Vertical and Inclined Anchors in Granular Soil

by
B. M. DAS, B.Sc.(Hons), B.Sc.(C.E.), Ph.D.
Assistant Professor, Department of Civil Engineering, Tri-State College, Angola, Indiana, U.S.A.
and
G. R. SEELEY, B.S.M.E., M.S.(Engr.Mech.), Ph.D.
Assistant Professor, Department of Civil Engineering, Tri-State College, Angola, Indiana, U.S.A.

1 INTRODUCTION

Shallow vertical anchors are generally used in the construction of sheet pile bulkheads. Small anchors are sometimes used at bends in pipelines under pressure to take the horizontal loading. The present practice of determining the ultimate pullout resistance of vertical anchors subjected to horizontal pull is generally based on classical passive earth pressure theories. But, since anchors with limited heights and widths ($B/h \leq 5$ to 6) placed at limited depths ($H/h \leq 5$ to 6) present a complex three-dimensional problem, the above procedure of ultimate capacity calculation results in uneconomical design.

Recent research work on shallow vertical anchors is limited. Ovesen (Ref. 5) conducted several model tests in sand and, on the basis of those tests, offered a general design procedure for a single or a series of anchors in a line. Using the test results of Ovesen, Hansen (Ref. 2) proposed a semiempirical equation for shallow anchor resistance in granular soil. Hueckel (Ref. 3), using square model anchor plates, qualitatively studied the effect of surface roughness and anchor inclination on the ultimate pullout capacity. Neely et al. (Ref. 4) proposed a simple method of calculating ultimate pullout resistance of small shallow square and rectangular anchors in sand, using force coefficients determined by an equivalent free surface method and nondimensional shape factors. The United States Department of the Navy (Ref. 6 & 7) conducted several large-scale field tests in a sandy beach area. Results of these tests will be discussed in Section 5 of this paper.

The purpose of this paper is to report the results of several laboratory model tests conducted to determine the ultimate pullout resistance of shallow vertical anchors (rectangular, square and circular). Based on the test results, a simple semiempirical relation has been developed. The effect of anchor inclination on ultimate pullout resistance for various depths of embedment is also presented.

2 NOTATIONS

- B = width of anchor
- d = diameter of circular anchor
- H = vertical distance between the surface of the sand to the bottom of the plate
- H' = average depth of embedment of the anchor plate
- P_u = ultimate horizontal pullout resistance of vertical anchor
- $P_{u\theta}$ = ultimate horizontal pullout resistance of anchors inclined at an angle, θ, with the vertical
- S = shape factor
- γ = bulk density of sand
- θ = anchor inclination with the vertical
- ϕ = angle of friction of the sand

3 MODEL TESTS FOR VERTICAL ANCHORS

Model tests were conducted in a sand box measuring 610 x 610 x 610 mm. A fine grained, oven dried silica sand was used for the test. The mechanical properties of the sand are as follows:

(i) Passing #40 U.S. sieve 55%

(ii) Passing #200 U.S. sieve. 0%

(iii) Compacted bulk density . . . . . 1.61 gm/cm^3

(iv) Uniformity coefficient 1.73

(v) Angle of friction. . . . . 34°

Sand was compacted in the box to the desired density in 50.8 mm layers to achieve a uniform density for the entire depth under consideration.

Several model anchor plates were used for the vertical pullout tests. The model test results of four square plates, four circular plates and three rectangular plates will be reported. All of the anchors were made from 3.18 mm thick aluminum plates, and the dimensions of the plates are given in Table I.

TABLE I

MODEL ANCHOR PLATE DIMENSIONS

Description	h (mm)	B (mm)	d (mm)	B/h
Square	38.1	38.1	--	1
	50.8	50.8	--	1
	63.5	63.5	--	1
	76.2	76.2	--	1
Rectangular	38.1	76.2	--	2
	38.1	114.3	--	3
	38.1	190.5	--	5
Circular	--	--	38.1	--
	--	--	50.8	--
	--	--	63.5	--
	--	--	76.2	--

The anchors were pulled by a cable 2.38 mm in diameter attached at the center of the plate. The cable passed over a smooth pulley attached to the outside of the sand box. Load was applied at the other end of the cable. The movement of the anchor was measured by two dial gauges, one on each side of the cable and above the pulley. A schematic diagram of the laboratory setup is shown in Fig. 1.

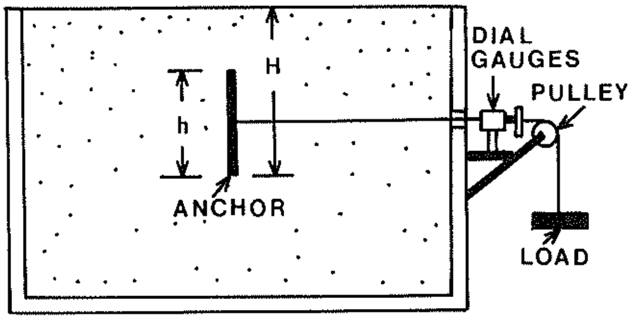

Fig. 1 Schematic diagram of laboratory test equipment

Pullout tests for all the anchors were conducted at various depths of embedment ($H/h \leqslant 5$). Ultimate pullout load for each test was determined from the load-displacement diagram where it suddenly failed or appreciable displacement occurred, due to small additional load application. Each test was repeated three times, and the variation of the ultimate pullout loads was within 2% to 5%. The ultimate horizontal pullout loads reported here are the average of three tests.

At the beginning of each test, sand was removed from the box and recompacted for the entire depth of embedment. Model test results for ultimate pullout loads at various depths of embedment are shown in Figs. 2 and 3.

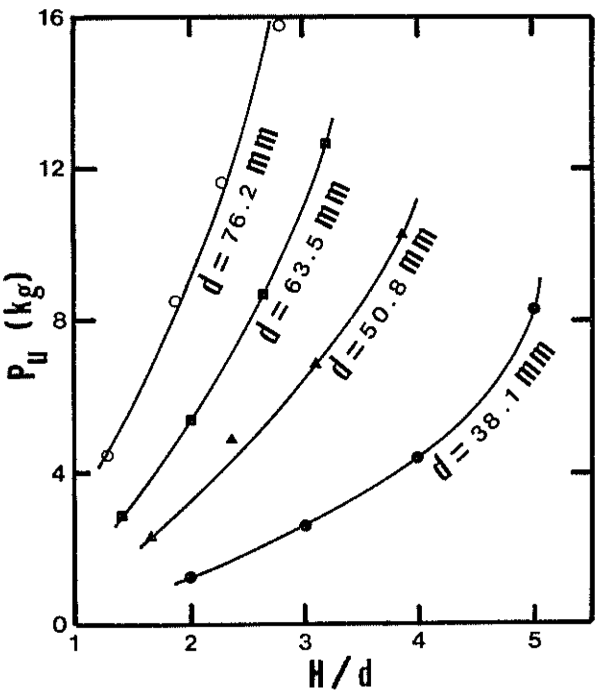

Fig. 2 Ultimate pullout resistance of circular anchors

4 INTERPRETATION OF TEST RESULTS

Ultimate pullout loads (P_u) from model tests can be presented in a nondimensional form as a ratio of $P_u/\gamma Bh^2$ for square and rectangular anchors. A nondimensional log-log plot of $P_u/\gamma Bh^2$ against

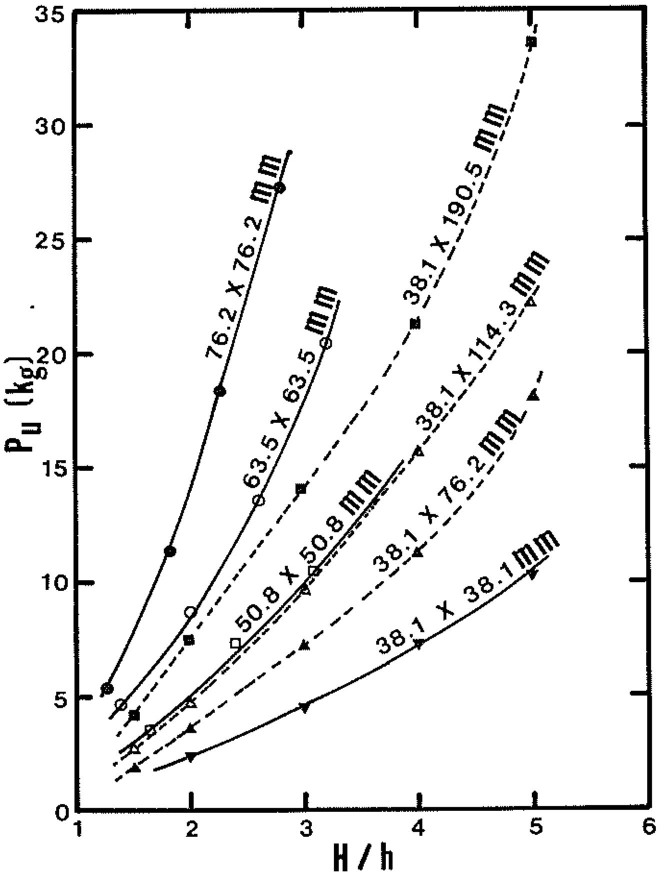

Fig. 3 Ultimate pullout resistance of square and rectangular anchors

H/h for the ultimate loads reported in Fig. 3 is given in Fig. 4. It appears that the plot can be represented in the form:

$$\frac{P_u}{\gamma B h^2} = K \left(\frac{H}{h}\right)^n \qquad (1)$$

where K is a function of width-to-height ratio B/h and the angle of friction ϕ, and n varies from about 1.8 for B/h = 1 to about 1.68 for B/h = 5.

In order to consider the dependency of n on the angle of friction, several tests were conducted with the same model anchor plates by varying the relative density of the sand. The tests did not show any appreciable difference in the range of values of n reported above. A plot of the variation of n with B/h is given in Fig. 5 and may be expressed by a general equation:

$$n = 1.83 - 0.03 \left(\frac{B}{h}\right) \qquad (2)$$

The factor K in Equation 1 may be represented as:

$$K = S \cdot P \qquad (3)$$

where P = nondimensional pullout resistance per unit length of a very long strip (plain strain case) with H = h, and S = shape factor.

Using the conventional curve (logarithmic spiral) surface of failure (Fig. 6):

$$P = \frac{(P_P - P_A) \cos \delta}{\gamma B h^2} \qquad (4)$$

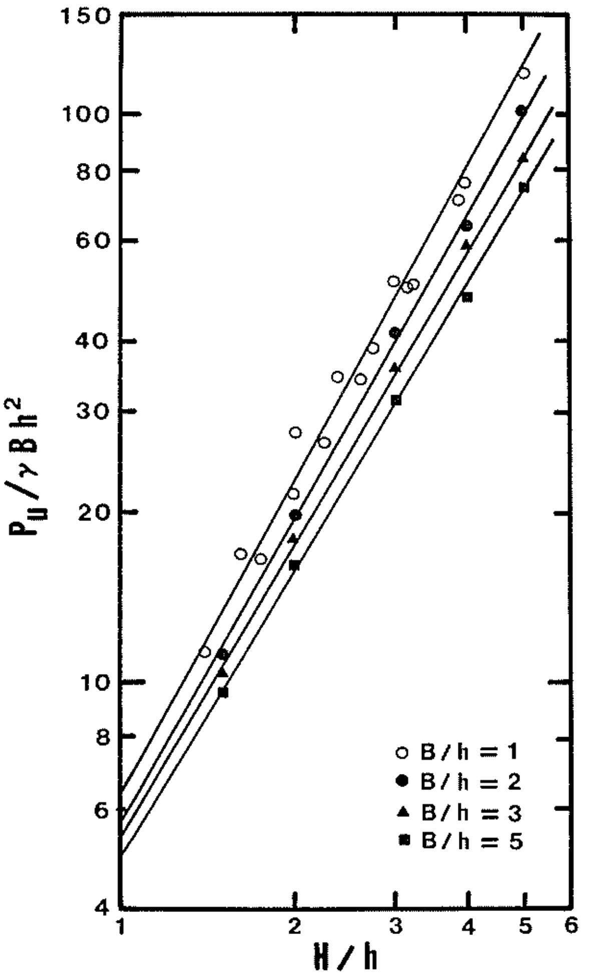

Fig. 4 Plot of $P_u/\gamma Bh^2$ against embedment ratio for square and rectangular anchors

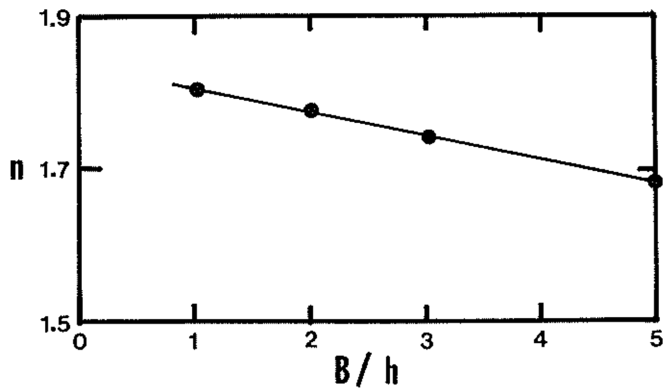

Fig. 5 Variation of 'n' with width-to-height ratio

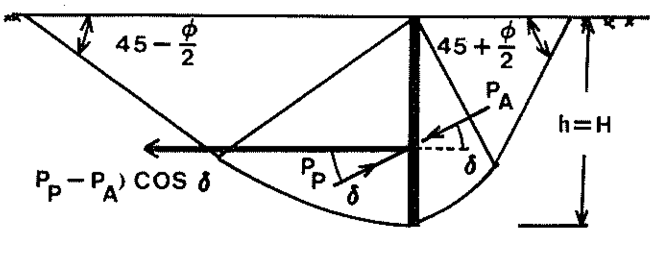

Fig. 6 Failure wedge for a long anchor (H = h)

where δ = angle of friction between the anchor plate and soil and P_P and P_A are the total passive and active pressures in front and back of a long plate of height h and width B, respectively. Hueckel (Ref. 3) conducted several tests on similar anchor plates with a wide range of roughness and did not observe any applicable change in the ultimate pullout resistance. Similar conclusions have been drawn by Neely et al. (Ref. 4). Hence, assuming $\delta = \phi$, and using the active and passive pressure values of Caquot and Kerisel (Ref. 1), P can be calculated for various angles of friction of sand. With less than 4% error, it appears that P can be approximated as:

$$P = (4.59 \times 10^{-5})\,\phi^{3.22} \qquad (5)$$

$$(\text{for } 28^\circ \leqslant \phi \leqslant 43^\circ)$$

where ϕ is expressed in degrees.

Thus, from Equations 3 and 5, the shape factor:

$$S = \frac{K}{(4.59 \times 10^{-5}\,\phi^{3.22})} \qquad (6)$$

The experimental nondimensional factor for various B/h values (Fig. 4) are given in Fig. 7. Thus, from Equations 1 and 6, the ultimate pullout resistance for single anchors can be given by the equation:

$$P_u = (4.59 \times 10^{-5})\,S\,\phi^{3.22}\left(\frac{H}{h}\right)^n \gamma B h^2 \qquad (7)$$

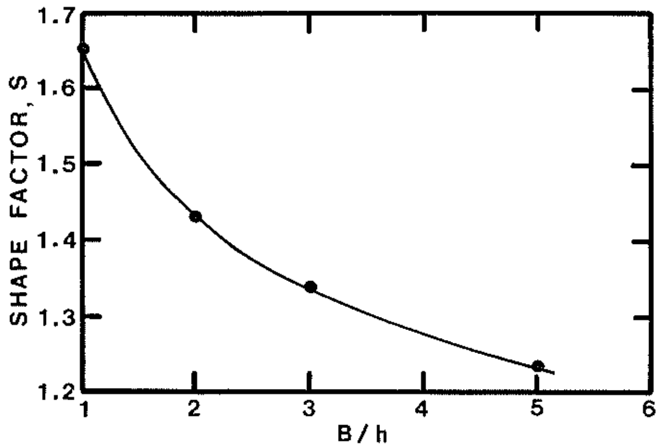

Fig. 7 Shape factors for square and rectangular anchors

In a similar way, the ultimate pullout resistance of circular anchor plates can by analyzed. A nondimensional plot ($P_u/\gamma d^3$ vs. H/d) for the ultimate loads for circular anchor plates reported in Fig. 3 is given in Fig. 8 and can be approximated as:

$$\frac{P_u}{\gamma d^3} = K_1 \left(\frac{H}{h}\right)^{1.8} \qquad (8)$$

where

$$K_1 = 0.66\,K_{(\text{square plate})} \qquad (9)$$

Using the shape factor for square plates, the ultimate load for circular anchor plates may be given by:

$$P_u = (5.02 \times 10^{-5})\,\phi^{3.22}\left(\frac{H}{d}\right)^{1.8} \gamma d^3 \qquad (10)$$

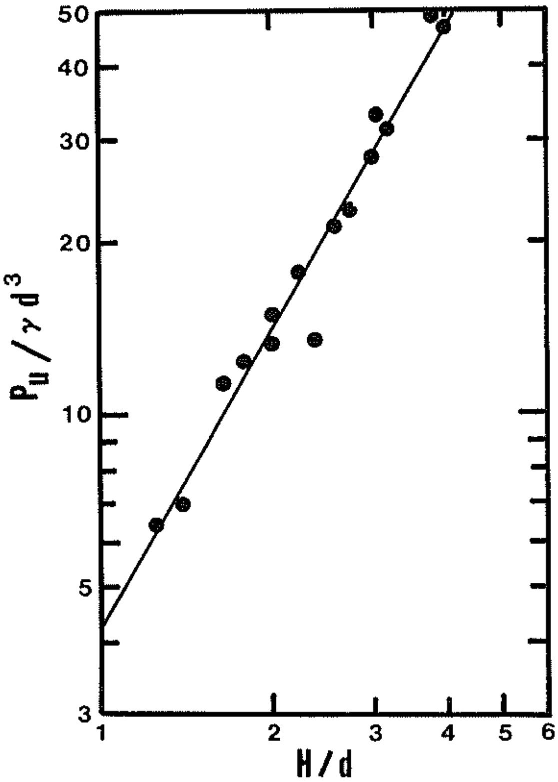

Fig. 8 Plot of $P_u/\gamma d^3$ vs. H/d for circular anchors

5 FIELD TEST RESULTS

Caution must be taken when small laboratory model test results are applied to full scale field work. However, enough full scale results are not available at the present time to assess the scale effect and validity of the generalized Equations 7 and 10.

The full scale tests of the United States Navy reported by Smith (Ref. 6 & 7) referred to in Section 1 will be compared with the present results. Most of the isolated anchors relevant to the present study had a B/h ratio of 1.25. The density of sand was 1.603 gm/cm^3 (100 pcf) and its angle of friction was 32°. The failure loads considered here correspond to a displacement of 4 inches for all cases. A comparison of the results of the field pullout tests with the present semiempirical relation (Equation 7) is shown in Fig. 9. Considering the compaction method (water compaction) and other factors associated in large scale field tests, a reasonably good agreement is noted.

6 EFFECT OF ANCHOR INCLINATION

In order to study the effect of anchor inclination on the ultimate horizontal pullout resistance, three anchor plates were tested at an inclination of ±20° and ±30° with the vertical.

It was felt that larger sized anchor plates would provide better results. For this part of the investigation, three aluminum anchor plates measuring 50.8 x 50.8 mm, 50.8 x 152.4 mm and 50.8 x 254.0 mm were used; thus providing a B/h ratio of 1, 3 and 5. All of the plates were 3.18 mm thick. Anchor inclination was achieved by attaching an aluminum wedge to the back of the anchor plate. Horizontal pull was applied at the geometric center of the plate by an anchor shaft (6.35 mm diameter) attached to the wedge and the plate. The shaft was

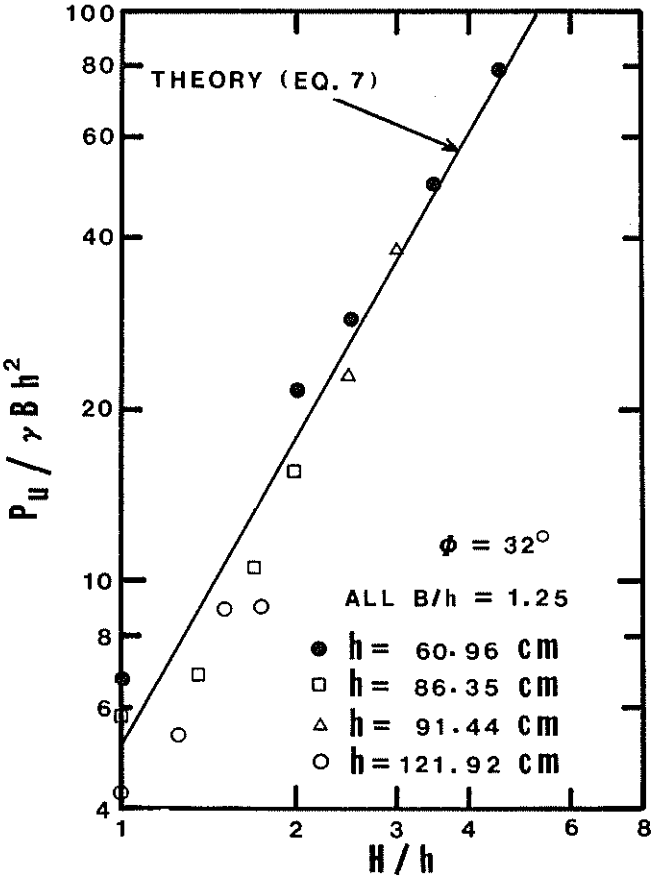

Fig. 9 Comparison of model tests with field test results (Smith, Ref. 6 & 7)

in turn attached to the cable which passed over the pulley.

Anchors inclined away from the direction of pull are referred to as negatively inclined, and those inclined in the direction of pull are positively inclined (Fig. 10).

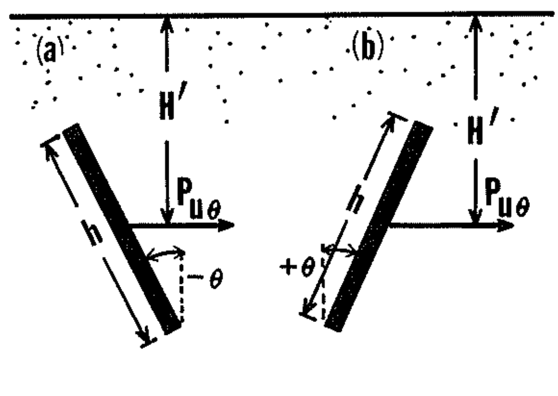

Fig. 10 Inclined anchor parameters

Fig. 11 shows the plot of the ratio of ultimate pullout resistance of inclined plates (θ =±30°) to that of vertical plates for various depth of embedment ratios (H'/h). The average embedment depth is defined as the vertical distance from the surface of the sand to the geometric center of the plate where the pull force is applied. It may be noted that, for vertical anchors (θ = 0), H' is equal to H - h/2.

For any given average depth of embedment,

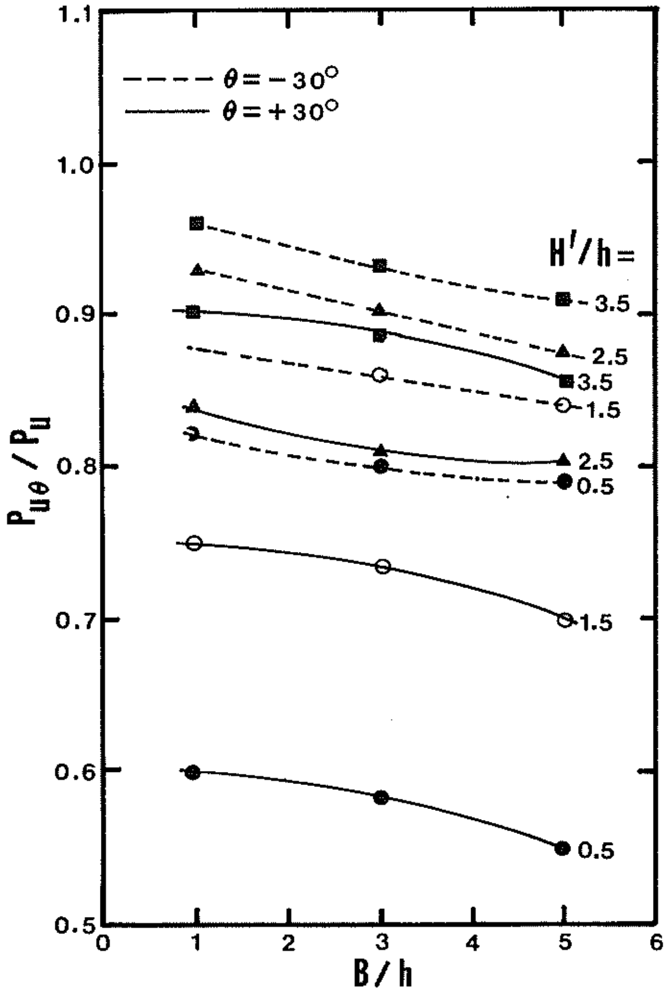

Fig. 11 Variation of $P_{u\theta}/P_u$ with width-to-height ratio of anchors ($\phi = \pm 30^{\circ}$)

vertical anchors showed higher resistance than inclined anchors. Also, $P_{u\theta}/P_u$ increased with the increase of the ratio, H'/h. Again, for all plates, under similar depths of embedment, negatively inclined plates showed higher resistance than those with positive inclination.

A similar trend of the ratio $P_{u\theta}/P_u$ was also observed for anchor plates inclined at ±20°.

7 CONCLUSION

Based on the model test results, semiempirical relations have been developed for isolated vertical square, circular and rectangular anchors (B/h ⩽ 5) in sand subjected to horizontal pull. The relations developed in this study are valid only for limited depths of embedment (H/h ⩽ 5).

Results of the present model tests have been compared with previously reported large scale field tests, and a good agreement is observed.

With h = d, the average ultimate pullout resistance of circular anchors is about two-thirds that of square anchors.

Several tests were conducted to study the effect of anchor inclination on the ultimate pullout resistance, which decreased with anchor inclination. For a given anchor and angle of inclination, negatively inclined anchor plates showed higher resistance than positively inclined anchor plates. Under the same average embedment ratio, H'/h, and similar inclination with the vertical, pullout resistance appeared to decrease with the increase of width-to-height ratio. More tests are needed to develop a working relation for inclined anchors.

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