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Experimental Investigations on Pullout Capacity of Vertical Anchors

K. Rajagopal* and V. Sri Hari†

Introduction

Anchors or buried structures, which can be idealised as anchors, form an important component of civil engineering projects. Typically horizontally placed anchors are used to support transmission towers etc. in which the predominant force is in the vertical direction and vertical plate anchors are used to support retaining walls in which the force is in the horizontal direction. Vertical anchors are also used to support horizontal loading which acts at bends in pipelines. These anchors can be used singly or in a group depending on the magnitude of the applied load. In general there are several types of anchors used for transferring loads to the surrounding soil. The vertical plate anchors derive their load carrying capacity from the passive resistance developed by the soil in front of the plate.

A number of researchers have studied the behaviour of these anchors through experiments, limit equilibrium and finite element based analytical methods. Neely et al. (1973) carried out extensive work on the pull out behaviour of vertical plate anchors. The behaviour of these anchors was studied through experimental and theoretical means. A comparison was made between the experimental and theoretical results and also with the available field data. It was concluded that the load displacement behaviour of these anchors was a function of ratio of width of anchor to its height and ratio of the embedment depth to the height of anchor. Das (1975) studied the pullout behaviour of square and circular vertical anchors embedded at shallow depths in cohesionless soils. Empirical relations were given for computing the

* Associate Professor, Department of Civil Engineering, Indian Institute of Technology - Madras, Chennai – 600036, India.

† M.S. Student (former), Department of Civil Engineering, Indian Institute of Technology - Madras, Chennai – 600036, India.

ultimate pull out capacity of square and circular anchors. The capacity of circular anchors was reported to be 66% that of a corresponding square anchor.

Rowe and Davis (1982) have reported results from two-dimensional finite element analyses of continuous vertical and horizontal plate anchors. The influence of embedment ratio, friction angle, dilation angle, initial stress state, anchor roughness and the orientation of anchor on the pullout behaviour of anchor were examined. It was observed that anchors with horizontal axis exhibited higher collapse loads, and greater contained plastic deformations before collapse, than vertical anchors. Further, it was reported that deep anchors of both types required larger deformations to develop peak capacity than those installed at shallow depths. Soil dilatancy was found to have a significant effect on the pull capacity of anchors for both types of anchors.

Dicken and Leung (1985) evaluated the available design methods in comparison with the recent conventional and centrifugal model test data for isolated (single) and continuous anchors embedded in dense sand. Conventional and centrifugal laboratory model tests were performed on vertical plate anchors. The test results from centrifugal model test indicated that the force coefficient decreased with increase in size of anchor. Hanna and Ranjan (1992) studied the problem of generalising the load displacement characteristics of shallow vertical anchor plates subjected to horizontal pull. The mathematical formula proposed by Trautman and Kulhaway (1988), which utilises a rectangular hyperbola to represent the load displacement curves for horizontal anchor plates subjected to vertical pullout, was modified for the vertical anchors subjected to horizontal pull. The data from the laboratory model pullout tests and the available field data was used for this purpose. Utilising the experimental data attempt was made to identify the displacements at 50% and 100% failure loads. The proposed approach provides the load displacement behaviour along the complete range of loading.

Tagaya, Scott and Aboshi (1988) have proposed formulas to estimate the uplift capacities of plate anchors placed in medium to dense sandy soil. The solution for shallow anchors proposed by Meyerhof (1973) was validated once again and a solution for the deep anchors from the theory of plasticity with the concept of cavity expansion was introduced. The results of elasto-plastic finite element analyses using the constitutive model proposed by Lade (1972) were compared to the results obtained from the centrifugal model tests. The shape factor of finite length anchor has been proposed as $S_h = 1 + H/L$ in which L and H are length and height of the anchor. For square and circular anchors, S_h is 2.0. The dimensionless ultimate uplift resistance factor increased linearly in the shallow regions as the relative embedment depth was increased and becomes constant after certain relative depth. Chattopadhyay and Pise (1986) proposed a theoretical model assuming a curved axi-symmetric failure surface through the surrounding soil to predict the ultimate breakout capacity of horizontal circular plate anchors embedded in sand.

Compared to the previous studies in this area, this investigation proposes to consider wider ranges of embedment depths, friction angles of soils, sizes and shapes of anchors. It is proposed to develop more generalised and simple equations to determine the pullout capacity of vertical plate anchors as a function of various parameters.

Test Facility

The pullout tests on vertical plate anchors were performed within a test tank of dimensions 0.8m long, 0.6m wide and 1.0m high. This tank was fabricated using 6mm thick mild steel plates and ISA sections. Transparent perspex sheet was provided on one of the longitudinal sides of the tank in order to be able to view the internal deformations of the soil. All the other sides of the tank were made of mild steel plates. The side walls of the test tank were stiffened with 40mm size L-angles (40 × 40 × 8mm) spaced at 400mm centre to centre to prevent their outward bulging.

Properties of the Soil Used in Tests

A poorly graded dry beach sand consisting of predominantly quartz mineral was used for these tests. The D_{10}, D_{30} and D_{60} of the soil are 0.15, 0.22 and 0.34 mm respectively. The coefficient of curvature (C_c) and coefficient of uniformity (C_u) of the soil are 0.95 and 2.26. According to the Indian Standard Classification System, this soil can be classified as a poorly graded sand with letter symbol SP.

The minimum and maximum unit weights of the soil were determined according to the relevant Indian Standard code and found to be 14.90 and 16.95 kN/m^3. The above tests were repeated for a minimum of three times and an average value was used. The relative density and the friction angle of this soil at various compaction levels was determined *a priori*. The soil as such was not subjected to any compaction in the tests but its density was maintained uniform by dropping it through a funnel from pre-determined heights. This technique of placing the sand is referred to as sand raining technique and was found to be convenient in controlling the soil properties during the tests. The relative densities and other shear strength properties of the sand used in the tests at various heights of fall are shown in Table 1.

The soil within the test tank deforms without developing any strains in the out-of-plane direction. This state of strain can be idealised as plane-strain

Table 1
Properties of the Soil

S. No.	Height of Fall (mm)	Unit Weight (kN/m^3)	Relative Density (%)	Friction Angle (ϕ^o)	Dilation Angle (ψ^o)
1	100	15.25	20.0	30	3
2	200	15.50	41.2	33	9
3	300	15.90	57.0	36	12
4	400	16.95	62.0	38	15

state. The strength of soil under this deformation conditions is better represented by properties from direct shear tests than from triaxial tests. Hence the shear strength properties of the soil were determined from direct shear tests. One of the important parameters considered in pull out tests on vertical plate anchors was the influence of relative density. Hence, the direct shear tests were carried out at three different relative densities to obtain the corresponding angles of internal friction. The dilation angle that controls the volume change behaviour of soil was defined as the ratio of the incremental vertical deformation and incremental shear deformation.

Pullout Tests

The influence of various parameters on the pullout behaviour of vertical anchors such as the shape and size of the anchors was studied by testing under different conditions. The different shapes tested were square, rectangular and circular. Three different sizes of square anchors viz. 25mm, 35mm and 50mm were tested. Tests were performed on rectangular anchors of size 100mm wide and 50mm in height. In order to study the effect of shape, further tests were performed on circular anchors having a diameter of 56.4mm which have an equal area of that of a 50mm square anchor. The anchors were tested at three different relative densities having internal friction angles of 33°, 36° and 38° respectively. The corresponding heights of fall required to develop the soil strengths are respectively 200mm, 300mm and 400mm.

The conventional definition of the embedment ratio (E_r) of vertical anchors is given in the literature as h/H in which h is the height of the soil above the bottom level of anchor and H is the height of the anchor. This definition can not consider the influence of any surcharge pressures acting on the surface of soil. Hence, this definition of embedment ratio was broadened by re-defining it as $\sigma_v/\gamma H$ in which σ_v is the vertical pressure at mid-depth of anchor, γ is the unit weight of the soil and H is the height of the anchor.

The 25mm square anchors were tested at embedment ratios of 4.5, 8.5, 10.5, 16.5 and 24.5. The 35mm square anchors were tested at embedment ratios of 2.09, 4.11 and 6.21. The behaviour of 35mm square anchors at higher embedment ratios was studied by testing anchors with a uniform surcharge applied on the surface of the soil. These anchors, placed at a depth of 400mm below the soil surface, were also tested with surcharge pressures (σ_v) of 25kPa and 50kPa. The corresponding embedment ratios for these two surcharge pressures, calculated using the following relation, were 58 and 97.9.

$$E_r = \frac{\sigma_v + \gamma \times 0.4}{\gamma H} \qquad (1)$$

The above series of tests were performed at a relative density of 41.2%. In the case of 50mm square anchors the embedment ratio was varied from 2.5 to 10.5 with an increment of 2. In order to study the influence of the relative density of the soil these tests were performed at three relative densities of 41.2%, 57% and 62%. The 100 × 50mm rectangular anchors were also tested at the same relative densities and embedment ratios.

The interaction behaviour of two anchors placed at different centre to centre spacing was studied by pulling them together. For these tests 50mm square anchors and 100 × 50mm rectangular anchors placed at centre to centre spacing(s) of 150, 200 and 300mm were used. The corresponding clear spacings were 100, 150 and 250mm for square anchors and 50, 100 and 200mm respectively for rectangular anchors. The above c/c spacings correspond to s/H ratios of 3, 4 and 6. All the tests were repeated twice and the average results are reported.

Test Arrangement

A pullout test arrangement was fabricated for conducting the model pullout tests on vertical plate anchors as shown in Fig. 1. This pullout arrangement can be bolted to the side projections of the walls at the front of the tank. This arrangement can be connected at different depths of the tank depending on the depth of embedment of anchor plate. The anchor plates were cut from a 6mm thick aluminium plate. These anchors were connected to a loading mechanism through a tie rod and a 3mm diameter brake line rope which passes through a pulley mechanism as shown in Fig. 1. The tie rods were of mild steel bars of 6mm diameter. The pullout loads were applied through hanging weights applied at the end of the rope. The

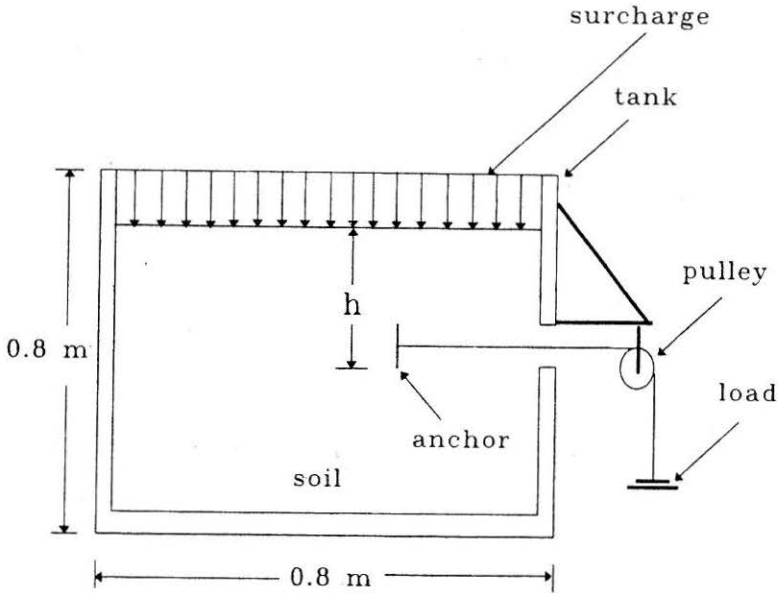

FIGURE 1 : Test Set-up for Pullout Tests on Vertical Anchors

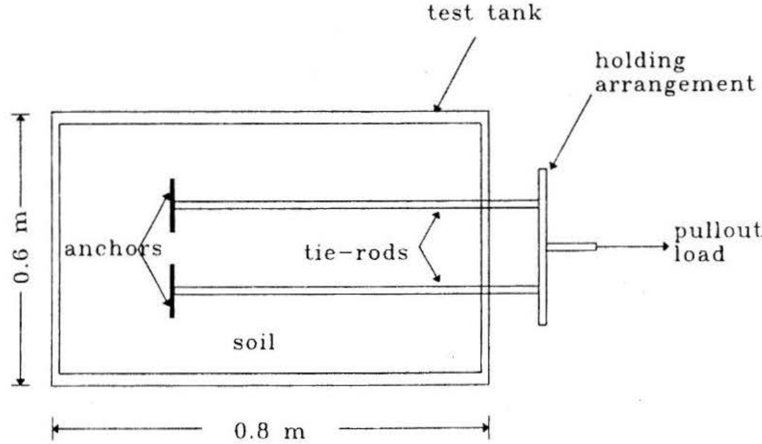

FIGURE 2 : Set-up for Pulling of Two Anchors at the Same Time

arrangement for pulling out two anchors together is shown in Fig. 2. In all the tests, the anchors were placed at a distance of 600mm from the front end of the tank. This distance was provided to eliminate the end effects on the anchor capacities.

Test Procedure

The sand was poured in the tank using the sand raining technique as described in the previous sections. The sand was poured into the tank from controlled heights up to the mid-depth of embedment and the anchor plate and connecting rod were put in place. Proper care was taken to maintain the horizontal alignment of the connecting tie rod. This was achieved by making the level of sand surface to be truly horizontal at the time of placing the tie rod and the anchor. The sand was then poured to the required depth of embedment of anchor. Then, one end of the cable passing through the pulley was connected to the projected end of the tie-rod and the other end of the cable was connected to a suspended loading platform as shown in Fig. 1.

The dial gauge for measuring the pullout displacements was then set up and the initial reading of the dial gauge was noted down before the application of the load. The pullout load was applied in small increments. Each load increment was kept constant until there were no further displacements from the load increment. The next increment of load was then applied and the corresponding displacement was noted down. This process was continued till the anchor finally pulled out from soil. The load increments were progressively reduced as the anchor neared the failure load. The failure load was defined as the load at which further increase in load resulted in excessive pullout displacements.

Results and Discussions

Single Anchors

The various pullout tests carried out on single vertical anchors and the corresponding results are shown in Tables 2 and 3. In these tables, the peak pullout load for each case is given in column 3. The corresponding anchor capacity per unit area is shown in column 4 as the ratio of peak load and the projected area of the anchors. The pullout load vs. displacement behaviour of different anchors at various embedment ratios is shown in Fig.s 3 to 6. The reproducibility of test results is clearly illustrated by close agreement of results between the two trials as illustrated in these figures. A comparison of the load developed per unit area for different sizes of anchors is shown in Fig. 7. The embedment ratios (E_r) for different anchors is also shown in the figure. All the tests were performed in soil with a relative density of 41.2%. It is clear that the square anchors have higher unit capacities than rectangular

Table 2
Influence of size and shape on pullout capacity of vertical anchors
(D_r = 41.7%, ϕ = 33°)

Anchor size (B × H mm)	Embedment ratio (E_r)	Measured Pullout capacity (N)	Unit pressure P_u/A (N/mm²)
25 × 25	4.5	35	0.056
	8.5	80	0.128
	12.5	140	0.224
	16.5	175	0.280
	24.5	270	0.432
35 × 35	3.4	63	0.051
	6.2	155	0.126
	9.1	245	0.200
	51.8	700	0.571
	97.8	1100	0.898
50 × 50	2.5	80	0.032
	4.5	220	0.088
	6.5	440	0.176
	8.5	590	0.236
	10.5	780	0.312
56.4 Ø Circular	2.4	85	0.034
	4.0	250	0.100
	5.8	400	0.146
100 × 50	2.5	134	0.027
	4.5	340	0.068
	6.5	620	0.124
	8.5	850	0.170
	10.5	1100	0.220

anchors. Smaller size anchors develop their ultimate capacity at smaller displacements as illustrated in the figure.

From the results of the above pullout tests it can be concluded that the pullout capacity of the anchors increase with the embedment ratio of the

Table 3
Influence of friction angle on the pullout capacity

Anchor size (BxH mm)	Friction angle (ϕ°)	Embedment ratio (E_r)	Pullout load measured (N)	Unit pressure P_u/A (N/mm^2)
50 × 50	36	2.5	95	0.038
	36	4.5	290	0.116
	36	6.5	500	0.200
100 × 50	36	2.5	160	0.032
	36	4.5	400	0.080
	36	6.5	660	0.132
50 × 50	38	2.5	110	0.044
	38	4.5	360	0.144
	38	6.5	605	0.242
100 × 50	38	2.5	190	0.038
	38	4.5	465	0.093
	38	6.5	740	0.148

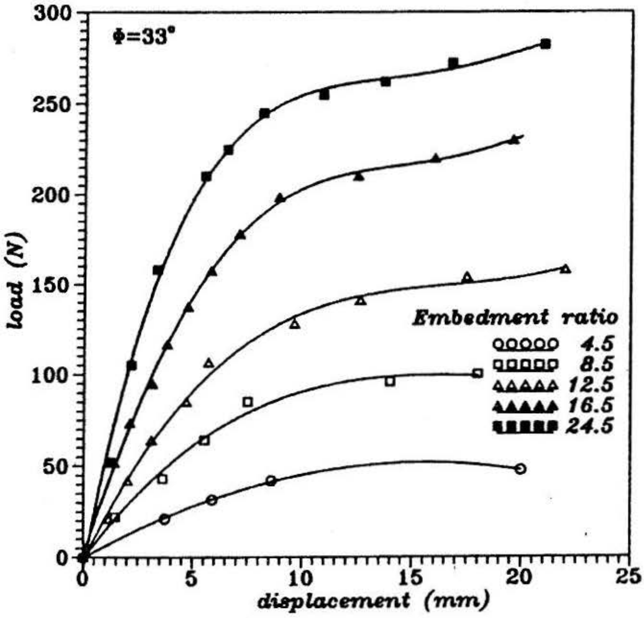

FIGURE 3 : Pullout Load – Displacement Behaviour of 25mm Square Anchors

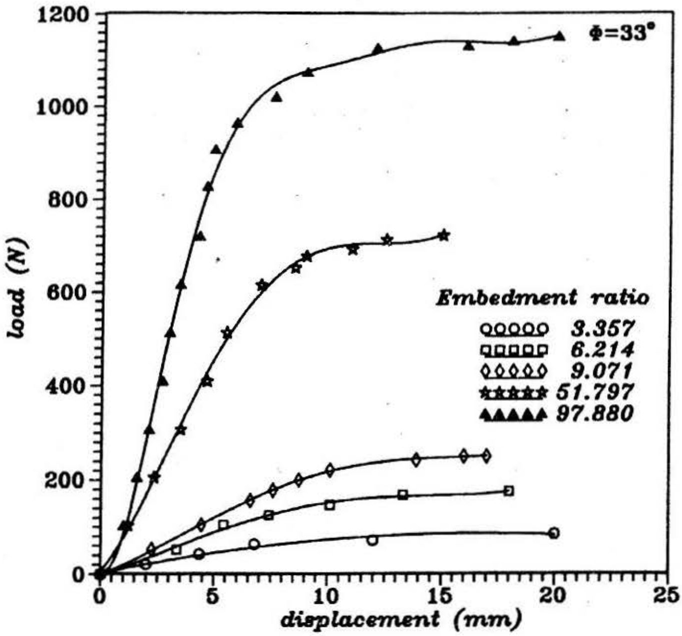

FIGURE 4 : Pullout Load – Displacement Behaviour of 35mm Square Anchors

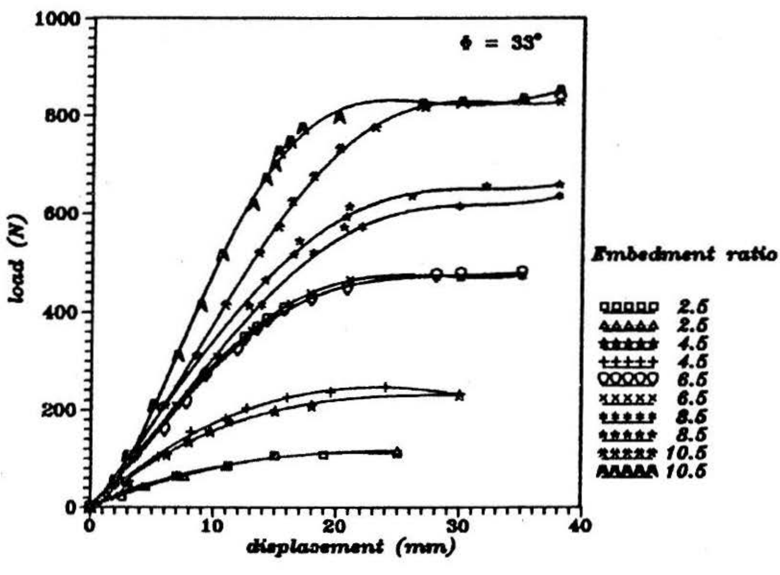

FIGURE 5 : Pullout Load – Displacement Behaviour of 50mm Square Anchors

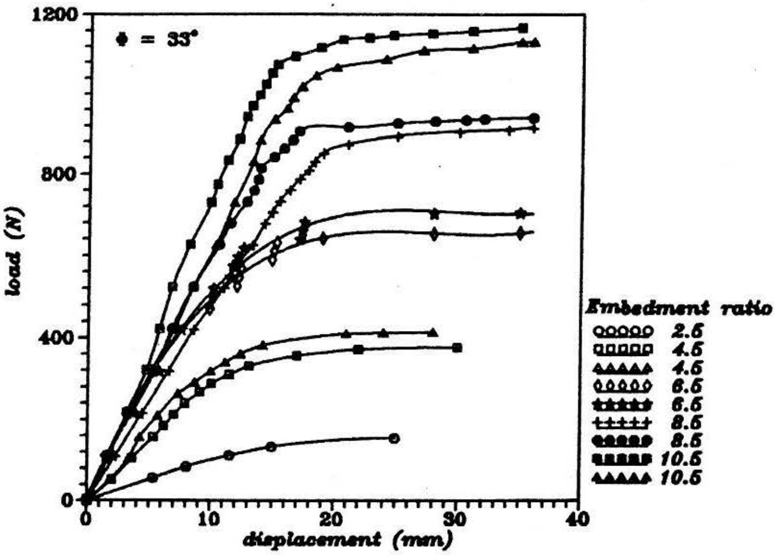

FIGURE 6 : Pullout Load – Displacement Behaviour of 100 × 50 mm Rectangular Anchors

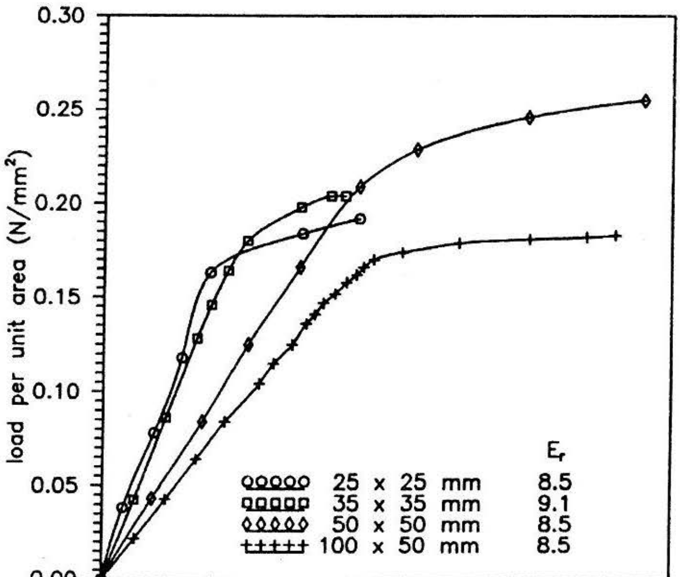

FIGURE 7 : Comparison of the Pullout Behaviour of Various Sizes of Anchors

anchor, size of the anchor and the relative density of the soil. A comparison of pullout loads of square and circular shaped anchors of equal areas shows that the efficiency of circular anchors is more or less the same as that of square anchors. Also, a comparison between the pullout loads of square and rectangular anchors shows that square anchors have more unit capacity than the rectangular anchors and are more efficient in carrying pullout loads. In other words, the anchors with lower aspect ratios (H/L) gave higher capacities. The reason for this is that as the anchor becomes wider, the percentage contribution of shear resistance from the side wedges formed on both sides decreases in comparison to the total resistance, Dicken and Leung (1985). For the same embedment ratio of square anchors, the capacity increases with size of anchor.

From the load displacement behaviour of these anchors it could be inferred that, in general, the displacement at which the peak pullout load occur increases with the embedment ratio and the size of the anchor. The increase in the load carrying capacity of the anchors with the embedment ratio is not linear in nature. The rate of increase of pull out capacity at shallow depths is more than at deep embedments.

Multiple Anchors

The results from tests on multiple anchors are shown in Table 4. The general trend observed from these results is that as the spacing between the anchors reduces the total pullout capacity of the anchors reduces. This pullout behaviour of anchors was observed for both square and rectangular anchors. This phenomena may be due to the locking of the soil between the anchors which tends to move the soil between the anchors along with the anchors. Because of this process, the combined anchors behave like rectangular anchors. The pullout capacity of the group of anchors was observed to increase as they are located farther apart in all the tests. The capacity of a group was found to be almost equal to the sum of the individual pullout capacities of the anchors, if they are located apart at c/c distances of more than 3 times the height of anchor.

Regression Analysis of Pullout Test Data

Based on the experimental data, the following generalized equation in non-dimensional form was developed to fit the pullout test data.

$$\frac{P}{L} = S_a C\left[1+\frac{H}{L}\right]^m \gamma H^2 \left(\frac{\sigma_v}{\gamma H}\right)^n K_p^q \qquad (2)$$

in which S_a = shape factor,

Table 4
Results from tests on multiple anchors

Anchor size (B × H mm)	Friction angle (ϕ°)	Embedment ratio (E_r)	Measured pullout load, P_u (N)		
			c/c spacing 150 mm	c/c spacing 200 mm	c/c spacing 300 mm
50 × 50	33	2.5	142	150	155
	33	4.5	350	390	420
	33	6.5	680	750	780
100 × 50	33	2.5	195	230	250
	33	4.5	590	620	660
	33	6.5	875	980	1150
50 × 50	36	2.5	170	184	190
	36	4.5	500	555	580
	36	6.5	830	930	980
100 × 50	36	2.5	250	325	320
	36	4.5	666	780	800
	36	6.5	990	1130	1220
50 × 50	38	2.5	187	205	215
	38	4.5	620	700	720
	38	6.5	930	1050	1150
100 × 50	38	2.5	310	360	380
	38	4.5	800	890	930
	38	6.5.	1100	1250	1480

C = a non-dimensional constant,
H = height of the anchors,
L = length of the anchors,
γ = unit weight of the soil,
σ_v = normal pressure at the mid-depth of anchor and
K_p = Rankine passive earth pressure coefficient.

In the above equation, the term H/L represents the aspect ratio of the anchors. For square and circular anchors its value is unity, and for the rectangular anchors used in the tests its value is 0.5. Its value is zero for continuous anchors.

The various constants in the equation were determined by regression analysis. A computer program was developed for this purpose using a subroutine ZXSSQ from the International Mathematical and Statistical Library (IMSL). This subroutine uses Marquardt's steepest descent algorithm for estimating the values of constants for regression analysis. This computer program determines the constants by minimising the difference between the experimentally observed pullout capacities and those predicted by the above equation. The process is started by giving initial estimates of various constants in the equation. The program modifies the values of constants in such a manner so as to minimise the error between the experimental and predicted pullout loads. Global minimum of the error was determined by repeatedly finding the constants with different initial estimates. The values of the constants which give the lowest error were reported as the best fit values.

Initially, the above equation was used to fit the entire range of data. However, it was not possible to fit the above equation for the entire range of embedment depth ratios with the same set of values for the above constants. This observation can be justified by the fact that the rate of increase in pullout capacity was higher at shallow embedments than at deeper embedments. Hence, the value of exponent in the embedment ratio term can be expected to be different for shallow and deep embedments. Although various strategies were tried out to fit a single equation for the entire range, good fit was not obtained. Hence, it was decided to split the data into two ranges of embedment ratios. By trial and error, good data fit was obtained for the data with the above equation for embedment ratios less than or equal to 15 ($E_r \leq 15$). The values of various constants obtained after regression analysis for this shallow range of embedment ratios are as follows:

S_a = 1.0 for square and rectangular anchors,
S_a = 0.80 for circular anchors,
C = 1.42,
m = 1.36,
q = 1.09 and
n = 1.46.

Equation 2 had to be slightly modified to the following form in order to obtain a good data fit for deeper embedment ratios ($E_r > 15$). This equation allows for higher rate of increase in pullout capacity up to E_r values of 15 and a lower rate of increase after 15.

$$\frac{P}{L} = S_a C\left[1+\frac{H}{L}\right]^m \gamma H^2 \left\{15^n + \left(\frac{\sigma_v}{\gamma H} - 15\right)^r\right\} K_p^q \tag{3}$$

Many constants in the above equation related to the shape of anchor and soil properties were found to be almost the same for both shallow and deep embedment ratios. Hence, it was decided to retain the previous values of S_a, C, m and q for deep embedment depths also. Only the exponent for the embedment ratio was allowed to vary for the deep embedment ratios and

Table 5
Comparison of Measured and Predicted Pullout Loads
(D_r = 41.2%, ϕ = 33°)

Anchor size (L × H) mm	Embedment ratio (E_r)	Pullout load (N)	
		Experimental	Empirical
25 × 25	4.5	35	30
	8.5	80	76
	12.5	140	134
	16.5	175	179
	24.5	270	202
35 × 35	3.4	63	54
	6.2	155	132
	9.1	245	229
	51.8	700	740
	97.8	1100	1036
50 × 50	2.5	80	102
	4.5	220	260
	6.5	440	411
	8.5	590	608
	10.5	780	828
100 × 50	2.5	134	138
	4.5	340	325
	6.5	620	556
	8.5	850	823
Circular 56.4	2.3	85	1021
56.4 mm Ø	4.0	250	236
	5.8	420	402

Table 6
Comparison of Measured and Predicted Pullout Loads
(D_r = 57%, ϕ = 36°)

Anchor size (L × H) mm	Embedment ratio (E_r)	Pullout load (N)	
		Experimental	Empirical
50 × 50	2.5	95	132
	4.5	290	311
	6.5	500	532
100 × 50	2.5	160	162
	4.5	400	383
	6.5	660	655

Table 7
Comparison of Measured and Predicted Pullout Loads
(D_r = 62%, ϕ = 38°)

Anchor size (L × H) mm	Embedment ratio (E_r)	Pullout load (N)	
		Experimental	Empirical
50 × 50	2.5	110	133
	4.5	360	313
	6.5	605	536
100 × 50	2.5	190	180
	4.5	465	424
	6.5	740	725

was obtained as 0.93. This value is much less than the corresponding value of 1.46 for shallow embedments. A comparison between the experimentally determined pullout capacities and those predicted from the equations are given in Tables 5 to 7.

The predictions from the above equations compare well with the field test data reported by Dickens and Leung (1985) and by Rowe and Davis (1982) as shown in Tables 8 and 9. In these tables, the force coefficient $M_{\gamma q}$, is defined as $P_u/\gamma H^2$ in which P_u is the ultimate pull out capacity of anchors. The reasonable comparison between the two sets of results indicates the reliability of Eqn. 2 for the prediction of pullout

Table 8
Comparison of Predictions with Data from Rowe and Davis (1982)

Anchor length L (mm)	E_r	Aspect ratio (H/L)	Soil density γ (kN/m^3)	Force coefficient $M_{\gamma q}$	
				Rowe and Davis	Equation 2
102	3	0 5	14.8	13.8	14 14
102	3	0.5	15.1	13.8	15.47
51	3	1	15.2	16.5	23.94
51	3	1	15.0	16.5	21.87

Table 9
Comparison of Predictions with Data from Dicken and Leung (1985)
(1 m square anchors, ϕ = 33°)

Embedment ratio (Er)	Force coefficient, $M_{\gamma q}$	
	Dicken and Leung	Equation 2
2	32	41
3	70	75
4	110	115
5	180	159
6	250	210

capacity of vertical anchors at shallow embedment depths. It is important to note that the results of Dicken and Leung (1985) were obtained from field tests on 1m size square anchors which are much larger than those used in the current tests. This shows the applicability of these equations for different sizes of anchors.

Discussion of Test Data

The results obtained from laboratory tests have clearly indicated that the pullout capacity of vertical anchors is a function of size and shape of anchors, shear strength properties of soil, and embedment depth of the anchor. Some general observations from these pullout tests are as follows:

1. Square shaped anchors are more efficient than the other shapes of anchors in resisting pullout loads. The efficiency of anchors was found to decrease with a decrease in the aspect ratio (H/L) of anchors.

2. The pullout force increased with anchor size, embedment depth and shear strength of the soil.

3. The displacement at the ultimate capacity of the anchor increased with the embedment depth due to the requirement of higher deformations necessary to develop peak passive resistance in soil at large depths.

4. The load carrying efficiency of anchors with a fixed height decreased as the width of the anchors increased. The reason for this is that the percentage contribution of capacity from wedges formed on the side decreases as the width of anchor increases.

5. Closely spaced anchors behaved like rectangular anchors thus reducing the load carrying efficiency of these anchors. When they were placed at c/c spacing of 3 times H, their capacity had approximately equalled that from individual anchors.

6. The anchor capacity was found to increase in almost linear proportion to the Rankine coefficient of passive earth pressure.

7. The rate of increase of anchor capacity was found to be higher in shallow embedment depth ranges than at deeper embedments.

8. Although the pullout displacement required to develop peak capacity varies with the embedment ratio, in general it can be observed from the experimental data that the ultimate capacity of the anchors for intermediate embedment depths (E_r = 5 to 10) is developed at a displacement of approximately $\frac{1}{3}$rd the anchor height. At extremely shallow embedment depths, the peak pullout force occurs at a lesser pullout displacement. The data reported by Neely et al. (1973) has also shown that for embedment ratios greater than 4, the peak pullout force happens at a displacement of approximately $\frac{1}{4}$th to $\frac{1}{3}$rd the anchor height. At very deep embedment depths, the peak pullout force happens at as high a displacement as H/2.

9. From the same data, it can be observed that $\frac{1}{3}$rd the ultimate pull out load occurs at a displacement of about $\frac{1}{10}$th the anchor height i.e. the pull out load of a 50mm anchor at 5mm displacement will be approximately equal to $\frac{1}{3}$rd the ultimate load. For very large embedment depths (E_r > 30) the force developed at this displacement is about $\frac{1}{4}$th the ultimate capacity.

Conclusions

This paper has presented results from a comprehensive range of pullout tests on vertical anchors. Based on the regression analysis of experimental data, simple equations were developed to estimate the capacity of these anchors. These equations represent the influence of various parameters on the anchor capacity. The predictions from these equations compare well with those from both laboratory and field test data reported in the literature. As such, these equations can be used for estimating the pullout capacities of vertical anchors under different field conditions. These estimated capacities can be safely used for the design of retaining walls supported by such anchors as demonstrated in another companion paper.

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References

CHATTOPADHYAY, B.C. and PISE, P.J. (1986) : "Breakout Resistance of Horizontal Anchors in Sand", *Soils and Foundations*, Vol.26, No.4, pp.16-22.

DAS, B.M. (1975) : "Pullout Resistance of Vertical Anchors", *Journal of Geotechnical Engineering Division, ASCE*, Vol.101, pp.87-91.

DICKEN, E.A. and LEUNG, C.F. (1985) : "Evaluation of the Design Methods for Vertical Anchor Plates", *Journal of Geotechnical Engineering Division, ASCE*, Vol.111, No.4, pp.500-520.

HANNA, A. and RANJAN, G. (1992) : "Pullout Displacement of Shallow Vertical Anchor Plates", *Indian Geotechnical Journal*, Vol.22, No.l, pp.55-62.

LADE, P.V. (1972) : "The Stress-Strain and Strength Characteristics of Cohesionless Soils, *Ph.D. Thesis*, Submitted to the Univ. of California, Los Angeles.

MEYERHOF, G.G. (1973) : "Uplift Capacity of Inclined Anchors and Piles", *Proc. of 8th Int. Conf. on Soil Mech. and Found. Eng.*, Vol.2, pp.167-173.

NEELY, W.J., STUART, J.G. and GRAHAM, J. (1973) : "Failure Loads in Vertical Anchor Plates in Sand", *Journal of Geotechnical Engineering Division, ASCE*, No.99, pp.669-685.

ROWE, R.K. and DAVIS, E.H. (1982) : "The Behaviour of Anchor Plates in Sand", *Geotechnique*, Vol.42, pp.25-41.

TAGAYA, K., SCOTT, R.F. and ABOSHI, H. (1988) : "Pullout Resistance of Buried Anchor in Sand, *Soils and Foundations*, Vol.28, No.3, pp.114-130.

TRAUTMANN, C.H. and KULHAWAY, F.H. (1988) : "Uplift Load-Displacement

Behaviour of Spread Foundations, *J. Geotech. Eng. Div., ASCE*, Vol.114, No.2, pp.168-184.

Notation

The following symbols have been used in the paper.

L	=	length of anchor
C	=	non-dimensional constant
D_r	=	relative density
E_r	=	embedment ratio
h	=	embedment depth of anchor
H	=	height of anchor
$M_{\gamma q}$	=	dimension-less force coefficient
ϕ	=	friction angle of soil
K_p	=	Rankine passive earth pressure coefficient
γ	=	unit weight of soil
σ_v	=	vertical pressure of soil
s	=	c/c spacing of anchors
S_a	=	shape factor of anchor