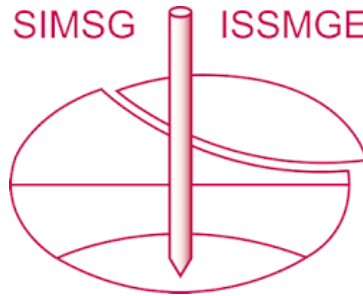


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Uplift capacities of vertical double-plate anchors in sand

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ABSTRACT: An experimental study on the uplift capacities of vertical double-plate square and vertical double-plate circular anchors in sand is presented. Uplift capacity depends on the size and shape of the anchor, along with the embedment depth. The study pioneers the use of multi-plate anchors, i.e., two vertical anchors attached to same tie rod along the same horizontal plane, with the application of horizontal load. The effectiveness of the same is described and compared with the existent use of single-plate anchors in sand.

1 INTRODUCTION

Numerous Geotechnical Engineering designs command the precise comprehension of the mechanics of the problems of foundations resisting the uplift forces by passive resistance of the soil. Soil anchors come into picture here. The anchors are of different types based on the angle of inclination, shape, and embedment ratio. Also, are the helical, block, shank, torpedo, suction anchors, based on the mechanism leading to development of uplift resistance in the structures used. Anchors have been used as a structural member in the foundation systems of the transmission towers, underground reservoirs below water table, sheet pile bulkheads, lateral load bearing structures. Anchors are also used for supporting diaphragm walls situated deep in the soil, for resisting wave action on offshore structures and for resisting buoyancy forces in buried pipelines.

The understanding of the use of these anchors comes from the research conducted by the scientific community. The earliest studies on anchorages date back to the 60's, with continued laboratory studies over a period of time, on plate anchors in varied densities of sand, and shape and sizes of anchor with varying angle of inclination of the pull applied. The vertical plate anchors are used to resist horizontal loading in the construction of sheet pile walls, at pressure pipeline bends, at the base of retaining walls to resist sliding (Das & Shukla, 2013). Hueckel (1957) and Hueckel et al. (1965) conducted model tests on vertical and inclined plates and studied the distribution of passive earth pressure on the surface of the square vertical plate embedded in soil respectively. Teng (1962), another pioneer in the area of vertical plate anchors, estimated the holding ca-

capacity of vertical anchors using the Rankine's lateral earth pressure. Ovesen and Stromann (1972) worked with the vertical anchor slabs and presented the design methods of the same in sand. Neeley et al. (1973), Das (1975), Das & Seeley (1975) and Das et al. (1977) are few researchers who showed interest in the study of vertical plate anchors. Dickin & Leung (1983) performed centrifuge model tests to predict the behavior of prototype vertical anchor plates, subjected to accelerations up to 40 gravities. Dickin & Leung (1985) presented the evaluation of design methods for vertical anchor plates. They presented the comparisons between the then existing design methods with the conventional and centrifuge results. A certain group of researchers put forth their studies on the numerical and analytical approaches to the earlier developed failure theories. Kumar & Sahoo (2012) used finite elements and limit analysis to find the upper bound solution for pullout capacity of vertical anchors in sand. Bhattacharya & Roy (2016) analyzed the variation of horizontal pullout capacity with width of vertical anchor plate. They used the lower-bound finite element limit analysis in conjunction with linear programming. The study results revealed that the pullout capacity factor increases continuously with decreases in the normalized width of the anchor plate for both loose and dense sands.

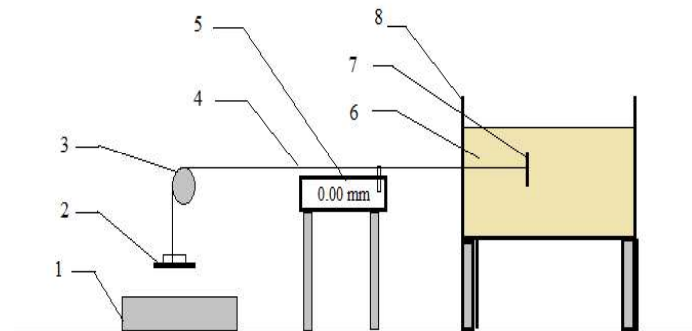
Bhattacharya & Kumar (2012) analyzed the horizontal pullout capacity of a group of two vertical strip anchor plates embedded in sand. They used lower bound finite element limit analysis. The pullout capacity of a group of two anchors was found to be a maximum of 43% more than the single vertical anchors. Sahoo & Kumar (2013) analyzed the horizontal pullout resistance of a group of two

vertical anchors in sand. They performed upper bound finite element analysis only on the shallow anchors. The analysis was based on a plane strain formulation. The authors pressed upon the need for a three-dimensional formulation, as in actual practice. Both Bhattacharya and Kumar (2012) and Sahoo and Kumar (2013), in their respective studies have placed the group of two anchors in the same vertical plane. A lot of work has been conducted by researchers on both single plate anchors and group action of the same arranged in parallel and square pattern. The present work throws light upon the possibility of using more than one plate anchor (along the same horizontal plane) to serve the same purpose, may be in a better way.

2 EXPERIMENTAL PROGRAMME

2.1 Methodology

The pullout tests on the single-plate and double-plate vertical anchors were performed in a tank of dimensions $1.0 \text{ m} \times 1.0 \text{ m} \times 1.2 \text{ m}$. Figure 1 shows the experimental setup of the vertical single-plate anchor. Figure 2 shows the experimental setup of the vertical double-plate anchor. A uniformly graded sand was used. The dry sand was compacted to a relative density of 65% (medium-dense) using rainfall technique. The unit weight of sand was 14.80 kN/m^3 . The apparatus of the test includes a loading system consisting of a loading frame connected by a cable system, tie rod, and dial gauges with magnetic stand, strainer and frame for sand raining.

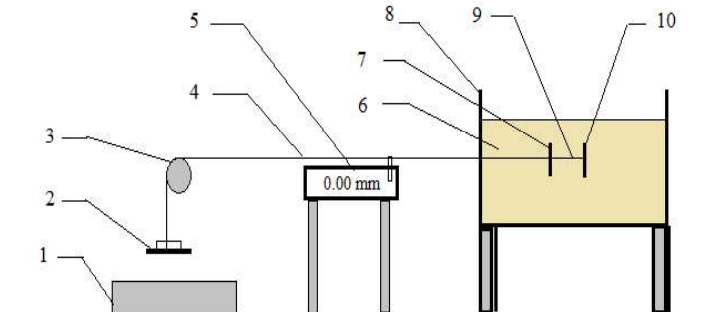


1-pedestal; 2-load hanger; 3-pulley; 4-steel wire; 5-dial gauge; 5-tie rod; 6-sand; 7-vertical single-plate anchor; 8-test tank containing sand.

Figure 1. Experimental set-up of the vertical single-plate anchor.

The anchor plates were 50 mm in size, square and circular in shape and of thickness 5 mm. The anchors were connected to a tie rod and pulled using a cable of 5 mm in diameter attached to the center of the pulley. The load was applied to the free end of the cable.

The anchor was gradually subjected to pullout load. A set of two dial gauges were used to record the displacements after each application of the load. Thus, the load-controlled tests were performed, and the corresponding readings of Pullout Load-Displacement were recorded till the ultimate shear failure occurred and the anchor system failed.



1-pedestal; 2-load hanger; 3-pulley; 4-steel wire; 5-dial gauge; 5-tie rod; 6-sand; 7-vertical single-plate anchor; 8-test tank containing sand; 9-tie rod of length equal to twice the size of the anchor; 10-vertical double-plate anchor.

Figure 2. Experimental set-up of the vertical double-plate anchor.

The total depth of the soil layer below the anchor plate was maintained to be 400 mm for all the tests conducted. The double-plate anchors basically consist of two single plate anchors attached to the same tie rod at a spacing equal to the size of the anchor (Figure 2). The distance between the anchor plate and the face of wall is maintained to be 300 mm throughout all the cases of the study.

The weight of the double-plate anchor system increases by an anchor plate and a tie rod of length equal to the diameter, as compared to the single-anchor plate system. The spacing chosen between the two plates for all the double-plate anchor system was equal to twice the size of the anchor plate. The embedment ratio (h/d) of 2, 3, 4 and 6 was selected for the study. The embedment length (h) is the height of the anchor plate from the top surface of the filled-up tank to the bottom edge of the anchor plate, and ' d ' is diameter of the anchor plate.

3 RESULTS AND DISCUSSION

3.1 Load-displacement of single-plate anchors

The variation of load with displacement for the pullout test on 50 mm single-plate circular anchor is presented in Figure 3. The pullout load at failure of 83 N, 139 N, 180 N, and 194 N were obtained at a displacement of 210 mm, 207 mm, 209 mm, and 209 mm for an embedment ratio 2, 3, 4, and 6 respectively. Similarly, the variation of load with displace-

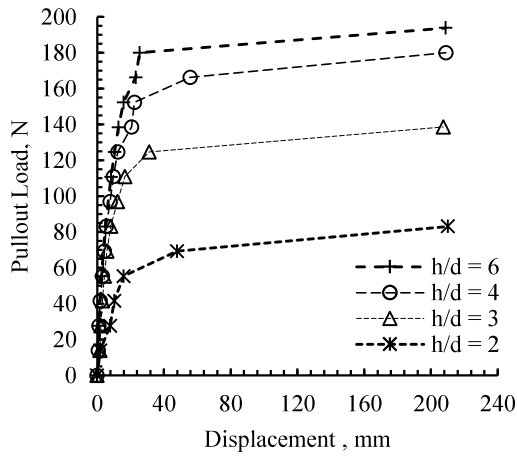


Figure 3. Load-displacement curves for 50 mm single-plate circular anchor.

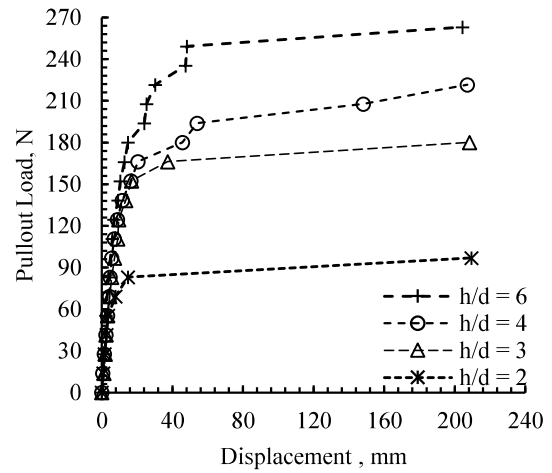


Figure 5. Load-displacement curves for 50 mm double-plate circular anchor.

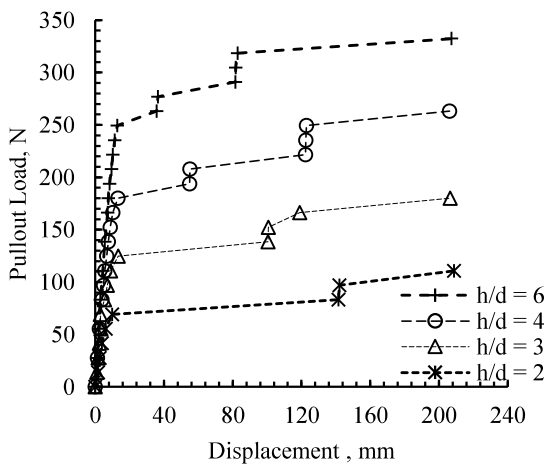


Figure 4. Load-displacement curves for 50 mm single-plate square anchor.

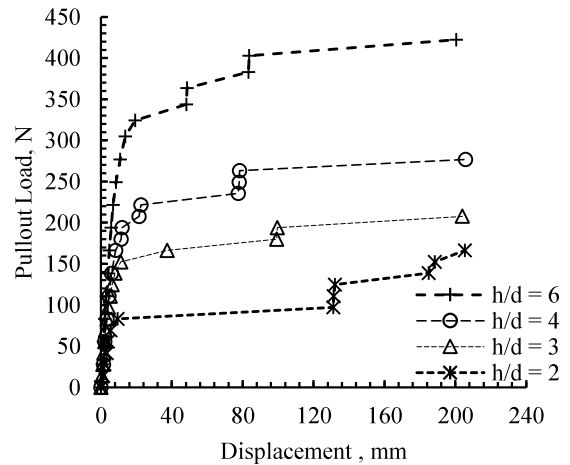


Figure 6. Load-displacement curves for 50 mm double-plate square anchor.

ment for the pullout tests on 50 mm single-plate square anchors are presented in Figure 4. The pullout load at failure of 97 N, 180 N, 222 N, and 263 N were obtained at a displacement of 209 mm, 208 mm, 207 mm, and 204 mm for an embedment ratio 2, 3, 4, and 6 respectively.

3.2 Load-displacement of double-plate anchors

The variation of load with displacement for the pullout test on 50 mm double-plate circular anchor is presented in Figure 5. The pullout load at failure of 111 N, 180 N, 263 N, and 332 N were obtained at a displacement of 209 mm, 207 mm, 206 mm, and 207 mm for an embedment ratio 2, 3, 4, and 6 respectively. Similarly, the variation of load with displacement for the pullout tests on 50 mm double-plate square anchors are presented in Figure 6. The pullout load at failure of 166 N, 208 N, 277 N, and 422 N were obtained at a displacement of 205 mm, 204 mm, 206 mm, and 201 mm for an embedment ratio 2, 3, 4, and 6 respectively. The increase in the

pullout load at failure of square anchors was found to be around 1.3 times that of the circular anchors.

3.3 Heave studies

For the tests on the embedment ratios 2, 3 and 4, heave was observed at the top surface of the test tank. Figure 7 shows the top surface of the test tank before test. Figure 8 shows the top surface of the test tank after the pullout test. Heave was observed when the passive failure surface developed in soil in front of the anchor intersected the top surface of the ground surface. Such anchors are famously categorized as shallow anchors. However, Figure 9 shows a different behavior. The conical depression observed is for an embedment ratio of 6, and is formed after the displacement of the anchor from its initial position and the subsequent void created behind the plate resulting in a conical depression. Such anchors are called deep anchors. The failure surface in such anchors do not reach the ground surface and form a bulb around the anchor.

3.4 Pullout loads at failure

The pullout load is mobilized by the development of the passive resistance of sand of the soil mass between the vertical anchor plate and the boundary face of the test tank. The pullout load at failure for 50 mm double-plate circular and square anchors were found to increase by 50% as compared to the single-plate circular and square anchors respectively. The inclusion of additional plate in case of the double-plate anchor encompasses more soil volume responsible for subsequent increased mobilization of passive resistance.



Figure 7. Top surface of test tank before test



Figure 8. Top surface of test tank after test (shallow anchors)



Figure 9. Top surface of test tank after test (deep anchors)

The study shows an increase in the pullout load failure with the increase in the embedment depth. Also, the increase in the pullout load at failure of square anchors was found to be around 1.3 times that of the circular anchors. The reason for both is

due to an increase in the soil volume with consecutive cases of increased embedment depth and 1.3 times more surface area in case of the square anchor.

The authors are of the opinion that more sensitive tests are to be conducted with lesser weight of the tie rod and the steel wire system for the tests on smaller embedment depths (like $h/d = 2$). The use of lesser weighted tie rod was not practiced in order to provide a uniform basis for comparisons.

The study proves the efficiency of the double-plate anchors. It makes way for more extensive and detailed research into the area of multi-plate vertical anchors and adds to the work of the previous works of the authors in Tilak & Samadhiya (2017) and Tilak & Samadhiya (2018). It steers the need for field studies and prototype studies in diverse conditions and a conscious shift in the interest, experimentations and practice of the research community and of geotechnical engineers from the existing use of single-plate anchors.

4 CONCLUSIONS

The study summarizes the following points.

1. Experimental study was conducted to study the use of vertical double-plate circular and square anchors. The study shows the variation of pullout load with the displacement of anchors.
2. The pullout load at failure of vertical plate anchor increased with the increase in the embedment depth.
3. The double-plate anchors provided more resistance to the pullout forces as compared to the single-plate anchors.
4. The square anchors provided more resistance to the pullout forces as compared to the circular anchors, both for single and double plates.
5. Heave was observed for shallow anchors of embedment ratios 2, 3 and 4.
6. The study summarizes the effect of inclusion of additional plate and proves the effectiveness of double-plate anchors subjected to horizontal loads at various depth.

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