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Model studies of uplift capacity behavior of square plate anchors in geogrid-reinforced sand

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Abstract. An experimental investigation into the uplift capacity of horizontal square plate anchors in sand with and without geogrid reinforcement is reported. 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. A series of three dimensional finite element analyses model was established and confirmed to be effective in capturing the behaviour of plate anchor-reinforced sand by comparing its predictions with experimental results. 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. A satisfactory agreement between the experimental and numerical results on general trend of behaviour and optimum geometry of reinforcement placement is observed. Based on the model test results and the finite element analyses, optimum values of the geogrid parameters for maximum reinforcing effect are discussed and suggested.

Keywords: reinforced sand; uplift capacity; square plate anchors; finite element method; model test

1. Introduction

There are many civil engineering structures need a foundation system that provide sufficient support by resisting loads that are affected by vertical and horizontal uplift forces. Examples include transmission towers, anchored bulkheads, submerged pipelines, and tunnels. Stability and support of such structures can be provided by transferring the loads from the structures foundation through the use of tension elements. These elements are soil anchors, which are generally fixed to structures and are embedded to sufficient soil depths to provide adequate amounts of support within required safety limits. Plate anchors are light structural members employed to withstand uplift forces. They are generally made of steel, precast concrete, poured concrete or timber and may be formed into shapes such as square, rectangular, circular and strip. Horizontal plate anchors can be constructed by excavating the ground to certain design depths, placing the plate in position, connecting to cable and then backfilling and compacting with good quality of soil material.

The wide range of applications of horizontal plate anchors has attracted researchers to achieve a more thorough understanding of behavior of uplift resistance of plate anchors. The uplift capacity

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of plate anchors depend on many factors, such as the shape and the size of anchor, the depth of embedment, and the soil conditions. Numerous methods of testing have been used to study the influence of different parameters on the uplift response of plate anchors, including model tests, analytical solutions, finite element simulations and plastic limit analyses.

Several theoretical and numerical studies have been performed to predict the influence of various parameters on the uplift response of horizontal plate anchors in sand (Mors 1959, Balla 1961, Meyerhof and Adams 1968, Rowe and Davis 1982, Tagaya *et al*. 1983, 1988, Vermeer and Sutjiadi 1985, Murray and Geddes 1987, Basudhar and Singh 1994, Rao and Kumar 1994, Smith 1998, Merifield and Sloan 2006, Samui and Sitharam 2009, Kame *et al*. 2012). A number of experimental investigations are reported by several researchers to evaluate the uplift capacity of plate anchors in cohesionless soil (Das and Seeley 1975, Rowe 1978, Ovesen 1981, Dickin 1988, Frydman and Shamam 1989, Murray and Geddes 1989, Dickin and Laman 2007, Bildik and Laman 2011, Bera 2014, Niroumand and Kassim 2014a, b, c, Zhu *et al*. 2014). The results of these investigations showed that the uplift capacity of the plate anchors can be significantly improved by increasing the size and depth of plate anchor. However, in some situations, it is generally not economical to increase the size and depth of plate anchors 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 search alternative methods to improve the uplift capacity of a horizontal plate anchor. 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. Plate anchors can be loaded by higher uplift forces 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 horizontal plate anchors in unreinforced sand have been carried out as mentioned before, investigations on the uplift capacity behavior of a plate anchor in geosynhetics-reinforced sand are very limited. So, the importance of reinforcement has received very little attention by researchers (Niroumand and Kassim 2013a). Krishnaswamy and Parashar (1994) conducted small-scale model tests to investigate the uplift behavior of plate anchors embedded in cohesive and cohesionless soil media with and without geosynthetic reinforcement. They reported that both cohesionless and cohesive soils can be employed to enhance the uplift capacity of plate anchors and footings, with geosynthetic inclusions. Ilamparuthi and Dickin (2001) studied the influence of soil reinforcement on the uplift performance of model belled piles or piers of various geometries embedded in sand. A cylindrical gravel-filled geogrid cell was located around the enlarged pile base. It was reported that uplift response increases with the diameter of the geogrid cell, sand density, pile bell diameter, and embedment depth. Ravichandran and Ilamparuthi (2004) studied the behavior of anchors in sand reinforced with single layer of geogrid. Niroumand *et al*. (2013) investigated the uplift response of symmetrical anchor plates with and without geogrid and grid fixed reinforced (GFR) reinforcement experimentally and numerically. They reported that using both geogrid and GFR reinforcement has a significant effect on improving the uplift capacity of circular anchor plates. Niroumand and Kassim (2013b) studied the uplift response of symmetrical anchor plates with and without geogrid reinforcement layers. They concluded that the uplift capacity of symmetrical anchor plates in loose and dense sands can be significantly increased by the inclusion of geogrid layers. Niroumand and Kassim (2014d) evaluated the uplift response of symmetrical anchor plates with and without grid fixed reinforced (GFR) reinforcement in model tests and numerical simulations. The results of the laboratory and numerical analysis are found to be in agreement in terms of the breakout factor and failure mechanism pattern.

The conclusion drawn from the literature is that most of the existing works are mainly focused on the capacity of anchor plates embedded in unreinforced soils. However, very few investigations have been reported in the area of anchor plates embedded in reinforced soil. The effect of soil reinforcement on stability of the soil and, hence, the anchor plate capacity has not yet been adequately discovered. Therefore, more investigations still remain to be carried out on the effect of soil reinforcement on the uplift capacity of anchor plates.

In the present study, uplift capacity behaviour of horizontal square plate anchors in sand reinforced with geogrid layers were investigated using laboratory model tests. The main purpose was to investigate and establish the relationship between the plate anchor response and the different geogrid parameters including the effect of the depth of the single layer of geogrid, number of geogrid layers, vertical spacing of geogrid layers, and length of geogrid layers. Also, the ultimate uplift response of anchor plate along with the influence of embedment depth, soil density and break-out factors were evaluated. In addition, three-dimensional numerical analyses were performed using the commercial finite element program "PLAXIS 3D Tunnel".

2. Experimental study

The experimental programme was carried out 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 Figs. 1 and 2.

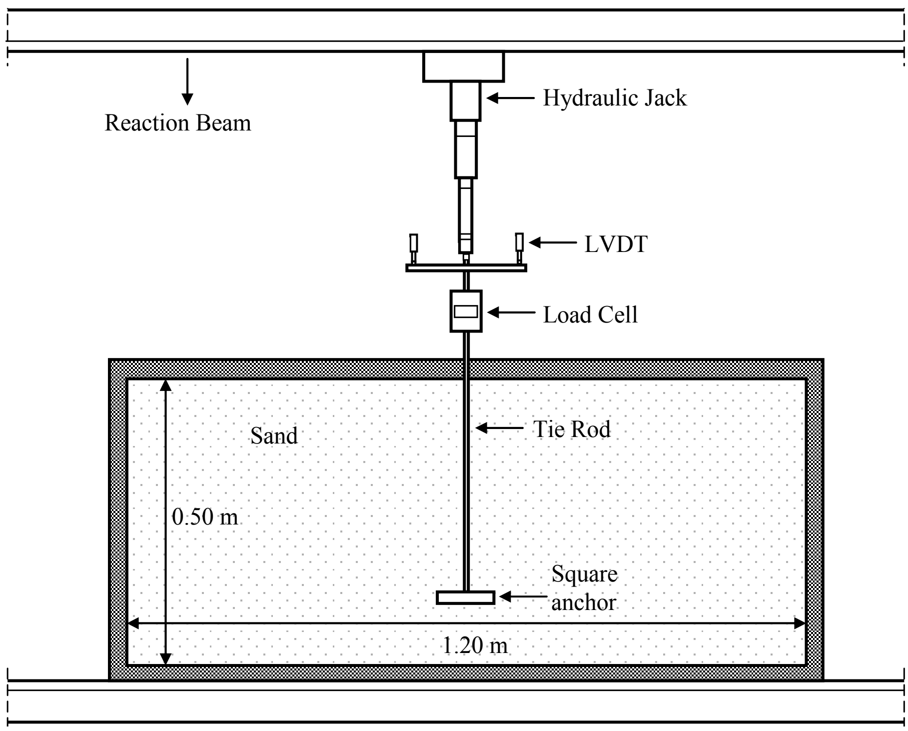

Fig. 1 General layout of apparatus for the model tests

Fig. 2 Test set-up

2.1 Test tank

Tests were conducted in a test box made of a steel frame having inside dimensions of 1.20 m × 0.70 m in top view and 0.50 m in depth as shown in Figs. 1 and 2. The bottom and vertical edges of the box were stiffened using angle sections to avoid lateral yielding during soil placement. The two sidewalls of the test box were made of 10 mm-thick glass to see the sand sample during preparation and particle displacements during the tests and the other sides consist of 20 mm-thick wooden plates.

2.2 Model plate anchor

Uplift tests were performed on square anchor plate which was fabricated from mild steel with 10mm thickness. In the tests, 50 mm × 50 mm square plate has been used.

2.3 Model soil

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. The particle size distribution of the sand was determined using the dry sieving method and the results are shown in Fig. 3. 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

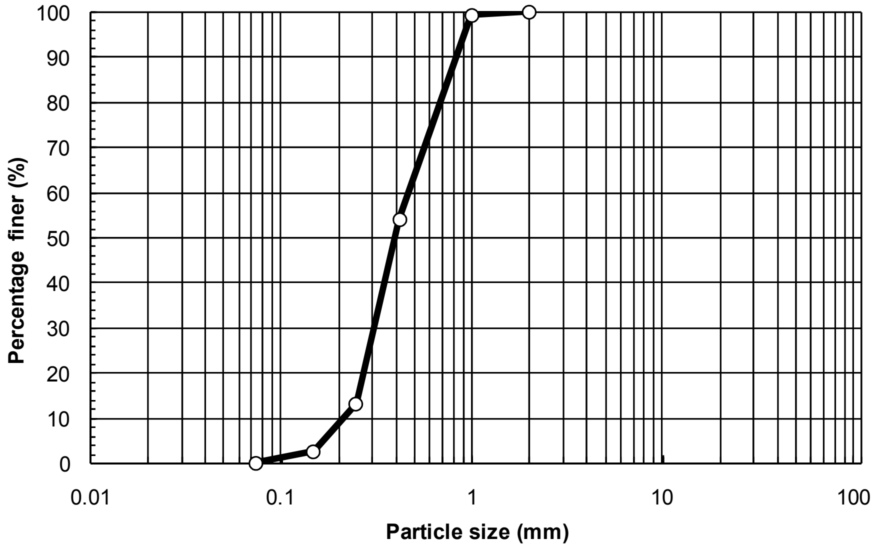

Fig. 3 Particle size distribution of the sand

Table 1 Properties of sand bed

Property	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	0.90
Specific gravity, γ (kN/m^3)	26.8
Maximum dry unit weight, $\gamma_{d\max}$ (kN/m^3)	17.6
Minimum dry unit weight $\gamma_{d\min}$ (kN/m^3)	14.7
Classification (*USCS*)	SP

Table 2 Properties of model geogrids

Property	SG Q1
Raw material	PP
Color	White
Max. tensile strength, md*/cmd** (kN/m)	60/60
Roll dimensions (m × m)	475 × 100

*md = machine direction, **cmd = cross machine direction experimental tests were conducted on samples prepared with average unit weights of 15.4 and 17.0 kN/m^3. Corresponding relative densities (D_r) of the samples were 35% and 85%, respectively. The estimated internal friction angle of the sand determined from triaxial tests using specimens at the same relative densities were 39° and 44°, respectively.

2.4 Details of geogrid reinforcement

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.

2.5 Preparation of the 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 sand at unit weights of, 15.4 and 17.0 kN/m^3. To maintain the consistency of in-place density throughout the test box, the same compactive effort was applied on each layer of sand. The difference in densities measured was found to be less than 1% throughout the test programme.

2.6 Model tests and test program

The unreinforced soil beneath the plate anchor was compacted in layers of 50 mm in thickness. Then the plate anchor 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 plate anchor was connected to a tie rod to apply the uplift load. The sand was then again deposited in layers into the testing tank over the plate anchor and layers were continued to be applied until the required surface level was reached. 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 0.96 mm/min for every uplift test. The uplift load was measured using a calibrated electronic load cell attached to the tie rod during the uplift test. Vertical displacements of the plate anchor were measured using two linear variable displacement transducers. For each test, uplift load-displacement measurements were recorded by an eight-channel data logger unit and converted to produce values of displacement and load using DIALOG software on a PC. 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, six series of tests were conducted to investigate the inclusion effect of the geogrid layers on the plate anchor behaviour. Tests were carried out to find out the best location, length, and configuration of the geogrid layers that give the maximum improvement in plate anchor response. Also, the effects of embedment depth and the relative density of sand on the behaviour of plate anchor were investigated. Each series of test was conducted to study the effect of one parameter while the other variables were kept constant. Fig. 4 and Table 3 summarize all test programs with constant and variable parameters used.

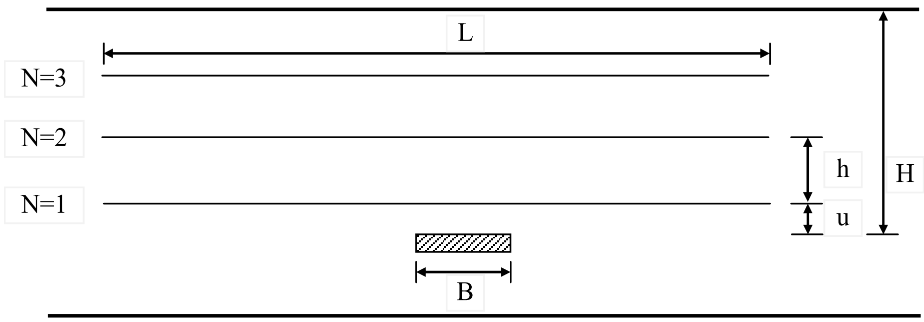

Fig. 4 Geometric parameters of model tests

Table 3 Model test program

Series	Constant parameters	Variable parameters
I	B = 50 mm, D_r = 35%, unreinforced	H/B = 1, 2, 3, 4, 5, 6
II	B = 50 mm, D_r = 85%, unreinforced	H/B = 1, 2, 3, 4, 5, 6
III	B = 50 mm, D_r = 35%, N = 1, L/B = 24	u/B = 0.00, 0.25, 0.50, 0.75, 1.00
IV	B = 50 mm, D_r = 35%, N = 2, L/B = 24, u/B = opt.	h/B = 0.25, 0.50, 0.75, 1.00
V	B = 50 mm, D_r = 35%, L/B = 24, u/B = opt., h/B = opt.	N = 1, 2, 3
VI	B = 50 mm, D_r = 35%, u/B = opt., N = 1	L/B = 1, 2, 3, 4, 5, 10, 20

The details of the tests are described below:

The primary purpose of test series I was to evaluate the effect of embedment depth (H) on the uplift capacity of plate anchor. Test series II was planned to examine the effect of the relative density (D_r) of sand on the uplift capacity of plate anchor for unreinforced case. Test series III, IV, V and VI aimed to obtain the effects of the depth of the top reinforcement layer (u), vertical spacing of geogrid layers (h), the number of the geogrid layers (N), and the length of each geogrid layer (L) on the uplift capacity of plate anchor. For each test series, model tests were conducted for unreinforced cases to compare the bearing capacity values with reinforced cases. Some tests were repeated at least twice to verify the consistency of the test data.

3. Numerical modeling

Series of three-dimensional finite element analyses on a model plate anchor-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 using the commercial program "PLAXIS 3D Tunnel" (version 2.0). The "PLAXIS 3D Tunnel" program is a geotechnical finite element package specifically intended for three-dimensional analysis of deformation and stability of tunnels, but can generally be used to analyze any geotechnical engineering project. The simple graphical input procedure enables a quick generation of complex finite element models, and the enhanced output facilities provide a detailed presentation of the computational results. The calculation itself is fully automated and based on robust numerical procedures. The geometry of the model plate anchor-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. In the numerical study, only a quarter of the plate anchor was modeled using symmetry conditions at the plate anchor centerline, to reduce the calculation time.

The Mohr–Coulomb Model (MCM) was used to describe the non-linear sand behaviour in this study. The model plate anchor was 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 = 1,100 kN/m, entered in units of force per unit width. The analyses were carried out using a three dimensional model in sand with two different densities as in the tests. In order to obtain the most suitable mesh for the study reported, preliminary computations using the five available levels of global mesh coarseness for a plate anchor in reinforced sand were conducted. A prescribed uplift load was then applied in increments accompanied by iterative analysis up to failure. Values of parameters used in the numerical investigation are shown in Tables 4-5. Shear strength and stiffness parameters representing sand conditions derived from series of drained triaxial compression tests. The 3D and sectional 2D finite element meshes used for analyses are shown in Figs. 5 and 6, respectively.

4. Results and discussions

The uplift capacity for the various arrangements of reinforcement, sand conditions, and embedment depth is discussed. In addition, a numerical study on the effect of reinforcing the sand on the behaviour of square plate anchor was carried out using the finite element method.

During most tests uplift resistance increased rapidly with anchor displacement in the initial stages, the rate of increase eventually reducing as the maximum (peak) resistance was approached. In this type of failure a peak value is clearly defined in the curve of displacement against uplift load. For the finite element analyses, a peak value is never observed. In this case choosing a single value of uplift capacity may be extremely subjective. In this study, the ultimate uplift capacity (T_u) and corresponding displacement were defined as occurring at the point where the displacements began to take place under essentially constant load.

Table 4 Values of sand parameters for loose and dense conditions used in analysis

Parameter	Loose sand	Dense sand
Unit weight, γ (kN/m^3)	15.4	17.0
Young's modulus, E (kN/m^2)	21600	30000
Poisson's ratio, ν (-)	0.25	0.25
Internal friction angle, ϕ (°)	39	44
Cohesion, c (kN/m^2)	0.5	0.5
Dilatation angle, ψ (°)	9	14

Table 5 Values of steel plate properties used in analysis

Parameter	Value
EI (kNm^2/m)	163
EA (kN/m)	3.4×10^5

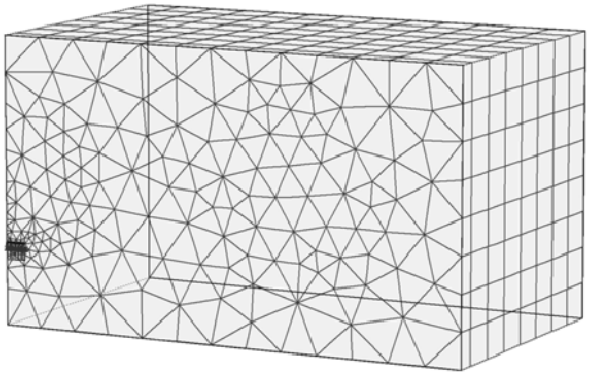

Fig. 5 3D finite element mesh generation

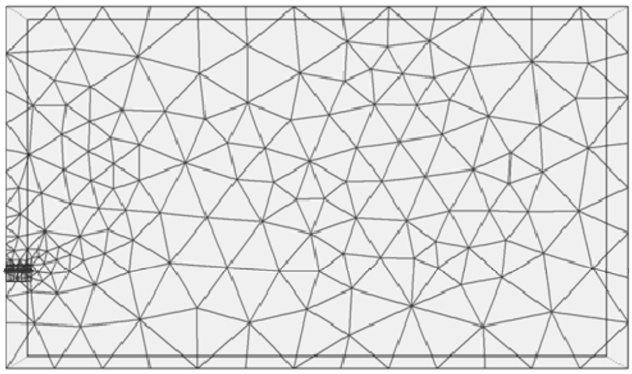

Fig. 6 Sectional 2D finite element mesh generation

Uplift capacities are often expressed in dimensionless form as breakout factors. The non-dimensional breakout factor, N_{qu} may be expressed as stated below

$$N_{qu} = \frac{T_u}{\gamma BLH} \tag{1}$$

where T_u is the maximum uplift capacity, γ is the soil unit weight, H is the anchor embedment depth and B and L are the anchor width and length, respectively.

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

$$UCR = \frac{T_{ur}}{T_u} \tag{2}$$

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

4.1 Effect of embedment depth

The tests in this series were conducted to determine the relation of uplift capacity, T_u and breakout factor, N_{qu} to embedment ratio, H/B. In the tests, 50 mm square plate anchor was used and the relative density of sand was $D_r = 35\%$. The H/B ratios were varied from 1.00 to 6.00. The variations of T_u-H/B and N_{qu}-H/B are presented in Figs. 7 and 8, respectively. The figures show that the general trends of finite element analysis agree well with those of the model tests. From Fig. 7, it can be seen that the ultimate uplift load, T_u increases significantly with an increase in embedment ratio, H/B. As seen from Fig. 7, plate anchor in maximum embedment ratio, H/B = 6, had a higher uplift capacity than in minimum embedment ratio such as H/B = 1. Also, from Fig. 8,

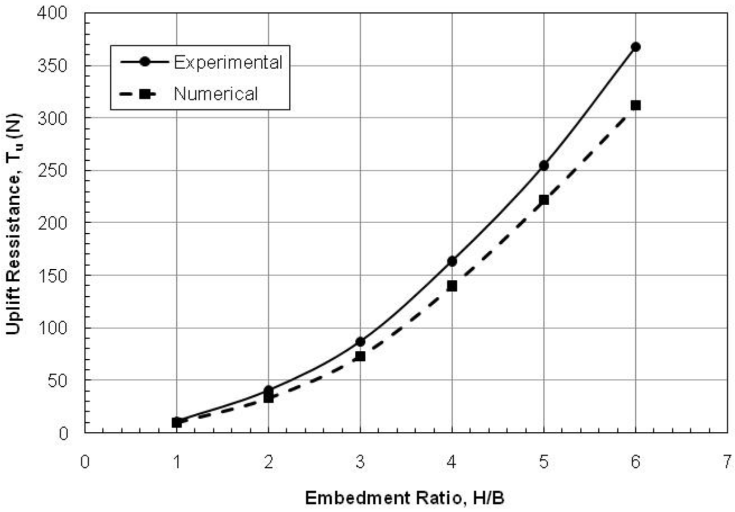

Fig. 7 Variations of T_u with H/B (loose sand)

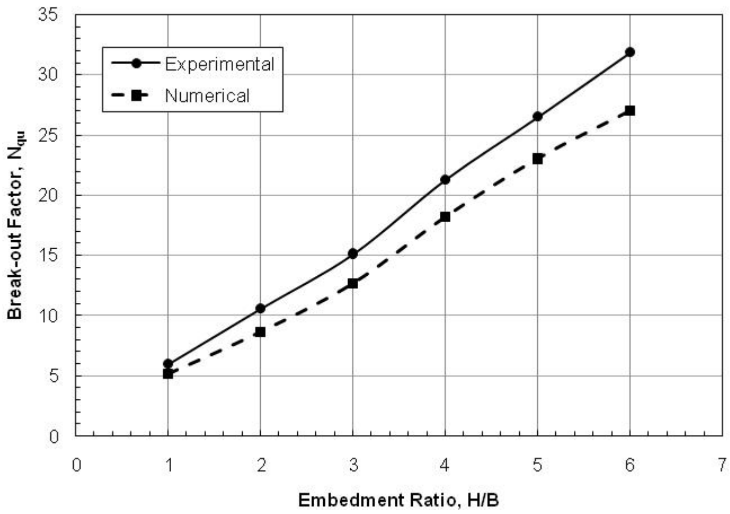

Fig. 8 Variations of N_{qu} with H/B (loose sand)

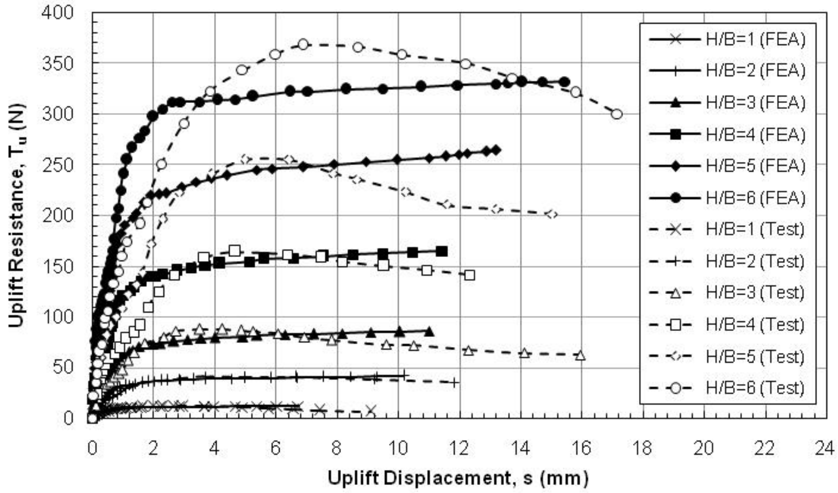

Fig. 9 Variations of N_{qu} with H/B (loose sand)

it is clear that; a significant, almost linear, increase in breakout factor with embedment ratio was obtained both experimentally and numerically.

The relations of the uplift load to uplift displacement, s in loose sand conditions for various values of H/B obtained from laboratory model tests and finite element analyses (FEA) are presented in Fig. 9. As seen from the figure, during the tests, uplift resistance increases rapidly with anchor displacement in the initial stages, the rate of increase reducing as the maximum resistance was approached. The variation of uplift load with displacement from the finite element analyses shows generally good agreement in the pre-peak region with the laboratory model test.

4.2 Effect of relative density of sand

In order to investigate the effect of relative density of sand on uplift capacity, series of model tests for plate anchor in sand with relative density of D_r = 85% were performed in addition to tests for D_r = 35%. In the tests, 50 mm square plate anchor was used and the H/B ratios were varied from 1.00 to 6.00.

The variations of T_u-H/B and N_{qu}-H/B both loose and dense conditions are presented in Figs. 10 and 11, respectively. Figs. 10 and 11 show that the values of T_u and N_{qu} increase with an increase in relative density of sand and embedment ratio, both experimentally and numerically. It is evidence that relative density of sand is one of the main parameters affecting the uplift capacity of the plate anchor.

This increase in uplift capacity of plate anchor with relative density of sand can be attributed to the weight of soil and shearing resistance. As known, the ultimate uplift capacity of a plate anchor is the sum of the weight of the soil and the plate anchor in the failure zone and the shearing resistance developed along the failure surface (Balla 1961). The weight of the soil increases with relative density and embedment ratio. In addition to those, failure surface length increases with embedment ratio. Thus, the uplift capacity of anchors in sand is strongly influenced by their embedment ratio and by the relative density of the sand.

The relations of the uplift load to uplift displacement in dense sand conditions for various

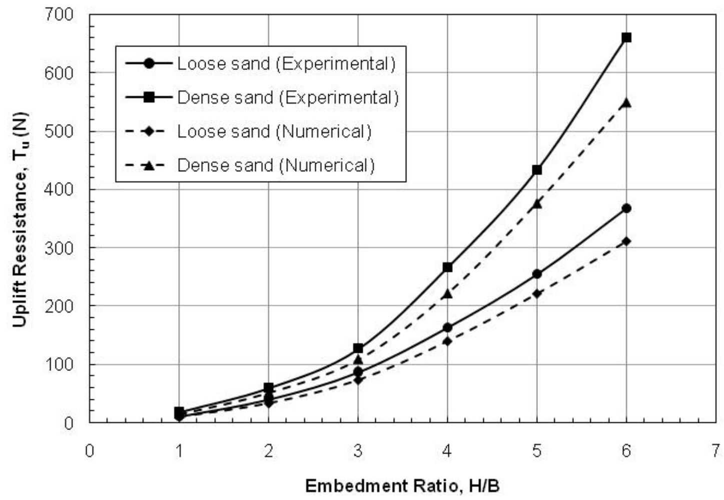

Fig. 10 Variations of T_u with H/B

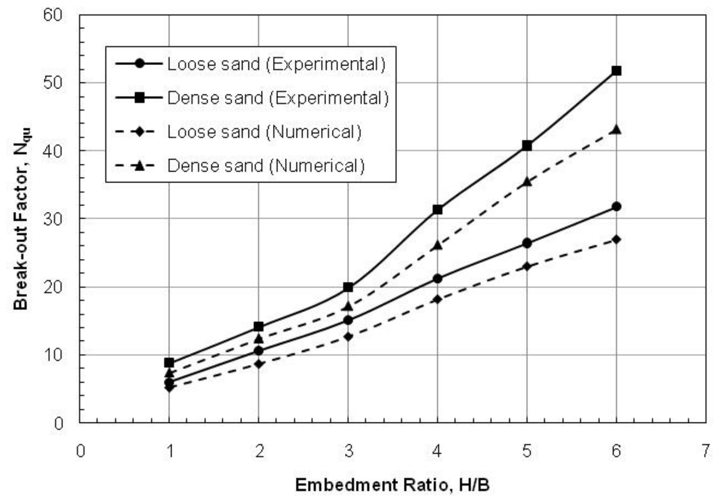

Fig. 11 Variations of N_{qu} with H/B

values of H/B obtained from laboratory model tests and finite element analysis are presented in Fig. 12. As seen from the figure, the variation of uplift load with displacement from the finite element analyses provides a reasonable fit with the experimental results.

4.3 Effect of first geogrid layer depth to the plate anchor

The tests in this series were conducted to determine the relation of uplift capacity to depth ratio, u/B. For the tests, the values of N, and L were kept constant as $N = 1$ and $L = 24B$. The width of the plate anchor was $B = 50$ mm, the relative density of sand was $D_r = 35\%$ and the embedment ratio was $H/B = 5$. In the tests SG Q1 geogrid was used as reinforcement. The u/B ratios were varied from 0.00 to 1.00.

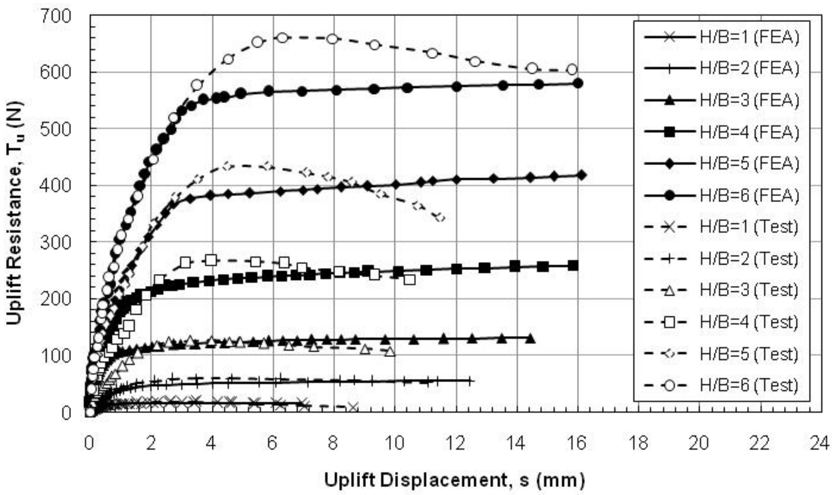

Fig. 12 Variations of T_u with s for different H/B ratios in dense sand conditions

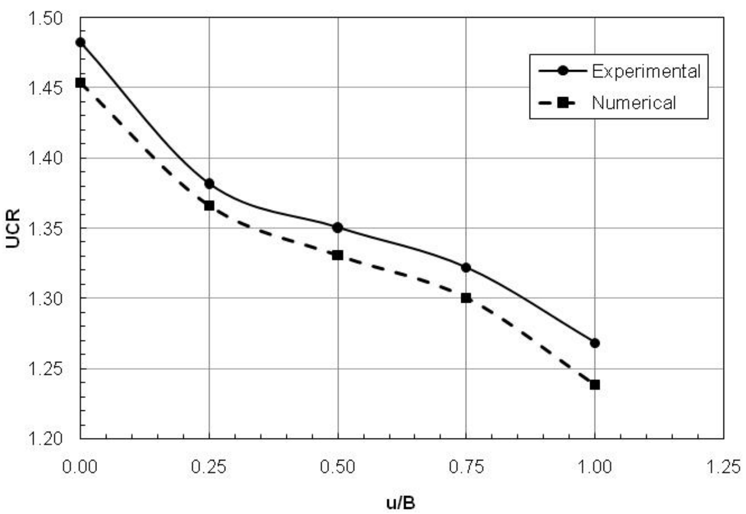

Fig. 13 Variations of *UCR* with u/B

Fig. 13 shows the relation of *UCR* to u/B obtained from model tests and finite element analyses. It can be seen from the figure that the effect of the depth to the first reinforcement layer on uplift capacity is clearly significant. Fig. 13 shows that, maximum improvement in the uplift capacity of plate anchor is achieved when the geogrid layer is placed directly on top of the anchor plate. The improvements in the uplift capacity of plate anchor decrease as the distance between the geogrid layer and the plate anchor increases.

The figure also shows that the general trends of finite element analysis agree well the model test results. It may be concluded that $(u/B)_{opt}$ is 0.00 for both model tests and finite element analyses. For values of u/B greater than 0.00, the *UCR* values decrease. At larger depths of embedment the contribution to the load transfer mechanism caused by the presence of the reinforcement reduces significantly. For u/B values of greater than 0.00, the entire system behaves more or less like unreinforced sand.

4.4 Effect of vertical spacing of reinforcement layers

The effect of vertical spacing of reinforcement layers (h) on uplift capacity was investigated using two layers of SG Q1 geogrid reinforcement with a top layer spacing of u = 0.00B. For the tests, the plate anchor width was B = 50mm, the relative density of sand was D_r = 35%, embedment ratio was H/B = 5 and length of reinforcement L was kept constant as 24B.

The vertical spacing ratios of reinforcement were varied from 0.25 to 1.00. Fig. 14 shows the

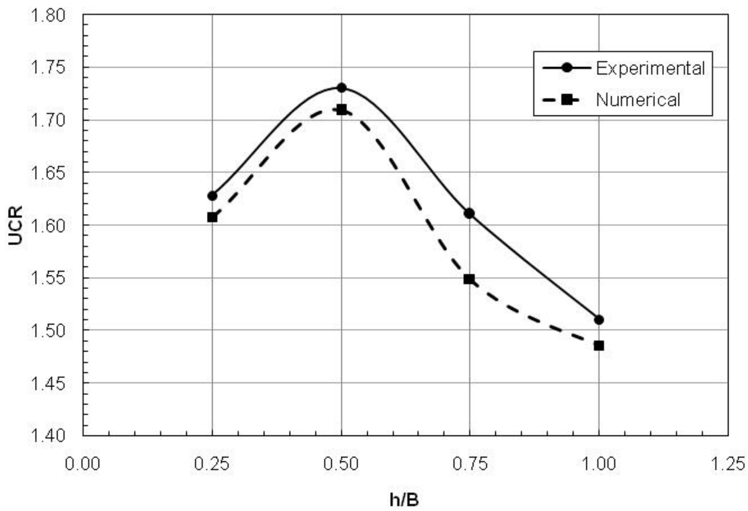

Fig. 14 Variations of *UCR* with h/B

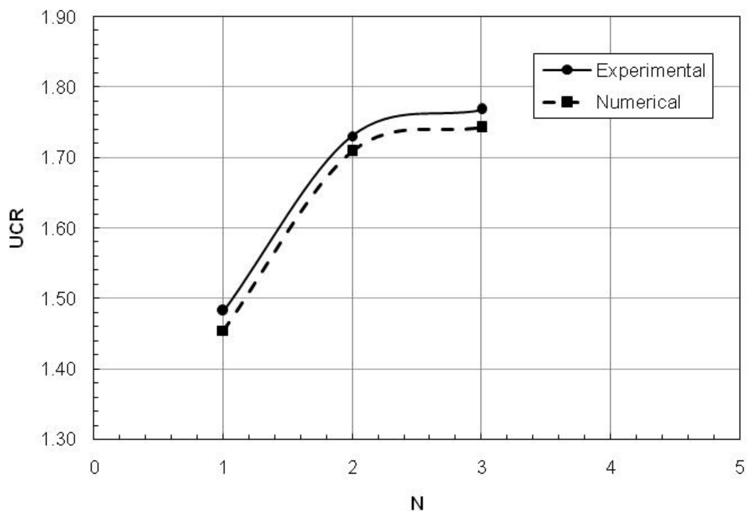

Fig. 15 Variations of *UCR* with N

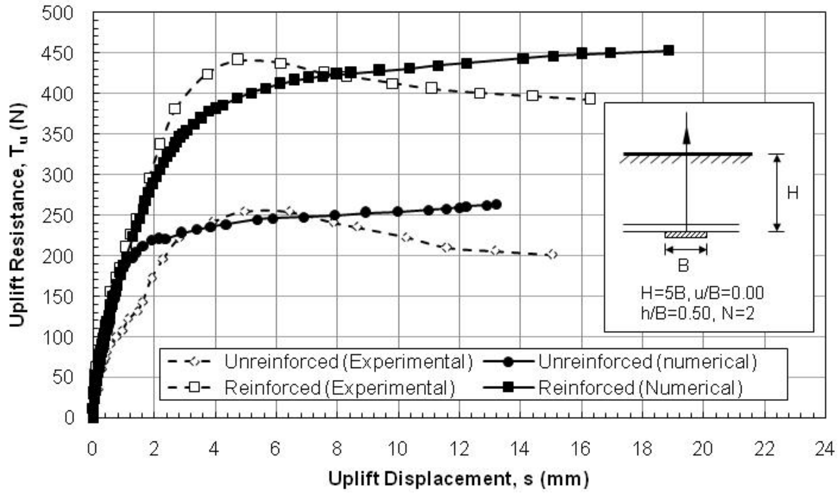

Fig. 16 Variations of T_u with s for unreinforced and reinforced cases

variation of *UCR* with *h*/*B*. It is evident that the *UCR* values increase with *h*/*B* up to a value of 0.50 and then decrease. Although the *UCR* values obtained from finite element analyses appears to be smaller than that for experimental results, the general trend of manner in which *UCR* varies with *h*/*B* is in good agreement with those from the model tests.

4.5 Effect of number of reinforcement layers

Series of laboratory model tests and finite element analysis were conducted on sand reinforced with multiple layers of SG Q1 geogrid. For the tests the values of *u*/*B*, *h*/*B* and *L* were kept constant as 0.00, 0.50, and 24*B*, respectively. Fig. 15 shows the variation of *UCR* obtained from model tests and numerical analyses with number of reinforcement layers; *N*. It can be seen from the figure that uplift capacity of plate anchor increases with an increase in *N*. A sharp increase in bearing capacity was observed for number of layers increasing up to two. However, the addition of more layers of reinforcement after the second did not contribute much to the uplift capacity improvement.

Fig. 16 shows the relations of the uplift load to uplift displacement in loose sand conditions for unreinforced and reinforced cases from laboratory model tests and finite element analysis. In the tests, the values of *H*/*B*, *u*/*B*, *h*/*B* and *N* were kept constant as 5.00, 0.00, 0.50, and 2, respectively. The figure shows that the general trends of finite element analysis agree fairly well with those of the model tests. For the same displacement values, the figure demonstrates that the inclusion of geogrid layers resulted in an increase in the uplift load capacity of the model plate anchor.

4.6 Effect of length of reinforcement layers

This series of tests were carried out to investigate the effect of the reinforcing element length on *UCR*. In these tests, the lengths of the geogrid layers were varied from 1*B* to 20*B*. For the tests, the values of *u*/*B* and *N* were kept constant as 0.00 and 1, respectively. Fig. 17 shows the variation of *UCR* with length of reinforcement, *L*. It can be seen from the figure that uplift capacity ratios obtained from tests and analyses increase rapidly with increasing reinforcement layer length, and remains relatively constant for L = 3B.

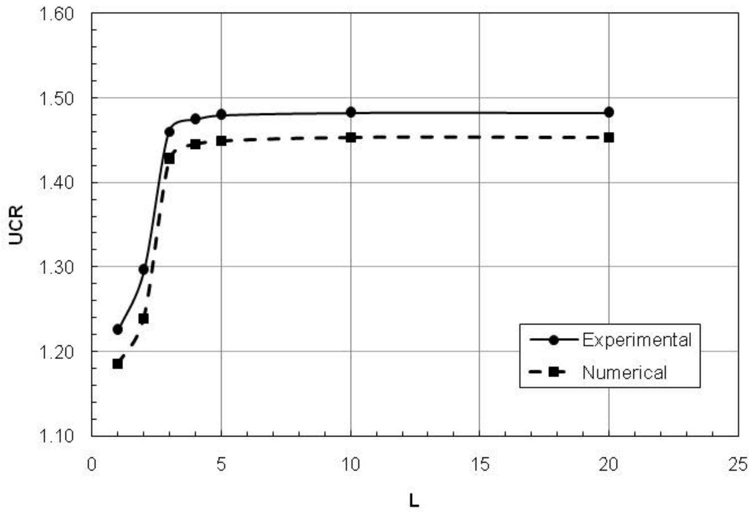

Fig. 17 Variations of *UCR* with *L*

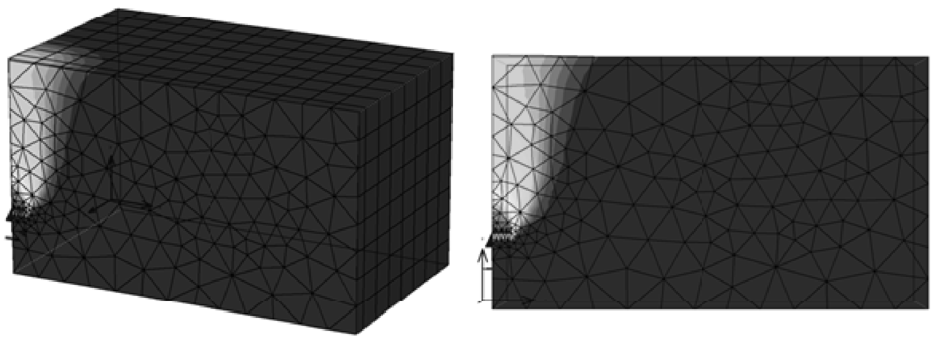

Fig. 18 Displacement contours for unreinforced sand

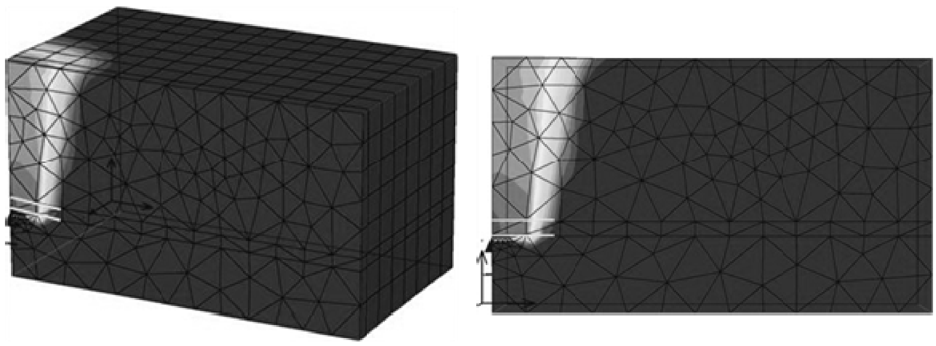

Fig. 19 Displacement contours for reinforced sand

5. Failure mechanism

In this section the failure mechanism of plate anchors in unreinforced and reinforced sand was investigated and discussed using "PLAXIS 3D Tunnel". The failure mechanism was examined based on the displacement contours obtained from numerical analysis.

Figs. 18 and 19 present displacement plots for unreinforced and reinforced cases at ultimate conditions, respectively. Fig. 18 shows that for unreinforced case, uplift loading of the plate anchor causes curved shear surface form beginning at the anchor and continue to develop until reaching the soil surface. The results of displacement contours obtained from "PLAXIS 3D Tunnel" on anchor plate embedded in geogrid-reinforced sand are shown in Fig. 19. Note that, two geogrid layers of L/B = 3 were placed at u/B = 0.00 and h/B = 0.50 for the reinforced case. The observed displacement vectors at failure for re inforced case are distributed for greater width and depth than that in unreinforced case. The displacement contours show that the geogrid reinforcements resist the shear stresses and deformations built up in the sand mass inside the loaded area and push them upward to stable layers of sand. Sand-geogrid interaction results in increasing the uplift capacity due to developed longer failure surface.

6. Conclusions

The uplift capacity of square plate anchors in geogrid reinforced sand was investigated experimentally and numerically. Based on the results, the following main conclusions can be drawn:

- Both experimental and numerical studies show that the uplift capacity and the break-out factors for square plate anchors in unreinforced sand increase with increases in anchor embedment ratio and relative density of sand.
- A significant improvement in plate anchor performance in sand can be obtained by using geogrid reinforcements, as the transfer of uplift loads through the geogrid layers and interlock between the geogrid and the sand reduce lateral and vertical displacements above the anchor.
- Depending on the geogrid arrangement, ultimate uplift capacity values can be improved by up to approximately 1.70 times those of the unreinforced case.
- To obtain maximum benefit from the reinforcement, the optimum depth-footing width ratio (u/B) is 0.00 and the optimum geogrid spacing-footing width ratio (h/B) is 0.50.
- The addition of more than two layers of geogrid did not contribute much to the uplift capacity improvement: thus the optimum number of layers of geogrid (N) is found to be two.
- The optimum length of geogrid layers (L) that contribute to the increase of uplift capacity is found to be $3B$. So, when the length of the geogrid layers is greater than $3B$, the bearing capacity remains relatively constant.
- A satisfactory agreement between the experimental and numerical results on general trend of behaviour and the critical values of the geogrid parameters is observed. However, the *UCR* values obtained from finite element analysis appears to be smaller than that obtained from the model tests.

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