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Investigation of the Uplift Capacity of Group Anchor Plates in Geogrid-Reinforced Sand

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Abstract

In this study, the uplift capacity of group anchors has been investigated in sand with and without geogrid reinforcement experimentally and numerically. While the investigated parameters are the effect of embedment ratio of anchors and number of geogrid layers for a single anchor plate and 2x2 anchor configuration, the constant parameters are spacing ratio between anchors, depth of the first layer of geogrid, vertical spacing ratio of geogrid layers and length of geogrid. Experimental studies have been modelled and analyzed with Plaxis 3D which is a finite elements software. The results obtained from both of the studies have been compared and the validity of the numerical analysis has been investigated on the uplift capacity of anchor plate. As a result, it was shown that depending on the reinforcement geogrid, the uplift capacity of anchor plate can be improved by up to 2 times that of the unreinforced sand.

Keywords: Laboratory test, Numerical analysis, Uplift capacity, Anchor plate, Geogrid

Geogrid Donatılı Kumda Grup Ankraj Plakalarının Çekme Kapasitesinin İncelenmesi

Öz

Bu çalışmada, geogridle güçlendirilmiş ve güçlendirilmemiş kum zemindeki grup ankrajların çekme kapasitesi deneysel ve sayısal olarak incelenmiştir. Tek ve 2x2 yerleşim düzenindeki ankraj plakalarında gömülme oranı ve geogrid tabakası sayısının çekme kapasitesine etkisi araştırılırken, ankrajlar arası mesafe oranı, geogrid tabakasının ilk derinliği, geogrid tabakaları arası düşey mesafe ve geogrid tabakasının uzunluğu sabit tutulmuştur. Deneyler sonlu elemanlar programına dayalı Plaxis 3D bilgisayar programı ile sayısal olarak modellenmiş ve analiz edilmiştir. Deneysel çalışmalar ve sayısal analizlerden elde edilen sonuçlar karşılaştırılmış ve sayısal analizin ankraj plakasının çekme kapasitesini tahminindeki başarısı araştırılmıştır. Sonuç olarak, geogridle güçlendirmenin ankraj plakasının çekme kapasitesini 2 kata kadar artırdığı görülmüştür.

Anahtar Kelimeler: Laboratuvar deneyi, Sayısal analiz, Çekme kapasitesi, Ankraj plakası, Geogrid

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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, long factory chimneys and sea platforms have been subjected to different loading conditions. These structures are under the influence of uplift loading conditions. Some examples of the mentioned loads are eccentricity based loads; lifting load in structures constructed afloat and lifting loads 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 load recently. These anchor systems are affected by some factors such as soil properties, embedment ratio and anchor group configuration [1].

Several theoretical and numerical studies were performed to predict the influence of various parameters on the uplift response of horizontal anchor plates in sand [2-10]. A number of experimental investigations were reported by several researchers to evaluate the uplift capacity of anchor plates in cohesionless soil [11-19]. The results of these investigations showed that the uplift capacity of the anchor plates can be significantly improved by increasing the size and depth of anchor plate. However, in some situations, it is generally not economical to increase the size and depth of anchor plates due to increase in cost of excavation, and problem of compacting fill material below possible existing water table at great depths. In such conditions, it is necessary to investigate alternative methods to improve the uplift capacity of an anchor plate. Application of geosynthetics inclusions is a well known alternative method of soil reinforcement that increases the resistance of soil due to interaction of soil and tensile elements. Anchor plates can be loaded by higher uplift loads due to use of geosynthetics reinforcement, which has got high mechanical and chemical resistance, high durability, and good interaction between soil and reinforcement. Although many studies on uplift capacity of anchor plates in unreinforced sand have been carried out as mentioned before, investigations on the uplift capacity behaviour of an anchor plate in geosynhetics-reinforced sand are still very limited [20].

Ilamparuthi et al. [21] conducted two series of uplift load tests on anchors embedded in submerged sand. First series of tests were in submerged sand and the second series of tests were in submerged sand reinforced with single layer of geogrid. The geogrid was positioned directly on the anchor and its width ratio was varied (B_r/B = 2, 3 and 4). Other parameters varied in both monotonic and cyclic mode of loading were embedment ratio of anchor (H/B=2, 3 and 4) and relative density of sand (loose, medium and dense conditions). Niroumand et al. [22] investigated the uplift response of symmetrical anchor plates with and without grid fixed reinforcement (GFR) in model tests and numerical simulations by Plaxis. Many variations of reinforcement layers were used to reinforce the sandy soil over symmetrical anchor plates. In the study, different factors such as relative density of sand, embedment ratios, and various GFR parameters including size, number of layers, and the proximity of the layer to the symmetrical anchor plate were investigated in a scale model. Niroumand and Kassim [23] evaluated the uplift response of symmetrical anchor plates with and without geogrid reinforcement layers in model tests and numerical simulations by using PLAXIS. Many parameters of the reinforcement layers were used to reinforce the sandy soil over circular, square, and rectangular symmetrical anchor plates of various sizes. In the study, different parameters such as relative density of sand and embedment ratios, in conjunction with geogrid reinforcement layer parameters including size, number of layers, and the proximity of the layer to the circular anchor plate were investigated in a scale model. Keskin [20] investigated the uplift capacity of horizontal square anchor plates in sand with and without geogrid reinforcement, experimentally. The investigated parameters were the effect of the depth of the single layer of geogrid, vertical spacing, number and length of geogrid layers, the effects of embedment depth, and relative density of sand. A series of three dimensional finite element analyses model was established and confirmed to be effective in capturing the behaviour of anchor plate-reinforced sand by comparing finite element method's predictions with experimental results.

In this paper, the uplift capacity of group anchors systems has been investigated in loose sand with and without geogrid reinforcement through experimental and numerical studies. While the investigated parameters are the effect of embedment ratio of anchors (H/B=2, 4 and 6) and number of geogrid layers (N=1, 2 and 3) for a single anchor plate and 2x2 anchor configuration, the constant parameters are spacing ratio between anchors (S/B=4), depth of the first layer of geogrid (u/B=0.00), vertical spacing ratio of geogrid layers (h/B=0.50) and length of geogrid (L/B=14). Furthermore, a series of three dimensional finite element analyses have been carried out and confirmed to be effective in capturing the behaviour of group anchor plates by comparing 3D-finite element methods predictions with experimental results.

2. MATERIALS AND METHODS

2.1. Experimental Study

The experimental program was carried out by using the facility in the Geotechnical Laboratory of the Civil Engineering Department of the Cukurova University. The facility and a typical model are shown in Figures 1 and 2.

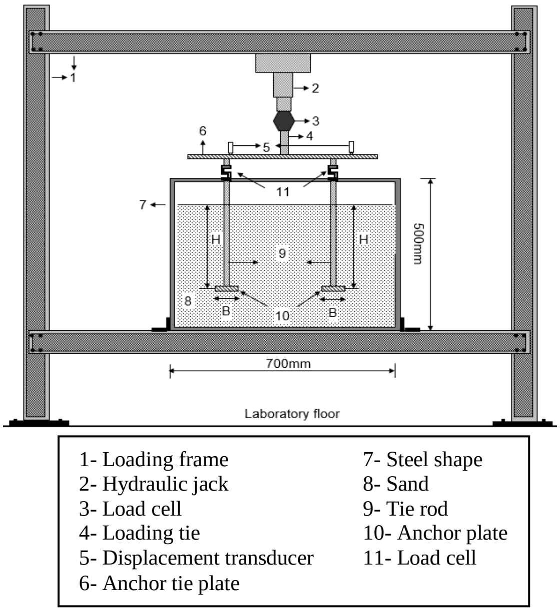


Figure 1. Test apparatus

Figure 2. Test setup

Tests were conducted in a test box made of a steel frame having inside dimensions of 700 mm×700 mm in top view and 500 mm in depth as shown in Figures 1 and 2. Uplift tests were performed on square anchor plate which was fabricated from mild steel with 10 mm thickness. In the tests, 50 mm×50 mm square plate was used. The model soil used throughout the model tests was uniform, clean and fine sand obtained from Seyhan River bed. Laboratory tests were conducted on representative sand samples for gradation, specific gravity, maximum and minimum densities and strength parameters. Using the Unified Soil Classification System, the material was determined to be poorly graded sand (SP). Table 1 summarizes the general physical characteristics of the sand. The experimental test was conducted on sample prepared with average unit weights of 15.7 kN/m^3. Corresponding relative density (D_r) of the sample was 35%. The estimated internal friction angle of the sand determined from triaxial test using specimens at the same relative densitiy was 38°.

Table 1. Properties of sand [1]

	Value
Coarse sand fraction (%)	0.0
Medium sand fraction (%)	46.9
Fine sand fraction (%)	53.1
D_{10} (mm)	0.20
D_{30} (mm)	0.30
D_{60} (mm)	0.50
Uniformity coefficient, C_u	2.50
Coefficient of curvature, C_c	0.50
Specific gravity, γ (kN/m^3)	26.8
Dry unit weight, γ_d (kN/m^3)	15.7
Classification (USCS)	SP

A white colored, SG Q1 type geogrid with maximum tensile strength of 60 kN/m was used as reinforcing material in the tests. SG Q1 type geogrid is made of stretched, monolithic polypropylene (PP) flat bars with welded junctions. The physical and mechanical properties of the geogrid as listed by the manufacturer are given in Table 2.

Table 2. Properties of geogrid [20]

Properties	SG Q1
Raw material	PP
Color	White
Max. tensile strength, md*/cmd**	60/60
Roll dimesions (m×m)	4.75×100

*md=machine direction, **cmd=cross machine direction

The unreinforced soil beneath the anchor plate was compacted in layers of 50 mm in thickness. Then the anchor plate was placed into position in the center of the tank on soil surface. The anchor was checked to be in a good position and a completely horizontal arrangement. The model anchor plate was connected to a tie rod to apply the uplift load. The sand was then again deposited in layers into the test tank over the anchor plate and layers were continued to be applied until the required surface level was reached. The uplift load was applied to the model anchor by a motor-controlled hydraulic jack system. The system attached to the loading frame located above the test box has a loading rate of approximately 4.705 mm/min for each uplift test. The uplift load was measured using a calibrated electronic load cell attached to the tie rod during the uplift test. The vertical displacements of the anchor plate were measured using two linear variable displacement transducers. For each test, the uplift load-displacement measurements were recorded by a data logger unit. The tests were continued until the applied uplift load clearly reduced or a considerable displacement occurred from a relatively small increase of uplift load.

In this study, four series of tests were conducted to investigate the effects of the embedment ratio and geogrid layers on the anchor plate behaviour. Each series of test was conducted to study the effect of one parameter while the other variables were kept constant. Figure 3 and Table 3 summarize all test programs with constant and variable parameters used.

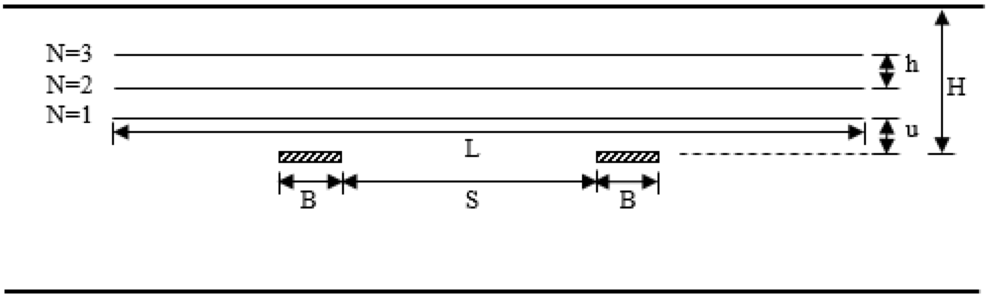


Figure 3. Geometric parameters of model tests

Table 3. Test program

	Constant parameters	Variable parameters
I	Single anchor, unreinforced, D_r=35%	H/B=2, 4, 6
II	Single anchor, D_r=35%, H/B=4, u/B=0, h/B=0.50, L/B=20	N=1, 2, 3
III	2x2 group anchor, unreinforced, D_r=35%, S/B=4	H/B=2, 4, 6
IV	2x2 group anchor, D_r=35%, H/B=4, S/B=4, u/B=0, h/B=0.50, L/B=20	N=1, 2, 3

2.2. Numerical Modeling

A series of three-dimensional finite element analyses on group anchor plate-soil system were carried out in order to validate the results of the laboratory model tests and to provide insights into the uplift behaviour within the soil mass. The finite element analysis was performed by using the commercial program "PLAXIS 3D Tunnel" (version 2.0). The geometry of the model anchor plate-soil system was assumed to be the same as the laboratory model. The same material of steel plate for anchor, geogrid, and sand were used in the numerical study. Only a quarter of the anchor plates were modeled using symmetry conditions at the anchor plate centerline, to reduce the calculation time. In the numerical study, the Hardening Soil Model (HSM) was used to describe the non-linear sand behaviour in this study. The anchor plates were modeled as elastic beam elements and the geogrid reinforcement was modeled by using elastic geogrid elements. The only property in a geogrid dataset is the elastic axial stiffness, EA = 1100 kN/m, entered in units of force per unit width. In order to obtain the most suitable mesh for the reported study, preliminary computations using the five available levels of global mesh coarseness for an anchor plate in reinforced sand were conducted in the analyses. As a result of mesh analysis, it was decided to use medium mesh density. A prescribed uplift load was then applied in increments accompanied by iterative analysis up to failure. The values of parameters used in the numerical investigation are shown in Tables 4 and 5. The 3D finite element mesh used in the analyses is shown in Figure 4.

Table 4. Properties of sand used in the analyses [1]

Properties	Value
Unit weight, γ (kN/m^3)	15.7
E_{50}^{ref} (kN/m^2)	21600
E_{oed}^{ref} (kN/m^2)	21600
E_{ur}^{ref} (kN/m^2)	64800
c (kN/m^2)	0.5
Ø (°)	38

Table 5. Properties of anchor plate in the analyses [1]

Properties	Value
EI (kNm^2/m)	1.667
EA (kN/m)	2.0×10^5

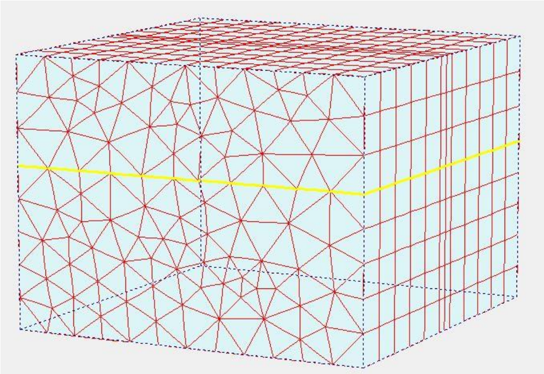


Figure 4. Finite element mesh (Plaxis 3D Tunnel)

3. RESULTS OF EXPERIMENTAL AND NUMERICAL STUDIES

The uplift capacities are often expressed in dimensionless form as breakout factor N_{qu} [14]. The breakout factor is determined by the following formula:

$$N_{qu} = \frac{T_u}{\gamma BLH} \quad (1)$$

in which N_{qu} is breakout factor, T_u is the uplift capacity, γ is soil unit weight, B is anchor width, L is anchor length and H is embedment depth.

In this study, the term "uplift capacity ratio" (UCR) has been used to express and compare the tests data of the reinforced and unreinforced soils. The following definition is used for UCR.

$$UCR = \frac{T_{ur}}{T_u} \quad (2)$$

in which T_{ur} and T_u are the uplift capacities for the reinforced and the unreinforced soils, respectively.

For group anchor plates, the uplift capacities are expressed as group breakout factor $N_{qu(group)}$. The factor is determined by the following formula:

$$N_{qu(group)} = \frac{T_{u(group)} \times 100}{N \times T_u} \quad (3)$$

in which $T_{u(group)}$ is total uplift capacity, N is number of anchor plate, T_u is the uplift capacity for a single anchor.

For group anchor plates, the uplift capacities are expressed as group uplift capacity ratio $UCR_{(group)}$. The ratio is determined by the following formula:

$$UCR_{group} = \frac{T_{ur(group)}}{T_{u(group)}} \quad (4)$$

in which $T_{ur(group)}$ and $T_{u(group)}$ are the uplift capacities of group anchor plates for the reinforced and the unreinforced soils, respectively.

3.1. The Effect of Embedment Ratio for a Single Anchor

The tests in this series have been conducted to determine the relation of the uplift capacity, T_u and breakout factor, N_{qu} to embedment ratio, H/B. In the tests, 50mm square anchor plate has been used and the relative density of sand was D_r=35%. The H/B ratios were 2, 4 and 6. The variations of T_u-H/B and N_{qu}-H/B are presented in Figures 5 and 6, respectively. The figures show that the general trends of finite element analyses agree well with those of the model tests. From Figure 5, it can be concluded that the uplift capacity, T_u increases significantly with an increase in embedment ratio, H/B. This increase can be explained as thickness of homogenous zone between anchor plate and soil surface is efficient and the uplift capacity increases with the increase of thickness of this zone. As seen from Figure 5, anchor plate with a maximum embedment ratio of H/B=6 has a higher uplift capacity than anchor plate with a in minimum embedment ratio of H/B=2. Also, from Figure 6, it is clear that; a significant, almost linear, increase in breakout factor with the embedment ratio has been obtained from both experimental and numerical studies.

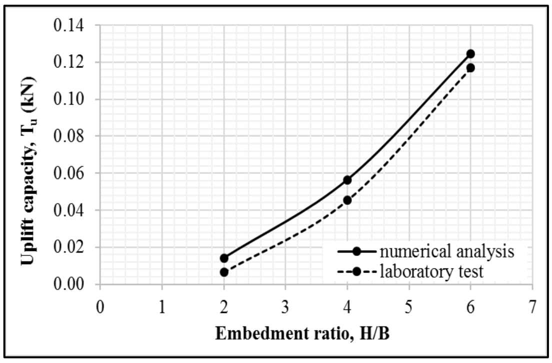


Figure 5. Variations of T_u with H/B

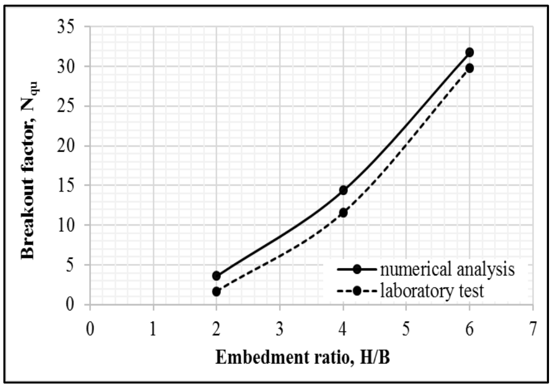


Figure 6. Variations of N_{qu} with H/B

Plaxis 3D Tunnel has been used to investigate the effect of embedment ratio of anchor plate on the displacement. The displacement contours are presented in Figure 7. The contours intensify around the plate with the increase of embedment ratio and diminish towards the soil surface. The displacement value is almost the same between the plate and soil surface for H/B=2. On the other hand, it is different between the soil surface and around the plate for H/B=4 and 6. The values of displacements around the plate when comparing the soil surface are 2 and 3 times for H/B=4 and 6, respectively.

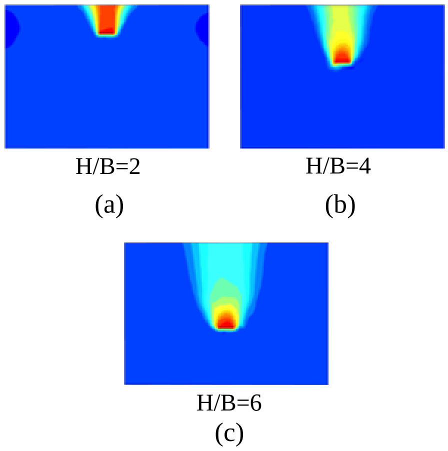


Figure 7. Displacement contours for an anchor plate

3.2. The Effect of the Number of Geogrid Layers for a Single Anchor

A series of laboratory model tests and finite element analyses were conducted in sand reinforced with multiple layers of SG Q1 geogrid. For the tests, the values of u/B, h/B, and L are kept constant as 0.00, 0.50 and 14B, respectively. Figure 8 shows the variation of UCR obtained from model tests and numerical analyses with number of geogrid layers, N (0, 1, 2 and 3). A sharp increase in uplift capacity has been observed initially with the increase of the number of geogrid layers up to two. This is indicating that the geogrid layers had significant effect on the UCR up to two geogrid layers. However, the addition of more layers of geogrid after the second one has not contributed much to the uplift capacity improvement.

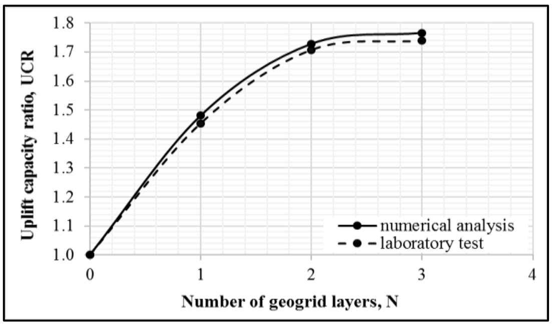


Figure 8. Variations of UCR with N

Plaxis 3D Tunnel has also been used to investigate the effect of number of geogrid layers on the displacement. The displacement contours are presented in Figure 9. As shown, the geogrid placed on the anchor plate has significantly absorbed the displacement and the displacements have been prevented to reach the soil surface because of the geogrid. The displacement contours obtained from numerical analysis has also shown that the addition of more layers of geogrid after the second one has not contributed much to the uplift capacity improvement. Hence, the optimum geogrid layer has been suggested as two for this study.

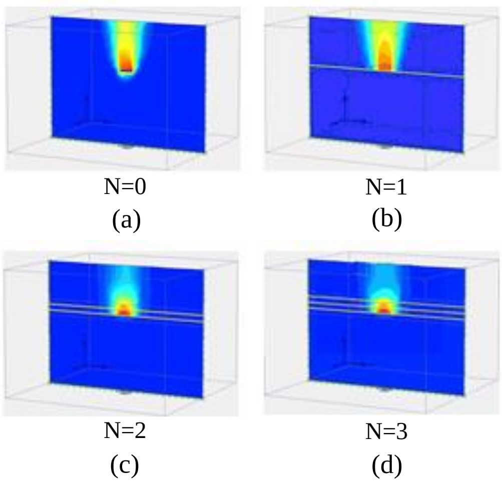


Figure 9. Displacement contours for an anchor plate with geogrid-reinforcement (H/B=4)

3.3. The Effect of Embedment Ratio for 2x2 Anchor Configuration

The tests in this series have been conducted to determine the relation of group uplift capacity, $T_{u(group)}$ and group breakout factor, $N_{qu(group)}$ on the embedment ratio, H/B for 2x2 anchor configuration. In the tests, 50mm square anchor plate has been used and the relative density of sand was D_r=35%. The H/B ratios were 2, 4 and 6. The variations of $T_{u(group)}$-H/B and $N_{qu(group)}$-H/B are shown in Figures 10 and 11, respectively. The figures show that the general trends of finite element analyses agree well with those of the model tests. As seen from Figure 10, the group uplift capacity, $T_{u(group)}$ increases significantly with an increase in embedment ratio, H/B. Anchor plate with maximum embedment ratio of H/B=6 has a higher uplift capacity than anchor plate with minimum embedment ratio of H/B=2. In case of the embedment ratio of H/B=6, the uplift capacity of anchor plate is approximately 8 times more than the uplift capacity of anchor plate embedded in H/B=2. Also, from Figure 11, it is clear that; a significant, almost linear, decrease in group breakout factor with the embedment ratio has been obtained from both experimental and numerical studies.

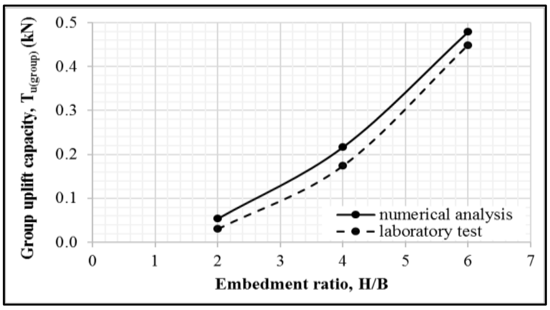


Figure 10. Variations of $T_{u(group)}$ with H/B

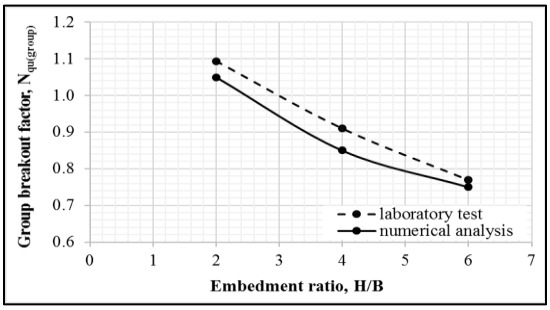
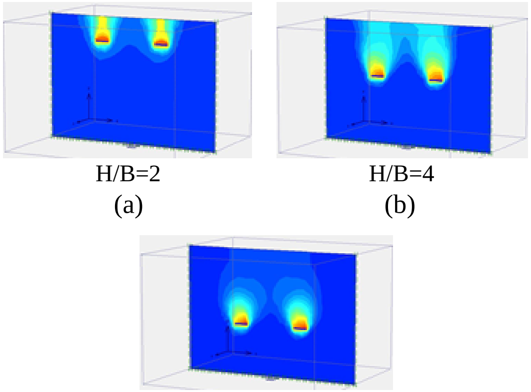


Figure 11. Variations of $N_{qu(group)}$ with H/B

The displacement contours are presented in Figure 12. The contours intensify around the plate with the increase of embedment ratio and diminish towards the soil surface. The displacement values around the plate when comparing the soil surface are different and these values are 2, 5 and 7 times for H/B=2, 4 and 6, respectively. Also, failure zones of the anchor plates have been affected more by each other with the increase of embedment ratio.



H/B=2 (a) H/B=4 (b) H/B=6 (c)

Figure 12. Displacement contours for 2x2 anchor configuration

3.4. The Effect of Number of Geogrid Layers for 2x2 Anchor Configuration

The tests in this series have been conducted to determine the relation of uplift capacity ratio, UCR_{group} and number of geogrid layers, N. In the tests, 50mm square anchor plate has been used and the delative density of sand was D_r=35%. Figure 13 shows the variation of UCR_{group} obtained from model tests and numerical analyses with number of geogrid layers, N (0, 1, 2 and 3). The curves of UCR_{group} are nonlinear with the increase of N. A sharp increase in uplift capacity has been observed with the increase of the number of geogrid layers increasing up to two. However, the addition of more layers of geogrid after the second one has not contributed much to the uplift capacity improvement.

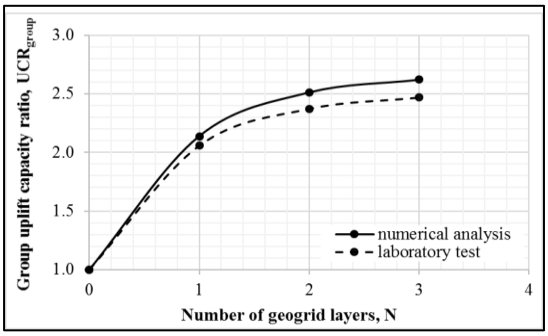
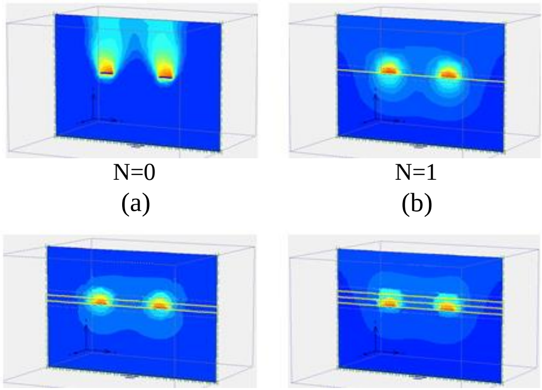


Figure 13. Variations of UCR_{group} with N



N=0 (a) N=1 (b) N=2 (c) N=3 (d)

Figure 14. Displacement contours for 2x2 anchor configuration with geogrid-reinforcement (H/B=4)

Plaxis 3D Tunnel has also been used to investigate the effect of number of geogrid layers on the displacement for 2x2 anchor configuration. The displacement contours are presented in Figure 14. As shown the geogrid placed on the anchor plates has significantly absorbed the displacement and the displacements have been prevented to reach the soil surface because of the geogrid. The displacement contours obtained from numerical analysis has also shown that the addition of more layers of geogrid after the second one has not contributed much to the uplift capacity improvement.

4. CONCLUSIONS

In this paper, the uplift capacity of anchor plate systems has been investigated in sand through experimental and numerical studies. Based on the results, the following main conclusions can be drawn:

- Both experimental and numerical studies show that the uplift capacity for a single anchor plate and 2x2 anchor configuration in sand conditions increases with the increase of embedment ratio.
- The uplift capacity ratio increases with the increase of the number of geogrid layers.

However, the addition of more than two layers of geogrid has not contributed much to the uplift capacity improvement.

- The displacement contours intensify around the plate with the increase of embedment ratio and diminish towards the soil surface for a single anchor and 2x2 anchor configuration.
- For a single anchor plate and 2x2 anchor configuration, it has been understood that the geogrid placed on the anchor plates has significantly absorbed the displacement and the displacements have been prevented to reach the soil surface because of the geogrid.

5. ACKNOWLEDGEMENTS

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