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Vertical Uplift Capacity of a Group of Equally Spaced Helical Screw Anchors in Sand

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Abstract: This paper presents the experimental investigations on the behaviour of a group of single, double and triple helical screw anchors embedded vertically at the same level in sand. The tests were carried out on one, two, three and four numbers of anchors in sand for different depths of embedment keeping shallow and deep mode of behaviour in mind. The testing program included 48 tests conducted on three model anchors installed in sand whose density kept constant throughout the tests. It was observed that the ultimate pullout load varied significantly with the installation depth of the anchor and the number of anchors. The apparent coefficient of friction (f^*) between anchor and soil was also calculated based on the test results. It was found that the apparent coefficient of friction varies between 1.02 and 4.76 for 1, 2, 3 and 4 numbers of single, double and triple helical screw anchors. Plate load tests conducted on model soil showed that the value of ϕ increases from 35º for virgin soil to 48º for soil with four double screw helical anchors. The graphs of ultimate pullout capacity of a group of two, three and four no. of anchors with respect to one anchor were plotted and design equations have been proposed correlating them. Based on these findings, it has been concluded that the load-displacement relationships for all groups can be reduced to a common curve. A 3-D finite element model, PLAXIS, was used to confirm the results obtained from laboratory tests and the agreement is excellent.

Keywords: Apparent Coefficient of Friction, Helical Screw Anchor, Installation Depth, Plate Load Test.

1. Introduction

Anchors are prefabricated foundations which are used for almost all types of structures e.g. transmission towers, radar towers, tall chimneys, suspension bridges, offshore structures, aircraft moorings, tunnels, buried pipelines under water etc. Anchors are structural elements used in Civil engineering applications to provide resistance against tension, compression and uplift. The past studies on pullout capacity and associated soil deformations of the anchors are very limited. Most of the studies on anchors have been carried out on horizontal anchors and there are much less research work reported on inclined and vertical anchors. Anchors are manufactured in variety of configurations such as plate anchors, pile anchors, grouted anchors, prestressed concrete anchors and single and multiple helical screw anchors. For helical screw anchors, screws are welded at a predetermined suitable spacing along the steel shaft. A screw anchor is installed in the ground by applying torque to the shaft. An axial compression force is applied to the shaft for its advancement into the soil.

The works on single helical screw anchor are many. However, hardly any work is available that examines the interference effect on the pullout capacity of a group of closely spaced anchors. Anchors are seldom used alone. They are always used in groups. Hence, the behaviour of group of anchors is of considerable importance. But very little literature has been published on the topic. In the present study, the influence of a group of 2, 3 and 4 no. of helical screw anchors having equal dimensions and placed vertically in a cohesionless medium, on the magnitude of the vertical uplift resistance has been examined. The test results reported are aimed to suggest empirical approach for design of group of anchors subject to tensile loads.

Meyerhof and Adams (1968) developed an expression to predict the anchor uplift capacity. They had concluded that the geometry of the failure surface is fairly distinct but varies in shape and extent with the H/B ratio and depends on the relative density of the sand. Laboratory vertical pulling tests on groups of circular anchors in sand have been reported by Hanna et al. (1972). The anchors were in groups of up to 25, at various spacing and at depth/diameter ratios of 6 and 12. The ultimate group resistances were compared with the theoretical values of Meyerhof and Adams (1968), and it was concluded that, although the theory predicted behavioral trends, the theoretical failure values were considerably in error. Meyerhof (1973) conducted experiments for identical test conditions and concluded that the pullout capacity of axially loaded inclined plate anchors exceeded that of vertical anchors.

Laboratory tests on steel ball anchors embedded in sand and pulled at angles of inclination up to 55º from the vertical have been reported by Larnach (1972 and 1973) for two anchors and for line groups of three and five anchors. In these tests the depth/diameter ratio was constant at 16, thus ensuring deep anchor behavior. He reported that the initial slope of the load pullout curve for grouped anchor plates is essentially linear and independent of inclination, spacing, and number of anchors in the group.

One thing common in all the above mentioned studies is that they are limited to anchors with a single helix. The proposed semi-empirical theories cannot be easily applied to the problem of multi-helix anchors in which a complication arises owing to the interaction between adjacent helices. This interaction can produce overlapping stress zones that affect the failure mode and ultimate capacity, as highlighted by Merifield and Smith (2010). Mitsch and Clemence (1985) suggested that the ultimate uplift resistance is made of the bearing resistance of the upper helix, frictional cylinder resistance and friction on anchor shaft. Ghaly and Hanna (1991) conducted experimental investigation on single and multiple helical screw anchors installed in dense, medium and loose dry sands. They concluded that the ultimate pullout capacity of screw anchors was a function of sand characteristics, anchor diameter and installation depth of anchor.

In general, anchor capacity is a function of (a) soil type and density; (b) the capacity of each individual bearing element (i.e. plate or helix); (c) the adhesion between the plate/shaft and surrounding soil; (d) the interaction between each bearing element; (e) the orientation of the anchor; and (f) the embedment depth. Any combination of these variables will significantly affect the observed mode of failure and thus the ultimate capacity of a buried anchor in tension.

The objectives of the present study are to develop understanding of multiplate anchor behaviour, their failure mechanism and to develop understanding of the interference effect on the pullout capacity of a group of closely spaced anchors. In the present work the experiments had been conducted to study the behaviour of helical screw anchors under application of axial pullout load by varying the number of anchors, number of screw blades in an anchor and installation depth. The present paper describes the behaviour (in laboratory scale) of group of helical screw anchors pulled vertically upward in medium dense sand. Here in this experimental investigation only one density of sand was used throughout. Also the spacing of the anchors was kept constant equal to 2.5 times the diameter of the screw of the anchor. In the published literature, this spacing was mentioned as one in which no interference happens from the adjacent anchors.

2. Experimental Setup

Laboratory tests were conducted to determine the uplift resistance of helical screw anchors. Although laboratory tests are not substitute of full scale field tests but tests at laboratory have an advantage of allowing a close control on some of the parameters affecting the uplift resistance of helical screw anchors. In this way behaviour of the small size anchor models in the laboratory could be of immense help in asserting the behaviour of full scale anchors in the field in actual condition. The experimental setup used for this work and the procedure adopted for testing of single and multiple helical screw anchors are described elsewhere Mittal & Mukherjee (2013). In this paper, the properties of soil and anchor, the test tank and the loading frame used in the experiments had been described in detail.

3. Test Procedure

Here it was assumed that at any stage, all the anchors,

I. Carry an equal magnitude of load, and,

II. Settle exactly to the same extent.

It was also assumed that during loading no tilting takes place and the anchors are perfectly rigid. Anchors were installed in the ground at a depth of 4, 6, 8 and 10 times the diameter of the screw of the anchor. The three dimensional view of the experimental setup is illustrated in Fig. 1.

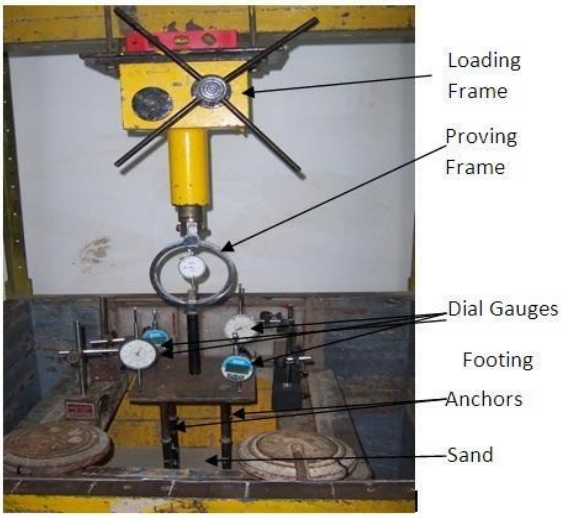

Figure 1: Complete setup for Pull-out Test of 4 Helical Screw Anchors

4 Parametric Study

Parametric study was conducted to determine the improved apparent coefficient of friction (f*) between the anchor and the soil and also increase in the value of angle of internal friction due to installation of anchor in soil.

Apparent coefficient of friction between the anchor and the soil (f*) plays an important role in determining the strength of anchors. In these experiments the value of f* ranged between 1.02 and 4.76. Typical values of f* for a group of 1, 2, 3 and 4 anchors are shown in the Table 1.

Table 1: Values of f* for a group of N_a = 1, 2, 3 and 4 helical screw anchors

n_b	H/B	f*			
		N_a=1	N_a=2	N_a=3	N_a=4
1	4	1.34	1.02	1.07	1.06
1	6	2.14	1.53	1.44	1.41
1	8	3.29	2.3	2.05	2.06
1	10	3.22	1.99	2.34	2.08
2	4	1.95	1.6	1.49	1.57
2	6	2.99	1.9	1.9	1.89
2	8	3.88	2.51	2.37	2.43
2	10	3.78	2.65	2.78	2.41
3	4	2.28	1.95	1.82	1.86
3	6	4.02	2.53	2.57	2.58
3	8	4.76	2.92	2.91	2.92
3	10	4.44	3.08	3.02	2.82

The increase in the value of φ can be calculated from the plate load test. The plate load tests were conducted on virgin soil and also on soil with 1, 2, 3 and 4 double helical screw anchors. A plate of dimension 150 X 150 mm was fixed on the top of the anchor with the help of nuts and bolts.

The ultimate bearing capacity for square footing was computed from the equation

$$q_u = 0.4\gamma_d \ B \ N_\gamma \quad \text{.............................. (1)}$$

where, q_u is ultimate bearing capacity, γ_d is dry unit weight of soil = 15.7 kN/m^3, B is width of the footing plate= 150 mm and N_γ = bearing capacity factor. Putting above values eq. 1 becomes as,

$$q_u = 0.942 \ N_\gamma \quad \text{...(2)}$$

The value of q_u was obtained from plate load tests for each test condition (i.e. on virgin soil and with 1, 2, 3 and 4 double helical screw anchors). The value of N_γ was then obtained by using Eq. 2. The value of φ for a particular N_γ was obtained from Mittal and Shukla (2009). The values of q_u, N_γ and corresponding φ are shown in Table 2.

This table shows that the value of angle of internal friction of the soil increased to approx 48^o after placing 4 screw anchors whose value was approx 37^o initially without any anchor. This indicates a significant increase in the value of φ after insertion of helical screw anchor.

Table 2: Values of increased φ for double helical screw anchor

Soil and Anchor	q_u (kN/m^2)	N_γ	φ
Virgin soil	69.76	74.05	37.12
Soil with 1 anchor	174.42	181.69	42.23
Soil with 2 anchors	283.41	295.22	45.24
Soil with 3 anchors	392.4	408.75	46.39
Soil with 4 anchors	566.8	590.42	48.24

5 Test Results and Discussions

Total 48 pullout (tension) tests were conducted by varying the following parameters

1. No. of anchors (N_a = 4, 6, 8 and 10)

2. No. of screw blades in anchor (n_b = 1, 2 and 3)

3. H/B ratio of anchor (H/B = 4, 6, 8 and 10) where H is the depth of the bottom of the anchor from the soil surface and B is the diameter of the screw blade.

The values of the ultimate pullout load of 1, 2, 3 & 4 numbers of helical screw anchors obtained from laboratory testing are tabulated in Table 2.

Table 2 Ultimate Pullout Loads of 1, 2, 3 & 4 Anchors Obtained from Laboratory Tests

n_b	H/B	$(Q_{up})_1$ (N)	$(Q_{up})_2$ (N)	$(Q_{up})_3$ (N)	$(Q_{up})_4$ (N)
1	4	93	137	221	294
1	6	373	539	760	991
1	8	1079	1545	1991	2747
1	10	1717	2158	3823	4513
2	4	118	196	270	392
2	6	490	613	883	1275
2	8	1226	1619	2197	3139
2	10	1962	2796	4414	5101
3	4	132	245	319	441
3	6	638	736	1177	1619
3	8	1471	1767	2600	3679
3	10	2256	3188	4689	5837

In the present experimental investigation, the experiments were carried out on a group of 2, 3 and 4 number of anchors arranged in linear, equilateral triangle and square pattern respectively.

An attempt has been made to express ultimate pullout capacity of multiple anchors in terms of single anchor. This is because it is relatively easy to test and analyse single anchor compared to multiple anchors. Keeping this point in mind the graphs of ultimate pullout capacity of multiple anchors with respect to single anchor have been plotted. A sample graph for four anchors versus one anchor is shown in Fig. 2. These curves provide the equations for ultimate pullout capacity of multiple anchors in terms of 1 anchor.

Based on the equations obtained for 2, 3 and 4 number of helical screw anchors from plots of ultimate pullout capacity of multiple helical screw anchors versus single helical screw anchor, a single equation for the determination of the ultimate pullout capacity of multiple anchors is proposed as mentioned in Equation 1.

$$(Q_{up})_n = N_a (Q_{up})_1^m \quad (1)$$

where, $(Q_{up})_n$ = ultimate pullout capacity of multiple helical screw anchors where n=2, 3 and 4 in our study, N_a = number of anchors whose value is equal to 2 for two number of anchors, 3 for three number of anchors and 4 for four number of anchors, $(Q_{up})_1$ = ultimate pullout capacity of single helical screw anchor and, m= a constant whose value we proposes as 0.95.

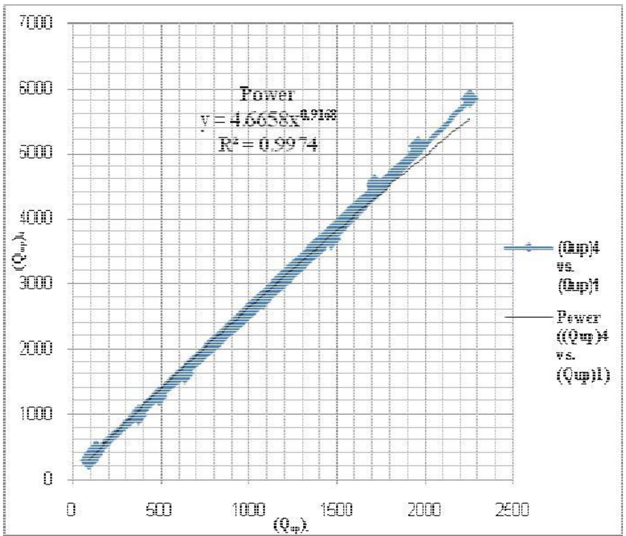

Fig. 2 Graph of ultimate pullout capacity of 4 anchors versus 1 anchor

By assuming the values of m and n as mentioned above, the values of ultimate pullout capacity of 2, 3 and 4 number of helical screw anchors has been calculated using Eq.1 as mentioned in Table 3. Now two sets of values of ultimate pullout capacity of 2, 3 and 4 number of helical screw anchors are available – one from the experimental investigation carried out in the laboratory, and the other from the equations proposed for multiple number of helical screw anchors as mentioned in Equation (1).

The empirical equation proposed here has some limitations.

Table 3 Ultimate Pullout Loads of 2, 3 & 4 Anchors Based on Equation Proposed

n_b	H/B	$(Q_{up})_2$ (N)	$(Q_{up})_3$ (N)	$(Q_{up})_4$ (N)
1	4	148	222	296
1	6	554	831	1108
1	8	1516	2274	3032
1	10	2370	3555	4740
2	4	186	279	372
2	6	716	1074	1432
2	8	1716	2574	3432
2	10	2682	4023	5364
3	4	206	309	412
3	6	926	1389	1852
3	8	2036	3054	4072
3	10	3062	4593	6124

(1) This is presuming that embedment depth, diameter and material of the anchor are same.

(2) All the soil properties i.e. relative density and angle of internal friction are same.

6 PLAXIS Finite Difference Analysis

The main objective of modeling helical anchor behaviour was to define the failure mechanism and load transfer behaviour. Upon calibration-verification with the experimental data, FEM provided insight into the effects of anchor loading on the surrounding soil. Based on the findings of the model and full-scale load test results, a methodology for calculating the anchor capacity was developed.

To account for the unique geometry of the problem a three-dimensional soil-foundation interaction software program, namely PLAXIS 3D Foundation Suite, was selected. A linearly elastic perfectly plastic model namely Mohr–Coulomb model was selected from those available in PLAXIS to describe the non-linear sand behaviour in the work. PLAXIS incorporates a fully automatic mesh generation procedure, in which the geometry is divided into elements of basic element type, and compatible structural elements. Five different mesh densities are available in PLAXIS ranging from very coarse to very fine. In this study fine mesh was adopted throughout which was shown in Fig. 3.

The numerical model was constructed to match the full scale geometry of the anchor in all regards excluding the helical shape of the bearing plates, which were modeled as circular discs rather than pitched plates. The Mohr–Coulomb model was used to represent the soil behaviour, for which cohesion and friction angle values were obtained through triaxial test results.

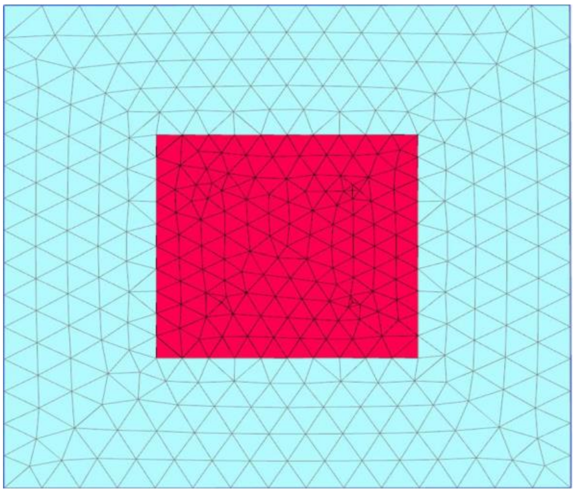

Fig. 3 Fine Mesh used in PLAXIS analysis

Values of soil parameters used in the investigation are shown in Table 4.

The helical screw anchor is represented by node-to-node anchor coupled with a circular plated attached to it. In PLAXIS soil/structure interface behaviour may be modeled using parameters generated using an interaction coefficient, Ri defined as the ratio between the shear strength of soil/structure interface and the corresponding shear strength of the soil. Fully rough interface conditions, $R_i = 1$, were assumed in this study.

Table 4: Properties of soil used in PLAXIS

Type of Soil	Loose	Medium Dense	Dense
c (Pa)	0	0	0
Φ	28	32 and 36	38 and 40

γ_d (kN/m^3)	13.73	15.7	17.66
N	0.25	0.3	0.4
E (MPa)	20	40	65

7 PLAXIS Results

In PLAXIS, pullout tests were carried out for embedment depth ratio of 4, 6 and 8. PLAXIS pullout results for 3 no. of anchors are shown in Table 5.

Table 5: PLAXIS Results of Pullout Tests for N_a=3

n_b	H/B	Φ (Degree)	γ (kN/m^3)	Failure Load, P_f (N)
1	4	32	15.7	716
1	4	40	13.73	167
1	6	38	15.7	245
1	6	40	17.66	284
1	8	32	15.7	355
2	4	32	15.7	148
2	6	38	15.7	85
2	6	40	17.66	282
2	8	36	13.73	442
3	4	32	15.7	147
3	4	36	15.7	163
3	4	38	15.7	85
3	6	38	15.7	192
3	6	40	17.66	232
3	8	36	13.73	430
3	8	36	17.66	533

To validate the results obtained from the laboratory tests, comparison of its results were done with PLAXIS results. This comparison was done in non-dimensional form. For comparison purpose a non-dimensional factor $P_f/(\gamma_d BH\delta_f)$ was defined where P_f is the failure load, γ_d is the unit wt. of sand, B is the diameter of the helical screw of the anchor, H is the embedment depth of the anchor and δ_f is the deformation of the anchor at failure.

The results obtained by conducting PLAXIS runs on the model similar to the one on which laboratory experiments were conducted were compared with results obtained by laboratory experiments themselves. Table 6 shows the comparison in non-dimensional form. From this table it is clear that the difference between laboratory test and PLAXIS results is within 10% which can be neglected.

Table 6: Comparison of Non-dimensional Parameter $P_f/(\gamma_d BH\delta_f)$ from Laboratory Experiment and PLAXIS Run for Pullout Tests

N_a	n_b	H/B	$P_f/(\gamma_d BH\delta_f)$		% diff
			LAB Test	PLAXIS	
1	1	4	759.43	694.32	8.56
1	1	6	529.15	562.21	6.05
1	2	6	203.99	184.14	9.36
1	3	6	304.39	279.05	8.22
2	1	6	208.25	186.61	10.09
2	2	6	179.51	161.88	9.49
2	3	6	289.38	260.78	9.69
3	1	6	258.16	232.95	9.69
3	2	6	305.29	278.83	8.52
3	3	4	1737.88	1923.37	9.62
4	1	4	435.49	400.20	8.04
4	1	6	344.23	311.16	9.59
4	3	4	2956.75	2734.12	7.54

8 Conclusions

The effect of interference due to a number of multiple helical screw anchors placed vertically in a granular sandy medium at different embedment depths has been investigated in this work by conducting a series of small scale model tests. As compared to the single isolated anchor, a group of two, three and four anchors yields a greater magnitude of uplift resistance.

Ultimate pullout capacity of helical screw anchor increase with increase in the embedment depth ratio of the anchor, no. of anchors and no. of screw blades in the anchor. Moreover, the increase is more pronounced with embedment depth ratio and no. of anchors whereas with no. of screw blades the increase is very marginal.

The ultimate aim of this work was to express ultimate pullout capacity of multiple helical screw anchors in terms of single helical screw anchor. So we have plotted graph of ultimate pullout capacity of 2, 3 and 4 number of anchors with respect to one anchor. In this way we have found equations to calculate ultimate pullout capacity of multiple anchors in terms of one anchor. The percentage difference between the values of ultimate pullout load obtained from laboratory tests and from the equation proposed falls within 10%. Hence it can be said that the proposed equation designs the anchors assembly amicably.

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