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Effect of shape on holding capacity of plate anchors buried in soft soil

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Plate anchor is one of the most common varieties of anchors used in the construction and maintenance work of various on-land and offshore structures. An accurate estimation of the uplift capacity of anchor foundations is necessary for an economical design as well as for the safety and stability of structures. This paper outlines the effect of shape of anchor plates on their breakout capacity, through a series of model tests. Both shallow and deep anchor behaviours were investigated under conditions developing suction force and without suction force. The results of these tests are presented in terms of load-displacement behaviour, variation of breakout factors (with and without suction force) with depth of embedment, the critical embedment depth of anchors and variation of suction force with embedment ratio. Further, the variations of breakout factor ratio with aspect ratio and embedment ratio are reported. Based on the experimental results and the model test results of other investigators an empirical relationship has been suggested to determine the shape factor and holding capacity of plate anchors buried in saturated cohesive soils.

Keywords: plate anchor; uplift capacity; soft clay; suction force; embedment ratio; shape factor

1. Introduction

Anchors form an important component of many civil engineering structures. The primary function of these anchors is to transmit upward forces to the soil at certain depth below the ground. In some structures, they are also designed to resist compressive forces, moments and combinations of these forces. In recent times, with the increase of offshore construction activities to tap the ocean resources, the use of an efficient and reliable anchorage system has become necessary. Different types of anchors are being used in the field depending upon the magnitude and type of loading, type of structure and sub-soil conditions. An extensive review of various types of anchors and their suitability in the field was carried out by Datta *et al.* (1985). Several efforts have been made to understand the behaviour of anchors in cohesive and cohesionless soils under both static and cyclic loading. However, most existing theoretical and experimental work has been focused on predicting the anchor behaviour and capacity more in cohesionless soil than in cohesive soil. A comprehensive review of these works is given by Das (1990) and Merifield *et al.* (2001). Researchers have attempted to predict the behaviour of anchors in the field by simulating field conditions in laboratory model tests, conducting large-scale field tests or by numerical and theoretical formulations. In this context, the laboratory model tests conducted by Adams and Hayes (1967), Ali (1968), Davie and Sutherland (1977), Das (1978, 1980), Das *et al.* (1985, 1989, 1995), Singh (1998), the field tests of Adams *et al.* (1967, 1971), the theoretical formulations of Balla (1961), Matsuo (1967), Meyerhof and Adams (1968), Vesic (1971), Rao *et al.* (1994), and the numerical works of Muga (1967), Davie and Sutherland (1977), Rowe and Davis (1982), Merifield *et al.* (2001, 2003) and Thorne *et al.* (2004) are noteworthy. The behaviour of anchors in the field depends upon the identification of various factors influencing the failure mechanism and hence the anchor capacity. This paper attempts to evaluate the effect of anchor shape on its breakout capacity. The holding capacity of any other shape of anchor may be estimated using the holding capacity of strip anchors and the appropriate shape factor.

2. Mechanism of failure of plate anchors

Uplift loading produces different stress changes in various regions of the soil. In the region below the anchor there is a reduction in the total vertical stress, whereas in the region immediately above there is an increase in total vertical stress. The surface directly above the anchor tends to bulge upwards with the intervening soil acting as a beam. Mechanisms by which a rapidly loaded anchor may fail in uplift are depicted in Figure 1. Figure 1(a) depicts a shallow anchor separated from the soil beneath. In this case, the failure occurs as a result of shearing of the soil along surfaces directly above the edge of the plate anchor and tensile failure of the soil occurs near the ground surface. Figure 1(b) shows the mechanism for a deep

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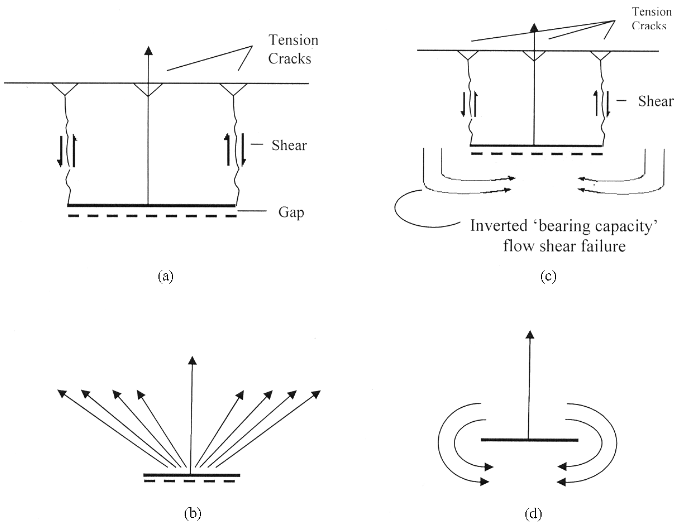

Figure 1. Mechanism of failure in uplift: (a) Shallow anchor separated from beneath; (b) Deep anchor separated from beneath; (c) Shallow anchor, joined to soil beneath; (d) Deep anchor, joined to soil beneath.

anchor, separated from the soil beneath. In this case, the mechanism of failure is by shearing and contained plastic flow occurs within the soil above the anchor plate without any surface effects. With the plate at great depth there is no significant expression and hence 'beam' action is absent. Figure 1(c) shows the mechanism for a shallow anchor bonded with the soil beneath. In this instance the failure is by tension near the surface resulting from 'beam' action. In addition, shear failure in a form of 'inverted bearing capacity' occurs as the soil flows around the base of anchor. Figure 1(d) shows the mechanism for a deep anchor bonded with the soil beneath. In this case the soil flows around the anchor and the failure is in shear and is contained locally within the soil (Thorne *et al.* 2004).

3. Breakout capacity of anchor

The vertical breakout capacity of the plate anchor embedded in saturated clay can be expressed as:

$$Q_u = Q_n + W_a + Q_s \tag{1}$$

where Q_u is the gross ultimate vertical breakout capacity, Q_n is the net ultimate vertical breakout capacity, W_a is the effective self weight of anchor and Q_s is the soil suction force.

Suction force develops beneath the anchors during uplift loading. When an uplifting force is applied to an anchor buried in saturated clay, the soil above the anchor is compressed while the soil below the anchor is relieved from stress, resulting in an increase of pore water pressure above the anchor accompanied by a decrease in pore water pressure below. This gives rise to a net downward force referred to as suction force. The magnitude of suction force is believed to be a function of embedment ratio, the coefficient of permeability, the undrained shear strength of clay, the amount of clay minerals present and the rate of loading (Das 1994). Suction force plays a major role in the selection of lifting equipment in seabed salvage operations and deciding the holding capacity of rapidly loaded anchors. However, in the design of a mooring system, suction force cannot be relied upon and should not be considered.

The net ultimate vertical breakout capacity of anchors is given by (Vesic 1971)

$$Q_n = A\,(c_u F_c + \gamma H) \tag{2}$$

$$Q_s = A\, c_u\, F_{sc} \tag{3}$$

where A is the base area of the plate anchor, c_u is the undrained unit cohesion of the soil, F_c is the non-dimensional breakout factor, F_{sc} is the non-dimensional suction breakout factor, γ is the unit weight of the soil and H is the depth of embedment of the anchor.

4. Literature review

A number of approaches are available to estimate the uplift capacity of plate anchors, which can be categorized as the theoretical approach, the numerical approach, model tests and full-scale field tests. However, major efforts have been made to estimate the holding capacity of anchors through laboratory model tests supported by full-scale field tests. Laboratory model tests on plate anchors embedded in clays of various consistencies have been conducted by Admas and Hayes (1967), Meyerhof and Admas (1968), Bemben and Kupferman (1975), Nhiem (1975), Davie and Sutherland (1977), Byrne and Finn (1978), Das (1978), Baba *et al.* (1989), Das *et al.* (1994) and Singh (1998). In most of the investigations the uplift capacity of the plate anchors was obtained either from stress-controlled tests or from strain-controlled tests by applying fixed rates of pullout velocity. These studies have been conducted on circular, square and rectangular or strip anchors, only, and no attempt has been made to correlate the breakout capacity of rectangular/square/circular anchors with that of strip anchors. Moreover, it can be seen that no coherent attempt has been made to quantify the effect of anchor shape on its breakout capacity. A correlation between the breakout capacity of strip anchor and that of anchors of any other shape has great significance as the majority of past research, either experimentally based or numerical analyses, is on strip anchors. The existing numerical analyses generally assume a condition of plane strain, and rigorous three-dimensional numerical analysis of anchors is scarce in the literature. However, in reality, anchors of various shapes and sizes are used in the field and therefore it is unlikely that the results obtained from plane strain analysis are applicable to these anchors. In such situations, the shape factor can be used to estimate the uplift capacity of anchors of any other shape.

The effect of the shape of plate anchors on their breakout capacity was studied by Das (1978). Tests were conducted on square and rectangular model plate anchors buried in a medium-stiff (c_u = 22.1 kPa) clay, both at shallow and deep locations. An empirical relationship has also been suggested in this study to correlate the breakout factors of rectangular anchors with that of square anchors. Das (1980) has proposed a procedure for the estimation of ultimate uplift capacity of square and rectangular anchors, located in saturated clay under undrained conditions, based on the model test results of Adam and Hayes (1967), Ali (1968), Bhatnagar (1969), Kupferman (1971) and Das (1978).

Rowe and Davis (1982) studied the undrained behaviour of plate anchors in clay using an elasto-plastic finite element analysis. The main analysis was done for plane strain conditions with a limited number of analyses for axisymmetric conditions. Based on this study the shape factor of a circular anchor is expressed as a function of embedment ratio. Merifield *et al.* (2003) quantified the effect of anchor shape on the holding capacity of horizontal anchors in undrained clay using three-dimensional numerical limit analysis. The ultimate uplift capacities of square, circular and rectangular anchors in clay were determined using the lower bound theorem of limit analysis and were compared to a previous study of strip anchors in clay (Merifield *et al.* 2001). An empirical relationship for the shape factor of anchors was proposed in this study.

5. Experimental work

5.1 *The model anchors*

Anchors of different shapes, i.e., circular (50 mm dia.), square (50 mm × 50 mm), strip (50 mm × 300 mm) and rectangular (50 mm width and aspect ratios of 2, 3 and 4) were used in this study. These anchors were made up of 6-mm-thick brass plates. However, for strip and rectangular anchors with L/B ratios more than two, extra stiffeners in the form of steel strips 15 mm wide and 8 mm thick were provided along the length of anchor plates. These were fixed to the anchor bolt to give extra rigidity to the plates. Stainless steel rods of 6 mm diameter were used as anchor rods and were connected to model anchors by threaded nuts fixed to the anchor plate. Elimination of suction was achieved by providing air vents at the base of the anchor plate and connecting them to the atmosphere by vented anchor pipes. In addition to this, to avoid any adhesion of anchor to soil, blotting paper was placed beneath the model anchor. Baba *et al.* (1989) and Das *et al.* (1994) had adopted a similar procedure to eliminate suction and adhesion forces beneath plate anchors in their model tests earlier.

5.2 *Soil used*

A high plastic commercial clay (low grade bentonite) which exhibits LL = 75% and PI = 44% was used in the present study. It contains 96.5% fine ($< 75\ \mu$m) and 3.5% coarse fractions. The X-ray diffraction pattern shows the presence of illite, kaolinite, chlorite and vermiculite clay minerals with quartz. The soil is classified as 'CH' in the Indian Standard soil classification system (IS: 1498–1970).

5.3 *Test set-up and loading arrangements*

Strip anchor with an L/B ratio of 6 was tested in a rectangular mild steel tank of plan area 600 mm × 302 mm and 600 mm deep whereas anchors of all other sizes were tested in a circular tank of diameter 560 mm and 710 mm deep. The anchors were pulled out by a motorized gearbox arrangement. A 5 horse-power DC motor with a speed control unit was used to supply the necessary power to pull out the anchors. In the present work the speed of the motor was adjusted by the speed control unit so as to give an anchor displacement rate of 3.5 mm/min. The pull-out displacement was transmitted to the model anchor through the anchor rod, connected to the loading arrangement by a tension proving ring and chain connector. The displacement of the anchor was measured with the help of a dial gauge of 0.01 mm sensitivity suitably connected to the anchor rod. A schematic diagram of the pullout test setup is given in Figure 2.

5.4 *Experimental procedure*

The pulverized clay was thoroughly mixed with the required amount of water to bring the consistency index (Ic) of the soil to 0.25. The consistency index is the ratio of the liquid limit minus the placement water content to the plasticity index of the soil. For the soil used in the present work, a water content of 64% gives a consistency index of 0.25. To achieve uniform moisture distribution, the wet soil was stored in air-tight plastic containers for 7–8 days before its use in the experimental work. The moist soil was placed in the test tank in small quantities by hand and patted uniformly. Because of the low consistency of the soil used no problem was faced in filling the test tank using this method. The average unit weight of the test beds achieved by this placement method was found to be 16.61 kN/m^3. Baba *et al.* (1989) and Datta *et al.* (1996) adopted a similar procedure for placing the soft soil in the test tanks. Care was taken to ensure that no air was entrapped. After filling the tank to the base level of the anchor, the anchor with the connecting rod was placed and the filling operation continued till the required embedment depth was achieved. The test tank with the embedded anchor was placed under the loading frame and was left undisturbed for 22 hrs by covering the soil with polythene sheets. Polythene sheets helps in minimizing the evaporation of water from the soil surface. The anchors were then pulled out at the rate of 3.5 mm/min. The movement of the anchor was recorded by a dial gauge of 0.01 mm sensitivity, suitably connected to the anchor rod. The resistance offered by the anchor to the pullout was measured by a tension proving ring. The readings of the tension proving ring were recorded

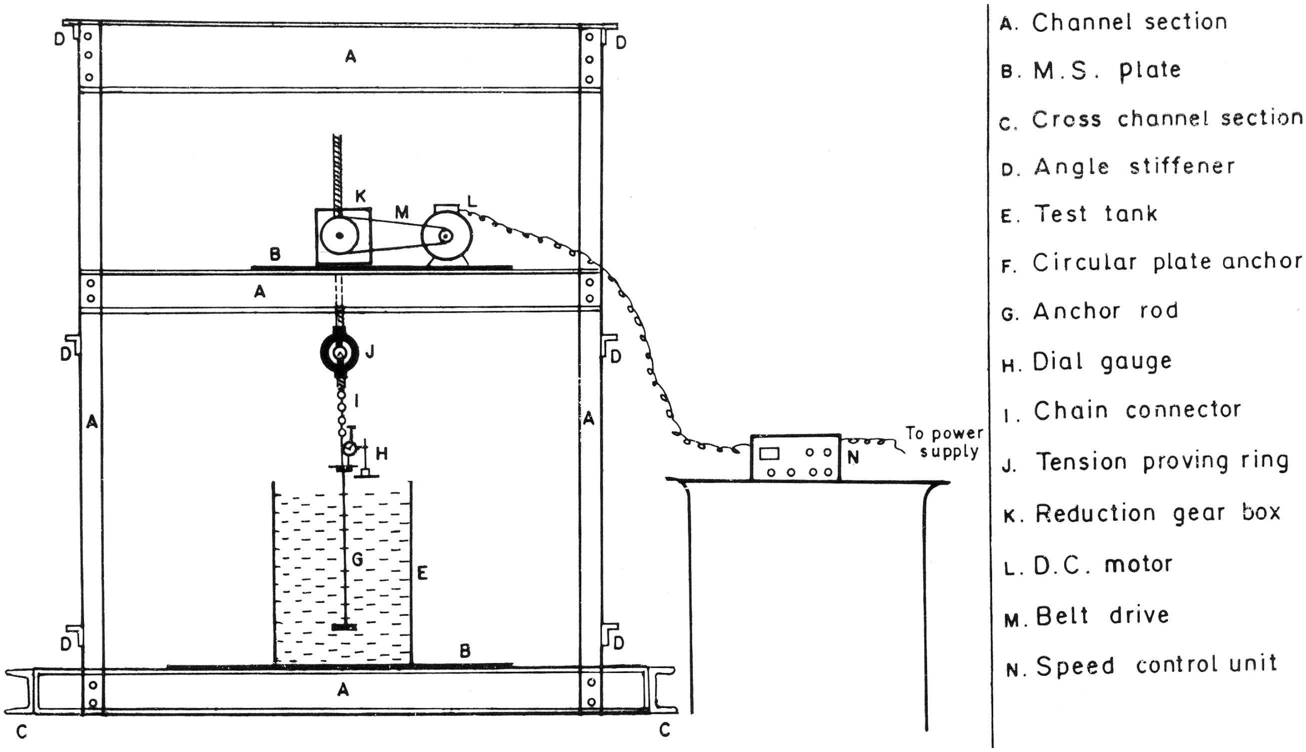

Figure 2. Schematic diagram of the pullout test set-up.

manually at regular displacements till there was a drop in the reading of the proving ring or the displacement became equal to the least dimension of the anchor. Baba *et al.* (1989) adopted a similar procedure to determine the uplift capacity of plate anchors buried in soft clays. The anchor resistance at various displacements was calculated from the proving ring readings using the proving ring constant. Care was taken to maintain the two important parameters of the test beds, the moisture content and the degree of saturation, at their desired values. This was determined by taking soil samples from the test tanks at random intervals. A total of 154 samples were taken from the test beds and the placement moisture content was calculated. The measured value of the moisture content of test beds varies between 63.3 and 64.5%, with an average value of 63.9% and standard deviation of 0.2946. The degree of saturation was calculated by taking undisturbed samples from the test tank and the average value was found to be 98.70%. The degree of saturation and coefficient of permeability of soil influence the magnitude of suction force and its contribution to the anchor capacity (Baba *et al.* 1989, Das 1994). However, an exhaustive study on these aspects was not carried out by the above investigators. The undrained unit cohesion of soil was measured at the end of each pullout test by an electrically operated vane shear test device at a depth of 100 mm from the surface of the soil bed and the average value was found to be 2.80 kPa. The maximum depth of embedment of plate anchors in this study being only 400 mm, the variation of unit undrained cohesion with depth is assumed to be insignificant, so a constant value has been adopted. In the present investigation the peak resistance offered during the pullout test was considered as the failure load and is used in the analysis of the test results.

6. Results and discussion

6.1 *Load-displacement behaviour*

Typical sets of load-displacement curves, obtained from the monotonic pullout tests, conducted on model strip (50 mm × 300 mm) anchors are shown in Figures 3 and 4. The curves in Figure 3 depict the relationship between pullout resistance and anchor displacement for the conditions when suction and adhesion forces were eliminated by ventilating the base of the anchor,

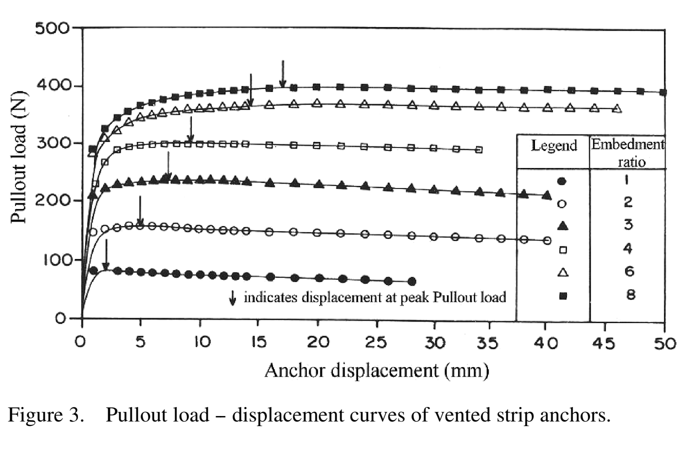

Figure 3. Pullout load – displacement curves of vented strip anchors.

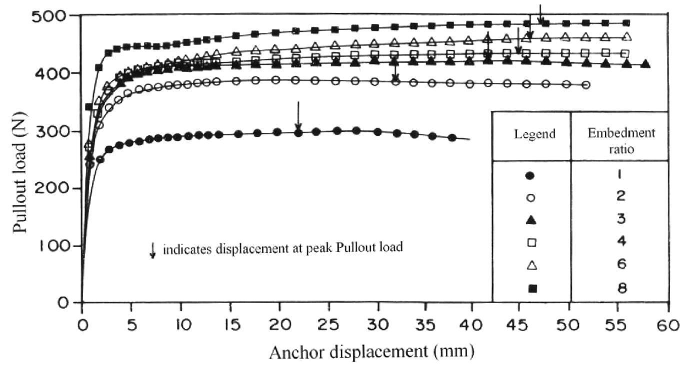

Figure 4. Pullout load-displacement curves of non-vented strip anchors.

while Figure 4 shows the curves in which these were allowed to develop. Two distinct phases of load-displacement behaviour of shallow anchors (H/B < 3) are observed (Figure 3). Initially the load increased very rapidly and reached a peak value at a very low anchor displacement. Tension cracks and upheaval of the soil at the ground surface were noticed at this stage. This is followed by a post-peak behaviour, characterized by a constant pullout resistance even up to large anchor movements. But the load-displacement curves for deep anchors (H/B > 4) consist of three phases: an initial phase with sharp rise in pullout resistance with the anchor displacement, followed by a gradual increase of pullout resistance until the peak load is reached, and finally the pullout resistance remains unchanged with further displacement. The post-peak behaviour of the deep anchor is characterized by a constant pullout resistance for a considerably high anchor displacement. Baba *et al.* (1989) and Datta *et al.* (1996) have also reported similar post-peak behaviour of deep anchors buried in soft saturated clays. The displacement at peak pullout load is found to increase with the increase in embedment depth of anchors.

The failure of the shallow anchor is associated with the development of a limited shear zone near the edge of the anchor and an almost rigid upward movement of a block of the soil directly above the anchor accompanied by large tension cracks and heave of the soil at the ground surface. The phenomenon of tension cracks and upheaval at the ground surface is not noticed for deep anchors. This indicates that for shallow anchor conditions the soil is stressed largely in flexure, whereas at large depths the flexing of soil mass is prevented by the weight of overburden resulting in no tension cracks. Earlier investigators such as Meyerhof and Adams (1968), Byrne and Finn (1978), Sutherland (1988) and Singh (1998) have made similar statements based on model tests on plate anchors buried in clays of different consistencies. The failure of shallow anchors due to flexing of soil above the anchor plate is also reported by Thorne *et al.* (2004) based on finite element analysis of strip anchors buried in uniform-strength clay. The failure of deep anchor occurs due to the extensive plastic deformation of the soil before collapse, which is apparent from the steady increase of pullout load up to a very high anchor movement. When suction and adhesion forces are allowed to develop a no-breakaway situation arises at the base of the anchors until cavitation or complete collapse of soil occurs. No breakaway of soil from the anchor base was noticed for non-vented anchors (suction and adhesion forces allowed to develop), located both at shallow and deep locations, even though the anchors were pulled out completely during experimentation. Contrary to this, for vented anchors a cavity almost equal to the size of the anchor was left over when the anchors were completely pulled out. This indicates that when suction and adhesion forces are allowed to develop a no-breakaway situation arises at the base of anchor leading to complete collapse of the soil. The contained plastic flow of soil before complete collapse gives rise to a gradual increase of uplift load up to substantial anchor movement.

6.2 *Uplift displacement factor*

Displacement corresponding to the peak pullout load for each test condition is determined from the load-displacement plots. This is expressed as a non-dimensional uplift displacement factor (δ). It is the ratio of anchor movement corresponding to the peak pullout load and the least dimension of the anchor. The variation of uplift displacement factor (δ) with the embedment ratio for circular and strip anchors for both the base conditions is illustrated in Figure 5. These curves can be divided into three segments: (i) an approximately linear one for shallow anchor depths followed by (ii) a short non-linear portion and finally (iii) almost a horizontal linear segment. But the extent of these phases depends upon the shape and base conditions of anchor. For vented anchors the initial linear phase persists comparatively up to a higher embedment ratio than the non-vented anchors. For example, a linear relationship between δ and H/B is noticed up to H/B of 4 for non-vented strip anchor, whereas for vented strip anchor this value is about two. Although there is some scatter of test points, it can be noted that the displacement required to reach peak pullout load is higher in case of strip anchors as compared to the circular anchors for similar test conditions. This indicates that more constrained plastic flow occurs in the case of strip anchors before failure than for circular anchors. The uplift displacement factor for deep non-vented anchors is around 0.80, whereas for vented anchors this value

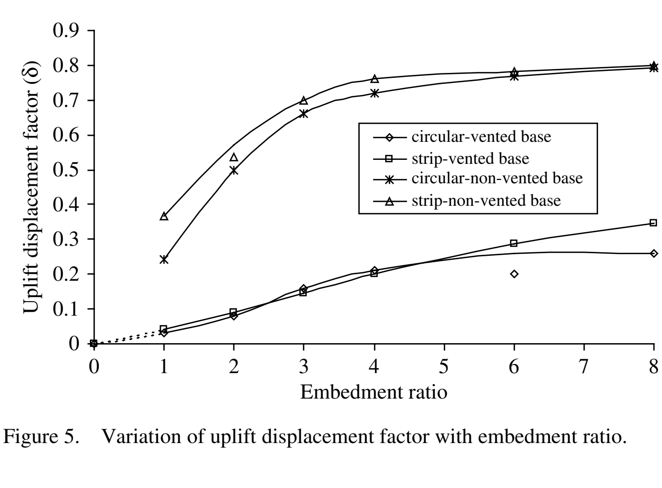

Figure 5. Variation of uplift displacement factor with embedment ratio.

is 0.30. This indicates that if suction force is allowed to develop, large anchor movement is required to mobilize the full anchor capacity.

6.3 *Variation of ultimate uplift pressure*

The ultimate uplift pressure of anchors was calculated from the peak pullout load and corresponding plan area of anchors. The variation of the ultimate uplift pressure with embedment ratio of anchors is shown in Figures 6 and 7. The ultimate uplift pressure is chosen here so that a comparison between different anchor shapes can be made directly. Figure 6 presents the variation of ultimate uplift pressure with embedment ratio of anchors when no suction and adhesion forces are allowed to develop, while Figure 7 shows the variations with full suction and adhesion forces. The curves in Figure 6 have an initial linear portion showing that the ultimate uplift pressure increases linearly with the increase of embedment ratio for shallow anchor conditions, followed by a non-linear variation with continuously changing slope representing the transition from shallow to deep anchor failure. The last portion of the curve is almost a straight line with mild upward slope. This indicates the amount of contribution by the effective overburden pressure, resulting from the increase in embedment depth of anchors. For all embedment depths a circular or a square anchor is found to be more effective than a rectangular one in resisting uplift load. As the aspect ratio (L/B) of rectangular anchors increases, the ultimate uplift load per unit anchor area decreases. Figure 7 shows only two different segments, an initial non-linear portion followed by almost a linear portion with mild upward slope, indicating that when suction and adhesion forces are allowed to develop, the shallow anchor behaviour is not that distinct for anchors embedded in soft saturated clay.

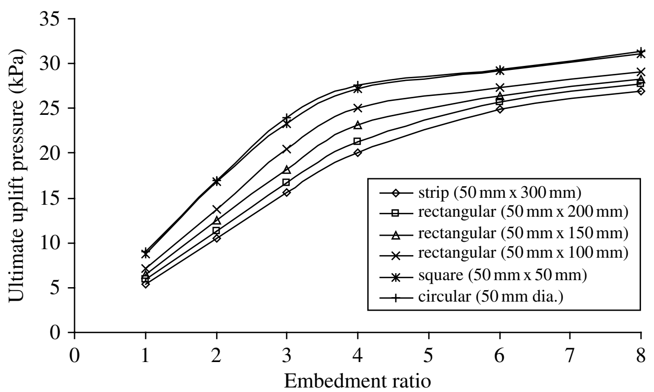

Figure 6. Variation of ultimate uplift pressure of vented anchors with embedment ratio.

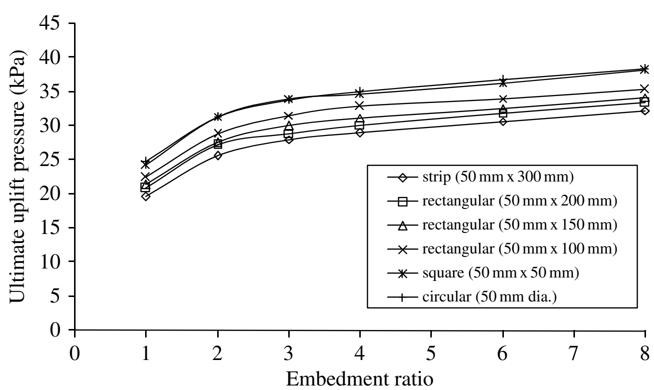

Figure 7. Variation of ultimate uplift pressure of non-vented anchors with embedment ratio.

6.4 *Contribution of suction force to breakout capacity*

The contribution of suction force to the breakout capacity is expressed as the ratio of suction force (Q_s) and the net ultimate breakout capacity of anchors (Q_0). Figure 8 shows the variation of Q_s/Q_0 with the embedment ratio, for different anchor shapes. The contribution of suction force to the breakout capacity is seen to vary widely depending upon the embedment ratio of anchors. At shallow depths the contribution of suction force to the breakout capacity is considerably high and decreases with the increase of embedment ratio. For the present test conditions the suction contribution beyond an embedment ratio of 5 was found to be only 22% irrespective of the shape of anchors studied. But this contribution at $H/B = 1$ is around 170% for square and circular anchors and about 260% for strip anchors. The contribution of suction force to breakout capacity is found to be more for rectangular anchors with higher L/B than the square and circular ones, particularly for shallow anchor locations.

6.5 *Breakout factors*

The breakout factors F_c, F_s and F_{sc} are calculated from the results of model tests using the following relationships

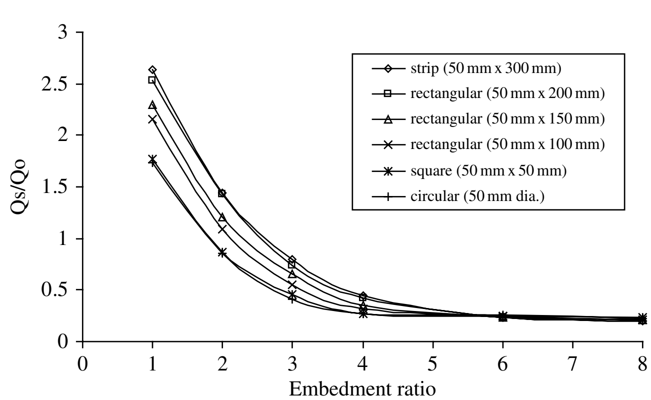

Figure 8. Contribution of suction force to breakout capacity.

$$Q_u = Q_o + Q_s + W_a \quad (4)$$

$$Q_o = A\,(c_u F_c + \gamma H) \quad (5)$$

$$Q_s = A\, c_u\, F_{sc} \quad (6)$$

$$F_s = F_c + F_{sc} \quad (7)$$

The variation of breakout factors F_c and F_s with the embedment ratio of anchors is given in Figure 9 and Figure 10, respectively. Figure 11 gives a comparison of breakout factors obtained from the present experimental work for square anchors for immediate breakaway conditions with the theoretical predictions of Meyerhof and Adams (1968), model test results of Das (1980) and lower bound limit analysis solutions of Merifield *et al.* (2003). Merifield *et al.* assumed the soil to be weightless in their analysis. The present experimental result compares well with the model test results of Das over the full range of embedment ratios and with those of Merifield *et al.* for shallow anchor conditions only. For deep anchor conditions the lower bound solutions proposed by Merifield *et al.* overestimate the breakout factors. The breakout factors obtained using the equation proposed by Meyerhof and Adams are clearly over-conservative and as much as 60% below the experimental values for shallow anchor conditions. However, for higher embedment ratios both the results match.

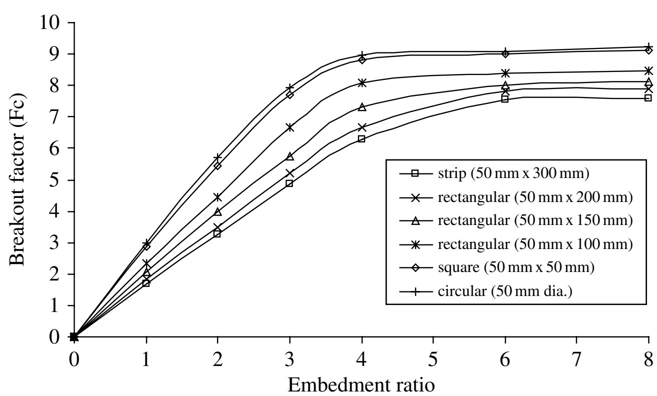

Figure 9. Variation of breakout factor (F_C) with embedment ratio.

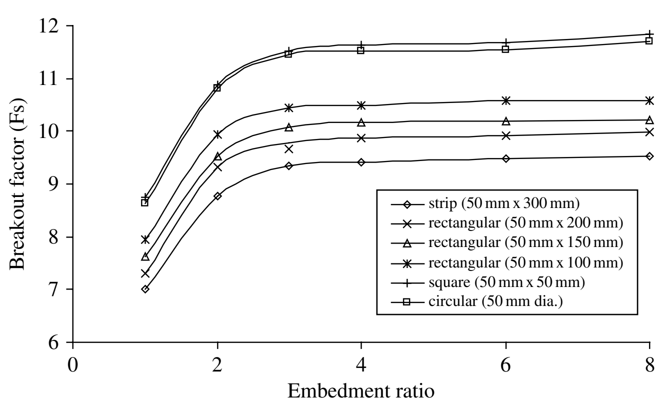

Figure 10. Variation of breakout factor (F_S) with embedment ratio.

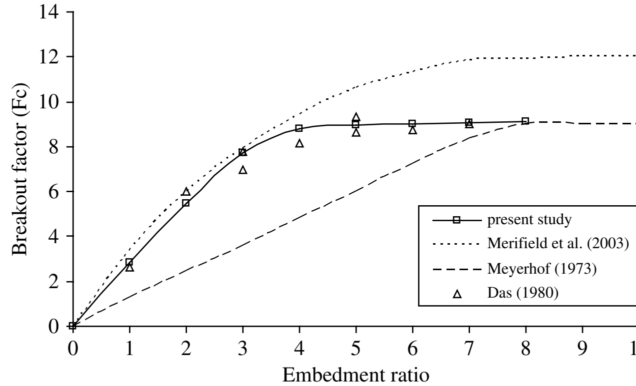

Figure 11. Comparison of breakout factors for square anchors in clay.

The model test results of Adams and Hayes (1967), Kupferman (1971), Das (1994) and the lower bound finite element predictions of Merifield *et al.* (2003) on circular anchors in cohesive soil are shown in Figure 12 along with the results obtained from the present model test. The experimental results of Adams and Hayes are grouped for two soil consistencies, i.e., soft and stiff, with undrained unit cohesion varying from 10.35 to 13.8 kPa and 96.6 to 172.5 kPa respectively. Figure 12 shows the average plot between F_c and embedment ratio for the above two soil consistencies. The present experimental results compare reasonably well with the results of Adams and Hayes for soft soil conditions. However, the F_c values obtained in stiff clay overestimate the present experimental results. The variation of F_c values with embedment ratio obtained by Kupferman shows a similar trend to the present test results but with higher values. The experimental F_c values obtained by Das for shallow anchor conditions underestimate the present test data. However, there is a good agreement between the experimental results of Das and the lower bound finite element predictions of Merifield *et al.* for shallow anchor conditions only. When compared to the lower bound finite element predictions of Merifield *et al.*, the present experimental data appear to be conservative for all embedment ratios, the deviations being more for deep anchor conditions.

The ratio of critical embedment depth of rectangular anchors to that of square anchors is denoted by non-dimensional parameters

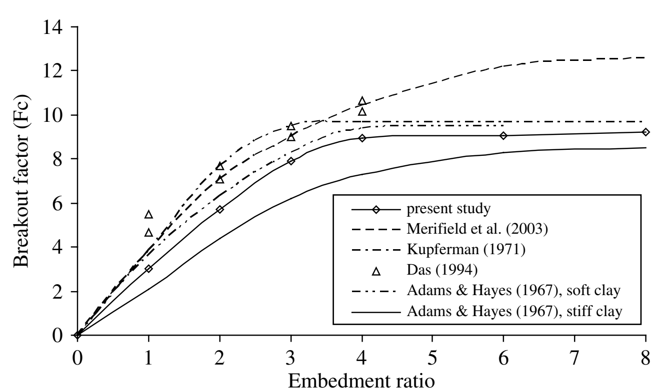

Figure 12. Comparison of breakout factors for circular anchors in clay.

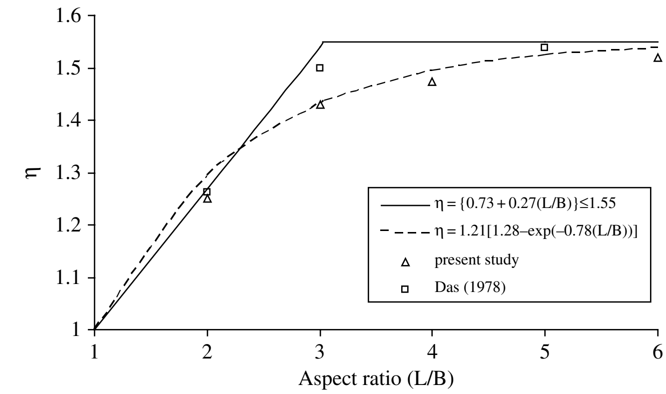

Figure 13. Variation of η with aspect ratio of rectangular anchors.

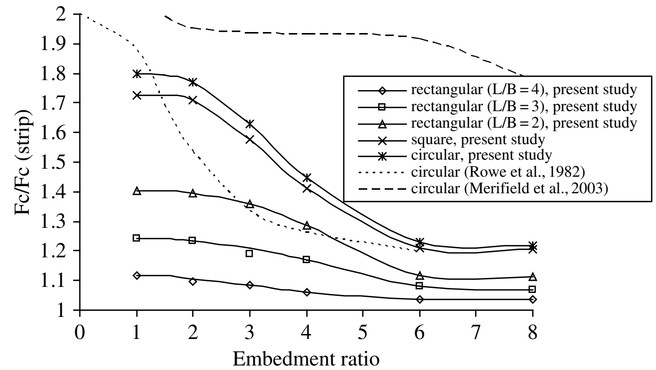

Figure 14. Variation of breakout factor ratio with embedment ratio.

η and η′ for vented and non-vented anchors, respectively. Figure 13 shows the variation of η with L/B ratio of rectangular anchors along with the model test results of Das (1978). The present experimental data and the model test results reported by Das fall slightly below the bilinear equation (Equation 8) suggested by Das. Hence, based on these experimental data an alternative relationship between η and L/B for rectangular anchors is suggested (Equation 9).

$$\eta = [0.73 + 0.27(\mathrm{L/B})] \leq 1.55 \tag{8}$$

$$\eta = 1.21\left[1.28 - \exp^{-0.78(\mathrm{L/B})}\right] \tag{9}$$

To the best of the authors' knowledge, no other published results on uplift capacity of plate anchors in saturated clay are available in the literature which correlate the critical embedment ratio of rectangular anchors to that of the square anchors. An empirical relationship between η′ and L/B values of rectangular anchors is proposed (Equation 10) based on the experimental model test results.

$$\eta' = 0.48\left[2.54 - \exp^{-0.75(\mathrm{L/B})}\right] \tag{10}$$

6.6 *Effect of shape*

The effect of shape on the breakout capacity of anchors is expressed in terms of the ratio of the breakout factor of a given anchor shape to that of the strip anchor (breakout factor ratio). Figure 14 shows the variation of breakout factor ratio with the embedment ratio of vented anchors. The curves in Figure 14 show an initial flat portion followed by a rapid decrease of breakout factor ratio with increase of embedment ratio and thereafter it tends to remain constant. For circular anchors the breakout factor ratio is 1.80 at an embedment ratio of one, which decreases to 1.22 at an embedment ratio of 6; thereafter it remains almost constant. Similar trends are also observed for other shapes of anchors. Further, it is observed that as the aspect ratio (L/B) of anchors increases the breakout factor ratio decreases. The breakout factor ratios suggested by Rowe and Davis (1982) from elasto-plastic finite element analysis and by Merifield *et al.* (2003) from lower bound finite element analysis of circular anchors are shown in Figure 14 for comparison. The predicted values of breakout factor ratio of Rowe and Davis show a similar trend to the experimental results. However, the shape factor proposed by Merifield *et al.* for circular anchors overestimates the present experimental results as well as the results of Rowe and Davis, particularly for higher embedment ratios. Other investigators such as Beard and Lee (1975) and Das (1978) have proposed empirical relations correlating the breakout factors of rectangular to those of square anchors (shape factor). The shape factor suggested by Beard and Lee for plate anchors was similar to that given by Skempton (1951) for the bearing capacity of rectangular foundations and is given by

$$S = \frac{F_{c(R)}}{F_{c(S)}} = 0.84 + 0.16(B/L) \tag{11}$$

Das found that the shape factor suggested by Beard and Lee does not compare well with the results of model tests, particularly for anchors at shallow depths, and suggested an empirical relationship for shape factor of plate anchors located at shallow depths (Equation 12).

$$S = \frac{F_{c(R)}}{F_{c(S)}} = 0.4 + 0.6(B/L) \tag{12}$$

Figure 15 shows the variation of shape factor of deep anchors with B/L as suggested by Beard and Lee (1975). The model test results of Das (1978) and the results of the present investigation are compared with those of Beard and Lee. It is observed that the experimental data do not fit well with the equation suggested by Beard and Lee. Hence, an alternative mathematical relationship giving the variation of shape factors of deep anchors with B/L is proposed in this study (Equation 13).

$$\mathrm{S}^* = 0.290\left[3.588 - \exp^{-1.938(\mathrm{B/L})}\right] \tag{13}$$

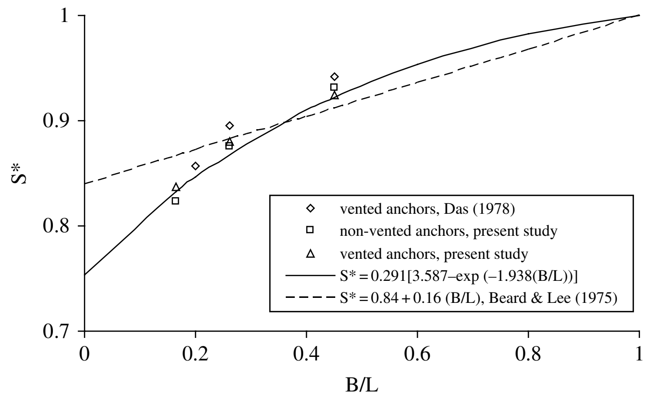

Figure 15. Comparison of shape factors for deep rectangular anchors.

7. Conclusions

The effect of anchor shape on the breakout capacity of plate anchors buried in saturated clay has been examined through a series of laboratory model tests. The shape factors obtained in the present model study have been compared with the empirical relationship given by Beard and Lee (1975), the model test results of Das (1978), the finite element solutions of Rowe and Davis (1982) and the lower bound limit analysis predictions of Merifield *et al.* (2003). Consideration has also been given to embedment depth and base conditions of anchors. The breakout factors obtained for circular and square anchors have been compared with the theoretical, experimental and numerical predictions of earlier researchers. Empirical relationships correlating the critical embedment ratio to the aspect ratio of rectangular anchors have been suggested for both the vented (immediate breakaway) and the non-vented (no breakaway) anchors. Developed suction force for no-breakaway conditions of anchors of different shapes, buried at both shallow and deep locations, has been quantified and its contribution to breakout capacity of anchors has been illustrated graphically.

Based on the results of the present laboratory model tests, the model test results, numerical and theoretical predictions of other investigators, the following conclusions are drawn:

- The breakout factors for square, circular and rectangular anchors are always greater than those obtained for strip anchors for comparable embedment ratios. The breakout factors obtained from the present model tests show a reasonably good agreement with the published results with minor scatter of points.
- The relative movement required to reach the peak pullout capacity is considerably higher for non-vented anchors compared to vented anchors for comparable test conditions. The uplift displacement factor of strip anchors is found to be more than for circular anchors, indicating that more constrained plastic flow occurs before failure of strip anchors than for circular anchors.
- The ultimate uplift pressure of square and circular anchors is found to be more than that of strip anchors under comparable test conditions. For example, the ultimate uplift pressure of square and circular vented anchors at an embedment ratio of two is 16.84 and 16.91 kPa respectively, compared to a value of 10.47 kPa for strip anchor. As the aspect ratio of rectangular anchors increases the ultimate uplift pressure decreases.
- Suction force forms a major part of the undrained breakout capacity of anchors located at shallow depths. For the present test conditions the suction contribution beyond an embedment ratio of 5 is found to be only 22% irrespective of the shape of anchors studied. But this contribution at $H/B = 1$ is around 170% for square and circular anchors and about 260% for strip anchors.
- The critical embedment ratio reflects the transition from shallow to deep anchor conditions and it is found to be a function of the shape of the anchor and the base conditions of anchor. For similar test conditions the critical embedment ratio of non-vented anchors is found to be less than that of vented anchors. Moreover, the critical embedment ratio of strip anchors is found to be more than that of the circular, square or rectangular anchors. Critical embedment ratio is found to increase with the aspect ratio of rectangular anchors. Based on the results of the present model tests and model test results of earlier investigators an empirical relationship correlating the aspect ratio of rectangular anchors to the critical embedment ratio is proposed.
- The shape factor of rectangular anchors is found to decrease with increase in aspect ratio. The shape factor of circular anchors obtained from the present model test show a similar trend to the predictions of Rowe and Davis obtained from elasto-plastic finite element analysis. However, the shape factor proposed by Merifield *et al.* for circular anchors overestimates the present experimental results as well as the results of Rowe and Davis, particularly for higher embedment ratios.
- The shape factors of deep rectangular anchors as suggested by Beard and Lee (1975) do not agree well with either the present experimental results or the model test results reported by Das (1980). An alternative relationship correlating the shape factor of deep rectangular anchors with the aspect ratio is proposed in this work.

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