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A STUDY ON PULLOUT CAPACITY OF HORIZONTAL AND INCLINED PLATE ANCHORS FOR OFFSHORE INSTALLATIONS

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ABSTRACT

Structures subjected to uplift tensile loading require anchoring systems to resist pullout loads. Anchors used in offshore installations can be broadly classified as gravity anchors, anchor piles and plate anchors. Plate anchors can be circular, square or strip in shape. The loading applied on plate anchors can be vertical or inclined or horizontal depending on the anchor orientation. In this paper, various experimental, theoretical and numerical studies for estimation of load capacity behavior of horizontal and inclined plate anchors have been reviewed. A parametric study of pullout capacity has been carried out for plate anchors embedded in sandy 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

Embedded anchors are extensively used where the foundations of structures are subjected to uplift tensile forces. They are necessary when the uplift load is greater than the self-weight of the structure. They allow the transmission of the pullout load to the soil at a greater depth and farther away from the structure. Anchors of various types are now used for the vertical uplift resistance of submerged pipelines and transmission towers, and for the inclined or horizontal tieback resistance of waterfront and earth-retaining structures. The anchors are mainly made of concrete or steel.

With the recent expansion of offshore exploration and production in deeper waters, they have a significant application based on technical and economic considerations. As a result, a number of embedded anchor systems are undergoing development or have been developed. They are commonly adopted in the mooring of various compliant platform types, which are to be located in deeper zones of the ocean. A proper understanding of the anchor response to loading is essential to evolve an acceptable design procedure.

Numerous researchers have proposed different approaches to estimate the pullout load-deformation response of plate anchors of various shapes in sandy soils. In this paper, they are summarized in terms of the procedures and relationships developed for determining the ultimate pullout capacity. Most of them are based on model and field tests, or on slip-line limit equilibrium analysis approach, and very few analyses have been based on rigorous numerical analysis. The static ultimate pullout capacity (UPC) for both horizontal and inclined plate anchors embedded in sandy soils is worked out by using the various correlations and techniques, and the computed results are presented and compared.

2. HORIZONTAL PLATE ANCHORS

The ultimate pullout capacity Q_u of a horizontal plate anchor in cohesionless soil can be expressed as:

$$Q_u = \gamma H A N_u \qquad (1)$$

where γ = unit weight of soil, H = embedment depth, A = Area of the plate, and N_u = breakout factor. The magnitude of this dimensionless breakout factor is influenced by the geometry of the failure surface developed within the soil mass, and is dependent on a number of factors including soil parameters, relative depth and anchor dimensions.

2.1 Based on experimental approach

Based on laboratory and field tests in dense sand, Balla (1961) found that for circular shallow anchors, the failure surface extended to the ground surface as circular arcs. The ultimate pullout capacity was shown to comprise of two components: weight of soil in failure zone, and the shearing resistance developed along the curved failure surface. The UPC was expressed as:

$$Q_u = H^3\gamma\left[F_1\left(\emptyset,\frac{H}{h}\right)+F_2\left(\emptyset,\frac{H}{h}\right)\right] \quad (2)$$

where h = diameter of plate. F_1 and F_3 are functions dependent on the angle of internal friction $\emptyset$ and embedment ratio H/h.

Andreadis & Harvey (1981**)** proposed an expression for UPC which was dependent on embedment ratio, anchor size and shape, and degree of soil disturbance. It was concluded that the proposed design procedure based on medium scale laboratory tests had shortcomings mainly related to scale effects present during repeated loading, and field scale tests were necessary to confirm the validity of the approach.

Murray & Geddes (1987) conducted several laboratory tests to take into account the effect of factors such as size and shape of plate, depth of embedment, sand density and plate roughness. They concluded that all methods overestimate the ultimate pullout capacity in medium to loose sand. The relation for UPC was proposed as:

For rectangular anchors,

$$\frac{Q_u}{\gamma AH} = 1+\left(\frac{H}{B}\right)tan\emptyset[1+\frac{B}{L}+\left(\frac{\pi}{3}\right)\left(\frac{H}{L}\right)tan\emptyset] \quad (3)$$

For circular anchors,

$$\frac{Q_u}{\gamma AH} = 1+2\left(\frac{H}{h}\right)\left(sin\emptyset+sin\frac{\emptyset}{2}\right)[1+\frac{2H}{3h}\ \tan\frac{\emptyset}{2}(2-\sin\Phi)] \quad (4)$$

where B = width of plate, and L = length of plate.

Frydman & Shaham (1989) performed pullout tests on prototype slabs placed at various inclinations and different depths in dense sand. A semi-empirical expression was found to reasonably predict the pullout capacity. Factors that accounted for the shape and the inclination were then provided for the estimation of the ultimate pullout capacity of any slab anchor.

Hanna et al. (2007) presented an analytical model to predict the pullout capacity and the load–displacement relationship for plate anchors in sand. The model was developed based on the failure mechanism deduced from laboratory testing, and the limit equilibrium technique was used. Expression was given to estimate the critical depth for a given anchor/soil conditions, which separated deep from shallow anchors. The radius of influence of a individual anchor on the ground surface was established, and accordingly the spacing between anchors could be determined to avoid interactions between anchors. The proposed theory compared well with theoretical and experimental data available in the literature.

2.2 Based on limit equilibrium approach

Meyerhof & Adams (1968) conducted a number of model and full-scale uplift tests of footings with special reference for transmission towers. They presented an approximate general theory for uplift capacity for a strip or continuous footing, by considering forces acting on a curved failure surface above the foundation. In sands, the geometry of the failure surface was found to be fairly distinct but varied in shape and extent depending on the depth/width ratio of the foundation and on the rigidity and relative density of the soil. Shape factors were applied to the general expression to account for the three-dimensional effect of individual square or circular footings.

Vesic (1971) studied the problem of an explosive point charge expanding a spherical cavity close to the surface of a semi-infinite soil mass. If the diameter of the cavity were made equal to a circular plate size, there would be an ultimate pressure that would shear away the soil located above the cavity. On the basis of this concept, he proposed that the ultimate pullout capacity of a horizontal plate anchor comprised of the vertical component of the force inside the cavity, effective self weight of the soil, and the vertical component of the resultant of internal forces.

Chattopadhyay & Pise (1986) proposed a theoretical model for evaluating the ultimate breakout resistance of horizontal plate anchors embedded in sand, by assuming a curved axisymmetric failure surface through the surrounding soil. It indicated the existence of a characteristic relative depth, beyond which breakout factor approached a constant value. It was capable of predicting the breakout factors for a wide range of values of angle of shearing resistance of sand.

Saran et al. (1986) proposed an analysis to predict the critical pullout load, the breakout load, and load-deformation characteristics of anchors using hyperbolic stress-strain curves of cohesive-frictional soils as the constitutive law. The analysis incorporated the effect of the shape of the anchor. Strip, square, and circular anchors were analyzed. Analytical data were compared with the available experimental results, which showed good agreement.

White et al. (2008) described a simple limit equilibrium solution for predicting the uplift resistance of plate anchors buried in sand. The geometry of the solution was selected to match model test observations. Simple charts were presented for the prediction of peak uplift resistance from the normalised burial depth, the critical state friction angle and the relative density of the backfill. It was shown that the solution for uplift resistance based on the limit theorems of plasticity was generally very unconservative due to an improbable uplift mechanism not seen in model tests. It was shown that for a frictional material obeying normality, there is no energy dissipation during shear, and hence the uplift resistance is simply the weight of the soil.

2.3 Based on finite element approach

Rowe & Davis (1982) considered the effects of soil dilatancy, initial stress state and anchor roughness on the pullout capacity. The numerical solutions presented were obtained from an elasto-plastic finite element analysis. This approach allowed the consideration of 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. They found that soil dilatancy had a significant effect on UPC, whereas roughness and initial stress state had negligible effects.

Vermeer & Sutjiadi (1985) considered straight rupture surfaces at an inclination to vertical equal to the soil dilatancy angle, and proposed the following simple relation for breakout factor:

$$N_u = 1 + \left(\frac{H}{B}\right) tan\emptyset_{ps} + cos\emptyset_{cv} \quad (5)$$

where $\emptyset_{ps}$ = soil friction angle in plane strain, and $\emptyset_{cv}$ = critical state friction angle in plane strain.

Merifield et al. (2006) applied three-dimensional numerical limit analysis and axi-symmetrical displacement finite element analysis to evaluate the effect of anchor shape on the pullout capacity of horizontal plate anchors in sand. The anchor was idealized as either square or circular in shape, and rigorous solutions were presented for the ultimate pullout capacity.

Kumar & Kouzer (2007) examined the vertical uplift capacity of strip anchors embedded horizontally at shallow depths in sand by using an upper bound limit analysis in conjunction with finite elements and linear programming. Even though the analysis considered the development of plastic strains within elements, it was noticed that the soil mass lying above the anchor remained rigid, and a planar rupture surface emanated from the anchor edge making an angle $\emptyset$ with the vertical. They found that the influence of angle of internal friction was higher at deep embedment depth.

3. INCLINED PLATE ANCHORS

In the pullout of inclined plate anchors, the force is transmitted perpendicular to the anchor plane. Inclination angle is defined as the angle between by the pullout direction and the vertical axis. Harvey & Burley (1973) proposed a method for inclined plate anchors based on slip line approach with similar assumptions considered by Balla (1961) for the case of horizontal plate anchors.

Based on limit equilibrium analysis, Meyerhof (1973) proposed the following equation for inclined UPC in granular soils:

$$Q_u = \frac{1}{2} k_b \gamma H^2 + \gamma h H cos^2\psi \quad (6)$$

where K_b = earth pressure coefficient, ψ = inclination of plate with vertical axis.

Rowe and Booker (1979) proposed an analytical technique for predicting the behaviour of an inclined anchor of a general shape by dividing it into a series of rectangular sub-regions. This approach was applied to a square anchor and solutions were presented in the form of influence charts for a range of Poisson's ratio, embedment ratio, anchor inclinations and load inclinations. The solutions were considered to be applicable for circular anchors also.

Hanna et al. (1988) developed an analytical method based on limit equilibrium approach for the estimation of UPC of strip anchors with inclination angle ψ varying from 0° to 60°, and proposed that:

$$Q_u = \gamma K_s \frac{Sin\emptyset}{Cos^2\psi}\left(H'^2 + \frac{h^2}{4} Sin^2\psi\right) + \gamma H' h \quad (7)$$

where H' = average depth of embedment, and K_s = punching uplift coefficient.

Ghaly (1997) studied laboratory and field results reported in the literature for shallow anchor plates of various configurations and embedded in sands. This data was incorporated in a generalized form to predict the ultimate horizontal pullout resistance of vertical anchor plates in terms of the influencing parameters. The following expressions were proposed for UPC:

For circular anchors,

$$\left(\frac{Q_u}{\gamma A H}\right) tan\emptyset = 5.5\,(H^2/A)^{0.31} \quad (8)$$

For square and rectangular anchors,

$$\left(\frac{Q_u}{\gamma A H}\right) tan\emptyset = 3.3\,(H^2/A)^{0.39} \quad (9)$$

Murray & Geddes (1989) presented laboratory experimental results for the ultimate passive resistance and corresponding displacements of rectangular anchor plates pulled at inclination angles through very dense sand. The results were compared with theoretical solutions based on the upper and lower bound limit theorems of soil plasticity.

Goel et al. (2005) worked out the breakout resistance of inclined plate anchors in sand out using limit equilibrium approach. The breakout resistance was calculated for different soil friction angles with varying relative depth ratio and anchor inclination. It was found that the breakout factor increased continuously with the inclination of the anchor. A comparison of the predicted values of breakout resistance from the proposed analysis with the experimental values of the other researchers showed reasonably good agreement.. The proposed breakout factor was:

$$N_q = \frac{4D}{\pi B} K \tan\emptyset \, I_i \, Sec^2 i \qquad (10)$$

where K = coefficient of earth pressure, I_i = coefficient of inclination, i = inclination angle of plate anchor.

4. RESULTS & DISCUSSION

To carry out a comparative study of the ultimate pullout capacity of horizontal and inclined plate anchors embedded in sand by using the above empirical and theoretical correlations, 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. For the inclined strip anchor, the embedment ratio is fixed at 3, and the inclination angle is varied from 0° to 90° from horizontal to vertical orientation. The properties of sandy soils adopted in the computations are presented in Table 1.

Table 1. Properties of sands.

Properties	Loose Sand	Medium Dense Sand	Dense Sand
Unit Weight (kN/m^3)	14	17	20
Friction angle (°)	30	35	40
Modulus of elasticity (kN/m^2)	20,000	25,000	30,000
Poisson's ratio	0.3	0.35	0.4

The ultimate pullout capacities computed from the experimental and theoretical predictions are plotted against embedment ratio in Figs. 1 to 6 for horizontal anchors and in Figs. 7 to 9 for inclined anchors, respectively. From a comparison of the anchor capacities for both dense sand and medium dense sand (Figs. 1 & 2), it is observed that Balla's correlation gives the highest values whereas that of Andreadis & Harvey provides the lowest values. For the loose sand (Fig. 3), Hanna et al.'s relationship yields the maximum values.

The vertical uplift capacities predicted from the experimental studies can be compared with those obtained from theoretical studies for the same relative density of sand and the corresponding embedment ratio. From the plots in Figs. 1 & 4 for loose sand, at an embedment ratio of 3, the experimental values range up to about 4000 kN and are higher than the theoretical values which do not exceed 2500 kN. However, at the same embedment ratio, both the values are comparable for both medium dense and dense sands, as observed from Figs. 2 & 5 and Figs. 3 & 6, respectively.

At the embedment ratio of 3, the inclined pullout capacities in loose sand range from about 500 kN to about 1000 kN for vertical orientation, with the values of Goel et al. increasing exponentially beyond 40° (Fig. 7). The same trend of the capacity increasing with anchor orientation is also observed for medium dense and dense sands (Figs. 8 & 9).

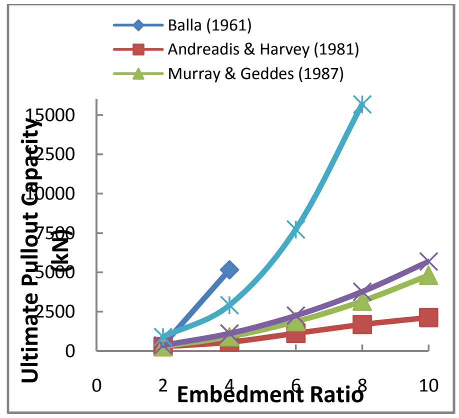

Figure 1. Variation of UPC of horizontal plate anchor in loose sand from experimental studies.

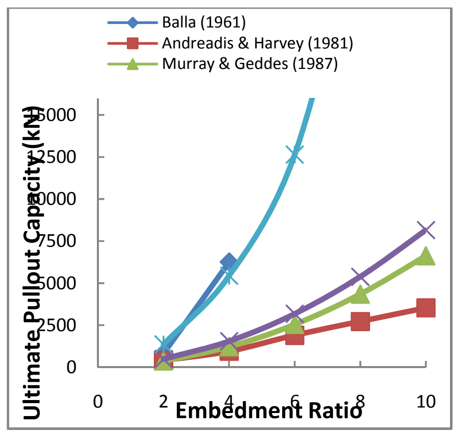

Figure 2. Variation of UPC of horizontal plate anchor in medium dense sand from experimental studies.

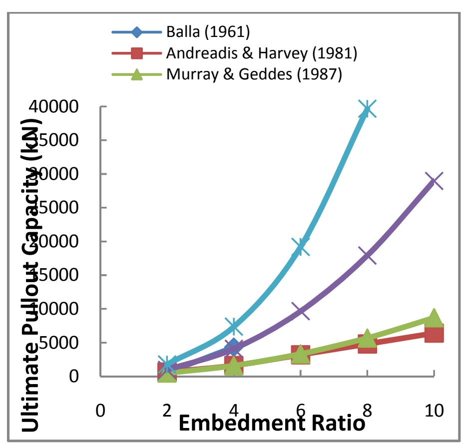

Figure 3. Variation of UPC of horizontal plate anchor in dense sand from experimental studies.

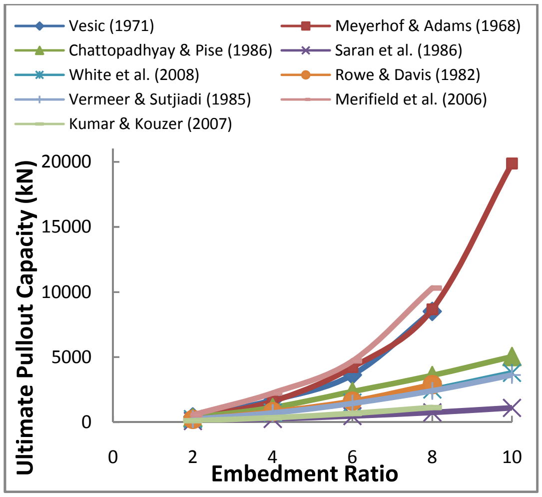

Figure 4. Variation of UPC of horizontal plate anchor in loose sand from theoretical studies.

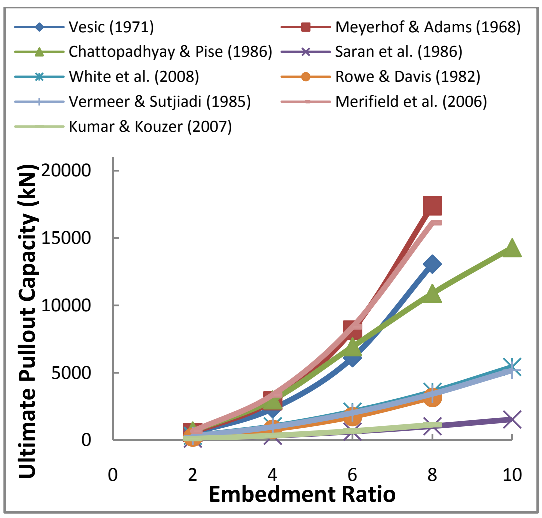

Figure 5. Variation of UPC of horizontal plate anchor in medium dense sand from theoretical studies.

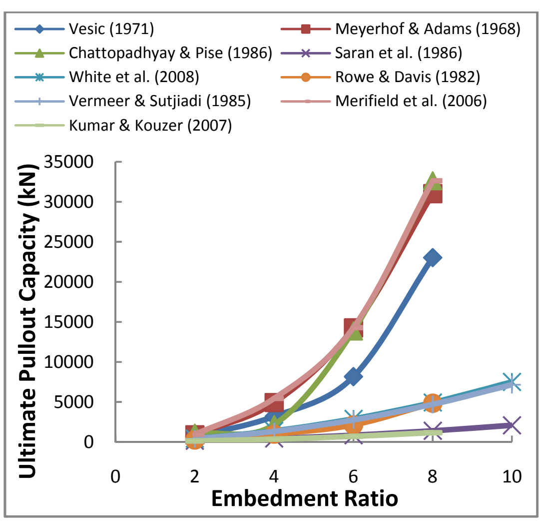

Figure 6. Variation of UPC of horizontal plate anchor in dense sand from theoretical studies.

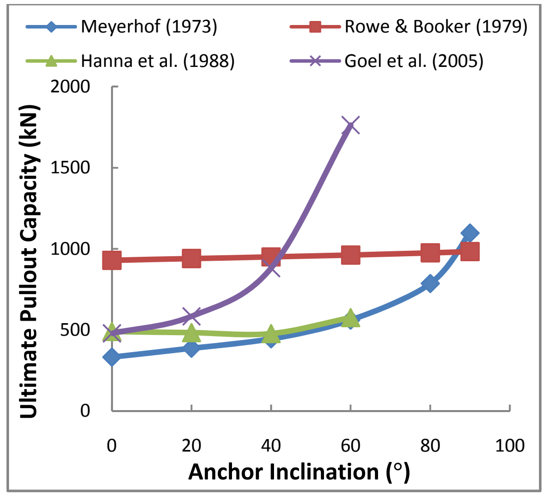

Figure 7. Variation of UPC of inclined plate anchor in loose sand.

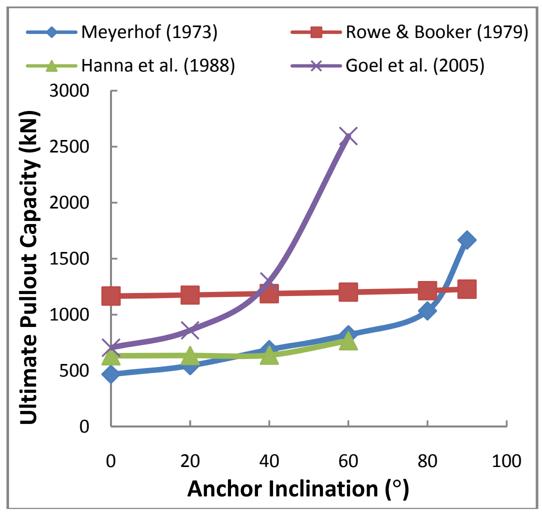

Figure 8. Variation of UPC of inclined plate anchor in medium dense sand.

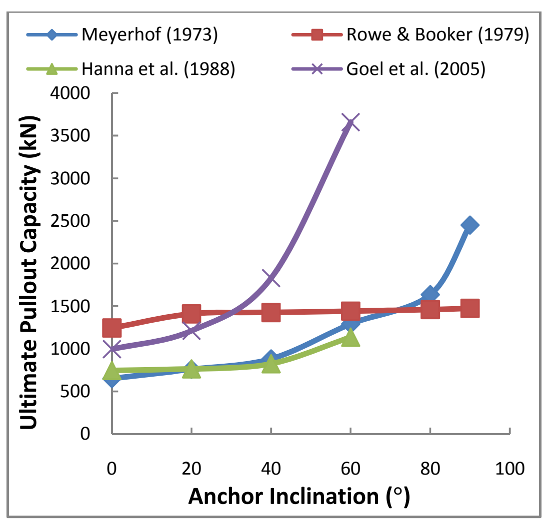

Figure 9. Variation of UPC of inclined plate anchor in dense sand.

5. CONCLUSIONS

In deep water offshore installations, plate anchors and their variants are being increasingly adopted. The anchors are placed at orientations between the horizontal and vertical depending on design requirements of the application. Due to the nature of loading on mooring systems used offshore, embedded plate anchors will be subjected to a wide range of sustained and repeated loads that will vary with the tautness of the mooring lines. The degree of soil disturbance adjacent to the anchor during installation will also affect the pullout capacity.

Various techniques and procedures based on experimental and theoretical studies found in the literature have been reviewed, and the ultimate pullout capacities of horizontal and inclined plate anchors have been computed by varying the embedment ratio and inclination angle. Comparisons have been made among the predicted values. As the embedment ratio increases, the breakout factor increases and tends to reach a maximum value. The breakout load also increases with anchor inclination for a deep anchor. It is recommended that the anchors be installed deeply so that inaccuracy in the embedded depth does not substantially affect the designed ultimate capacity.

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