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Technical Note

Effects of Cohesion and Surcharge on Pullout Capacity of Vertical Anchors

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Introduction

Vertical anchors are generally provided to resist tensile forces occurring often behind earth retaining structures. These anchors are normally idealized in the form of rigid plates buried inside soil mass so as to simplify the determination of their load – deformation response. Considerable efforts have been made by a number of investigators, on both experimental and theoretical grounds to provide a suitable design methodology for such anchors. Amongst different theoretical approaches available till date, most prominent ones are those of Terzaghi (1943), Ovesen (1964), Meyerhof (1973), Neely et al. (1973), Rowe and Davis (1982), Murray and Geddes (1989). Earlier theories (for instance Terzaghi, 1943; Ovesen, 1964 and Meyerhof, 1973) were primarily based on passive and active earth pressures coefficients for retaining walls. These theories, however, were found suitable only for shallow embedded anchors as the effect of the burial depth of anchor was considered mostly in an empirical manner (Dicken and Leung, 1985). With the advent of high speed digital computers, solutions for the anchor problems have been obtained with the application of rigorous techniques, like the method of characteristics (Neely et al., 1973), limit analysis (Murray and Geddes, 1989) and non-linear finite element method (Rowe and Davis, 1982). Neely et al. (1973) used the concept of equivalent free surface, as was introduced earlier by Meyerhof (1951) in finding the bearing capacity of shallow to deep embedded foundations, and determine the pullout capacity of vertical anchors in cohesionless material. The theory was shown to predict reasonably well the anchor pullout behaviour for the

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effect of soil density. However, the theory could not be used perhaps so widely as corresponding effects of surcharge and cohesion were not investigated. In the present article, the theory Neely et al. (1973) has been applied to examine the influence of surcharge pressure and soil cohesion on the ultimate pullout capacity of vertical anchors. While carrying out the analysis, an immediate break away of the soil mass from the back of anchor, which usually occurs at low levels of stresses (Rowe and Davis, 1982), has been assumed. Results have been given in the form of non-dimensional pullout factors by considering comprehensively the effect of the roughness of anchors and soil friction angle. Comparison has also been made with the available results of Rowe and Davis (1982), using non-linear finite element, to support the validity of the findings noticed from the study.

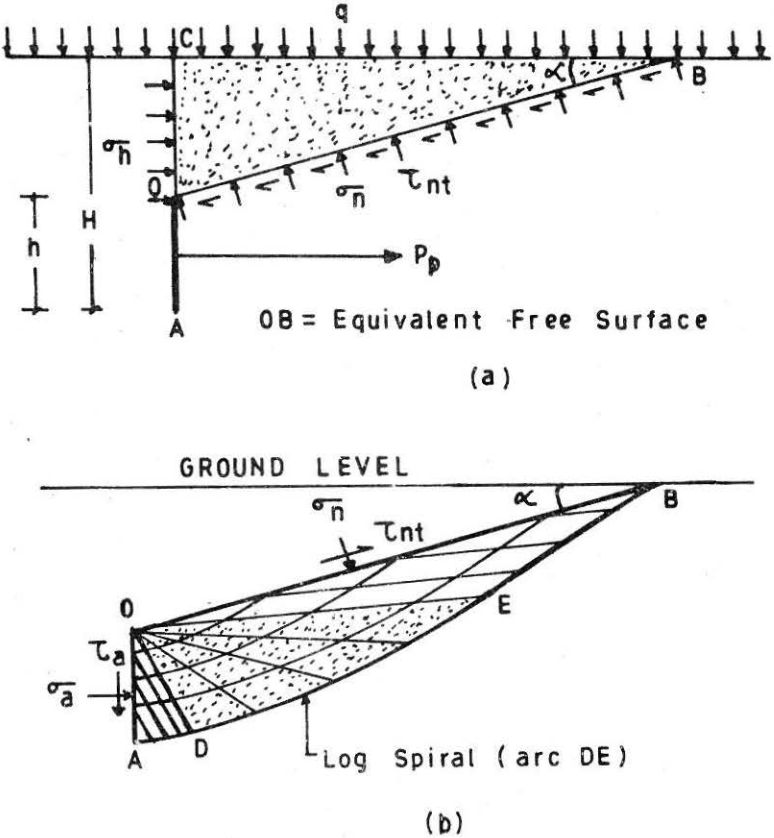

FIGURE 1 : **Equivalent Free Surface and Failure Mechanism**

Problem

A vertical anchor of height h, embedded at a depth H from the ground surface as shown in Fig. 1(a), is subjected to horizontal pullout load. It is to determine the magnitude of failure load under the condition that an immediate breakaway of the soil mass from the back surface of anchor occurs.

Method

When an immediate separation of the soil mass from the back surface of the anchor is assumed, the magnitude of pullout force becomes simply equal to the resultant passive pressure at the face of anchor. While evaluating the passive resistance, the effect of the shearing resistance of the soil mass above the anchor level can be considered by following the theory of Neely et al. (1973). Using this theory, the magnitude of the passive resistance can easily be determined once the stresses on the so called equivalent free surface are known. Based on experimental observations, Neely et al. approximately specified the stresses on the equivalent free surface by imposing either a Rankine active state (K_a - condition) or at rest state (K_o - condition) for the soil mass just vertically above the anchor. Later, after performing the analysis, it was found that between these two imposed states of stress for the soil mass vertically above the anchor, K_1 - condition results in only a little lower magnitude of failure loads as compared to K_o - condition; the maximum difference was seen to be hardly 10%. In a similar way, while determining the effect of surcharge and cohesion on the pullout capacity of vertical anchors during the present course of investigation, the state of stress for the soil mass vertically above the anchor is assumed to be K_a and K_o condition. The soil medium is specified as weightless, and as an approximation, the distribution of the stresses on the equivalent free surface is assumed to be uniform.

Based on the above approximations and by considering static equilibrium of the soil wedge OBC (refer Fig. 1a), the resultant stresses on the equivalent free surface will be given by the following expressions :

$$\sigma_n = \left[\sigma_h \sin^2\alpha + q\cos^2\alpha\right] \tag{1a}$$

$$\tau_{nt} = 0.50\left[\sigma_h - q\right]\sin(2\alpha) \tag{1b}$$

wherein, σ_n = normal stress on the equivalent free surface,

τ_{nt} = shear stress on the equivalent free surface

σ_h = normal stress on the vertical line OC,

q = surcharge pressure on ground, and

α = inclination of the equivalent free surface with the horizontal.

Compressive normal stresses are taken as positive, and the direction of the positive shear stress τ_{nt} is indicated in Fig. 1.

The magnitude of σ_h is given below :

$$\sigma_h = q(1-\sin\phi) \quad \text{for } K_o-\text{condition along OC,} \tag{2a}$$

$$\sigma_h = q/N_\phi - 2c/\sqrt{N_\phi} \quad \text{for } K_a-\text{condition along OC} \tag{2b}$$

in which $N_\phi = \tan^2(45+\phi/2)$,

ϕ = the angle of shearing resistance of soil mass, and

c = unit cohesion.

From the known state of stress along the equivalent free surface, the required magnitude of the passive resistance at the face of anchor has been determined by making use of the method of characteristics (Sokolovoski, 1960). Along the face of the anchor itself, the boundary condition was prescribed in terms of anchor – soil interface roughness angle δ defined in the following manner :

$$\tau_a = \sigma_a \tan\delta + c[\tan\delta/\tan\phi] \tag{3}$$

wherein, σ_a = normal stress on the face of the anchor, and

τ_a = shear stress on the face of anchor

Results

As the medium was taken to be weightless and also as the distribution of the stresses on the equivalent free surface was assumed to be uniform, the distribution of the passive pressure at the face of anchor was found to be invariably uniform. Corresponding shear pattern comprise of a radial shear zone bounded by an arc of logarithmic spiral and sandwiched in between two planer shear zones as illustrated in Fig. 1b.

The magnitude of the passive resistance p_p was expressed in terms of non-dimensional pullout factors F_c and F_q for the effect of cohesion and surcharge respectively, in the following manner :

$$p_p = c \cdot F_c + q \cdot F_q \tag{4}$$

The variation of pullout factors F_c and F_q with embedment ratio H/h, for different values of ϕ and δ/ϕ, is shown in Fig. 2 to Fig. 7. In case of K_o – condition for the soil mass above the anchor, both the factors F_c and F_q increase invariably with the increase in value of embedment ratio. In case of K_a – condition, the increase of both the factors F_c and F_q with depth, takes place only upto an inclination of the equivalent free surface equal to $(45+\phi/2)$. At greater depths, no more increase in the values of F_c and F_q occurs as at such depths the equivalent free surface lies within the zone of Rankine active shear and as a result, the region of radial shear does not extend with the increase in the depth of anchor. The value of embedment ratio H/h corresponding to $\alpha = (45+\phi/2)$ was referred to as $(H/h)_{cr}$, and its variation with respect to ϕ for different values of δ, ranging from 0 to ϕ, is shown in Fig. 8. The value of $(H/h)_{cr}$ increases continuously with the increase in the values of both ϕ and δ/ϕ.

For magnitudes of H/h smaller than $(H/h)_{cr}$, factor F_c as well as F_q varies only marginally as the stress state is changed from K_o to K_a condition. The difference is almost negligible in the case of factor F_q whereas factor F_c in K_o – condition becomes a little smaller as compared to that for K_a – condition, the maximum difference is around 10%. However, for values of $H/h > (H/h)_{cr}$ pullout factors F_c and F_q in the case of K_o – condition become significantly greater as compared to K_a – condition; the difference increases continuously as the magnitude of the embedment ratio H/h is increased. For K_a as well as for K_o stress condition, the values of both the pullout factors increase considerably with the increase in the magnitudes of ϕ and δ.

Comparisons

In order to check the validity of the findings observed from the study, the theoretical results of Rowe and Davis (1982), considering an immediate breakaway of the soil mass from the back of anchor, using non-linear finite elements, were selected, and these results were compared with those obtained from the present analysis. The comparison of pullout factors for the effect of cohesion and surcharge, with $\delta = 0$, is shown respectively in Fig. 9 and Fig. 10. The results of Rowe and Davis lie in between those obtained using the present analysis on the basis of K_o and K_a conditions. In a manner similar to the results of present analysis for K_a – condition, factors F_c and F_q from the theory of Rowe and Davis do become constant after a certain

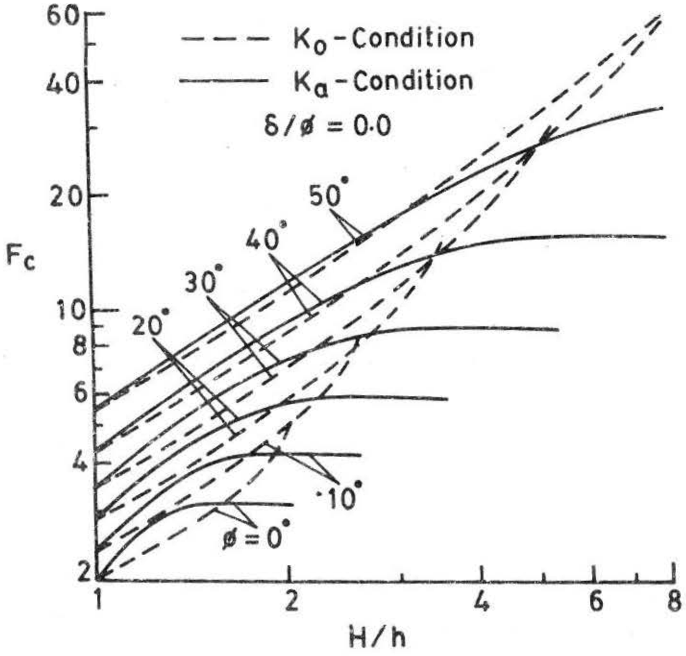

FIGURE 2 : Variation of Pullout Factor F_c for $\delta/\phi = 0$

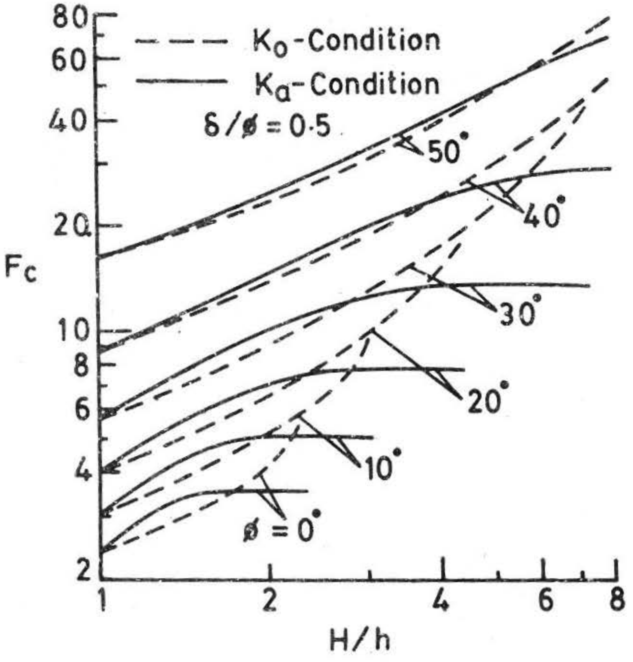

FIGURE 3 : Variation of Pullout Factor F_c for $\delta/\phi = 0.5$

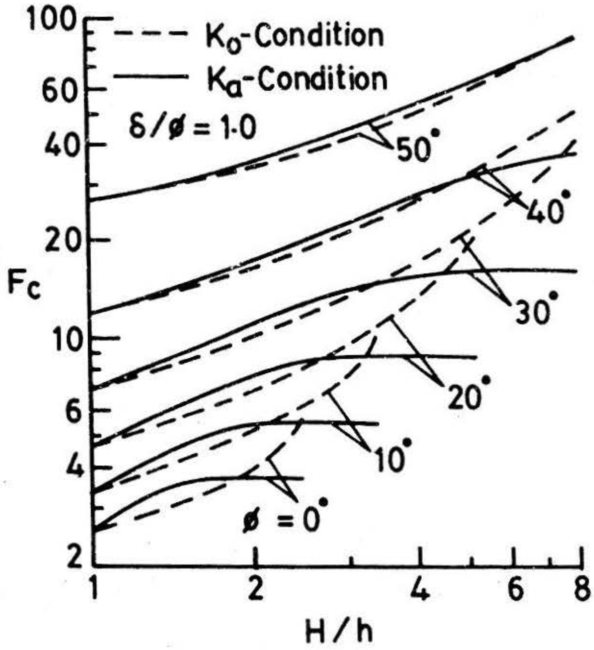

FIGURE 4 : Variation of Pullout Factor F_c for δ/ϕ = 1.0

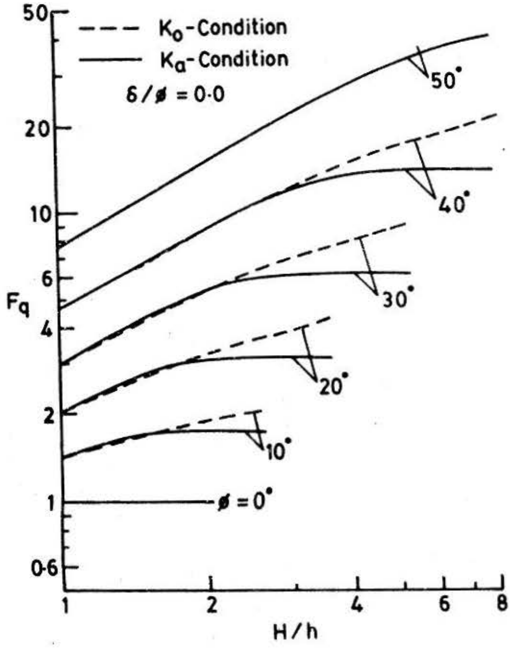

FIGURE 5 : Variation of Pullout Factor F_q for δ/ϕ = 0

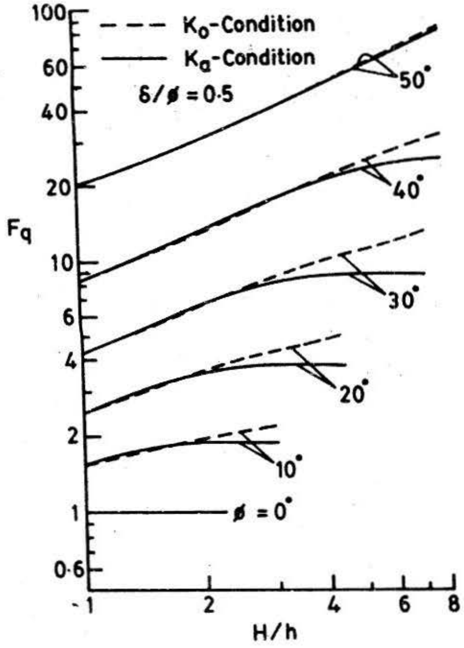

FIGURE 6 : Variation of Pullout Factor F_q for $\delta/\phi = 0.5$

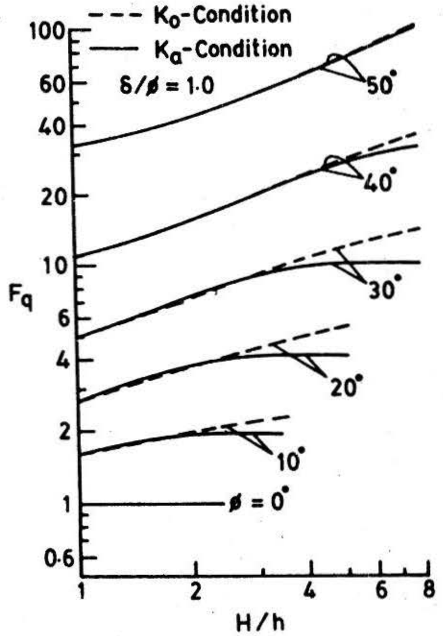

FIGURE 7 : Variation of Pullout Factor F_q for $\delta/\phi = 1.0$

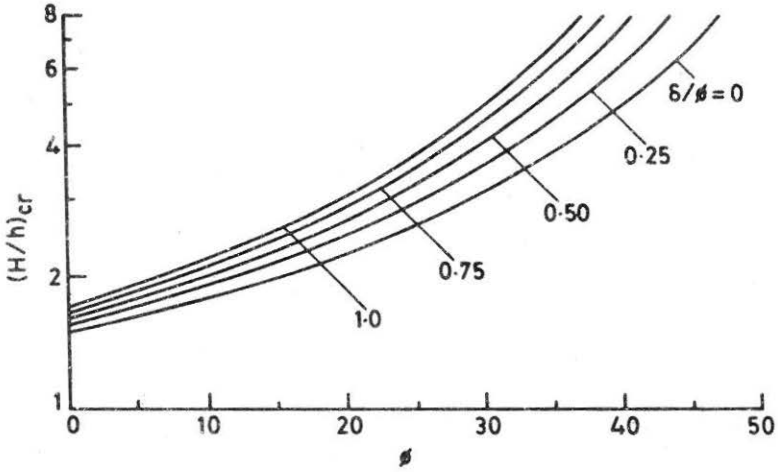

FIGURE 8 : Variation of $(H/h)_{cr}$

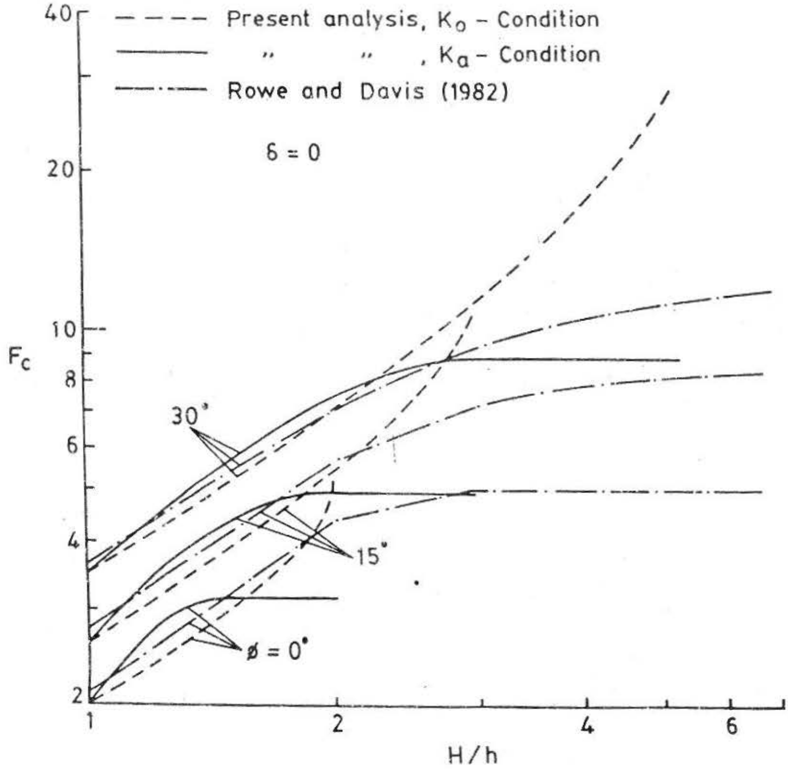

FIGURE 9 : Comparison of Pullout Factor F_c with the Theory of Rowe and Davis (1982)

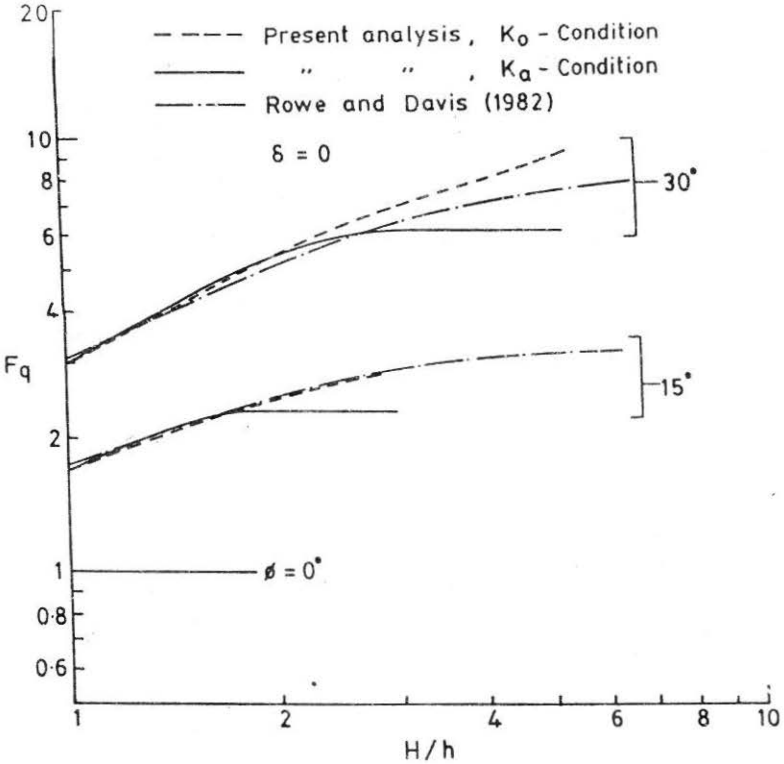

FIGURE 10 : **Comparison of Pullout Factor F_q with the Theory of Rowe and Davis (1982)**

value of H/h, which is generally higher as compared to $(H/h)_{cr}$ determined from the present analysis. The comparison, therefore, clearly supports the assumption of K_a stress condition for the soil mass vertically above the anchor, made in the theory of Neely et al. (1973), as it in general provides safer results. Comparisons in the case of rough anchors could not be made as the results for the effects of cohesion and surcharge were only reported for smooth anchors by Rowe and Davis (1982), and also none of the other available theories provides the solution for the problem by considering an immediate separation of the soil mass from the back surface of anchor.

Conclusions

The theory of Neely et al. (1973), which was earlier employed to find the density component of the pullout capacity of vertical anchors, holds equally good for determining the corresponding effects of cohesion and surcharge by considering an immediate separation of the soil mass from the back of anchor. In order to arrive at an approximate distribution of the stresses on the equivalent free surface, the soil mass just above the anchor can be assumed in a K_a stress condition without resulting in any significant error, and also this approximation ensures safer design. For K_a – condition, both the factors F_c and F_q increase with embedment ratio upto $H/h = (H/h)_{cr}$, beyond which these factors become invariant with respect to variation in embedment ratio. The magnitude of $(H/h)_{cr}$ increase both with ϕ and anchor – soil interface roughness angle. Pullout factors increase considerably with the increase in the values of δ and ϕ.

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