MULTIBELL AND BLOCK ANCHOR CAPACITIES IN SAND

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ABSTRACT

For the support of retaining structures, the use of anchors is often required. A sizeable number of these are either block anchors or multibell anchors with the enlargement of the section at predetermined locations. The pullout capacity of a block anchor normally depends very much on the peripheral friction on its shaft whereas that of a multibell anchor is predominantly dependent on the earth pressures on the faces of the bells. A laboratory-scale investigation was undertaken to study the effect of anchor length on friction, and therefore pullout capacity, on horizontal block and multibell anchors at different embedment depths in sand. The behaviour of multibell and block anchors in purely granular soils was also investigated by means of a two-dimensional pin model analogy and the patterns of the soil flow at failure were qualitatively examined in line with classical plasticity theories. Results obtained from tests in sand showed that for anchor lengths up to forty diameters, the shaft friction of a block anchor increases linearly at each embedment depth considered. A factor α applied to relate the measured friction with that obtained analytically was constant for lengths exceeding a minimum at each depth. α increased sharply for decreasing lengths less than this minimum. The increase in capacity of the multibell anchor was compared with that of a block anchor. A factor β which was the ratio of the multibell friction to block friction was found to be constant for lengths greater than the minima above. For decreasing lengths less than the minima, β decreased.

Key words : block anchors, earth pressure, horizontal load, model test, multibell anchors, pin model analogy, pullout capacity, sand, theoretical modelling (IGC : E 5/E 3)

INTRODUCTION

The use of multibell and block anchors for the support of retaining structures is widespread. Their importance cannot be overemphasised as they represent the bulk of soil anchor types used for such purpose. Multibelling of an anchor gives rise to an

improved pullout capacity which results from the extra passive resistance that is offered by the soil against the translation of the increased crosssectional area of the anchor at the location of the bell. Where multibell anchors are used, the main concern is the broad problem of how these anchors affect the stability of the supported structure.

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Manuscript was received for review on May 26, 1984.

Written discussions on this paper should be submitted before July 1, 1985, to the Japanese Society of Soil Mechanics and Foundation Engineering, Sugayama Bldg. 4F, Kanda Awaji-cho 2-23, Chiyoda-ku, Tokyo 101, Japan. Upon request the closing date may be extended one month.

However, not much attention has hitherto been given to studying the effect of bell spacings on the pullout capacities of multibell anchors with specified number of bells. With block anchors, the advantage is derived mainly from the soil-anchor shaft friction on the surface of the block.

In this paper, a study has been undertaken to investigate the effect of bell spacing on anchor capacity for horizontal anchors and results obtained are compared with those for block anchors of the same diameters as the multibell anchors and with lengths the same as the over all distances between the bells. A simple approach is also advanced to theoretically model the anchor behaviour.

GROUND ANCHOR TYPES

The types of anchors to be used in a particular situation and the method by which they would be installed are usually dictated by the type of structure being restrained and the properties of the soil mass. While some anchors are grouted into rocks, others in the form of deadman blocks depend largely on the passive resistance the soil medium can offer. Yet others, especially injection anchors, depend largely on the shear strength between the grout and the surrounding soil and on the bond between the grout and the tendons. The design of ground anchors is also affected by the kind of connection that is required between the anchor and the structure. In this case, the flexibility, and therefore the allowable movements, of both the anchoring system and the structure at the soil-structure interface play an important role.

Injection anchors are by far the most commonly used system of anchorage in soils in civil engineering practice. Such anchors are mainly used for providing temporary support for the sides of deep excavations (Hanna and Littlejohn, 1969). Their use for permanent purposes are at the moment still decided on conservative designs. Realistic and economic designs must necessarily await the outcome of sufficient

research such as may be carried out on the problem of creep at the grout-soil interface (Ostermayer, 1974) and that of loss of load in the tendons with time (Stille, 1976). The use of injection anchors is moreover limited to soil conditions where grouting is possible: it is for example difficult to properly grout into soft clays.

A comprehensive state-of-the-art of the design and construction of anchors for use in medium-to-hard rock and concrete has been given by Littlejohn and Bruce (1975/76) and also by the British Steel Corporation, B. S. C. (1972). For anchorage in soft rocks, gravel, sand and clay, the use of steel bars in tensioning anchors is not very common but not unusual (B. S. C., 1972). However, anchorage tendons are most commonly made up of many intertwined high tensile steel strands. There are basically three soil anchorage systems (Mitchell, 1974), the particular problems of the constructional conditions dictating what modifications, if any, would be necessary to suit the particular situation.

Type 1:

This is a cylinder filled with grout and it is an anchorage type not commonly used for soils but for rocks. This is because the strength of the anchorage is derived not so much from the grout-tendon bond as it is from the grip between the grout and the surrounding soil.

Type 2:

For this type, a cylinder is enlarged by grouting under high pressure. In general, the anchor hole is drilled with a rotary drill housed in an outer casing. When the total length of the anchorage has been achieved, the tendon is put in place and the grouting commenced as the casing is withdrawn. With the correct grout pressure, the diameter of the grouted zone may be up to four times that of the original anchor hole. It cannot be overemphasised that the construction of this type of anchors always requires care since the success of the anchor depends

Fig. 1. Types 1 to 3 soil anchors

to a large extent on the grouting pressure (Jorge, 1969) which in turn is influenced by the permeability of the soil-to-grout penetration and also by the overburden pressure. This type of anchorage is most useful in cohesionless soils. In clayey soils where voids are not as easily filled, the anchor diameter is enlarged by the high pressure. Sometimes, to facilitate effective grouting into clays, small gravels are forced into the walls of the anchor hole mechanically prior to grouting.

Type 3:

This is a multibell type consisting of a cylinder mechanically enlarged at one or more predetermined positions along the length by means of an expanding cutting tool. It is probably the most effective anchorage system among the three. The reams so made can have diameters up to four times that of the original hole. Types 1 to 3 soil anchors are as shown in Fig. 1.

ESTIMATION OF ANCHOR CAPACITY

Because of the relative strengths of the anchor tendons, the grout material and the surrounding soil, the criterion for defining

the collapse of an anchor is dictated by the soil properties rather than the make-up of the anchor itself. The ultimate pullout capacity of an anchor thus varies considerably with soil type, depth of embedment and method of loading.

Much work has been reported in the literature on the pullout behaviour of plate anchors in uplift or in supporting retaining structures (Adams and Hayes, 1967; Adams and Klym, 1972; Akinmusuru, 1978; Balla, 1961; Biarez et al, 1965; Das, 1975; Hanna and Sparks, 1973; Harvey and Burley, 1973; Larnach, 1972; Neely, 1971; Ovesen, 1964; Smith, 1962; Vesic, 1971; Yilmaz, 1971). The problem of shaft friction on the periphery of anchor blocks have however attracted relatively less enthusiastic attention. While the capacities of plate anchors are derived principally from passive resistance on the plates, the capacities of block anchors depend also on shaft-soil roughness, shaft length and long-term soil behaviour resulting in the advent of creep.

In the absence of very reliable prediction methods, the design of anchors is mostly done based on site experience and empirical design rules. Littlejohn (1970) expressed the ultimate pullout load Q_u of an anchor as

$$\text{and } \left. \begin{aligned} Q_u &= m L \tan \phi \text{ for sand} \\ Q_u &= n H D L c_u \text{ for clay} \end{aligned} \right\} \quad (1)$$

where L is the fixed anchors length, D the anchor diameter, ϕ is the friction angle and c_u the undrained soil strength, and m and n are parameters which depend on method of installation and stressing, soil type, site conditions and anchor inclination. The variety of the factors governing the values of m and n obviously indicate that the range of applicability of these relations would be limited. For supporting retaining structures, these parameters are also compounded by depths of embedment and distance of the anchors from the retained structure. This is so because the shape and extent of the slip surface at failure of the retaining structure influence the distance an anchor is from the wall. It is also worth noting that anchor size depends on the local practice

the designer is used to. For example, in European practice, anchor bores are of the order of 4 in.-6 in. (0.10 m-0.15 m) in diameter whereas bores of up to 12 in.-16 in. (0.3 m-0.4 m) are quite commonplace in American practice.

Hanna (1968) suggested that the fixed anchor length and the pullout capacity of an anchor in clay should be determined rather like a tension pile by separating the pullout resistance into part shaft friction, part end-bearing and part suction. He later (1973) expressed the pullout capacity Q_u of an inclined anchor as

$$Q_u = \sum c_a \cdot \pi D \cdot \Delta L \quad (2)$$

where c_a is the unit adhesion on the shaft. The expression is similar to that proposed by Littlejohn (1970) for cohesionless soils.

The ultimate capacity problem, it has been suggested (Taylor et al, 1975), may be classified into six loading modes, each category offering a unique load estimate for any particular anchor: for a cohesive or cohesionless soil, the loading may be short-term static, long-term repeated or long-term static. The calculation method to be used depends on the soil properties known or assumed. Different soil conditions are assumed and charts are available for determining pullout capacities. Because of the apparent lack of consensus brought about by the insufficient understanding of anchor behaviour, one has to depend on codes which themselves are based on site experience and empirical studies.

The bulk of the work on horizontal anchors (Akinmusuru, 1978; Huckel, 1970; Neely, 1971; Ovesen, 1964; Smith, 1962) have had to do with plate anchors with no shaft friction. However, one relevant field study of considerable merit is that due to Ostermayer (1974). The work reported by him on the resistance to pullout of anchors in well-graded noncohesive soils show that for a given soil the ultimate pullout capacity increases rapidly with increase in soil density. The capacity of an anchor generally increases with increase in its fixed length in such a way that increasing the fixed length beyond

about sixty times the nominal bore diameter of the anchor hole becomes uneconomical (bore diameters of 4 in. (0.1 m) in normal European practice). The rate of increase of the peripheral friction along the shaft of a fixed anchor length generally decreases with increasing shaft diameter and also with increasing anchor length. This, according to him, may be due to the fact that larger elastic deformations of the anchor result in a progressive failure at the grout-soil interface. (Calculations of skin friction were based on the premise that at failure the shear stresses on the shaft of an anchor are uniformly distributed over the surface of the grouted shaft).

The result of Ostermayer's limited field tests in cohesive soils indicate that within practical bore diameters, the skin friction per unit area of anchor shaft is independent of the shaft diameter. Thus, the maximum resistance to pullout increases with increasing shaft diameter. Also, the skin friction is approximately independent of the fixed length but increases with increasing soil consistency and decreasing plasticity. Ostermayer's observations on the creep behaviour of anchors under stress in cohesive and uniformly graded non-cohesive soils show the level of importance creep considerations should be given. This was recently been examined (Akintilo, 1981) and it has been shown that the pullout load-displacement behaviour and the ultimate capacity values of such anchors are influenced by creep displacements. The work of Kulhawy et al (1979) on a cohesionless soil however gave no room for creep displacements.

It appears that when compared with block anchors, the literature has been tacitly quiet on the effect of multibelling on anchor capacity, especially on the effect of bell spacings.

PLANE STRAIN CONSIDERATIONS

In analysing the load and deformation response of a soil to external loading on a

subsurface structure, it is often very useful to have a fore-knowledge of the likely paths the soil grains would follow at failure. This is particularly relevant when applying some plasticity theories to the soil behaviour which is the basis for all limiting equilibrium analyses and has been shown to be useful in foundation analyses (Meyerhof, 1951) and to problems involving anchorages (Balla, 1961 ; Ovesen, 1964) and cofferdams (Mazurkiewicz, 1972).

It is worth noting that many techniques have been developed for monitoring the movements of soil grains in granular materials. Carr (1970) installed specially-made movement gauges in the soil and by measuring such movements in the vertical and horizontal directions, could trace the grain movement in any direction. Another method consists of using colourings to layer

the soil around the structure in a transparent box (Baker and Kondner, 1965). The Cambridge method (James and Bransby, 1971) consists of monitoring the movements of lead shot markers embedded in the soil by means of an X-ray photography technique.

It has been shown (Schneebeli, 1957) that planar conditions in a frictional soil can be effectively simulated by using steel pins to represent the soil. It is a most satisfactory method as it eliminates the end effects of test boxes on the soil movements and so guarantees plane strain conditions. This method has been extensively used for various foundation simulations (Boucraut, 1964 ; mazurkiewicz, 1972 ; Ovesen, 1964).

In this paper, the Schneebeli pin model method has been used to explain the behaviours of multibell and block anchors in sand. Typical multibell and block

(a)

(b)

Fig. 2. Multibell and block anchorage arrangements for pin model analogy tests

(a)

(b)

Fig. 3. Failure paths around multibell and block anchors in two-dimensional tests

anchorage arrangements for horizontal anchors are shown in Fig. 2. The testing procedure is similar to that described elsewhere (Akinmusuru, 1978) on single anchor plates. Time exposure photographs taken of the failure zones of typical multibell and block anchors are shown in Fig. 3. The following observations can be made about their shapes.

(a) For the same length, there is close similarity in the failure zones obtained for both multibell and block anchors.

(b) As with all single anchor tests (Akinmusuru, 1978) no portion of the failure zone extends below the base of an anchor.

(c) Each anchor, multibell or block, carries more load than a plate anchor of the same diameter and at the same depth, the difference between them being the contribution of the friction along the anchor length.

(d) A typical rupture line may be divided essentially into three parts: a curved active, a near-horizontal linear and a curved passive, the linearity and horizontality of the middle section being more pronounced for the block.

Because of the roughness of the surfaces of the block anchor, much friction is created along the surface and also within the "soil grains" parallel to and above the block length. A typical slip line therefore has a trough shape. The reasoning behind the near-W shape of a typical slip line obtained for a multibell anchor may be explained along a different line. The active zone of the trailing plate and the passive zone of the leading plate are fully mobilised. The leader, it appears, carries more load than a single plate anchor would because the trailer disturbs the mobilisation of the active pressures behind it which would normally have decreased its pulling capacity. With similar reasoning, for the trailer, the mobilisation of its passive pressure is hampered by the movement of the leader. The gain in resistance by the leader it seems reasonable to assume, is thus countered by the active zone behind the trailer. The soil

Fig. 4. Assumed failure patterns around single, block and multibell anchors

confined between the plates is moved literally as a block for small spacings between the plates. As spacing increases, more room becomes available for the mobilisation of the passive pressure on the trailer thereby resulting in increased pullout capacity. Thus, with increased length of a block anchor or increased spacing of a multibell anchor, pullout capacity increases.

In Fig. 4, the rupture patterns of a block anchor and a multibell anchor have been compared with that of a single isolated vertical plate anchor. On both active and passive sides of a single anchor, it may be assumed that, along the lines of the classical general soil shear failure, there exists the zones I, II and III as follows:

I-zone of elastic equilibrium. This zone is essential when computing soil capacity by a limiting equilibrium method of analysis. It is nonexistent however if a slip line method of analysis (for example, Sokolovskii's, 1965) is used in a computation. (Note that there is no reason why the portion of the slip line in this zone could not be other than linear, for example circular, provided that the slip line meets the anchor plate at the statically correct

angle).

II-zone of radial shear. This is basically a Prandtl zone consisting of a system of straight lines radially emanating from the apex, and a system of logarithmic spirals with the apex as their pole.

III-zone of plastic flow. This is a Rankine zone consisting of two systems of straight parallel lines intersecting each other at $(90 \pm \phi)$ degrees.

In comparison with a single plate anchor, it appears that for a block anchor, zone I is nonexistent and that zone II has been largely depleted. Only zone III appears intact. The effect of the length of the block is to bring about a new friction zone IV since its size and extent depend on the anchor-soil cleavage as well as the length. In the case of multibell anchors, the interaction of trailer passive zone and leader active zone brings about the near-W shape observed, the size depending on the spacing between bells.

It may be noted that while in the case of a plate anchor (Akinmusuru, 1978) a depth-to-base of anchor of 6.5 times the anchor diameter was defined as the depth demarcating shallow from deep locations, in the case of multibell and block anchors, such a demarcating depth is not unique as this depends on the extent of the oblong shape of the failure zone which is in turn dependent on the length of the anchor block (or the spacing between reams in a multibell anchor): the longer the anchor, the deeper such a demarcating depth is.

A SIMPLE THEORETICAL MODEL

Consider a horizontal block anchor (Fig. 5), embedded in a deep homogeneous purely granular sand bed, that has diameter h and length ρh where ρ is the nondimensional measure of block length in diameters. Let the depth of embedment to the centre of the anchor be λh where λ is the nondimensional depth. Let the soil be characterised by a friction angle ϕ and unit weight γ . Let Q_a and Q_p be the active and passive forces

Fig. 5. Geometry of the block anchor problem

at the ends of the block and F_u the friction on the shaft at failure. Therefore, pullout capacity, Q_u can be expressed as

$$Q_u = Q_p - Q_a + F_u \quad (3)$$

Assuming Rankine conditions,

$$Q_p = \frac{1}{4} \Pi \gamma \lambda k_p h^3 \quad (4)$$

and

$$Q_a = \frac{1}{4} \Pi \gamma h k_a h^3 \quad (5)$$

where k_p and k_a are the coefficients of passive and active pressures respectively.

$$\text{Also, } F_u = \Pi \gamma \lambda \rho h^3 \tan \delta \quad (6)$$

where δ is the angle of shaft-soil friction.

$$\therefore Q_u = \frac{1}{4} \Pi \gamma \lambda h^3 [(k_p - k_a) + 4 \rho \tan \delta] \quad (7)$$

$$\text{Since } k_p = \frac{1}{k_a} = \frac{1 + \sin \phi}{1 - \sin \phi} \quad (8)$$

it can be shown that

$$k_p - k_a = 4 \tan \phi \sec \phi \quad (9)$$

$$\therefore Q_u = \Pi \gamma \lambda h^3 (\tan \phi \sec \phi + \rho \tan \delta) \quad (10)$$

The value of δ is usually unknown but must necessarily lie between zero and ϕ . It may be taken from the recommendations of Potyondy (1961) in which values have been derived for various δ/ϕ ratios for different soil-structure surfaces. Alternatively, the value may be assumed (Bowles, 1977) as

$$\delta = \tan^{-1} \left(\frac{2}{3} \tan \phi \right) \quad (11)$$

$$\therefore Q_u = \frac{2}{3} \Pi \gamma \lambda h^3 \tan \phi [1.5 \sec \phi + \rho] \quad (12)$$

from which the friction component is given by

$$F_u = \frac{2}{3} \Pi \gamma \lambda \rho h^3 \tan \phi \quad (13)$$

Eq. (13) would be affected by many factors which include depth of embedment (that is, whether the embedment depth is shallow

or deep), method of soil compaction, initial stress state within the soil as typified by the overconsolidation ratio, and method of anchor installation. Thus, Eq. (13) may be re-written to allow for the diverse influences, that is

$$F_{u(\text{block})}(\text{theory}) = \alpha \gamma \lambda \rho h^3 \tan \phi \quad (14)$$

in which α is a factor that is a measure of the above influences on F_u . (Note that the constant $2H/3$ in Eq. (13) has been absorbed into the value of α .)

For a multibell anchor, the movement of the soil between the anchor plates would also generate some friction. This however does not lend itself to an easy modelling as has been possible with the block anchor. However, if the multibell anchor is compared with the block anchor, an expression for the friction, $F_{u(\text{multibell})}$ may be written in the following form:

$$F_{u(\text{multibell})} = \beta \cdot F_{u(\text{block})} \quad (15)$$

where the factor β is a measure of how much friction is brought about around a multibell anchor as compared with a block anchor.

LABORATORY EXPERIMENTS

Model experiments were performed on block and two-plate multibell anchors in a homogeneous sand bed. The test flume was a 13 mm thick well-stiffened wooden box of length 2.25 m, width 0.5 m and height 0.5 m open at the top and having a 7.5 mm hole drilled along the centre-line of one of the 0.5 m $\times$ 0.5 m vertical faces 0.38 m from the top to allow for the passage out of the box of the anchor rod. The soil used was uniformly graded dry sand passing through British Standard (B.S.) No. 14 sieve and retained on B.S. No. 200 sieve; $D_{50} = 0.43$ mm and $D_{10} = 0.14$ mm; specific gravity = 2.70. The tests were carried out at a density of 1635 kg/m^3 (16 kN/m^3) and a friction angle of 35° . The earth bed was prepared by placing the sand in the test flume in 25 mm layers and compacting each layer to the same state of compaction with

the same compactive effort. The method of compaction ensured a uniform state of compaction with good repeatability. Anchor plates for use in a multibell anchor were 42 mm diameter steel plates 6 mm thick. The pullout rod was a long 6 mm diameter rod passing through the centres of the plates, one plate being at one end of the rod and the other positioned at the required spacing. The free end of the pullout rod was passed through the hole in the front of the test flume. At all times, the pullout rod was positioned horizontally. A block anchor was made by sealing the ends of a galvanised steel tube 42 mm outside diameter with 42 mm diameter steel plates, the length of the tube being the overall length of the block anchor. The pullout rod was then screwed into the centre of one of the sealing plates.

For each test, the sand was compacted into the box until the level of the base of the anchor assembly was reached. The anchor was then put in place, the pullout rod passing through the hole made for the purpose in the front face of the test box. The soil was then compacted around and above the anchor until the required height of soil above it was reached. To the free end of the pulling rod was attached a flexible wire which was passed horizontally over a pulley to a vertical loading pan. To load the anchor, a small load was placed on the pan and the corresponding movement of the tip of the pulling rod was monitored on a dial gauge. Further load increments were applied and corresponding displacements measured. The graph of the load versus displacement was plotted and the ultimate failure load was determined from the graph using the method described elsewhere by

Fig. 6. Schematic representation of a multibell anchor test

the author (Akinmusuru, 1982). In most cases, ultimate pullout capacity was followed by strain hardening of the soil.

The test arrangement is shown schematically in Fig. 6 for a multibell anchor.

TEST RESULTS

Following the suggestions made elsewhere (Akinmusuru, 1978), tests were performed at the two depths-to-centre-of-anchor of 2.5 and 8.5 times the anchor diameter (respectively corresponding to depths-to-base of 3 and 9). Initial tests were carried out on a single plate anchor at these depths to serve as comparators for the multibell and block anchor tests results. The ultimate pullout load at each depth obtained as the average from three tests were 14.07 kg (0.14 kN) at the depth of 2.5 diameters and 39.9 kg (0.39 kN) at 8.5 diameters. These corresponded to unit pressures of 10.16 Mg/m² (99.63 kN/m²) and 28.80 Mg/m² (282.52 kN/m²).

Block Anchors

Eq. (13) shows that the contribution of friction on a block anchor would be obtained from subtracting the pullout capacity of a plate anchor from that of the block anchor. Figs. 7 and 8 are graphs of the friction forces obtained in the experiments against the anchor length ρ in diameters for the two test depths of embedment. They show that the peripheral friction on the block

increased linearly with increasing block length, the graphs passing through the origins of coordinates. This implies that within the range of block lengths tested (up to 40 anchor diameters), the pullout capacity of the block anchor increased linearly with increasing length.

Fig. 8. Variation of friction with block anchor length ($\lambda=8.5$)

Fig. 9. Variation of theoretical F_u/α with block anchor length ($\lambda=2.5$)

Fig. 7. Variation of friction with block anchor length ($\lambda=2.5$)

Fig. 10. Variation of theoretical F_u/α with block anchor length ($\lambda=8.5$)

Fig. 11. Variation of experimental α with block length ($\lambda=2.5$)

Fig. 12. Variation of experimental α with block length ($\lambda=8.5$)

From Eq. (14), the quantity

$$\frac{F_{u(\text{block})}(\text{theory})}{\alpha} = \gamma \lambda \rho h^3 \tan \phi \quad (16)$$

The right-hand side of Eq. (16) implies that $F_{u(\text{block})}(\text{theory})/\alpha$ would vary linearly with length ρ . This relationship is shown for depths of 2.5 and 8.5 diameters in Figs. 9 and 10 respectively.

To obtain the experimental values of α for each anchor length, the following relationship can be used:

$$\alpha_{(\text{experimental})} = \frac{F_{u(\text{measured})}}{\gamma \lambda \rho h^3 \tan \phi} \quad (17)$$

The variations of this parameters with anchor length are shown in the graphs in Figs. 11 and 12 for the two embedment depths. They show that the α -values are approximately constant for anchor lengths greater than about 15 diameters for embedment depth of 2.5 diameters and about 10 diameters for depth of 8.5 diameters. For lengths less than these, α rises steeply for decreasing lengths. The shape of the graphs

for very small lengths can be understood from consideration of the shapes of the two-dimensional pin model analogy for blocks (Fig. 3) and for plate anchors (Akinmusuru, 1978). It is obvious that for very small block lengths, contributions due to peripheral friction would be practically negligible. With length ρ tending to zero, α in Eq. (17) increases infinitely.

Multibell Anchors

Since it has been shown that the behaviour of a multibell anchor is difficult to model in details as that of the block anchor, it seems that Eq. (15) may be adequate to relate the multibell anchor behaviour to that of the block anchor. The values of β so obtained have been plotted in Figs. 13 and 14 respectively for the two test depths. Results show that the values of β initially increased up to anchor lengths (or multibell spacings) of about 15 diameters after which β practically remained constant. For a very small multibell anchor length, the passive zone in front of the trailing plate cannot be fully mobilised and therefore, the full potential of the multibell arrangement

Fig. 13. Variation of β with anchor length ($\lambda=2.5$)

Fig. 14. Variation of β with anchor length ($\lambda=8.5$)

cannot be fully utilised. As multibell spacing increases, this is enhanced more and, at 15 diameters, the full mobilisation is achievable. Irrespective of the spacing after 15 diameters (at least up to the maximum of 40 diameters investigated), although the failure zones around the bells of the anchor no longer overlap, the fact that the passive zone of the trailing bell passes through soil that has been sheared by the leading bell means that the passive pressure in front of the trailer cannot be as high as that in front of an equivalent isolated plate anchor. Thus, the maximum value of β is always less than unity. Also, since the value of β completely depends on the friction on the block, the multibell friction being constant for any particular length (Eq. (15)), it follows that the magnitude of the maximum constant value of β would depend on the anchor shaft-soil friction angle δ . The trend of Figs. 13 and 14 should however be the same for all δ possibilities. It appears reasonable to assume that for a block anchor that has been constructed by grouting under high pressure, the friction between the grout and the soil would be maximum, that is

$$\delta = \phi \quad (18)$$

This would necessarily alter Eqs. (11)-(13) and the friction $F_{u\phi}$ for $\delta = \phi$ would then be

$$F_{u\phi} = \Pi \gamma \lambda \rho h^3 \tan \phi \quad (19)$$

The value of α in Eq. (14) would correspondingly be affected. The patterns of the results in Figs. 11 and 12 would however remain essentially unaltered. It may be noted that the constant values of α and β obtained in Figs. 11-14 depend on their depths of embedment.

CONCLUSIONS

A laboratory-scale study has been carried out to investigate the effects of length and shaft friction on block anchor capacities and also to compare the capacities so obtained with those of corresponding multibell anchors, these anchors being the types

normally required to support retaining structures. The qualitative behaviour of block and multibell anchors in sand have been found modellable in a two-dimensional pin model to be analogy. It has been further shown that for both anchor types, there are many similarities in the patterns of soil flow at failure. From both the pin model analogy and the experiments in sand, the following can be deduced:

(1) As the anchor length becomes reduced to zero, the capacity approaches that of a single isolated vertical plate anchor and the contribution of shaft friction is thus reduced to zero.

(2) The contribution of shaft friction for a block anchor is brought about by the roughness of the shaft of the block while that of a multibell anchor on the other hand results from the interaction of the passive zones of the trailer bells and the active zones of the leaders. This is the cause of a near-W shape observed in the 2-D analogy for the soil flow around a multibell anchor. For the same anchor size and depth of embedment, the friction on a multibell anchor is less than that of a block anchor.

(3) It was established that within the range of block anchor lengths investigated (up to 40 anchor diameters), the contribution of friction to pullout capacity increased linearly with increasing length at the depths of embedment under consideration. A factor α applied to the theoretical value of shaft friction was found to be constant for lengths greater than 15 diameters for embedment ratio of 2.5 diameters and 10 diameters for embedment ratio of 8.5. The magnitude of this constant depends on embedment depth. The factor α increased sharply with decreasing anchor lengths less than those stated above.

(4) A factor β that compares the friction on a multibell anchor with that of a block anchor has also been shown to be dependent on the anchor length. β increased with increasing anchor length up to 15 diameters for embedment ratio of 2.5 diameters and 10 diameters for embedment

ratio of 8.5 after which it remained constant for increasing lengths. It is worth noting that for any embedment depth, the range of lengths for which α is constant is the same for β . For shorter lengths, α increases sharply and β decreases for decreasing anchor lengths. The values of α and β are influenced by the depths of embedment.

(5) The simple theoretical modelling of the friction, and therefore the pullout capacity, of a block or multibell anchor in purely granular soils described in this paper show close agreement between calculated and measured friction forces on an anchor for length beyond a minimum value, this minimum being dictated by the embedment depth.

ACKNOWLEDGEMENT

The author wishes to express his gratitude to Mr. J.C. Ezech for assisting with the experiments.

NOTATION

- F_u = friction on the anchor shaft
 $F_{u(\text{block})}$ = measured friction on block anchor
 $F_{u(\text{block}) (\text{theory})}$ = theoretical value of friction on block anchor
 $F_{u(\text{multibell})}$ = measured friction on multibell anchor
 h = anchor diameter
 k_a, k_p = coefficients of active and passive pressure
 Q_a, Q_v = active and passive forces on the ends of anchor
 Q_u = ultimate pullout capacity of anchor
 α = shaft friction factor
 $\alpha (\text{experimental})$ = value of α derived from experimental data
 $\beta = F_{u(\text{multibell})} / F_{u(\text{block})}$
 δ = angle of soil-anchor friction
 γ = unit weight of soil
 λ = depth-to-centre of anchor expressed in anchor diameters
 ϕ = angle of internal friction of soil
 ρ = anchor length in anchor diameters

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