BEHAVIOUR OF PLATE ANCHORS EMBEDDED IN TWO-LAYERED CLAY SOILS

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SYNOPSIS

Plate anchors are the most common type of anchors used in civil engineering construction for resisting uplift forces. Not much work has been reported indicating the behaviour of anchors in layered soils. In this paper, the behaviour of plate anchors buried in a two-layered clayey soil has been highlighted using model plate anchor of 50 mm diameter embedded in clay. A marine clay is used in the investigation at two different water contents to provide two different layers of soft and medium stiff clayey beds. The investigations are conducted in three different phases, viz. plate anchor in homogeneous clayey beds, plate anchor in medium stiff clayey bed overlain by soft clayey bed and plate anchor in soft clayey bed overlain by medium stiff clayey bed. The tests are conducted at different embedment ratios and the results are discussed in terms of pull out load versus displacement curves. The behaviour of a plate anchor buried in medium stiff clayey bed overlain by soft clayey bed, is explained in terms of shallow and deep anchor conditions. For a plate anchor buried in soft clay overlain by medium stiff clay, it is found that anchor displacement is high before the resistance from the top layer mobilizes.

INTRODUCTION

Plate anchors are among the most common types of anchor used in civil engineering construction as they represent an economical alternative to gravity and other embedded anchors for resisting uplift forces. Typically, such anchors are used to support transmission towers and to secure submerged pipelines, moorings and cables to the sea bed. Many investigators have reported the behaviour of plate anchors embedded in clayey soils (Meyerhof & Adams, 1968; Vesic, 1971; Davie & Sutherland, 1977 and Das, 1978). All of these studies were conducted in homogeneous clayey soils only. But it is also of interest to know the behaviour of a plate anchor in layered soils. A review of the literature shows that few investigators have studied the behaviour of plate anchors in layered soils.

Stewart (1985) was among the first who studied the behaviour of plate anchors in layered soils. He assessed the behaviour of plate anchors buried in a clay soil overlain by a sandy soil through an experimental programme. From this study, it was found that sandy soil in the upper layer increased the ultimate uplift capacity of plate anchor compared to its value when embedded in a clay soil alone. He found

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that large displacements were required to mobilize the frictional resistance of the overlying sandy soil. Sutherland (1988) pointed out that in practice little real benefit to uplift capacity could be achieved by placing a sandy soil over a plate anchor embedded in clay. It was suggested that if a sand overburden was to be used, a more sensible solution would be to place the anchor on the surface of the clay layer and then place sandy soil on top. Bouazza & Finlay (1990) reported the behaviour of a plate anchor buried in a two layered sandy soil. This testing programme was conducted on a 37.5 mm diameter plate anchor buried in dense sandy soil overlain by loose or medium dense sandy soil. From these studies, it was concluded that the ultimate uplift capacity was dependent on the relative strength of the two layers, the depth ratio of embedment and the thickness of the upper layer.

From the literature, it is clear that no work has been done to study the behaviour of plate anchors in layered clayey soil. Hence, in this paper, an attempt has been made to study the behaviour of plate anchors buried in two layered clayey soil by conducting experiments on model plate anchors. Fig. 1 shows the explanatory sketch of the problem. The total depth of embedment of plate anchor of diameter, D is H. The thickness of the bottom layer (layer 1) in which anchor is embedded is H_1. The undrained shear strength, water content and density of this layer 1 are $(C_u)_1$, w_1 and γ_1, respectively. The thickness of the overlying layer (layer 2) is H_2. The parameters for layer 2 are $(C_u)_2$, W_2 and γ_2. The experimental details of the work are presented in the next section.

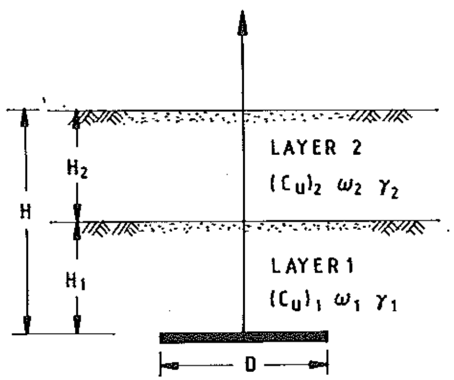


Fig. 1 Plate Anchor in Layered Clayey Soils

EXPERIMENTAL WORK

Model Plate Anchor Used

Tests were conducted on a model circular plate anchor of 50 mm diameter which was made from a mild steel plate of thickness 5 mm. A steel rod having a diameter of 2.5 mm was welded to the centre of the plate.

Soil Used

A marine clay from the coastal deposit in the east coast of India which consisted of 90% of silt and clay fraction (< 0.075 mm) with 10% of sand (passing through 4.75 mm sieve and retained on 0.075 mm sieve was used). The liquid limit (LL) is 82% and plastic limit (PL) is 32%.

Test Tank

The tests were conducted in a cylindrical test tank of 700 mm diameter and 750 mm height. During testing, care was taken in maintaining the distance between the anchor centre and tank walls to be more than 5 times the plate diameter to minimize the side effects (Davie & Sutherland, 1978).

Experimental Set-up

The experimental set-up is shown schematically in Fig. 2. The load was measured using a load cell of 500 N capacity and an upward displacement of the anchor was measured with the help of an inductive displacement transducer with ± 20 mm travel. For tests where the anchor's movement was greater than ± 20 mm a transducer with ± 200 mm travel was used. The outputs from the load cell and the inductive displacement transducer were fed to a multichannel carrier frequency amplifier and the signals were amplified and recorded by means of data acquisition system. As shown in Fig. 2, an arrangement was made at the bottom of the test tank to eliminate suction below the bottom of the plate anchor.

Testing Procedure and Programme

The two layers of soil considered for testing were at two different water contents to simulate soft and medium stiff consistency soil beds. One layer was at a soft consistency [I_c = (LL - water content)/(LL-PL)] of 0.17 with a undrained shear strength (C_u) of 2.2 kPa. The other layer was at a medium stiff consistency of 0.74 with a C_u of 17.5 kPa. The tests were conducted in three phases namely, (1) Tests on a plate anchor buried in a homogeneous soil bed (conducted at two water contents up to an embedment ratio, H/D of 7.0). (2) Tests on a plate anchor buried in medium stiff clayey bed overlain by soft clayey bed (up to a H/D of 5.0) and (3) Tests on a plate anchor buried in a soft clay bed overlain by a medium stiff clay bed (up to a H/D of 4.0).

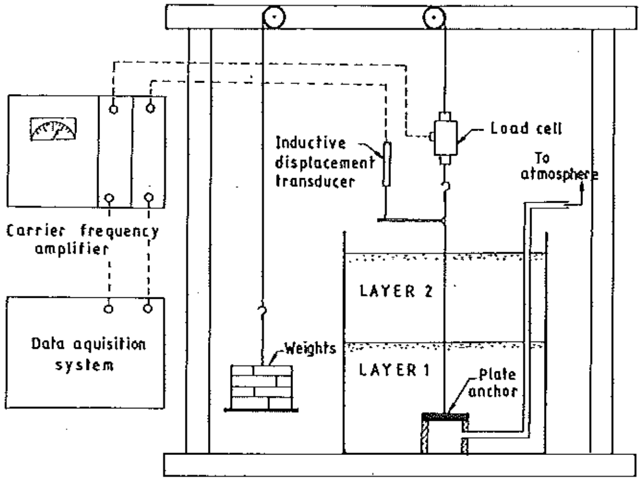


Fig. 2 Schematic Diagram of Experimental Set-up

After the anchor was located in position, the soil was placed in the test tank in hand compacted layers. After hand packing, each layer was pressed with a template so as to remove entrapped air and ensure homogeneity. There was no difficulty involved in placing the soil using this procedure during the preparation of homogeneous soil bed. However, during the preparation of layered soil beds, extreme care was needed to prevent the penetration of one type of soil bed into the other. This was especially required during the placing of the medium stiff clay bed over the soft clay bed. At the interface of two layers, the medium stiff clay soil of 10 to 25 mm thickness was placed gently without applying much pressure on the underlying soft clay layer. Further filling was similar to that of a homogeneous bed. At the end of each test, soil at the interface of two layers was separated and removed.

The undrained shear strength (C_u) of the two soil beds was measured using the field in-situ vane shear apparatus. The densities were 15.5 kN/m^3 and 17.3 kN/m^3 for soft and medium stiff clay beds respectively. The degree of saturation of the soil beds was nearly 1.0.

RESULTS AND DISCUSSIONS

The test results are presented in this section in three parts. The first part deals with the behaviour of plate anchors buried in homogeneous soil bed. The second part deals with the behaviour of plate anchors buried in medium stiff clayey bed overlain by soft clayey bed and third part deals with the behaviour of plate anchors buried in soft clayey bed overlain by medium stiff clayey bed.

Behaviour of a Plate Anchor Buried in Homogeneous Soil Bed

The load displacement curves for the plate anchor buried in soft clayey bed up to a H/D of 7.0 (C_u = 2.2 kPa) are presented in Fig. 3. From this figure, it can be seen that as the H/D increases, the gross ultimate uplift capacity (Q_g) also increases. For values of H/D greater than 2 to 2.5, the increase in the capacity is not much. The reason for this behaviour is very clear. After a H/D of 2.0 to 2.5, the anchor may be behaving as a deep anchor and hence, further increase in H/D does not increse the capacity much (Vesic, 1971 and Das, 1978). The behaviour of plate anchor buried in a medium stiff clay bed (C_u = 17.5 kPa) up to H/D of 7 displays similar behaviour. However the increase in capacity is greater up to a H/D of 4.0, beyond which only a minor increase is observed. It can be seen that the capacities are many times more and displacements are less when compared with the soft clay bed case because of the increase in C_u. From the gross ultimate uplift capacities (Q_g), the net ultimate capacities, Q_u (Q_g - self weight of the anchor) are calculated and are presented in Fig. 5 against H/D for the soil beds prepared at both consistencies. The breakout factors (N_{cu}) are calculated using the following equation (Vesic, 1971) and are presented in Fig. 6.

$$Q_u = A\,(C_u\,N_{cu} + \gamma\,H) \quad (1)$$

where A = area of plate anchor, γ = density and H = depth of embedment of plate

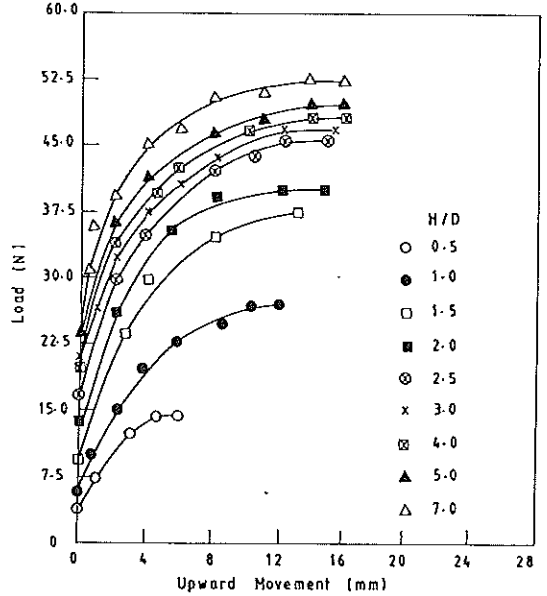


Fig. 3 Load-upward Movement Curves for Homogeneous Soil Bed

anchor. For the purpose of comparison the values reported by Ali (1968) at a C_u of 5.3 kPa and Das (1978) at a C_u of 22.5 kPa are presented in the same figure. It can be seen that there is a good comparison.

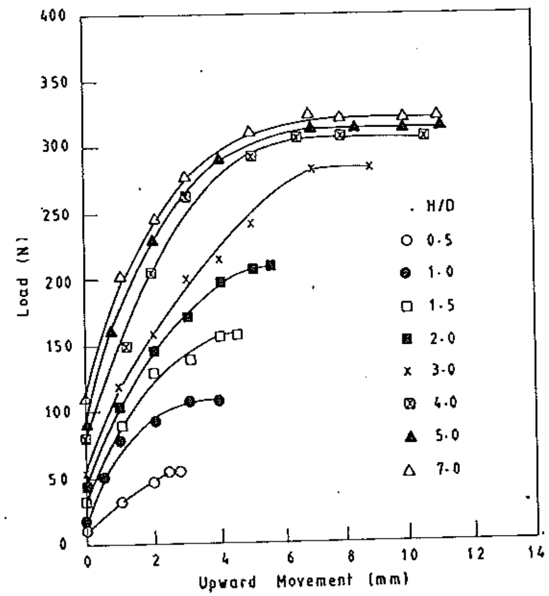
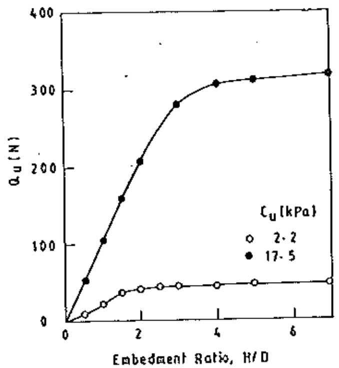


Fig. 4 Load-upward Movement Curves for Homogeneous Soil Bed



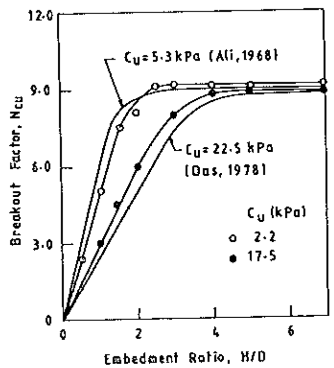


Fig. 5 Variation of Q_u with H/D **Fig. 6 Variation of N_{cu} with H/D**

Behaviour of Plate Anchor Buried in a Medium Stiff Clay Bed Overlain by a Soft Clay Bed

The behaviour of plate anchor under these conditions is explained in terms of load displacement curves. The upper layer thickness is expressed in terms of non-dimensional top layer thickness factor, H_2/D where H_2 = thickness of the overlying layer. In this case, it is the ratio of thickness of the top soft clay layer and the diameter of the plate anchor. In each figure, the upper and lower boundaries of capacity at the same H/D are presented for the purpose of comparison. The maximum value can be taken at $H_2/D = 0$ representing homogeneous medium stiff clay layer and the lowest value can be taken at $H_2/D = H/D$ (i.e. $H_1 = 0$) representing homogeneous soft clay layer.

Fig. 7 presents the load displacement curves at a H/D of 1. In this figure the results corresponding to H_2/D = 0, 0.5 and 1.0 are presented. When $H_2/D = 0$, the soil bed is homogeneous medium stiff clay and the anchor capacity is found to be about 110 N. Similarly when $H_2/D = 1$, the soil bed is homogeneous soft clay and the anchor's capacity is found to be about 27 N. Further, $H_2/D = 0.5$ which is corresponding to a test result of layered soil where the anchor is buried in a medium stiff clay bed of thickness (H_1/D) 0.5 overlain by a soft clay bed of thickness (H_2/D) 0.5, the capacity of the anchor is around 65 N which is inbetween the upper and lower boundaries. From this test, it is clear that there is a marginal increase in capacity due to the overlying soft clay i.e. the capacity of the plate anchor at a H/D of 0.5 in a medium stiff clay bed is 54 N. Because of the additional overlying soft clay (H_2/D = 0.5), the capacity is increased to 65 N which is nearer to the capacity of a plate anchor buried in a homogeneous soft clay layer of H/D = 0.5 alone.

Thus it can be said that, the capacity of a plate anchor buried in layered soils under these conditions is equal to the sum of the individual capacities of a plate anchor buried in two layers separately.

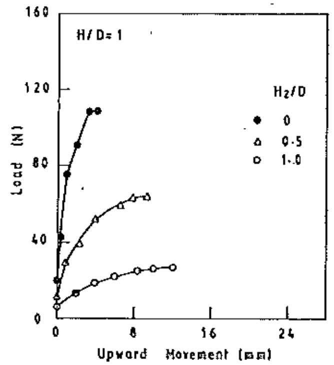


Fig. 7 Load-Upward Movement Curves for Layered Soil Bed (H/D = 1)

Figs. 8 and 9 present the load displacement behaviour at a H/D of 2 and 3 respectively. Similar behaviour that discussed previously is observed. In all these cases, during testing it was observed that there was surface heave with tensile cracks on the surface and this indicates the propagation of a failure surface to the soil surface. From the above discussions, it can be concluded that in the case of a shallow anchor buried in layered soils, as the failure surface extends to ground surface, the capacity depends on both of the soil layers and is approximately equal to the sum of capacities of plate anchor buried in two homogeneous layers separately.

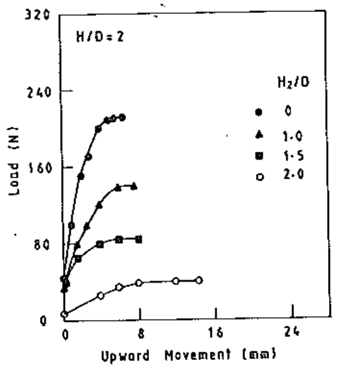


Fig. 8 Load-Upward Movement Curves for Layered Soil Bed (H/D = 2)

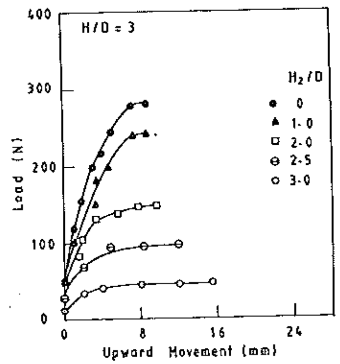


Fig. 9 Load-Upward Movement Curves for Layered Soil Bed (H/D = 3)

However, at higher H/D value of 4 (Fig. 10) a different type of behaviour is observed. From Fig. 10, it can be observed that the capacities are almost the same for the conditions conforming to H_2/D of 0, 1, 1.5 and 2.0. In the case of a medium stiff clay with bed thickness, H_1/D of 2 to 2.5, the anchor's capacity equals the deep anchor's capacity. It should be mentioned here that a deep anchor is one in which the ultimate load is not affected by ground line geometry. At ultimate load, a deep anchor exhbits a local shear failure, wherein only the clay immediately above and around the anchor is subjected to strain (Das, 1978 and Stewart, 1985). So in this case, the local failure may be limited to a depth of 2 to 2.5 times the 'D' and hence the maximum deep anchor's capacity is independent of the strength of the overburden. The anchor's behaviour for both shallow and deep embedment conditions in layered soils is explained in Fig. 11. In this figure, the failure surface indicated in dotted lines is shown. A similar type of behaviour is also observed at H/D of 5 (Fig. 12). Here also the capacities are almost same as the deep anchor capacity at H_2/D of 0, 1, 2 and 3.

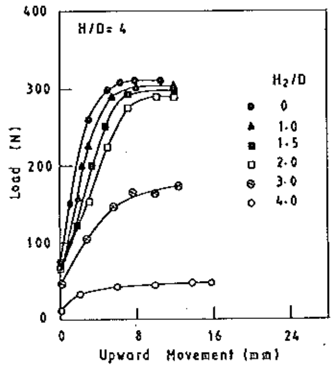


Fig. 10 Load-Upward Movement Curves for Layered Soil Bed (H/D = 4)

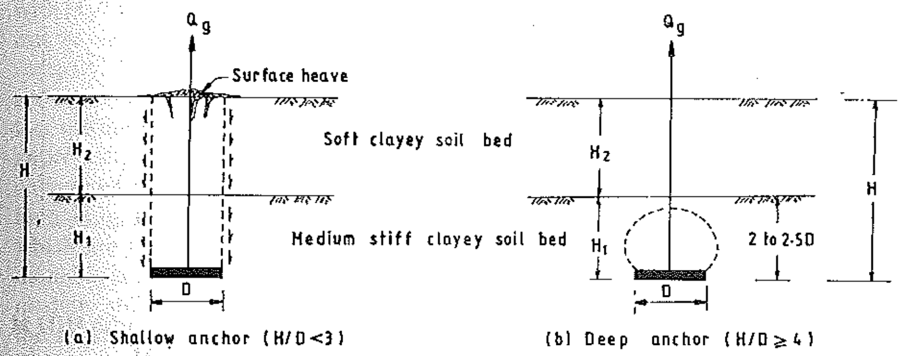


Fig. 11 Behaviour of Plate Anchor in Layered Soils

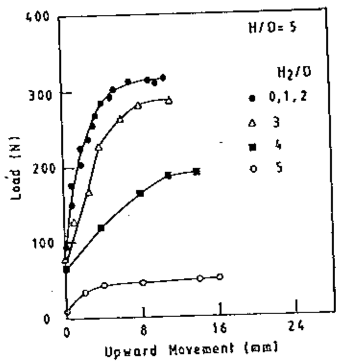


Fig. 12 Load-Upward Movement Curves for Layered Soil Bed (H/D = 5)

All the test results in this phase of testing are summarized in Figs. 13 and 14. Fig. 13 presents the variation of Q_u with H/D for different values of top layer thickness, H_2/D (shown in dotted lines). It can be seen that all the capacities are falling inbetween the upper ($H_2/D = 0$) and lower boundaries ($H_2/D = H/D$). It can be seen that as the H/D is increasing for any constant value of H_2/D, the Q_u values are increasing because of the increase in medium stiff clay bed thickness. Fig. 14 presents the variation of Q_u with upper soft layer thickness at constant H/D values. It can be seen from this figure that in the case of H/D of 4 and 5, up to upper layer thickness, $H_2/D = 2$, the capacities are same as deep anchor's capacity. For any constant value of H/D, as the thickness of the upper soft layer increases there is a reduction in the capacity.

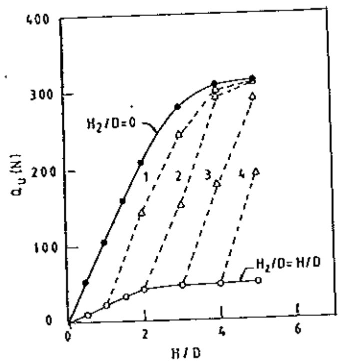


Fig. 13 Variation of Q_u with H/D at Different Values of H_2/D

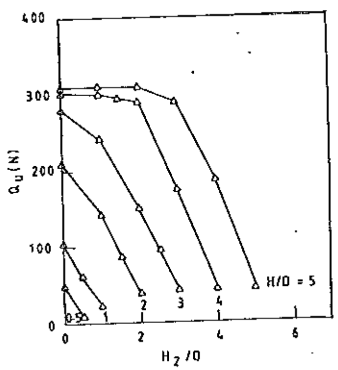


Fig. 14 Variation of Q_u with H/D at Different Values of H/D

Behaviour of Plate Anchor Buried in Soft Clayey Bed Overlain by a Medium Stiff Clay Bed

In this phase of testing, the top layer is a medium stiff clay bed and the non-dimensional top layer thickness is indicated by H_2/D. Figs. 15 and 16 present the behaviour of anchor at H/D of 1 and 2 respectively. In these cases, it can be seen that the capacity of plate anchor in layered soils is within the range of upper and lower boundaries of capacity. Further, the capacities are found to be somewhat lower in comparison to the sum of capacities in individual homogeneous layers. One more observation is that ultimate capacities are attaining at higher displacements.

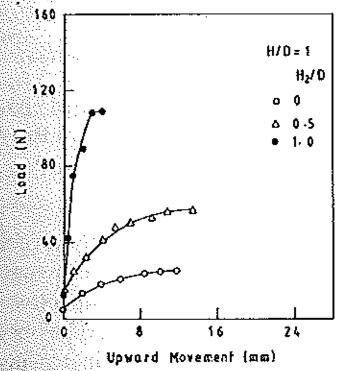


Fig. 15 Load-Upward Movement Curves for Layered Soil Bed (H/D = 1)

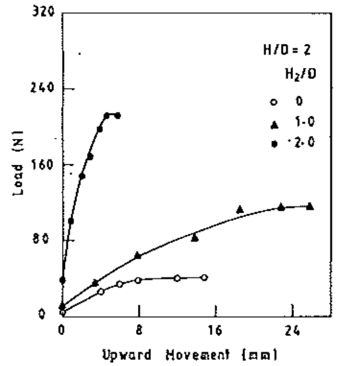


Fig. 16 Load-Upward Movement Curves for Layered Soil Bed (H/D = 2)

Figs. 17 and 18 represent the behaviour at H/D or 3 and 4 respectively. Here it can be seen that the capacities are increased because of the overlying medium stiff clay bed. However, before attaining these capacities, the anchor was displaced by a distance equal to the thickness of the soft layer. For an example in the case of test with H_2/D of 2.5 and H/D of 3, the anchor is buried in a soft clay bed of 25 mm and it can be seen that the anchor moved 25 mm before there was a sudden increase in capacity. Similarly in the case of H_2/D of 2.0, it was displaced by a distance of around 50 mm (soft clay layer thickness). So it can be said that before mobilizing the top medium stiff clay bed resistance, the anchor is getting punched through the entire soft clay bed. A similar type of behaviour can be observed in Fig. 18 which corresponds to a H/D of 4. Eventhough the overlying medium stiff clay bed is increasing the capacity, higher displacements are required to mobilize the resistance which are not allowed in the field. For example, when a plate anchor of 300 mm diameter is installed in a soft clayey bed of 600 mm ($H_1/D = 2$) overlain by 600 mm medium stiff clayey bed ($H_2/D = 2$), it requires a movement of 600 mm to mobilize the resistance from top layer which is not at all acceptable in the field situations. Therefore it is better to terminate the plate anchor in the medium stiff clay layer without touching the bottom soft clayey layer.

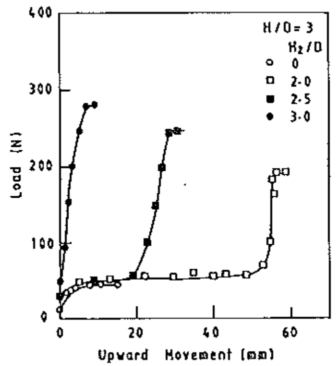


Fig. 17 Load-Upward Movement Curves for Layered Soil Bed (H/D = 3)

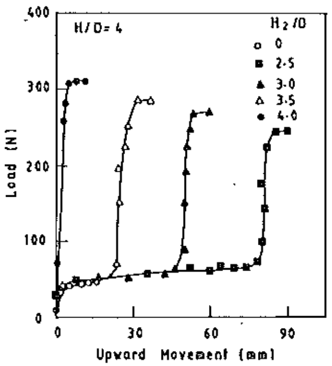


Fig. 18 Load-Upward Movement Curves for Layered Soil Bed (H/D = 4)

Fig. 19 presents the summarized test results in terms of variation of Q_u with H/D at different values of top layer thickness (H_2/D). It can be seen that all the values are lying inbetween the upper and lower boundaries of capacity. Fig. 20 presents the variation of Q_u with upper layer thickness of H_2/D. It can be observed as the H_2/D is increasing for any value of H/D, the capacities are also increasing due to the increase in thickness of the top medium stiff clay bed. Further at any particular value of upper layer thickness, irrespective of H/D value, the capacities are almost the same because of the capacity mainly depends on the upper medium stiff clay bed thickness.

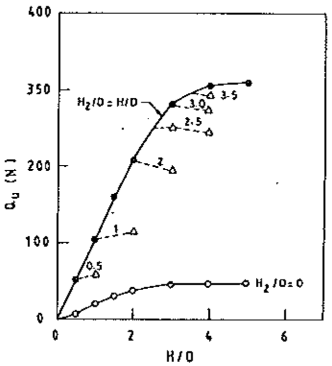


Fig. 19 Variation of Q_u with H/D at Different Values of H_2/D

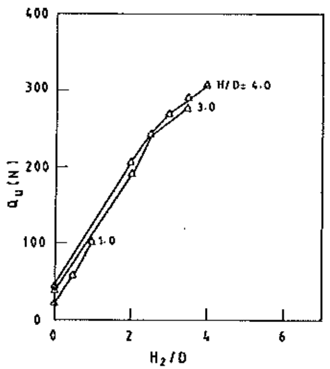


Fig. 20 Variation of Q_u with H_2/D at Different Values of H/D

CONCLUSIONS

Based on the experimental results the following conclusions can be drawn:

The uplift capacities of plate anchors buried in a homogeneous clay bed depend upon the depth of embedment and undrained shear strength of the clay. The break-out factors established are in good agreement with the those from previous investigations.

In the case of plate anchors buried in a medium stiff clay bed overlain by a soft clay bed, the behaviour can be explained in terms of shallow and deep anchor conditions. Up to H/D of 3, where the behaviour seems to be shallow anchor condition, the capacities can be calculated as the sum of the capacities of plate anchor buried in individual layers separately. Beyond H/D of 4, for the plate anchor buried in a medium stiff clay bed with H_1/D of 2 to 2.5 the capacities are found to be equal to that of a deep anchor capacity irrespective of the strength of the top soft layer. This behaviour may be because of the local failure mechanism involved in deep anchors.

For plate anchors buried in a soft clay bed overlain by a medium stiff clay bed, the anchor has to punch through the entire thickness of the soft clay bed to mobilize the resistance from the overlying medium stiff clay bed. As such higher movements are not acceptable in the field, the best solution is to terminate the anchor in a medium stiff clay bed.

REFERENCES

ALI, M.S. (1968) : Pullout resistance of anchor plates and anchor piles in soft Bentonite clay, M.S. Thesis, Duke University, Durham, NC, USA.

BOUAZZA, A & FINILAY, T.W. (1990) : Uplift capacity of plate anchors buried in a two layered sand, Geotechnique, Vol. 40, No. 2, pp. 293-297.

DAS, B.M. (1978) : Model tests for uplift capacity of foundations in clay, Soils and Foundations, Vol. 18, No. 2, pp. 17-24.

DAVIE, J.R. & SUTHERLAND, H.B. (1977) : Uplift resistance of cohesive soils, Journal of Geotechnical Engineering Division, ASCE, Vo. 103, No. GT9, pp. 935-952.

DAVIE, J.R. & SUTHERLAND, H.B. (1978) : Modelling of clay uplift resistance, Journal of Geotechnical Engineering Division, ASCE, Vol. 104. No. GT6, pp. 755-760.

MEYERHOF, G.G. & ADAMS, J.I. (1968) : The ultimate uplift capacity of foundations, Canadian Geotechnical Journal, Vol. 5, No. 4, pp. 225-244.

STEWART, W. (1985) : Uplift capacity of circular plate anchors in layered soil, Canadian Geotechnical Journal, Vol. 22, pp. 589-592.

SUTHERLAND, H.B. (1988) : Uplift resistance of soils, 28th Rankine Lecture, Geotechnique, Vol. 38, No. 4, pp. 493-516.

VESIC, A.S. (1971) : Breakout resistance of objects embedded in ocean bottom, Journal of Soil Mechanics and Foundation Engineering, ASCE, Vol. 97, No. SM9, pp. 1183-1205.