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Experimental investigation of the uplift capacity of group anchor plates embedded in sand

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Abstract. In this study, the uplift capacity of anchor plates embedded in sand was investigated by conducting model tests. Square shaped anchors were used in the tests and parameters such as relative density of sand, embedment ratio (H/B), spacing ratio between anchors (S/B) and anchor configuration affecting the uplift capacity were investigated. Breakout factor and group efficiency which are dimensionless parameters were used to show the results. A series of finite element analyses and analytical solutions were additionally performed to ascertain the validity of the findings from the laboratory model tests and to supplement the results of the model tests. It can be concluded that the embedment depth in dense sand soil condition is the most important parameter with respect to the other parameters as to influencing the uplift capacity of group anchors.

Keywords: anchor plates; laboratory tests; uplift capacity; breakout factor; group efficiency

1. Introduction

Nowadays, various kinds of structures are needed due to the changes in necessities. Depending on these needs, it has become inevitable to use the foundation systems in different types. Foundation systems of specific structures such as high-voltage power lines, communication towers (radio and television towers etc.), long factory chimneys, sea platforms (dock structures made in seafloor, platforms underwater and wave breaker structures etc.), columns carrying the advertising boards and signs in freeways and railways and pipelines have been subjected to different loading conditions. These structures are under the influence of uplift loading conditions. Some examples of the mentioned forces are eccentricity based forces; lifting force in structures constructed afloat, forces in cables and lifting forces in empty silos.

Although it is generally enough for foundation systems to be analyzed and designed in terms of compression loads, some foundation systems should be designed by analyzing them in terms of uplift load. Especially the foundation systems under uplift loads should be designed according to the factors affecting the uplift capacity. Anchor systems have been used effectively in structures subjected to uplift force recently. These anchor systems are affected by some factors such as soil properties, loading conditions, embedment ratio and anchor group configuration.

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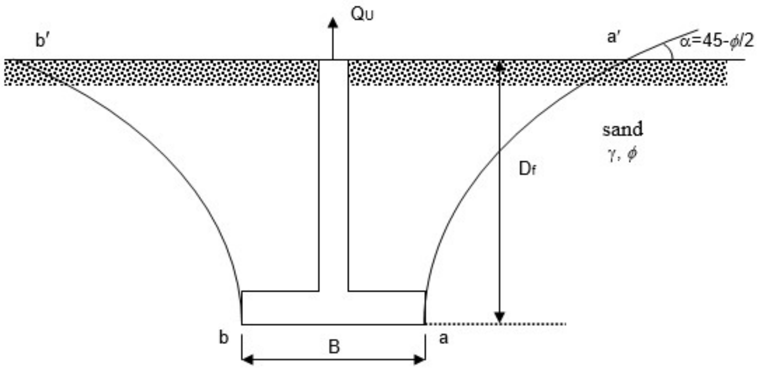


Fig. 1 Balla's theory for shallow circular foundation subjected to uplift load (Das 1999)

The foundations can be subjected to uplift loads under some certain conditions. The design of these foundations should be achieved considering the safety factors.

A shallow foundation of which width is B and depth is D_f is shown in Fig. 1 (Das 1999). The uplift capacity of the foundation, Q_u, is stated as the total of the weight of the foundation and soil in the failure area and frictional resistance of the soil formed through surface of failure (Das 1999).

If the foundation is subjected to an uplift load, typical shape of failure surface in the soil is accepted as in Fig. 1. Here, the intersection of failure surface and soil level make an angle α. The value of α changes depending on the consistency in clay soil and density in sand soil.

There are many experimental and theoretical studies to investigate the behaviour of anchor systems. Balla (1961) proposed a method to predict the ultimate uplift capacity of anchor plate and he developed a shearing resistance during the failure surface. Balla (1961) determined the shape shear surfaces for horizontal shallow anchors in dense cohesionless soil. Baker and Kondner (1966) approved Balla's findings regarding the behavioral difference of deep and shallow anchors in dense cohesionless soil. Adams and Hayes (1967) carried out large scaled field experiments on anchors for the construction of broadcasting line towers. Meyerhof and Adams (1968), Das and Seeley (1975), Andreadis *et al*. (1981), Murray and Geddes (1987) conventionally investigated the behaviour of anchors by doing small scaled experiments in laboratory. Vesic (1971) developed a study examining the uplift capacity of shallow circular and strip foundations, and investigated the effects of different embedment depths and angle of internal friction with theoretical approaches. He concluded that breakout factor increases with the increases of embedment ratio and angle of internal friction. Besides, Ovesen (1981), Tagaya *et al*. (1988), Dickin (1988) and Dickin and Leung (1990, 1992) obtained the necessary data for intended stress conditions on full scale prototypes by using centrifuge modeling technique. Dickin and Laman (2007) carried out modelings in Plaxis and centrifuge experiments in order to identify the uplift strength of strip anchor which has 1 m width in sand soil. They observed that the density of sand soil and the ratio of anchor embedment affect the uplift capacity. When the results of the experiment, theoretical studies and Plaxis analysis were compared, they observed that the values are compatible. Consoli *et al*. (2013) carried out a series of model tests to investigate the kinematics of failure and the uplift response of circular anchor plates embedded in sand-cement stabilized backfill. Experimental results showed that the uplift capacity of anchor plates embedded in sand backfill layers increases considerably with the increase of embedment ratio. Bhattacharya and Kumar (2014a) performed analyses using the lower bound limit analysis, finite elements and linear optimisation to find the vertical uplift resistance of horizontal plate anchors embedded in sand and subjected to a combination of pseudo-static horizontal earthquake body forces and the seepage forces. The effect of the embedment ratio and internal frictional angle of sand were investigated. The results obtained from the analyses were compared with the available literature. They were noted that the uplift resistance reduced continuously with the increase of the magnitudes of the earthquake acceleration coefficient and the hydraulic gradient. The uplift resistance increased continuously with the increase of the values of embedment ratio and the internal friction of sand. Bhattacharya and Kumar (2014b) determined the uplift capacity of an inclined strip plate anchor embedded in sand by using the lower bound theorem of the limit analysis in combination with finite elements and linear optimization. The numerical results in the form of uplift factors were presented by changing gradually the inclination of the plate from horizontal to vertical. The uplift resistance increased significantly with the increase of the horizontal inclination. The effect of the anchor plate–soil interface friction angle on the uplift resistance became extensive for a vertical anchor but remained insignificant for a horizontal anchor. The results from the analysis matched well with the theoretical and experimental results reported in literature. Niroumand and Kassim (2014) carried out both physical model tests and numerical simulations to investigate the uplift response of symmetrical square anchor plates in loose sand. In these tests, they also researched the uplift responses for a certain maximum displacement and compared the results obtained from physical model tests and numerical simulations. The results showed that the finite element findings are higher than the experimental findings in loose sand. Keskin (2015) carried out model tests into the uplift capacity of horizontal square plate anchors in sand with and without geogrid reinforcement. The parameters investigated are the effect of the depth of the single layer of geogrid, vertical spacing of geogrid layers, number of geogrid layers, length of geogrid layers, the effects of embedment depth, and relative density of sand. The results showed that the geogrid reinforcement had a considerable effect on the uplift capacity of horizontal square plate anchors in sand. The improvement in uplift capacity was found to be strongly dependent on the embedment depth and relative density of sand.

Even though there are plenty of theoretical and experimental studies about a single plate anchor, the studies about behaviour of group anchors are limited. Laboratory work on the horizontal translation of rows of three square plates in sand was reported by Hueckel (1957), who found that, below a particular spacing of the plates, the ultimate load capacity of the group decreased as the spacing was further reduced. Smith (1962) also performed tests on the horizontal translation of groups of three anchors in sand, under full-scale field conditions, and reported results in broad agreement with the findings of Hueckel. A further study of the interference effects of horizontally translated anchors in sand is that of Neely (1971). Using square plates, he examined, at laboratory scale, the effect of horizontal spacing on rows of two and four plates at different depth/plate size ratios. The work was extended to cover the case of the horizontal translation of a pair of plates placed vertically one above the other with an overall height/plate size ratio of five. 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 spacings 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. Laboratory tests on steel ball anchors embedded in sand and pulled at angles of inclination up to 55° from the vertical were reported by Larnach (1972, 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. In the vertical uplift of a line of five anchors, the two outside anchors exhibited the highest pullout resistance, the central anchor of the group recorded the next highest resistance, while the lowest resistance was associated with the two remaining interior anchors. Geddes and Murray (1996) investigated the uplift capacity of group anchors with model-scale vertical pulling tests in 1×2, 2×2 and 1×5 configurations. The tests were carried out for a single depth of embedment. They examined effect of spacing between anchors and they compared results with the value of group efficiency. They reported that at a critical separation ratio (S/B = 2.9), the maximum efficiency of 100% was reached and maintained at that level with further increase in separation. Besides, it was investigated the uplift capacity of each anchor for 1x5 configurations. While the end anchors carried the greatest uplift loads, the middle anchor carried the least loads in the linear group of five. In the present work, the effects of relative density of sand, embedment ratio and anchor configuration have also been considered differently from the work of Geddes and Murray (1996). Vanitha *et al*. (2007) investigated the relation of the rates of different embedment depth, anchor width and spacing between anchors, parameters with load displacement, strength and group effeciency in group anchors subjected to uplift loads in 2×2 configurations by doing experimental studies. In that study, they found out that group effeciency increased depending on the increase in uplift load with the rise of embedment depth ratio, anchor width ratio and spacing ratio between anchors. Kumar and Kouzer (2008) investigated the effect of spacing of a group of two and multiple rough strip anchors, having equal widths and placed horizontally in a cohesionless soil, the vertical uplift resistance using upper-bound analysis coupled with a simple rigid wedge mechanism bounded by a planar rupture surface. It was observed from various theoretical and experimental studies that the vertical uplift resistance of anchors in a group reduced quite significantly with the decrease of the spacing between the anchors. Kumar and Bhoi (2009) measured the ultimate uplift strength of a group of strip anchor placed in sand. In the study, they analyzed the effect of spacing between anchors on uplift strength for various combinations of anchor embedment ratios and angle of internal friction of the soil. They concluded that uplift strength decreases with the decrease in spacing and this decrease is affected by the embedment ratio and angle of internal friction. Bildik *et al*. (2012) investigated the effect of number of anchors, embedment ratio, soil density and spacing between anchors on uplift capacity of group anchors in strip by using finite elements method. The results were denominated as group effeciency that is a non dimensional parameter. It was concluded that group effeciency increases with the increase of the spacing between anchors. Also soil density and embedment ratio are the main parameters affecting the uplift capacity. Bhattacharya and Kumar (2013) investigated the horizontal uplift capacity of a group of two vertical strip plate anchors by using the lower bound finite element limit analysis. In these analyses, they found that the uplift resistance for a group of two anchors increases with the increase of embedment ratio. Demir and Ok (2015) carried out both experimental and numerical investigations into the uplift capacity of helical anchor in soft clay. The results of physical and computational studies investigating the uplift response of helical anchors in soft clay showed that maximum resistances depend on anchor embedment ratio and anchor spacing ratio. Ghosh and Santhoshkumar (2015) investigated the effect of interference on the uplift capacity of two closely spaced horizontal strip anchors embedded in cohesionless soil. The analysis was performed using the method of stress characteristics coupled with the limit equilibrium approach. The effects of surcharge and unit weight of soil on the uplift resistance of anchors were determined in terms of uplift capacity factors. A detailed parametric study was carried out by varying the spacing between two anchors, embedment ratio, and soil friction angle. The results of the numerical analysis were compared with the available theoretical and experimental data reported in the literature. It was observed that the ultimate uplift capacity of anchors increased with the increase of embedment ratio, but reduced with a decrease in the spacing ratio. Emirler *et al*. (2015) investigated numerically the uplift behaviour of group anchor plates embedded in sandy soil by using Plaxis. A series of three-dimensional non-linear finite element analyses were performed. The effect of parameters such as spacing between anchors (S/B = 1, 2, 3 and 4), embedment ratio of anchors (H/B = 2, 5 and 8), relative density of sand, and configuration of anchor plates (1×4 and 2×2) were investigated. The results were presented in terms of the uplift capacity and breakout factor for single anchor plate, and also the value of group efficiency for group anchor plates. In the analysis, they observed that the uplift capacity and the breakout factor increase as the embedment ratio increases, for both relative densities. They concluded that the embedment ratio of anchor plates (H/B) and relative density of sand were main parameters effecting the uplift capacity of anchor plates. The results showed that for all analysis, the value of group efficiency increased with the increase of spacing of between anchors. The value of group efficiency increased 35% for both loose and dense sands at H/B = 2 (spacing ranging from S/B = 1 to 4). The increment ratio was less for H/B = 5 and 8 when comparing with the increment ratio of H/B = 2. It was concluded that the group efficiency increased approximately 100% when being an optimum spacing between the anchors. The results of 2×2 anchors group were moreless similar with the results of 1×4 anchors group.

In this study, the uplift capacity of group anchor systems has been investigated experimentally. For experimental studies, a mechanism in which anchor systems can be modeled in small-scale has been prepared in the laboratory. The effects of parameters such as relative density of sand, embedment ratio, spacing ratio between anchors and anchor configuration on the uplift capacity have been investigated in the experiments. In addition to this, a series of finite element analyses and analytical solutions were performed to ascertain the validity of the findings from the laboratory model tests and to supplement the results of the model tests.

2. Experimental studies

The experimental studies have been conducted in the laboratory of Civil Engineering Department of Cukurova University. A commercial Hi-Tech Magnus steel frame system has been used in the tests.

2.1 Loading system

The loading frame used in the experimental studies consists of U-300 profile post from four STIII steel and U-300 profiles, two of which attached below and two of which attached above on these posts. The space between frame edge posts is 4.6 m, the width is 60 cm and the height is 2.4 m. Load transfer has been provided to the foundation on the soil with the electrical loading system mounted on the frame. Loading apparatus used in the experimental study has been specially produced and obtained by mounting it to Hi-Tech Magnus frame. Loading apparatus is speed-controlled and loading arm can reciprocate. Motion energy in loading apparatus is produced by electric motor. Horizontal rotation induced from the motor used in loading has been transformed to vertical movement with the help of cast redactor in 4 Hp power. This transformation is enabled with the help of the gear mounted in redactor and motor and the linkage between gears (see Fig. 2).

Fig. 2 Control unit system

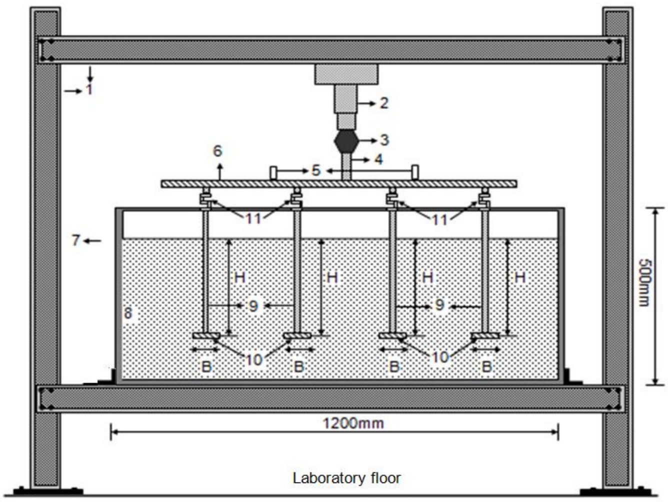
2.2 Test box

In this study a series of laboratory model tests were performed in a test box which provides the plane strain condition. Thus, the test box was designed as a steel frame with inside dimensions of 1200 mm (length), 700 mm (width), 500 mm (depth) as shown in Fig. 3 (Emirler 2013). The test box has been splitted into 2 different boxes; one is square and the other is rectangular in 700 mm (length), 700 mm (width), 500 mm (depth) and 1200 mm (length), 350 mm (width), 500 mm (depth) sizes respectively, by means of intermediate elements with the purpose of using it more effectively. The two side walls of test box were made of 20 mm thick plexiglass to see sand sample during preparation and observe the sand particle deformations in the tests. The other side walls of test box were made of 20 mm thick wood. The inside walls were polished in order to minimize friction between the inside walls of test box and sand. Test box has been mounted in a stationary way on loading frame that has been fixed on laboratory floor (see Figs. 4(a)-(b)).

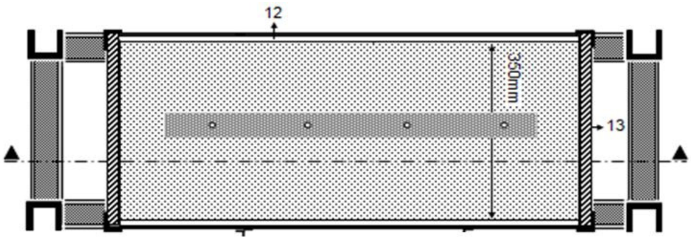
2.3 Model anchor plate

Model anchor plates used in experimental studies have been obtained from rigid plates in 10 mm thick and they are in square shape in 5 cm × 5 cm size (see Fig. 5).

Fig. 3 Test box



(a) Front view



(b) Plan view

1- Loading frame
2- Motor controlled hydrolic jack
3- Load cell
4- Loading head
5- Displacement meter
6- Anchor connector plate
7- Steel profile
8- Model soil
9- Uplift stick
10- Anchor plate
11- Load cell
12- Plexiglass surface
13- Wooden layer

Fig. 4 Test apparatus

Fig. 5 Model anchor plates

Fig. 6 Data recording unit

2.4 Data recording system

Load and displacement values obtained from the tests have been transferred to data logger which is TDS-530 produced by Tokyo Sokki company and works as resistance based. The data logger has 30 channels and 1000 data reading capacity in 0.4 second. Data obtained by data logger are transferred to TDS-7130 program. The results obtained here have been transformed to numerical values (see Fig. 6).

In tests, electronic load cells that have 2 kN and 10 kN capacities have been used to read the load values applied to model anchor plate. The displacements occurred as the result of uplifting the model anchor plates have been read by displacement transducers (LVDTs) with an accuracy of 0.01% of full range (50 mm).

2.5 Soil properties

In the experimental study, sand samples brought from Seyhan River bed in Cukurova Region have been used. Sand samples have been sieved by being washed from sieves number 18 (1 mm dia.) and 200 (0.074 mm dia.) according to ASTM D2487 (American Standards of Testing Materials) standards in the laboratory of Civil Engineering Department of Cukurova University. Sand samples that are among number 18 and 200 sieves at the end of the sieving process have been dried in an oven. A series of tests have been conducted to obtain the shear strength and index parameters of the sand used in the experimental study.

Sand samples have been sieved from a predetermined batch of sieves according to ASTM D2487 standards and grain size distribution has been obtained (see Fig. 7). From grain size distribution curve, soil class has been identified as poorly graded fine and clean sand (SP) according to the Unified Soil Classification System (USCS). Test results of sieve analysis have been given in Table 1.

Minimum ($\gamma_{d\min}$) and maximum ($\gamma_{d\max}$) dry unit weights of test sand have been determined according to the ASTM D4253 and D4254. Using the methods stated in the ASTM D4253 and D4254, dry unit weights corresponding to certain relative density values have been obtained. Sand samples in model tests have been placed into the box and their internal friction angles are 38° for relative densities D_r = 35% ($\gamma_{\min}$ = 15.7 kN/m^3) and 45° for D_r = 85% ($\gamma_{\max}$ = 17.0 kN/m^3).

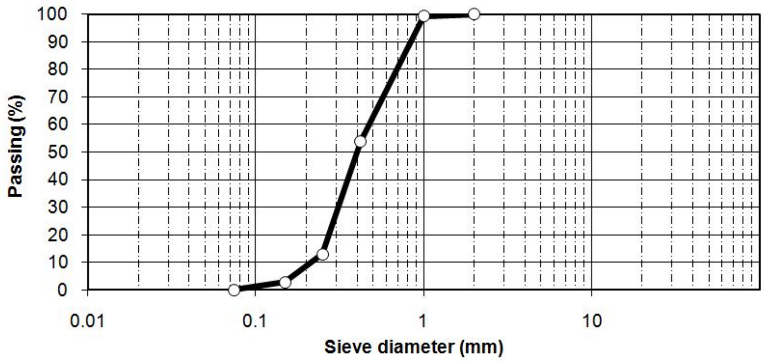


Fig. 7 Grain size distribution curve of sand

Table 1 Results of sieve analysis

Granulometry parameters	Value
Percentage of coarse sand (%)	0.0
Percentage of medium sand (%)	45.90
Percentage of fine sand (%)	54.10
Effective grain size, D_{10} (mm)	0.20
D_{30} (mm)	0.30
D_{60} (mm)	0.50
Coefficient of uniformity, C_u	2.50
Coefficient of curvature, C_c	0.90
Soil class (USCS)	SP

Fig. 8 Test setup and vibration device

2.6 Preparation of the dense sand bed

The sand bed was prepared by using the same compaction procedure in equal layers of 50 mm thick. In this method the quantity of sand for each layer, which was required to produce a specific relative density, was first weighed and placed into the box and compacted by a hand-held vibratory compactor until achieving the required layer height to ensure uniform compaction. The inner surfaces of the test box were marked at 50 mm intervals to make easy the preparation of the sand bed in layers. The model tests were performed with the dense sand for internal friction angle of 45°. To maintain the consistency of in-place density throughout the test box, the same compactive effort was applied on each layer of sand (see Fig. 8).

2.7 Effect of loading rate on the uplift capacity

Static vertical loads were applied to the model anchors by a motor controlled hydraulic jack system. The loadings have been carried out in the tests until failure occurs between model anchors and soil medium. At the first stage, tests have been conducted with 2 different loading rates (0.941 and 9.41 mm/min). The results of these different loading rates are shown in Fig. 9. As seen there, loading rate has no significant effect on the uplift capacity and the remaining tests have been carried out with an average loading rate value of 4.705 mm/min to reduce the duration of test.

2.8 Effect of load cell sensitivity on the uplift capacity

Sensitivity of the load cell used in experimental studies is one of the important factors on the test results. The effect of load cells on the tests has been investigated by measuring the uplift

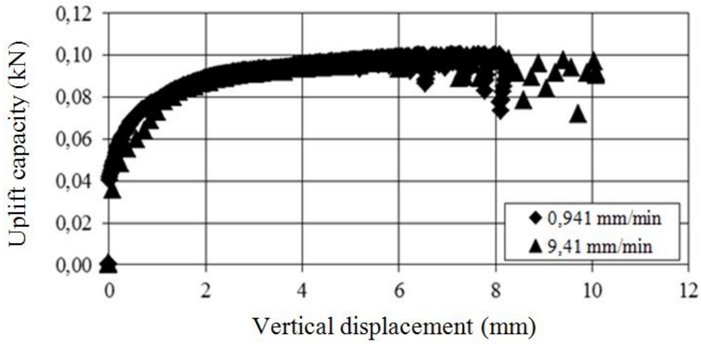


Fig. 9 Effect of loading rate on the uplift capacity

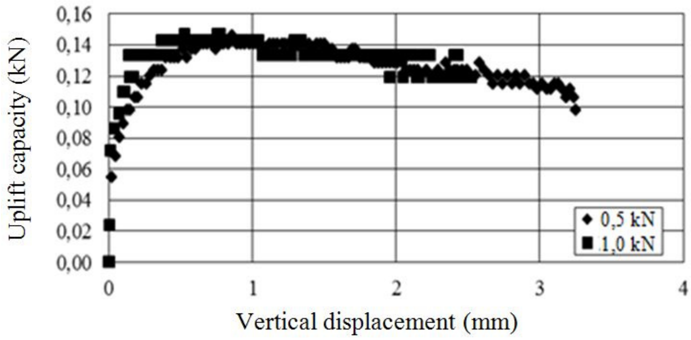


Fig. 10 Effect of load cell sensitivity on the uplift capacity

capacities of embedded anchor plates in low depth with two different load cells. The results have shown that load cell sensitivity does not have an important effect on uplift capacity; however, fluctuations are less in data obtained by low capacity load cell in load-displacement curves (see Fig. 10).

Laman (1995) carried out a series of centrifuge tests to investigate the moment carrying capacity of short pier foundations. In these tests, the effect of sensitivity of load cells was also investigated. It was concluded that fluctuations were less in data obtained by low capacity load cell than the data obtained by higher capacity load cell in load-displacement curves.

2.9 Test program

The uplift capacity of an anchor equals to the soil weight inside the free zone over anchor subgrade level, frictional resistance through free surface and the weight of anchor. The relative density of sand soil, spacing between anchors, embedment ratio of anchors and configuration are important parameters affecting the uplift capacity of group anchors. The laboratory model tests on single and group anchor plates have been carried out in this study to investigate the effect of these parameters on the uplify capacity of anchor plates. Test program has been given in Table 2.

The breakout factor (F_q) and the group efficiency (F_{group}) that are non dimensional parameters have been used to show the test results.

$$F_q = \frac{Q_u}{\gamma_d \times A \times H} \tag{1}$$

Where,

F_q : Breakout factor

Q_u : Uplift load

γ_d : Dry unit weight of the soil

A : Area of anchor plate

H : Embedment depth

$$F_{group} = \frac{Q_{total} \times 100}{N \times Q_u} \tag{2}$$

Where

F_{group} : Group efficiency

Q_{total} : Total uplift load of anchors

Q_u : Uplift load of a single anchor

N : Anchor number

Table 2 Test program

Test series	Dry unit weight of the sand (γ_d, kN/m^3)	Anchor shape	Anchor size (B, mm)	Embedment ratio (H/B)	Spacing ratio between anchors (S/B)
Loose 1×1	15.7	Square	50	From 1 to 8	-
Dense 1×1	17.0	Square	50	From 1 to 8	-
Dense 1×2	17.0	Square	50	5	From 1 to 4
Dense 1×4	17.0	Square	50	2, 5, 8	4
Dense 2×2	17.0	Square	50	2, 5, 8	4

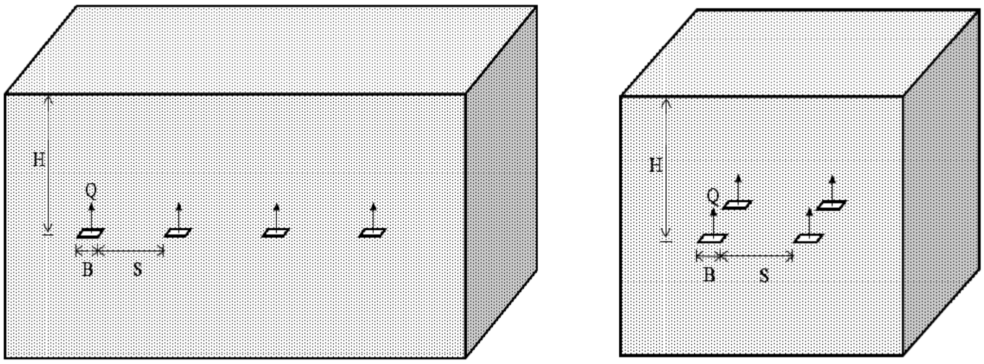


Fig. 11 Anchor configurations for 1×4 and 2×2

3. Test results

3.1 Effect of relative density of sand on the uplift capacity

Since, the shear strength parameter, cohesion is zero in sand soils, bearing capacity depends directly on ϕ angle. One of the most important parameters affecting the angle of internal friction (ϕ) of sands is the relative density of sand. The other parameters affecting the angle of internal friction (ϕ) are grain size distribution, grain shape and mineral structure of sand grains. The conditions of sand soil such as dry state or under water level do not affect ϕ angle too much (Ozaydın 1989).

The uplift capacities of anchor plates placed inside the sand soil prepared at two different densities have been investigated in the tests. The internal friction angle in loose condition is 38° for dry unit weight of $\gamma_{d\min}$ = 15.7 kN/m^3 (D_r = 35%) and the internal friction angle in dense condition is 45° for dry unit weight of $\gamma_{d\max}$ = 17.0 kN/m^3 (D_r = 85%). Sand soil has been placed in the box in layers of 5 cm thick sand. The results of the tests conducted to investigate the effect of relative density on the uplift capacity of anchor plates have been shown in Fig. 12.

The load-displacement curve of anchor plate starts doing asymptote has been described as failure load and transposition corresponding to this load has been described as displacement at failure load. According to the test results, anchor plate embedded in dense sand has uplift capacity

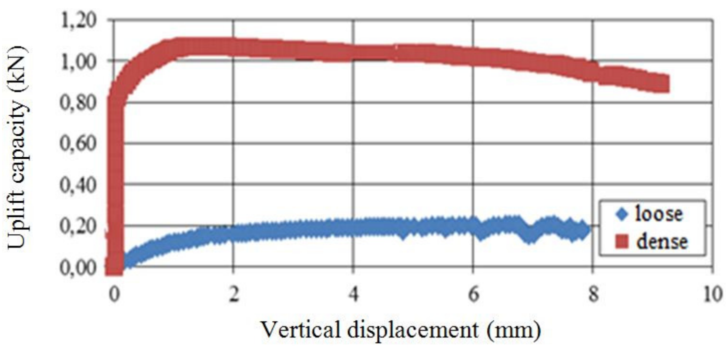


Fig. 12 Effect of relative density of sand on the uplift capacity

6 times more than the anchor plate embedded in loose sand for H/B = 8. As a result of this study, it can be concluded that the relative density is one of the main parameters affecting the uplift capacity of anchor plates.

Kumar and Bhoi (2009) carried out a series of small scale model tests to investigate vertical uplift capacity of strip anchors in sand. In these tests, the effect of relative density of sand on the uplift capacity was also investigated. They observed that the uplift capacity increased significantly with the increase of relative density of sand. Keskin (2015) carried out model tests and according to these studies, the uplift capacity for plate anchors in sand increased with the increase of density of sand.

It was understood from foregoing studies that the effect of relative density of sand was one of the most important parameters on the uplift capacity.

3.2 Effect of embedment ratio on the uplift capacity

Another parameter affecting the uplift capacity of anchor plates is the depth of the anchor. A series of tests have been conducted at different embedment ratios on anchor plate in order to see the effect of embedment ratio H/B on the uplift capacity. The graph of the uplift capacity depending on embedment ratio in loose and dense sand soil conditions for one anchor plate has

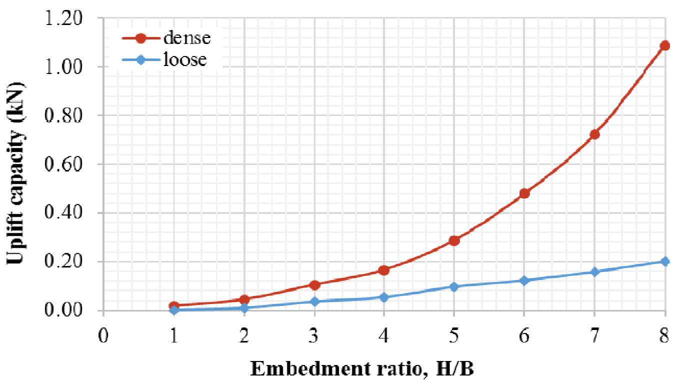


Fig. 13 Effect of embedment ratio on the uplift capacity

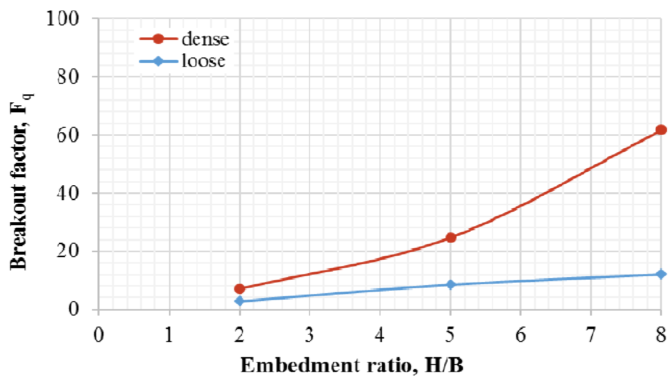


Fig. 14 Effect of embedment ratio on the breakout factor

been shown in Fig. 13.

It has been understood from the graph that the uplift capacity of the anchor plate increases nonlinearly with the increase of embedment ratios (H/B = 2, 5 and 8). This increase can be explained that thick of homogenous zone between anchor and soil surface is efficient and the uplift capacity increases with the increase of thick of this zone. Hence, the uplift capacity in dense sand soil is significantly more than in loose sand soil.

Vanitha *et al*. (2007) carried out experimental investigations on model single pile anchor and pile group anchors of configuration 2×2 subjected to uplift loads. In these tests, effect of embedment ratio on the uplift capacity has also been investigated. It was concluded that the uplift capacity for plate anchors in sand increased with the increase of embedment ratio.

The breakout factor is a non-dimensional parameter of the uplift capacity and the graph of breakout factor for embedment ratios (H/B) of 2, 5 and 8 has been shown in Fig. 14.

3.3 Determination of optimum spacing ratio between anchors

A series of tests have been conducted for 1×2 group anchor system in dense soil condition to investigate the effect of spacing ratio between anchors on the uplift capacity. In these tests, the ratio of the embedment depth (H/B) is constant and its value is 5. Also, the spacing ratio between anchors (S/B) has been increased from 1 to 4.

The group efficiency is non-dimensional parameter of the uplift capacity of group anchor plates and the graph of group efficiency (F_{group}) for spacing ratios (S/B) of 1, 2, 3 and 4 has been shown in Fig. 15.

As seen, the group efficiency increases with the increase of the spacing ratio between anchors. If the spacing ratio between anchors is S/B = 1, group efficiency is about 0.75. So, group efficiency is lower than the total of each anchor uplift capacity. When the spacing ratio between anchors is S/B = 4, the group efficiency (F_{group}) approaches to 100%. This value (S/B = 4) has been accepted as optimum spacing ratio between anchors. Hence, remaining tests have been continued keeping the spacing ratio between anchors as S/B = 4.

Geddes and Murray (1996) carried out model scale vertical pulling tests on groups of square anchor plates. In these tests, spacing ratio between anchors on the group efficiency has also been investigated. It was concluded that the group efficiency in sand increased with the increase of spacing ratio between anchors.

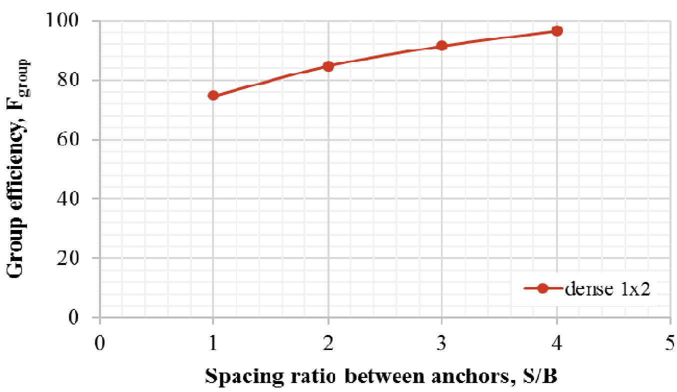


Fig. 15 Effect of spacing between anchors on F_{group}

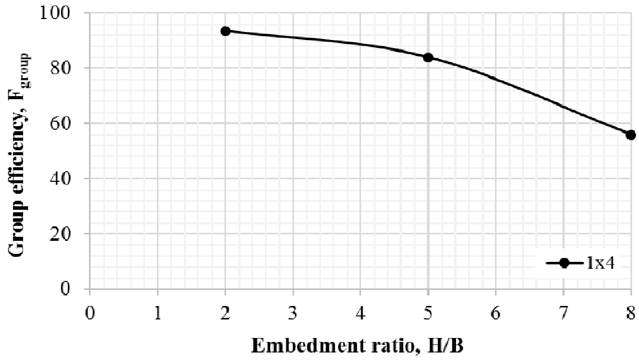


Fig. 16 Effect of embedment ratio on F_{group} for 1×4 anchor group

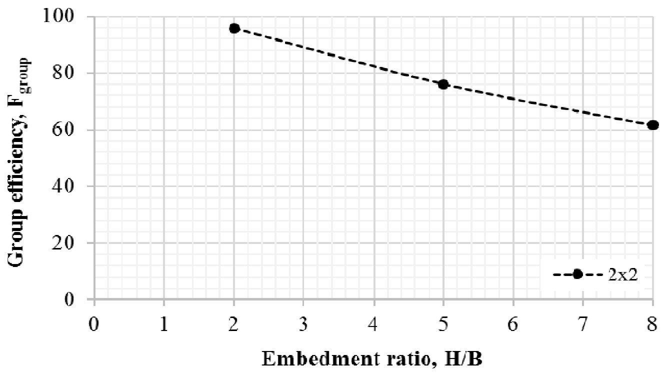


Fig. 17 Effect of embedment ratio on F_{group} for 2×2 anchor group

3.4 Effect of embedment ratio and configuration of anchor groups on the group efficiency

A series of tests have been conducted on 1×4 and 2×2 anchor groups in dense sand condition to investigate the effect of embedment ratio and these anchor configurations on the group efficiency (F_{group}). The graphs obtained from these tests are shown in Figs. 16-19, respectively.

As seen, the group efficiency decreases with the increase of embedment ratio for both cases. The group efficiency has ranged from 95% to 55% on 1×4 anchor group for the embedment ratios of 2 to 8, respectively and the variation of this value is parabolic (see Fig. 16). However, the group efficiency has ranged from 95% to 60% on 2x2 anchor group for the same embedment ratios and the variation of this value is linear (see Fig. 17).

It has been thought that the decrease of the group effeciency with the increase of embedment ratio is derived from an interaction which occurs the failure area between anchors. Because this area between anchors at H/B = 2 is less than at H/B = 8 as shown in Fig. 18.

Another conclusion is that this interaction has caused an area where anchors affect each other. The overlapping soil area arises from 2×2 anchor group is larger than the area of 1×4 anchor group. As a result of this, 1×4 anchor group has more group efficiency than 2×2 anchor group. Graphs belong to the study are given in Fig. 19.

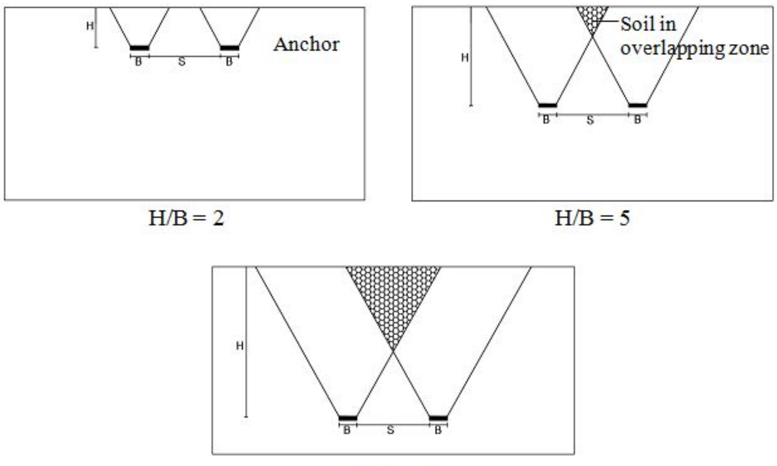


Fig. 18 Schematic failure area of group anchors in different embedment ratios

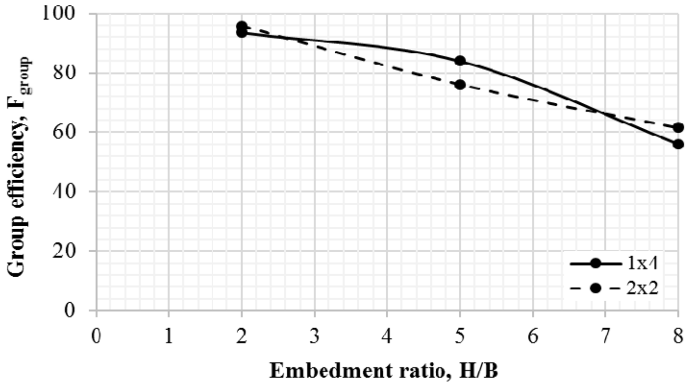


Fig. 19 Comparison of configuration of anchor groups on group efficiency

4. Comparison of laboratory model test results with numerical and analytical results

A series of three-dimensional finite element analyses and analytical solutions on an anchor plate-soil system have been carried out in order to validate the results of the laboratory model tests. Both numerical analyses and analytical solutions on a single anchor plate have been carried out for two different relative densities as loose and dense sand conditions. The numerical analyses have been conducted for all embedment ratios of H/B (from 1 to 8). However, the analytical solutions have been carried out for five different embedment ratios of H/B (from 1 to 5) since this analytical method gives the results for only shallow anchor plates.

4.1 Numerical modeling

The finite element analyses have been performed by using the commercial program Plaxis 3D.

The geometry of the anchor plate-soil system has been assumed to be the same as the laboratory model. An elasto-plastic hyperbolic model described as the Hardening Soil Model (HSM) has been used from those available in Plaxis 3D to describe the nonlinear sand behavior. The anchor plate has been modelled as a plate element with the unit weight of γ = 77 kN/m^3, Young's modulus of E = 3×10^7 kN/m^2 and thickness of d = 0.01 m. Five different mesh densities are available in Plaxis 3D ranging from very coarse to very fine. As a result of mesh analysis, it has been used medium mesh density in this study. The uplift capacity of anchor plates has been determined according to plastic calculation and staged construction in the analyses.

4.2 Analytical method

The analytical solution has been performed by using Meyerhof and Adams' Theory (1968). The parameters of soil and anchor plate have been assumed to be the same as the laboratory model. According to this theory, the uplift capacity of shallow anchor plate was determined by the following formula

$$Q\ (\alpha = 0°) = \gamma D^2 K_u \tan\varphi + \gamma BD \tag{3}$$

They have suggested that the value of δ (which is inclination angle of the resultant passive force with the horizontal) can be approximated to be equal to 2/3φ. They have also assumed that

$$K_p \tan\delta = K_u \tan\varphi \tag{4}$$

Where,

Q : uplift resistance
γ : unit weight of soil
D : average depth of embedment
B : width of anchor
K_p : passive earth pressure coefficient
K_u : nominal uplift coefficient
δ : inclination angle of the resultant passive force with the horizontal
φ : internal friction angle

4.3 Comparison of the results

Both numerical analyses and analytical solutions on a single anchor plate have been carried out for two different relative densities as loose and dense sand conditions.

As seen from Fig. 20, the results of laboratory model tests and analytical solutions are quite compatible for the relative density of D_r = 35%. In addition to this, the numerical analyses have given more uplift capacity values according to the other two methods. However, the uplift capacities obtained from laboratory model tests and numerical analyses are in considerable well agreement with the increase of embedment ratio for loose sand condition.

Fig. 21 shows the uplift capacities obtained from these three methods for D_r = 85%. As seen, the results are very compatible for the embedment ratios of up to 5 for dense sand condition, however a little difference has occurred in the uplift capacity with the increase of embedment ratio for laboratory model tests and numerical analyses.

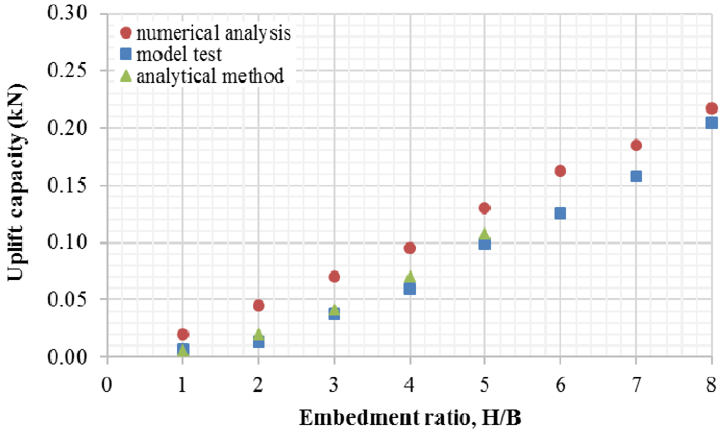


Fig. 20 The effect of embedment ratio on the uplift capacity for D_r = 35%

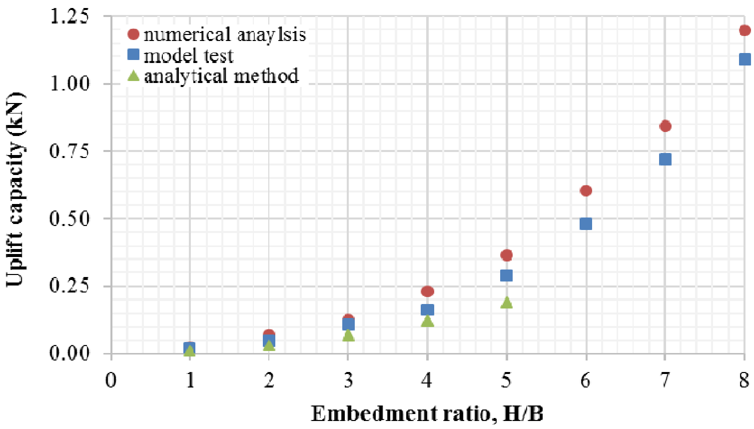


Fig. 21 The effect of embedment ratio on the uplift capacity for D_r = 85%

5. Limitations

In this study, the model tests were conducted on a small scale model anchor plates, while the sand particles were used with the same dimensions as in the prototype. Therefore, model anchor or the soil may not play the same role as in the prototype and it might cause some influence on the model test results. But, this study can be evaluated as a useful basis for further research in which the results of this study can be of support with full-scale loading tests or centrifugal model test studies.

6. Conclusions

In this study, the parameters affecting the uplift capacity of anchor plates embedded in sand soils have been investigated. In the tests, the effect of loading rate, relative density of sand and embedment ratio on uplift capacity have been determined for a single anchor plate. Also for group anchor plates, the effect of embedment ratio in dense sand, spacing ratio between anchors and anchor configuration on uplift capacity has been investigated. The results have been presented in the form of non-dimensional parameters F_q and F_{group}. Based on the test results, the following main conclusions can be drawn.

- The model tests have been conducted at 2 different loading rates and it has been concluded that loading rate has no effect on uplift capacity.
- The studies show that the anchor plate embedded in dense sand has 6 times more uplift capacity than the anchor plate embedded in loose sand for H/B = 8.
- According to the test results, the uplift capacity and the breakout factor increase with the increase of embedment ratios. This increase can be explained that the thicknesses of homogenous zone between anchor and soil surface is efficient and the uplift capacity increases with the increase of thicknesses of this zone.
- The group efficiency increases with the increase of the spacing ratio between anchors. When the spacing ratio between anchors is S/B = 4, the group efficiency (F_{group}) approaches to 100%. This value (S/B = 4) has been accepted as an optimum spacing ratio between anchors.
- The tests have been conducted on 1×4 and 2×2 anchor groups in dense sand condition. The group efficiency decreases with the increase of embedment ratio for both configurations. It has been inferred that decreasing of the group efficiency is derived from an interaction which occurs the failure area between anchors.
- 1x4 anchor group has more group efficiency than 2×2 anchor group. Because the soil overlapping area affected from 2×2 anchor group is larger than the are of 1×4 anchor group.
- From comparisons of the results of laboratory model tests, numerical analyses and analytical solutions, it has been understood that the results of laboratory model tests and analytical solutions are quite compatible for loose sand condition (D_r = 35%). The numerical analyses have given more uplift capacity values according to the other two methods. However, the uplift capacities obtained from laboratory model tests and numerical analyses are in good agreement with the increase of embedment ratio.
- Further, the uplift capacities obtained from these three methods are very compatible for the embedment ratios of up to 5 for dense sand condition (D_r = 85%), but a little difference has occurred in the uplift capacity with the increase of embedment ratio for laboratory model tests and numerical analyses.

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