charts which can be used in hand calculations for determining design failure loads.

Saran et al. (1986) proposed an analytical procedure to predict the load-displacement characteristics of plate anchors in c-Ø soils using a non-linear constitutive relationship. Expressions were presented to obtain critical
loads and breakout loads for strip, square, and circular anchors. The validity of the proposed theory was established by comparing it with large field and laboratory data, and it was found to be valid for shallow anchors only. The change in behaviour between shallow and deep anchors is explained with the help of critical depth ratio, which varies with size and shape of anchor as well as soil parameters. In soft clays, the critical depth ratio for strip anchors is about 1.5 to 2 times that for circular/square anchors. The values are 3 for strip anchors and 1.75 for circular anchors. They proposed the following expression for ultimate pullout capacity:

\[
Q_u = A(cF_c + \gamma HF_r)
\]

where \( \theta \) = angle of internal friction of soil, and \( F_c \) & \( F_r \) = breakout factors dependent on depth to width ratio.

For strip anchors:

\[
F_c = H/B = 2\lambda
\]

\[
F_r = 1 + \lambda tan \theta
\]

For square and circular anchors:

\[
F_c = 4\lambda (1 + \lambda tan \theta)
\]

\[
F_r = 1 + 2\lambda tan \theta + \left( \frac{\lambda^2}{2} \right) tan \theta
\]

Rao & Kumar (1994) used the method of characteristics coupled with a log-spiral failure surface to develop a theory for vertical uplift capacity of shallow horizontal strip anchors in a general c-\( \theta \) soil. They adopted a methodology similar to that used in finding the bearing capacity of foundations under compression, and separated the effects of cohesion, surcharge, and density on the uplift capacity. The theory was shown to be capable of predicting accurately anchor pullout behaviour in clays and also in loose and medium-dense sands. The proposed equation for net ultimate pullout capacity per unit length of the strip anchor in clays is:

\[
Q_{u,net} = cF_c + qF_q + 0.5\gamma BF_r
\]

where \( c \) = cohesion of soil, \( \gamma \) = unit weight of soil, \( B \) = width of plate anchor, and \( F_c, F_q, F_r \) = uplift capacity factors which are functions of embedment ratio and soil friction angle.

Merifield et al. (2003) applied three-dimensional numerical limit analysis to evaluate the effect of anchor shape on the pullout capacity of horizontal anchors in undrained clay. The anchor was idealized as either square, circular, or rectangular in shape. Estimates of the ultimate pullout load were obtained by using a newly developed three-dimensional numerical procedure based on a finite-element formulation of the lower bound theorem of limit analysis. This formulation assumed a perfectly plastic soil model with a Tresca yield criterion. They presented results in the familiar form of breakout factors based on various anchor shapes and embedment depths, and also compared them with existing numerical and empirical solutions. They expressed the ultimate pullout of plate anchors as follows:

\[
Q_u = AcuN_c
\]

where \( N_c = N_{co} + \left( \frac{\gamma H}{c_u} \right) \)

\[
N_{co} = S \left[ 2.56 \log_e \left( \frac{2H}{B} \right) \right]
\]

and \( S \) = shape factor

Song et al. (2008) studied the behaviour of circular and strip plate anchors during vertical pullout, with fully attached and vented rear faces of anchors, in uniform and normally consolidated clays by means of small strain and large deformation finite element analyses. They proposed the following relation for vented strip plate anchors:

\[
Q_u = AcN_c
\]

where \( N_c = 8.6 + 2.2(H/B) \) for \( H/B \leq 1.4 \)

\[
N_c = 11.7 \quad \text{for} \quad H/B \geq 1.4
\]
Khatri & Kumar (2009) employed an axisymmetric static limit analysis formulation in combination with finite elements to obtain the vertical uplift resistance of circular plate anchors, embedded horizontally in a clayey stratum whose cohesion increases linearly with depth. The variation of the uplift factor with changes in the embedment ratio was computed for several rates of increases of soil cohesion with depth. It was noted that in all cases, the magnitude of the uplift factor increases continuously with depth up to a certain value of critical embedment ratio, beyond which it becomes essentially constant.

Wang et al. (2010) performed three-dimensional large deformation finite-element analyses to investigate plate anchor capacity during vertical pullout. Continuous pullout of plate anchors was simulated, and the large deformation results for strip, circular, and rectangular anchors were compared with model test data, small strain FE results, and plastic limit solutions. The effects of anchor roughness, aspect ratio, soil properties, and soil overburden pressure were investigated. It was found that the anchor roughness had minimal effect on anchor performance. The soil beneath the anchor base separates from the anchor at a certain embedment depth near the mudline, once tensile stresses were generated. The ratio of separation depth to anchor width was found to increase linearly with the ratio of soil undrained shear strength to the product of soil effective unit weight and anchor width, and was independent of the initial anchor embedment depth. They expressed the maximum uplift capacity of rectangular plate anchors as follows:

\[ Q_u = A_c u N_c \]  
\[ N_c = N_{co} + \left( \frac{\psi}{c_u} \right) \]  

where \( N_{co} \) = anchor capacity factor in weightless soil.

3. Pullout Capacity of Inclined Plate Anchors

Studies related to the pullout capacity of inclined plate anchors embedded in clay are limited. In the pullout of inclined plate anchors, the force is transmitted perpendicular to the anchor plane. Inclination angle is defined as the angle between the anchor plane and the horizontal. Das (1985) performed tests on square model plate anchors in saturated clay or nearly saturated clay soils. Based on the experimental results, he proposed the following relationship for ultimate pullout capacity:

\[ Q_u = A_{cu} F'_c + W \cos \psi \]  

where \( F'_c \) = average breakout factor, \( W \) = weight of soil located immediately above the anchor, \( \psi \) = anchor inclination with the horizontal.

Merifield et al. (2005) applied numerical limit analysis and displacement finite-element analysis to evaluate the stability of inclined strip anchors in undrained clay. Consideration was given to the effects of embedment depth and anchor inclination. The ultimate pullout capacity is expressed as:

\[ Q_u = A_{cu} N_c \]  
\[ N_c = N_{co} + \sqrt{\psi} \]  

\( N_{co} \) = breakout factor which takes care of inclination of plate anchor. Breakout factors based on various anchor geometries were presented in the form of charts to facilitate their use in solving practical design problems.

4. Comparison of Pullout Capacities

To carry out a comparative study of the magnitudes of ultimate pullout capacity of plate anchors embedded in clay obtained by using correlations of the above empirical, theoretical and numerical approaches, calculations have been made for a strip anchor of 2 m width and unit length. If the correlation is applicable only for a circular or square anchor, the equivalent area is taken into consideration. The embedment ratio of the horizontal strip anchor is varied from 2 to 10. The properties of the three clayey soil types used in the computations are presented in Table 1.
Table 1. Properties of clayey soils.

<table>
<thead>
<tr>
<th>Property</th>
<th>Soft Clay</th>
<th>Medium Clay</th>
<th>Stiff Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit weight (kN/m³)</td>
<td>15</td>
<td>18</td>
<td>21</td>
</tr>
<tr>
<td>Undrained cohesion (kN/m²)</td>
<td>12.5</td>
<td>25</td>
<td>50</td>
</tr>
<tr>
<td>Young’s modulus (kN/m²)</td>
<td>25,000</td>
<td>30,000</td>
<td>35,000</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.35</td>
<td>0.40</td>
<td>0.45</td>
</tr>
</tbody>
</table>

The variations of ultimate pullout capacity of the horizontal plate anchor with embedment depth, computed from the various approaches, are illustrated in Figs. 1 to 3 for the clayey soils of different strengths. The pullout capacity values in ascending order are presented in Tables 2 & 3 for shallow anchors and deep anchors, respectively. An embedment ratio of 4 has been considered for shallow anchors whereas a ratio of 10 has been taken for deep anchors.

![Fig. 1. Variation of ultimate capacity of horizontal plate anchors in soft clay.](image1)

![Fig. 2. Variation of ultimate capacity of horizontal plate anchors in medium clay.](image2)
Fig. 3. Variation of ultimate capacity of horizontal plate anchors in stiff clay.

Table 2. Ultimate pullout capacity of shallow plate anchors.

<table>
<thead>
<tr>
<th>Theory</th>
<th>Depth (m)</th>
<th>Soft Clay</th>
<th>Medium Clay</th>
<th>Stiff Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rao &amp; Kumar (1994)</td>
<td>8</td>
<td>82</td>
<td>120</td>
<td>195</td>
</tr>
<tr>
<td>Saran et al. (1986)</td>
<td>8</td>
<td>175</td>
<td>224</td>
<td>325</td>
</tr>
<tr>
<td>Khatri &amp; Kumar (2009)</td>
<td>8</td>
<td>250</td>
<td>500</td>
<td>1000</td>
</tr>
<tr>
<td>Merifield et al. (2003)</td>
<td>8</td>
<td>277</td>
<td>445</td>
<td>650</td>
</tr>
<tr>
<td>Das (1978)</td>
<td>8</td>
<td>280</td>
<td>324</td>
<td>381</td>
</tr>
<tr>
<td>Meyerhof (1973)</td>
<td>8</td>
<td>297</td>
<td>387</td>
<td>550</td>
</tr>
<tr>
<td>Meyerhof &amp; Adams (1968)</td>
<td>8</td>
<td>336</td>
<td>536</td>
<td>936</td>
</tr>
<tr>
<td>Vesic (1971)</td>
<td>8</td>
<td>345</td>
<td>593</td>
<td>1067</td>
</tr>
<tr>
<td>Wang et al. (2010)</td>
<td>8</td>
<td>390</td>
<td>588</td>
<td>936</td>
</tr>
<tr>
<td>Song et al. (2008)</td>
<td>8</td>
<td>435</td>
<td>870</td>
<td>1740</td>
</tr>
<tr>
<td>Rowe &amp; Davis (1982)</td>
<td>8</td>
<td>930</td>
<td>1476</td>
<td>2472</td>
</tr>
</tbody>
</table>

Table 3. Ultimate pullout capacity of deep plate anchors.

<table>
<thead>
<tr>
<th>Theory</th>
<th>Depth (m)</th>
<th>Soft Clay</th>
<th>Medium Clay</th>
<th>Stiff Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rao &amp; Kumar (1994)</td>
<td>20</td>
<td>102</td>
<td>157</td>
<td>270</td>
</tr>
<tr>
<td>Khatri &amp; Kumar (2009)</td>
<td>20</td>
<td>280</td>
<td>560</td>
<td>1120</td>
</tr>
<tr>
<td>Saran et al. (1986)</td>
<td>20</td>
<td>452</td>
<td>577</td>
<td>827</td>
</tr>
<tr>
<td>Merifield et al. (2003)</td>
<td>20</td>
<td>580</td>
<td>863</td>
<td>1126</td>
</tr>
<tr>
<td>Meyerhof (1973)</td>
<td>20</td>
<td>605</td>
<td>794</td>
<td>1140</td>
</tr>
<tr>
<td>Das (1978)</td>
<td>20</td>
<td>690</td>
<td>810</td>
<td>912</td>
</tr>
<tr>
<td>Song et al. (2008)</td>
<td>20</td>
<td>765</td>
<td>1530</td>
<td>3060</td>
</tr>
<tr>
<td>Wang et al. (2010)</td>
<td>20</td>
<td>800</td>
<td>1120</td>
<td>1640</td>
</tr>
<tr>
<td>Meyerhof &amp; Adams (1968)</td>
<td>20</td>
<td>905</td>
<td>1404</td>
<td>2404</td>
</tr>
<tr>
<td>Rowe &amp; Davis (1982)</td>
<td>20</td>
<td>4475</td>
<td>6550</td>
<td>10100</td>
</tr>
</tbody>
</table>
From a comparison of the predicted horizontal anchor capacities, it is observed that the approach proposed by Rao & Kumar (1994) gives the lowest values, whereas the method of Rowe & Davis (1982) provides the highest values. The uplift capacities in soft clay are ranging from 82 kN to 930 kN for shallow anchors and from 102 kN to 4475 kN for deep anchors, respectively. There are differing assumptions in the various approaches as to the shape of the failure surface or the form of failure. The theories are not directly comparable since each includes different parameters in its solution. The soil compressibility, soil permeability, and loading rate are other variables. The actual magnitude of any adhesion or suction force beneath the anchor is also highly uncertain.

For inclined anchor analysis, the same strip plate anchor is now placed at 6 m depth with the embedment ratio fixed at 3. The inclination angle with the horizontal is varied from 0° to 90°. The direction of pullout is perpendicular to the anchor face. The variations of ultimate pullout capacity of the inclined plate anchor are depicted in Figs. 4 to 6 for different strengths of the clayey soil. The approach of Das (1985) predicts higher values than those provided by the method of Merifield et al. (2005).

Fig. 4. Variation of ultimate capacity of inclined plate anchors in soft clay.

Fig. 5. Variation of ultimate capacity of inclined plate anchors in medium clay.
5. Conclusions

Procedures and correlations from different approaches found in literature for determining ultimate pullout capacity of plate anchors have been reviewed. Most studies have been concerned with either vertical or horizontal pullout loading, and the effect of anchor inclination has received little attention. In clayey soils, the failure surface is complicated due to the development of tensile stresses. The ultimate pullout capacities obtained from these methods have been compared by using common soil data of different strengths, and by varying the embedment ratio or the inclination angle. The difference in the pullout capacities between shallow and deep anchors has been examined. The ultimate capacity is a function of the undrained shear strength of the soil. In several applications, the anchors are to be placed at inclined orientations depending on the type of loading. In the sea environment, inclined anchors will be more suitable for floating structures. It is recommended that the anchors be installed deeply so that inaccuracy in the embedded depth does not substantially affect the designed ultimate capacity.

References