NUMERICAL ANALYSIS OF VERTICAL UPLIFT RESISTANCE OF HORIZONTAL STRIP ANCHOR EMBEDDED IN COHESIVE–FRICTIONAL WEIGHTLESS SOIL

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ABSTRACT
With an application of the finite element analysis, the vertical pullout capacity of a horizontal strip plate anchor placed in a cohesive-frictional (c-ϕ) soil has been computed. The variation of the uplift factors N_c , N_q and N_γ, due to the contributions of soil cohesion, surcharge pressure and unit weight, respectively, has been evaluated for different friction angles (ϕ) and embedment ratios (*H/B*). These break-out factors increase continuously with the increase of embedment ratios. The variation of N_q and N_γ has found almost linear and N_c varies nonlinearly with the friction angle.

Keywords: Anchor; numerical analysis; uplift capacity; finite element analysis

INTRODUCTION
Plate anchors are light structural members employed to withstand uplift forces for conditions, where immediate breakaway occurs. Plate anchors are commonly used in transmission tower, sheet piles, retaining wall, deep water offshore developments, and airport hangars. (Hanna et al. 2014; Merifield and Smith 2010; Sahoo and Kumar 2012a; Sutherland et al. 1983). During the last 50 years, numerous experimental and numerical investigations have been conducted by several researchers to evaluate the pullout capacity of plate anchor. Experimental studies include (i) conventional 1-g laboratory model tests (Das and Seeley 1975; Neely et. al. 1973; Ranjan and Kaushal 1977; Rokonuzzaman and Sakai 2012) and (ii) centrifuge model tests (Dickin and Laman 2007). While, numerical study consists of (i) lower bound limit analysis (Merifield et al. 2006; Meyerhof 1973), (ii) upper bound limit analysis (Kouzer and Kumar 2009; Merifield and Sloan 2006; Sahoo and Kumar 2012a), (iii) method of characteristic (Kumar and Rao 2004; Neely et al. 1973) and (iv) Finite element method (Kumar and Kouzer 2008; Merifield et al. 2006; Murray and Geddes 1987; Rowe and Davis 1982; Sahoo and Kumar 2012b).The pullout capacity of soil anchors are mainly influenced by anchor geometry, embedded ratio, soil-anchor interfaces and local soil conditions. Several researchers have investigated the effect of anchor geometry on the pullout capacity of plate anchor and recommended shape factors for the design engineers (Hanna and Ranjan 1992; Hanna et al. 2011). Kumar and Kouzer (2008) studied the effect of embedment ratio and frictional angle on the pullout capacity of plate anchor in sand and found that the uplift capacity increases with the increases with the increase in the embedment ratio and the frictional angle. Furthermore, plate anchor could be installed vertically and horizontally as per the requirements. Horizontal anchors are generally used to resist vertical uplift forces for the foundations of structures such as transmission towers, pipelines buried under water, and dry docks (Deshmukh et al. 2011; Kumar and Kouzer 2008; Merifield and Sloan 2006; Merifield et al. 2001). Moreover, it is noted from the literature that most of the study are conducted to evaluate the pullout capacity factor in either dry sand (c=0) or saturated clay (ϕ=0). According to the author's knowledge, limited information is available in the literatures that estimate the pullout capacity of plate anchor in c-φ soil. Although, Kumar and Naskar 2012 studied on the vertical uplift capacity of a group of two axial anchors in a c-φ soil using the lower bound finite element limit analysis and showed the variation of the uplift capacity factors, N_c and N_γ, with the change in embedment ratio and vertical spacing.

In this study, an extensive elasto-plastic finite element analysis has been performed to investigate the pullout behavior of horizontal plate anchor in frictional cohesive soil (c-φ soil). In order to investigate the effect of embedment ratio on the pullout capacity, anchor plates were buried at different embedment ratio. Furthermore, the effect of frictional angle of soil on the pullout capacity factors N_c, N_q and N_γ, due to the components of cohesion, surcharge pressure and soil weight, respectively are also investigated. The results have been compared with the existing results reported in the literature and design charts have been proposed for predicting the pullout capacity of anchor plates

PROBLEM DEFINITION

A typical layout of a strip plate anchor having width *B* and thickness *t* is shown in Figure 1. The anchor plate is considered perfectly rigid and embedded in a cohesive-frictional (c-ϕ) medium. The ground surface is horizontal and a uniform surcharge of q= 18 kN/m^2 is applied on the top surface. The anchor plate is embedded at a depth of H from the ground surface, which is varied through a wide range of embedment ratio (H/B=1 to 10). The collapse load (q_u) per unit length of the plate anchor is computed for the immediate breakaway (vented) of the anchor plate i.e. anchor interface separates immediately upon pullout action. The uplift capacity factors N_c, N_q and N_γ are calculated by assuming the principle of superposition using equation (1).

$$q_u = cN_c + qN_q + BH\gamma N_\gamma \quad (1)$$

The bearing capacity factor N_c, N_q and N_γ have been computed separately by taking, (i) $c \neq 0$, but q=0 and γ=0, (ii) c=0, but $q\neq0$ and γ=0 and (iii) c=0, but q=0 and $\gamma\neq0$, which signifies the validation of the principle of superposition.

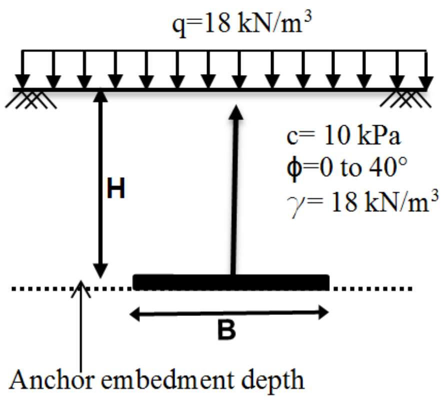

Fig. 1. Definition of the problem

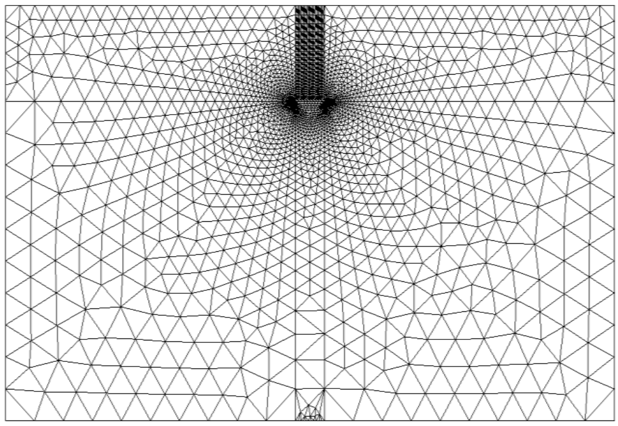
Fig. 2. FE mesh (H/B=3 , B=1m)

FINITE-ELEMENT MODEL

An extensive elaso-plastic finite element (FE) analysis was conducted using ABAQUS to determine the ultimate pullout load of strip anchor in c- ϕ soil. The present numerical analysis are carried out on isotropic and homogeneous soil with associative Mohr-Coulomb yield criterion and is defined by the cohesion value c, angle of internal friction ϕ, and dilatancy angle ψ. In this study, a strip rigid plate is made contact with the soil domain, which is displaced progressively along the pullout direction. The interfaces between the anchor plate and soil domains are defined as (i) tangential behavior and (ii) normal behavior. In tangential behavior, a penalty friction formulation is used with a friction coefficient of 0.4, while in normal behavior hard contact is defined for pressure overclosure. Separation after contact is also allowed. The FE analyses are based on six-noded modified triangular elements. Figure 2 presents a typical two-dimensional finite-element mesh for a strip plate anchor embedded at H/B=3 and B=1m. The analyses assume a perfectly rigid plate anchor, with incremental displacement being prescribed on the anchor nodes in contact with the soil. The dimensions of soil domain are selected in such a way that the stress and displacement gradients at boundaries would decrease and become zero. The soil domain is extended to 10*B* in horizontal directions from the edge of the anchor for the embedment ratio (*H/B*) 1 to 9. However, it is not sufficient for the *H/B*=10 and therefore, the soil domain is extended to 20*B*. This extension of soil boundaries is sufficient for the computation of N_c, but it is proved insufficient for determination of N_q and $N_{\gamma,}$ especially when the rotation of anchor is greater than 67.5 degree. Thus, the soil domain is extended to 20B in horizontal directions for embedment ratio 6 and 8, and 30B for 10. However, the vertical boundaries are remaining 10B from the bottom of the anchor for all cases. Zero-displacement boundary conditions are applied to prevent out-of-plane displacements of the vertical boundaries and the base of the mesh is fixed in all three coordinate directions. To obtain more accurate results, elements are kept very small near the plate, increasing gradually in size and moving away from the plate. To determine the collapse load of the footing, displacement based analyses are performed. The total displacement is applied over a number of sub-steps and the uplift pressure is then calculated by summing the nodal forces along the pullout direction divided by the footing area.

RESULTS AND DISCUSSIONS

The validity of the numerical results for the horizontal anchor is established through verification against published results before conducting the detailed parametric study. The designed FE model is validated for the pullout capacity factor N_c of a strip anchor in weightless soil (γ=0). It can be seen in Figure 3 that N_c for horizontal anchor agrees well with the numerical solution obtained by Yu et al. (2011) and Merifield et al. (2001). N_c values for horizontal are closer with the upper bound solution up to a embedment ratio of 3 then deviates and maximum differences are found 6.6% for horizontal anchor. Note that, the current FE results, Yu et al. (2011), Merifield et al. (2001) and Rowe & Davis (1982a) stay close together for shallow embedment ratio (H/B=2). FE result of Rowe & Davis (1982a) shows lower values and almost constant at large embedment ratio (H/B>3). These differences may be due to truncation criterion, where the pullout capacity was taken at a displacement as 15-20 % of anchor width rather than the ultimate capacity for large embedment ratio.

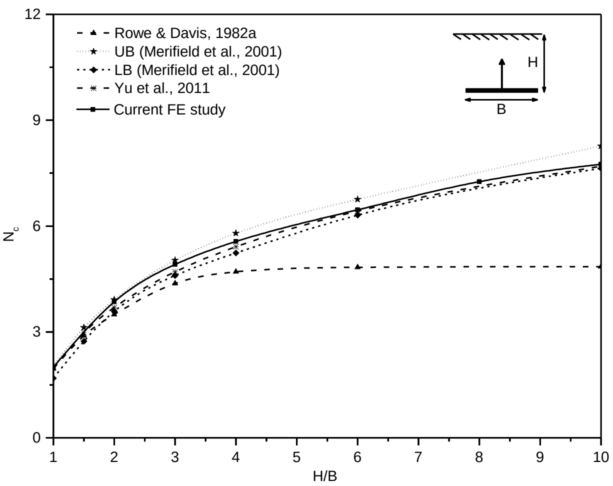

Fig. 3. Comparison of the bearing capacity factor Nc for plate anchors in weightless uniform soil

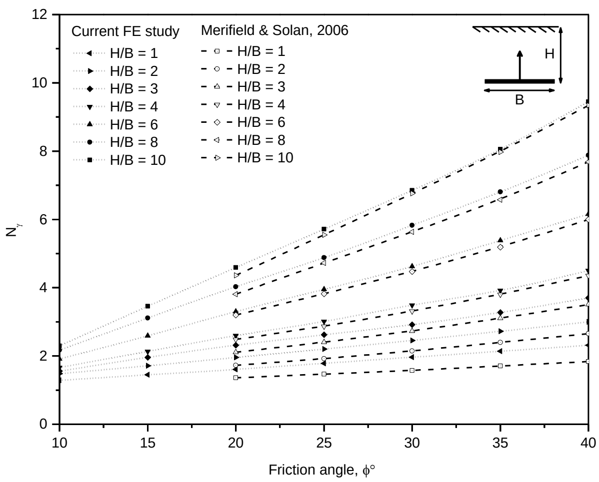

Fig. 4. Effect of friction angles, ϕ on Nγ at different embedment depth (H/B)

The pullout capacity factor N_γ due to the contribution of soil weight for different embedment ratio and friction angle is shown in figure 4. The effect of friction angle on anchor breakout factor due to the contribution of soil weight is obtained for different combination of embedment depth and anchor rotation is shown in figure 4. For the purpose of validation, the current finite element results are compared with the lower bound solution obtained by Merifield and Solan (2006) which is shown in figure 4. The anchor break-out factor N_γ varies almost linearly with the friction angle as found by Merifield and Solan (2006). This trend is found similar as the variation of N_q (see Fig. 7) but in contrast with the variation of N_c (see Fig. 5).The current finite element results are found higher than the lower bound solution of Merifield and Solan (2006) at al embedment depths and the difference between the two decreases at higher embedment depth.

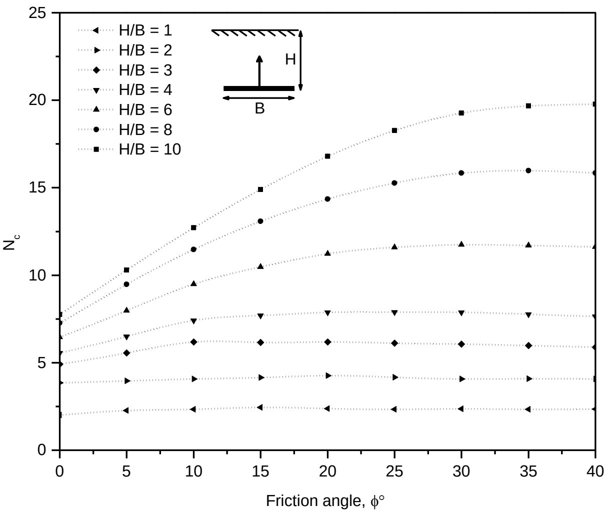

Fig. 5. Effect of friction angles, ϕ on Nc at different embedment depth (H/B)

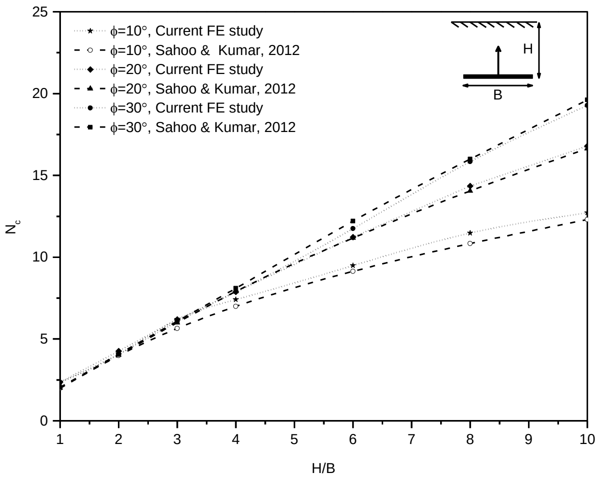

Fig. 6. Comparison of factor Nc for horizontal anchor at different friction angles, ϕ

The variation of break-out factor N_c with friction angle (ϕ) ranging from 0 to 40° at an interval of 5° corresponding to different embedment depth (H/B) is presented in Figure 5. It can be seen that N_c increases gradually with friction angle upto the peak point and after that friction angle does not show any significant effect. This trend is found similar as found by Rowe and Davis (1982a) and Kumar and Naskar (2012). It is also noted that, N_c increases with the friction angle upto 20 degree for embedment ratio 1 to 3. After that, the peak value of N_c is shifted to 5 degree apart (i.e. 25° for H/B=4) from embedment ratio 4 to 10.This peak value is different for different embedment ratio.

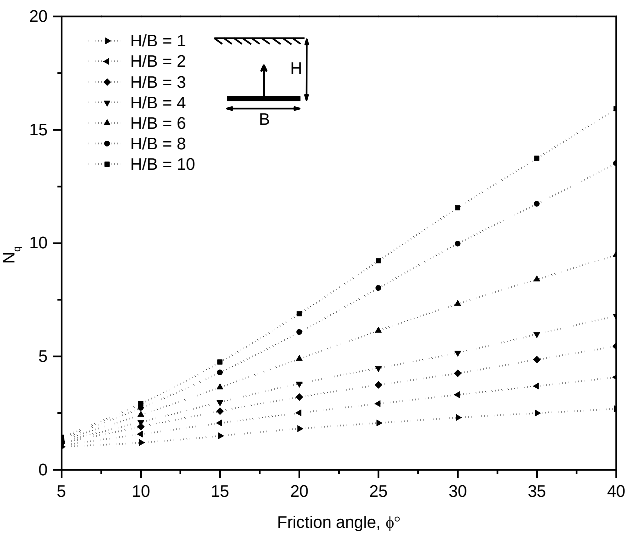

Fig. 7. Effect of friction angles, ϕ on Nq at different embedment depth (H/B)

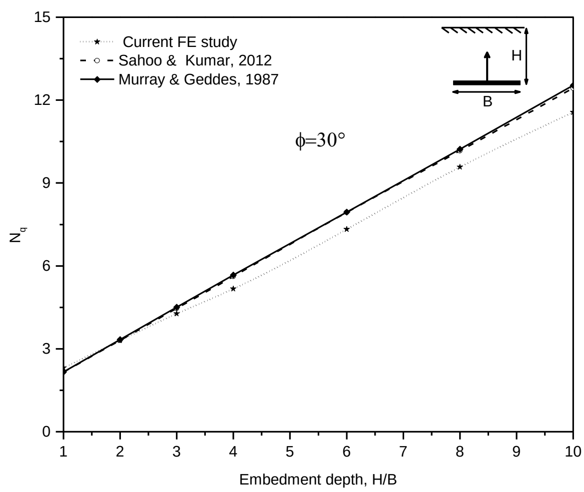

Fig. 8. Comparison of factor Nq for horizontal anchor at ϕ=30°

For example, maximum value of N_c is found 6.18 and 11.74 at a friction angle 20° and 30°, for embedment ratio of 3 and 6, respectively. For the purpose of validation, the values of N_c obtained from current finite element studies are compared with the Sahoo and Kumar (2012) based on upper bound finite element analysis. Three friction angles (i.e. 20°, 30°, 40°) are considered in the following comparisons, which are shown in the Figure 6. Present finite element results are found almost same as Sahoo and Kumar (2012) particularly at friction angle 30° and 40°, respectively. But, a small difference upto 5.6% are found at friction angle of 10° and embedment ratio of 8.

The variation of uplift factor (N_q) due to the contribution of surcharge pressure with friction angle is obtained for different embedment ratio is shown in Fig. 7. Friction angle, ϕ varies from 5° to 40° at an interval of 5°. It is found that for a given embedment ratio, the breakout factors increase almost linearly with an increase the soil friction angle, which is in contrast with the variation of N_c. It also represents the comparison of break-out factor with previous available data. As per author knowledge, little studies were performed to determine the effect of surcharge pressure on anchor break-out factor N_q. For this reason, the values of N_q (see Fig. 8) obtained in current finite element analysis are compared only with those obtained in simple upper bound analysis by Murray and Geddes (1987) and Sahoo and Kumar (2012), respectively. It shows that, at a low embedment depth upto 2, the break-out factor N_q is found same as Murray and Geddes (1987) and Sahoo and Kumar (2012). The difference increases with the increase of embedment depth and the variation is almost linear as found by Murray and Geddes (1987) and Sahoo and Kumar (2012).

CONCLUSION

A rigorous finite element investigation has been performed to determine the pullout capacity of strip anchor in c-ϕ soil. Consideration has been given to the effect of soil friction angle and anchor embedment ratio on anchor pullout capacity factor N_c, N_q and N_γ. At a given embedment ratios, anchor break-out factors N_γ and N_q increase continuously with the friction angle. But, their does not exist any peak point on N_γ and N_q which is in contrast with the trend of N_c. The variation of N_q and N_γ has found almost linear and N_c varies nonlinearly with the friction angle.

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