

A study on pullout behavior of plate anchor in reinforced soft clay

Narayan Roy*¹, Sibapriya Mukherjee^{2a} and Ambarish Ghosh^{3b}

¹Department of Civil Engineering, Jadavpur University, Kolkata, India

²Department of Civil Engineering, Narula Institute of Technology, Agarpara, Kolkata, India

³Department of Civil Engineering, Indian Institute of Engineering Science and Technology (IIEST), Shibpur, India

(Received February 24, 2024, Revised October 25, 2024, Accepted November 27, 2024)

Abstract. Anchor foundation systems are widely used to withstand uplift or pullout loads. Structures like tall buildings, transmission towers, jetty structures etc. experience such loads which can hinder the stability of the structure. Plate anchors develop resistance from the imposed soil weight and the shear stress along the failure surfaces formed during pullout, as the plate experiences the pullout load. Thus, the pullout load is resisted. The paper studies the pullout behavior of plate anchor using extensive laboratory model tests. The effect of different sizes of plate anchors, their embedment and different position of reinforcement on the pullout behavior have been studied. Different non-dimensional parameters have been used to represent the pullout behavior and the improvement in pullout capacity. Further, this study aims to identify the enhancement of pullout capacity over unreinforced soil due to the inclusion of reinforcement. For this, a parametric study has been carried out by conducting pullout tests with model square, rectangular and strip anchors embedded in unreinforced and reinforced soil made up of artificially prepared compacted Kaolin as clay bed. The outcomes have been presented in different non-dimensional form, such as: embedment ratio (H/B), relative depth of reinforcement (H'/H), size of plate (L/B), and relative ultimate displacement (δ_u/B), and the influence of different parameters has been studied. Breakout factors for anchors of different sizes have been obtained from the ultimate pullout loads for both reinforced and unreinforced soil. Pullout capacity of plate anchors gets increased due to geotextile reinforcement in the embedded soil irrespective of depth of embedment of anchors. Considering all the parameters used in the present study such increase is about 47 to 63% in cases of square and rectangular anchors compared to 36% in strip anchor. Further, the position of geotextile also significantly influences the pullout behavior of anchor. Maximum increase in pullout load is achieved for reinforcement nearer to the plate.

Keywords: embedment ratio; geotextile; plate anchor; soil flow mechanism; ultimate pullout load

1. Introduction

With the growing need for infrastructural development due to rapid urbanization, many civil engineering structures like transmission towers, tall buildings and chimneys, jetty structures, submerged platform, mooring systems etc., which are being constructed are largely susceptible to uplift or pullout loads. Submerged platform and mooring systems are the example of structures subjected to uplift load, whereas, rest of the above-mentioned structures are some of the examples of structures which experience pullout load. To ensure the stability of such structures, the magnitude of uplift or pull coming on the structure including foundation needs to be well addressed, otherwise it may lead to the separation of foundation and surrounding soil, and therefore, tilt of the structure can ultimately result into collapse of the structure. To cope with such scenarios, anchor foundation systems are largely used. Different types

of anchor foundation systems (plate, belled, under-reamed pile, pedestal, helical anchors, and grillage) have been used to meet the need of increased demand for foundations that can resist the pullout loads. Plate anchor is one such type of foundation system which develops resistance from the soil weight in addition to the shear stress along the failure surfaces formed during pullout or uplift. Several theoretical and experimental studies have been conducted to find out the pullout behavior of plate anchors embedded in different types of soil over the last five decades remarkably by Adams and Meyerhof (1968), Rowe and Davis (1982), Saran and Rao (2002). It has been shown by the researchers that the uplift or pullout capacity of anchors can be enhanced by using the anchors in a group, increasing unit weight of the soil in which the anchor is embedded, by adjusting the embedment depth and anchor size etc.

Experimental/ numerical investigations were performed by several researchers to study the uplift behavior of plate anchors embedded in sand. The studies reported that the uplift capacity gets significantly affected by relative density and embedment ratio (Ilamparuthi *et al.* 2002, Saran and Rao 2002, Ravichandran *et al.* 2008). Inclusion of geosynthetic reinforcement is observed to enhance the pullout load capacity of plate anchor significantly (Krishnaswamy and Parashar 1994, Saran and Rao 2002, Ravichandran *et al.* 2008, Dash and Choudhary 2019). Most of the studies uses cohesionless soil as foundation material

*Corresponding author, Assistant Professor
E-mail: narayan.roy.civil@jadavpuruniversity.in

^aProfessor
E-mail: sibapriya.mukherjee@gmail.com

^bProfessor
E-mail: ambarish@civil.iiests.ac.in

for experimental investigation. The position of placement of reinforcement above the top of anchor plate influences the pullout capacity substantially (Saran and Rao 2002). The orientation of placing of the reinforcing material (horizontal and vertical) can also affect the uplift behavior. The plate anchors are observed to exhibit higher uplift capacity in the presence of vertical reinforcement due to better interlocking than in the presence of horizontal reinforcement (Ravichandran *et al.* 2008). Some studies have also been conducted to examine the efficacy of the inclusion of geotextile ties and how it influences the uplift behavior of anchors placed within sand. The uplift capacity of anchor was found to increase due to the inclusion of tie and the optimum number of layers of ties is obtained as two (Ghosh and Bera 2010). Some studies attempted to investigate the scope of using geocell/ geogrid as reinforcing material and its mechanism in enhancing the pullout capacity (Ilamparuthi *et al.* 2008, Rahimi *et al.* 2018a, b, Dash and Choudhary 2019, Yunkul *et al.* 2021). Plate anchor foundation can also be used near the slope. A decrease in uplift capacity is observed as the distance between the crest of a slope and edge of plate anchor decrease (Bhattacharya and Sahoo 2017). Plate anchors can also be used as inclined anchor and multi-plate vertical anchors (Tilak and Samadhiya 2022, Zhuang *et al.* 2022). It is observed that as the inclination angle increases, the capacity also increases and it is most prominent when the inclination increases from 45 to 90 degrees (Zhuang *et al.* 2022). The works related to pullout behavior of multi-plate vertical anchors in sand reveals that for double-plate and triple-plate vertical anchors, the pullout capacity increase with placement and embedment ratio (Tilak and Samadhiya 2021, Tilak and Samadhiya 2022). The stiffness and opening size of geosynthetic reinforcing material can also affect the pullout behavior further (Kingshri *et al.* 2005). Attempts have also been made to study the behavior of horizontal and inclined anchor foundation using limit analysis (Kumar 2003, Bhattacharya and Kumar 2014a, Merifield *et al.* 2003). Some studies also explored the pullout capacity of vertical anchors in sand and proposed some design chart considering limit equilibrium method of analysis (Jadid *et al.* 2018, 2019, Shahriar *et al.* 2020).

Some previous studies are also there to examine the behavior of shallow plate anchors in cohesive soil with and without reinforcement. The uplift behavior was found to get affected by the embedment depth, type of geosynthetics used and by the ratio of the area covered by geosynthetic used as reinforcing material to the area of plate anchor (Nene and Garg 1991, Krishnaswamy and Parashar 1994, Merifield *et al.* 2001, Banerjee and Mahadevuni 2017).

Grouping of anchors can also be an effective mean to increase the pullout capacity (Banerjee and Mahadevuni; 2017). Woven geotextile as reinforcing material results in a greater increase in uplift capacity in comparison with non-woven geotextile (Nene and Garg 1991). In a numerical study on two-layered clayey strata, higher breakout factor is observed for strong clays overlying soft clays than soft clays overlying strong clay (Park and Lee 2021). Sometimes, it also becomes necessary to study the uplift behavior under cyclic loading. Some studies worked on to

examine the behavior of plate anchors under cyclic loading and post cyclic as well (Ponniiah and Finlay 2011, Biradar *et al.* 2019, Zhou *et al.* 2020, Ravishankar *et al.* 2022).

Study can also be conducted to examine the uplift behavior of plate anchor foundation subjected to seismic loading (Choudhury and Rao 2004, Shiau *et al.* 2024, Bhattacharya and Kumar 2014b).

From the previous works presented above, it is quite evident that works on pullout capacity of plate anchors in unreinforced cohesive soil has either been predicted by few model tests or by limited numbers of numerical/ analytical methods. Established formulae for the pullout capacity based on these above studies are also limited in case of unreinforced soil. On the other hand, very few experimental or analytical methods are reported for pullout capacity of plate anchors in reinforced cohesive soil. Soft clay materials always bring challenges to the practicing engineers and researchers for its complex and time dependent behavior. Very often the structures that can experience pullout/ uplift loads are constructed on soft cohesive soil without an alternative due to rapid urbanization and development of infrastructure. With the growing applicability of geosynthetic as reinforcing material, one can take the advantage of inclusion of geosynthetics in order to increase the pullout load with reduced anchor size (Banerjee and Mahadevuni 2017). Application of geosynthetic reinforcement can be considered as possible alternative in enhancing the anchor capacity. So, rigorous parametric studies considering different aspect of plate anchor, reinforcement and foundation material need to be performed so that the reliability and applicability of plate anchor foundation in reinforced cohesive soil can be increased. Hence, considering all the above aspects, it is prudent to make an endeavor in this present investigation to carryout extensive model tests with plate anchors in reinforced cohesive soil to investigate the pullout capacity. With this in view, the present work is taken for the purpose of gaining a clear understanding of the pullout behavior of plate anchors in reinforced clay using extensive laboratory model tests.

2. Materials and their properties

In order to carry out model studies in the laboratory, it is required to prepare repeatedly the foundation medium (both reinforced and unreinforced cases) for the anchor plates in an identical manner to achieve identical placement density and other relevant engineering properties for all the tests. Commercially available Kaolin procured from the company *Modern Rock and Clay pvt Ltd*, Kolkata, India was used as cohesive soil for the model study. In order to carry out the study for reinforced soil, woven geotextile sheet of 0.343 mm thickness and size four times of width of plate were used in all model tests done with reinforced soil. The geotextile used in this study has been acquired from *Z-Tech (India) Private Limited*, Kolkata – 29, India and the anchor plates and experimental setup used in the study have been fabricated locally by *Eletech*, Kolkata-34, India.

Table 1 Properties of the soil bed used in the experiment

Properties	Value
Liquid limit (w_l)	48%
Plastic limit (w_p)	24%
Optimum moisture content (OMC)	20%
Maximum dry density (γ_d)	16.24 kN/m ³
Avg. moisture content of compacted soil during testing	38%
Unit wt. of compacted soil during testing	18.0 kN/m ³
Undrained cohesion (c)	15.0 kN/m ²
Angle of internal friction (ϕ)	7°
Grain size distribution	Sand (0%), Silt (58%), Clay (42%)

Table 2 Physical and mechanical properties of geotextile

Physical/ Mechanical Properties	Value
Thickness	0.365 mm
Mass per unit area	146 gm/m ²
Tensile strength	27.6 kN/m
Elongation at maximum load	28.8%
Load at 10% elongation	15 N/m

2.1 Tests on Kaoline

The experimental procedure for routine tests on Kaolin used was followed according to IS specification in which tests like Grain Size Distribution (IS: 3104-1965), Atterberg Limit (IS :2720 Part V, 1965), Standard Proctor Test (IS: 2131-1963) and Undrained Shear Strength were conducted. For undrained shear strength, the test was done with Kaolin compacted to a water content of 30% and density 18 KN/m³. Routine laboratory tests on Kaolin soil samples yielded the properties presented in the Table 1. Optimum moisture content and maximum dry density of the soil sample were found as 16.24 kN/m³ and 20%, respectively. Grain-size distribution of the sample depicts the presence of percentage of sand, silt and clay as 0, 58 and 42%, respectively. Undrained cohesion of the soil sample was found to be 15 kN/m².

2.2 Tests on geotextile

Tests were conducted on the geotextile used in the experiment to determine its various physical and mechanical properties and are provided in the Table 2. The thickness was measured using a thickness gauge under a gradually applied pressure of approximately 2 kPa whereas the mass per unit area was obtained by taking weights of several test samples of known area, taken from several positions of the fabric sample. Uniaxial tensile strength of geotextile was carried out using 200 mm wide sample according to wide-width tensile test, ASTM D 4595. Tensile strength of the sample is found to be 27.6 kN/m and the elongation at maximum load is 28.8%. Modified direct shear test was performed to obtain the interface friction between the soil and geotextile. From the normal stress vs.

shear stress plot, the angle of friction ϕ_u and adhesion (C_a) between soil and reinforcement were evaluated as $C_a = 5$ kPa and $\phi_u = 9.5^\circ$.

3. Methodology

3.1 Test programme

Pull-out tests were conducted with horizontal anchor plates embedded in reinforced soil. Widths of anchor plates used were 50 mm, 75 mm and 100 mm for square anchors. Rectangular anchors of 50 mm width were used for aspect ratios (L/B), as 2.0, 4.0, 6.0 and Strip anchor is considered with same width for $L/B = 8.0$. All such shapes of anchor plates were embedded in soil with H/B of 1 to 4, 6 and 8. Position of geotextile was varied in each of the tests and kept as 0.25 H, 0.5 H and 0.75 H above the top of the plate, H being the depth of embedment of anchor plates in soil.

The details of the entire model anchor test programme are presented in Table 3. The entire programme consists of seven test series named as BP1 to BP7. In each test series with a particular L/B ratio, tests have been conducted for six different H/B ratios. The H/B values are taken as 1, 2, 3, 4, 6 and 8. At a particular H/B ratio, tests have been performed for three different positions of geotextile. So, for a single test series with a particular L/B ratio, considering H/B and position of geotextile, total 18 numbers of tests have been performed. And in total for seven tests series, 126 numbers of tests are performed in the laboratory. Table 4 presents a sample expanded details of test series BP1. A particular test has been named as P-H-G-L for better clarity and understanding (Table 4). Here, P, H, G & L signify the size of anchor plate, depth of embedment, position of geotextile and L/B ratio, respectively. So, P1-H1-G1-L1 stands for the test which falls in the test series BP1 with anchor plate size 50×50 , H/B ratio 1, position of geotextile at 0.25H, and L/B ratio 1.

3.2 Test setup

The complete experimental set up used for model anchor test is shown in Fig. 1. The complete test set-up consists of a Foundation tank (D), model anchor plate (A), loading frame (C), pulling system (F) and dial gauge (E). Each of the above items has been illustrated in the Fig. 1(a).

In the present investigation two different types of foundation tanks were utilized. Out of these two tanks, the first one is a square shaped tank of size 650 mm \times 650 mm (internal dimension) with a height of 800 mm is fabricated with Mild Steel Plates by welding and providing angles at the top and bottom corners of the tank as shown in Fig. 1(a).

As the depth of tank is limited to 800 mm, tests for higher embedment depth as well as higher sizes of plate anchors could not be done in this tank and particularly for strip anchors ($L/B > 5$), the second tank was fabricated as shown in Fig. 1(b). The size of this tank was kept as 500 mm \times 1000 mm \times 1200 mm deep and fabricated with a movable ebonite wall to carryout tests in three chambers of sizes 200 mm \times 1000 mm (chamber 1), 300 mm \times 1000 mm

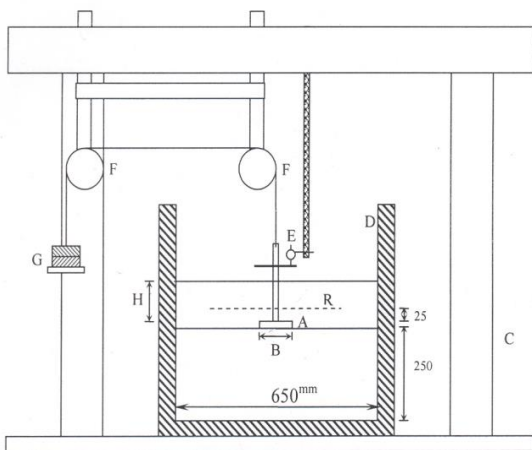
Table 3 Concept of the entire model anchor test programme

Test series	Anchor size	L/B ratio	Embedment ratio (H/B)	Position of geotextile
BP1	50 × 50	1	1, 2, 3, 4, 6 & 8	[0.25H, 0.5H & 0.75H]*
BP2	75 × 75	1	1, 2, 3, 4, 6 & 8	[0.25H, 0.5H & 0.75H]*
BP3	100 × 100	1	1, 2, 3, 4, 6 & 8	[0.25H, 0.5H & 0.75H]*
BP4	50 × 100	2	1, 2, 3, 4, 6 & 8	[0.25H, 0.5H & 0.75H]*
BP5	50 × 200	4	1, 2, 3, 4, 6 & 8	[0.25H, 0.5H & 0.75H]*
BP6	50 × 300	6	1, 2, 3, 4, 6 & 8	[0.25H, 0.5H & 0.75H]*
BP7	50 × 400	8	1, 2, 3, 4, 6 & 8	[0.25H, 0.5H & 0.75H]*

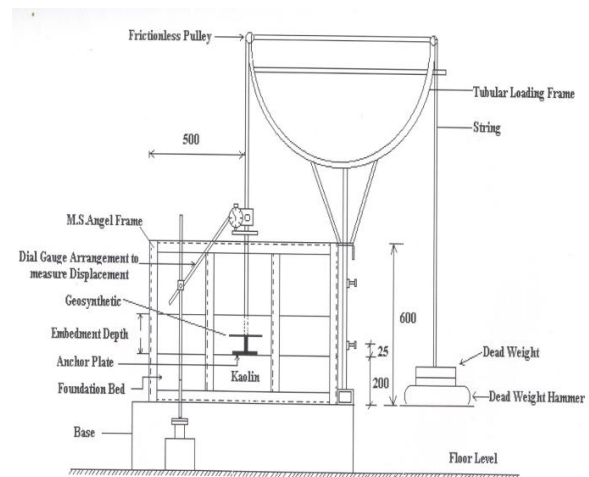
*For each H/B, three position of geotextile, so for each BP: 18 number of tests

Table 4 Test programme for model anchor test in reinforced soil

Series	Test Nomenclature	Anchor size (mm) (L × B)	L/B ratio	Embedment ratio (H/B)	Position of geotextile
BP1	P1-H1-G1-L1	50 × 50	1	1	0.25H
	P1-H1-G2-L1	“	“	“	0.50H
	P1-H1-G3-L1	“	“	“	0.75H
	P1-H2-G1-L1	50 × 50	1	2	0.25H
	P1-H2-G2-L1	“	“	“	0.50H
	P1-H2-G3-L1	“	“	“	0.75H
	P1-H3-G1-L1	50 × 50	1	3	0.25H
	P1-H3-G2-L1	“	“	“	0.50H
	P1-H3-G3-L1	“	“	“	0.75H
	P1-H4-G1-L1	50 × 50	1	4	0.25H
	P1-H4-G2-L1	“	“	“	0.50H
	P1-H4-G3-L1	“	“	“	0.75H
	P1-H5-G1-L1	50 × 50	1	6	0.25H
	P1-H5-G2-L1	“	“	“	0.50H
	P1-H5-G3-L1	“	“	“	0.75H
	P1-H6-G1-L1	50 × 50	1	8	0.25H
	P1-H6-G2-L1	“	“	“	0.50H
	P1-H6-G3-L1	“	“	“	0.75H



(a)



(b)

Fig. 1 (a) Schematic diagram for model anchors test and (b) Schematic diagram for model anchors test

and 400 mm × 1000 mm for tests with model square anchor of 75 mm & 100 mm and for rectangular and strip anchors of width 50 mm and L/B of 6 and 8. The side walls were fixed to the ebonite base with the help of mild steel angle

frames, nuts and bolts. Suitable stiffener of mild steel angles was fixed with the long wall to impart sufficient rigidity to the structure.



Fig. 2 (a) Different sizes of model anchor plates (b) Dead load used for the test and

Both square and rectangular anchors plates of different sizes were made from 8 mm thick mild steel plate. For square anchors the sizes were kept as 50 mm × 50 mm, 75 mm × 75 mm and 100 mm × 100 mm (Fig. 2(a)). In case of rectangular and strip anchors, the width was kept as 50 mm with L/B as 2, 4, 6 and 8. All such anchor plates used in the investigation were rough. The load frame for the smaller tank has been fabricated with ISMB 200 from which the pulley system has been suspended as shown in Fig. 1(a).

The capacity of the frame is about 10 kN and resting on the floor. For the larger tank a tubular loading frame was fabricated with two 40 mm diameter frictionless pulley attached to the corner of the frame so that a steel string when passed over the pulleys remain horizontal as shown in Fig. 1(b).

In order to apply pullout load, a vertical mild steel shaft of 10 mm diameter was fitted with anchor plate by removable bolt and the other end of the shaft which was threaded was attached to a hoisting plug. One end of the steel string which passed over the pulley system was fitted with the hoisting plug attached to the anchor shaft and the other end was fixed with a mild steel hanger for applying incremental pullout load. Dead loads of different magnitudes (Fig. 2(b)) were applied on the hanger. In order to measure the axial movement of the anchor plate, two dial gauges of sensitivity 0.1 mm were used. They were allowed to rest on a bar.

3.3 Test procedure

Pull out tests for all the anchors of different geometry embedded in reinforced and unreinforced soil were tested in both reinforced and unreinforced soil as described below. Depending on the size of anchor plate and embedded depths tests were carried out either in the smaller foundation tank or larger tank. In the smaller tank of size 650 × 650 × 800 mm square anchors of 50 mm and 75 mm and rectangular anchors of 50 × 100 mm were tested. For all other size of anchors the larger tank of 500 × 1000 × 1200 mm deep was used for testing. All the model anchor tests were carried out following the under mentioned steps given below:

(a) Preparation of Soil Bed

To provide soil cushion for the plate anchor, a soil bed

thickness of 200 mm was prepared during experiments. Preparation of the bed was done by mixing known quantity of dry Kaolin with a predetermined amount of water so it leads to a consistency index of 0.60 and moisture content of 38%. The soil was compacted in layers of 50 mm with 75 blows from a 70 N rammer and the height of drop was maintained 300 mm to achieve desired density of 18 kN/m³. The placement moisture content and degree of compaction was chosen by conducting pilot tests earlier. The pilot tests indicated that the moisture content and compaction would result in the desired density of 18 kN/m³ and shear strength of 15 kN/m².

b) Placement of Anchor

In each test the anchor model plate connected with 10 mm diameter shaft was lowered into the foundation tank vertically and placed horizontally at the centre of the prepared soil bed. In order to eliminate soil adhesion, a filter paper of anchor size was placed below the model anchor plate so that the anchor may move upward freely during pullout. Sufficient precaution was taken to keep the anchor plate system vertical. Fig. 3(a) shows the placement of anchor plate in soil during a test.

c) Preparation of Embedded Soil

After placement of the anchor at the desired depth of embedment in the foundation tank for a particular desired H/B , the Kaolin was mixed with appropriate quantity of water was compacted in layers of 50 mm thickness with the same procedure adopted for the preparation of foundation bed. For this purpose, the anchor plate with the shaft was tied properly in position so that there is no movement of the plate anchor during compaction.

d) Placement of Reinforcement

Reinforcement in the form of geotextile sheet was placed in single layer at the desired location within the embedment depth. The position of geotextile was varied from the top of plate as 0.25 H, 0.5 H and 0.75 H, H being the embedded depth of anchor plate. In each test the horizontal extent of geotextile sheet was kept equal to four times the plate size as beyond this extent no appreciable change in pullout capacity was noticed from pilot tests done earlier. For allowing anchor shaft to penetrate the geotextile sheet, one hole of 10 mm diameter was made at the center of the geotextile sheet (Fig. 3(b)). The geotextile sheet was

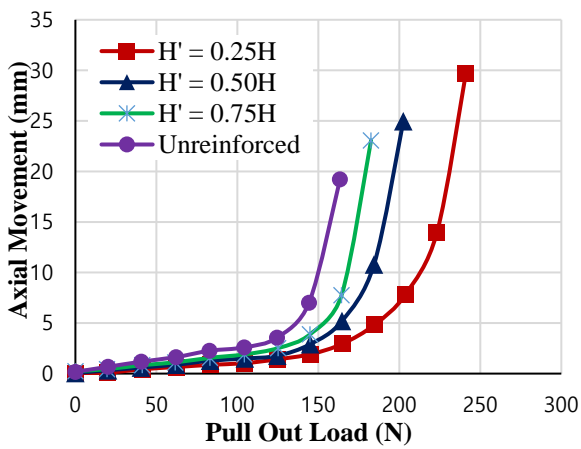


(a)

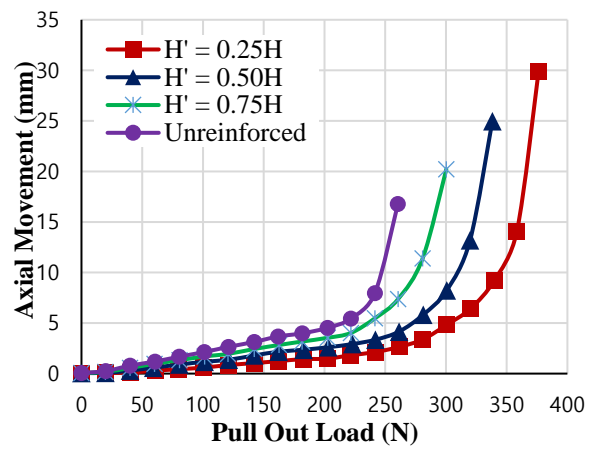


(b)

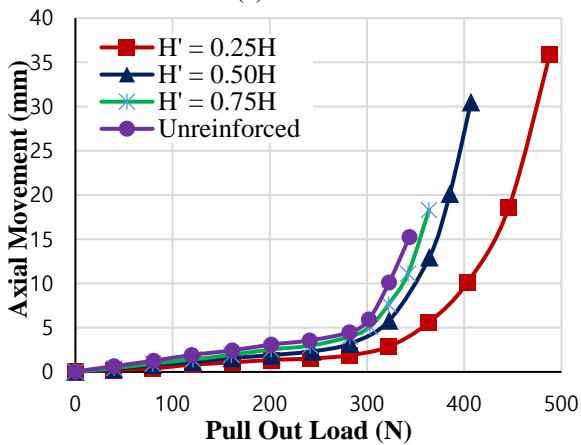
Fig. 3 (a) Placement of anchor plate in soil (b) Geotextile with 10mm diameter hole at the center



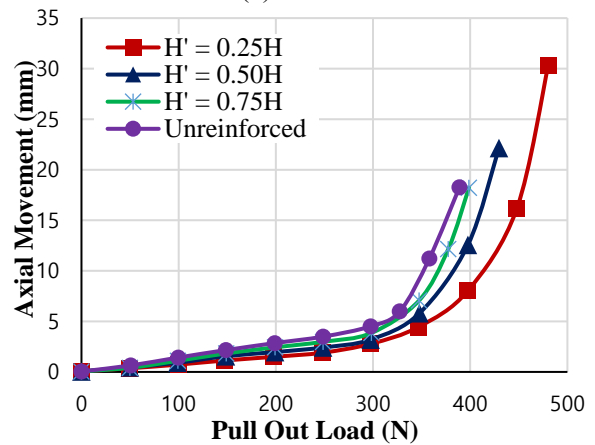
(a) $H/B = 1$



(b) $H/B = 2$



(c) $H/B = 3$



(d) $H/B = 4$

Fig. 4 Axial movement vs load plot for 50×50 plate size with different H/B

placed at the desired depth above the top of plates and thereafter subsequent layers of soil were placed above the geotextiles and compacted up to the desired height following the same procedure of compaction of soil above the anchor plate and the soil cushion below the anchor plate.

e) Loading Arrangement

After preparation of embedded soil, the anchor shaft was connected to steel wire attached to the shaft and allowed to

pass over two frictionless pulleys. The other end of the cable was attached to a hanger for applying dead loads. Dial gauges of least count .01 mm were placed on a steel plate attached to the anchor shaft to measure the upward displacement of the anchor plate during application of pullout load.

f) Pullout Test of Anchor Plate

The anchors were subjected to different incremental loading by dead loads placed on the hanger with appropriate

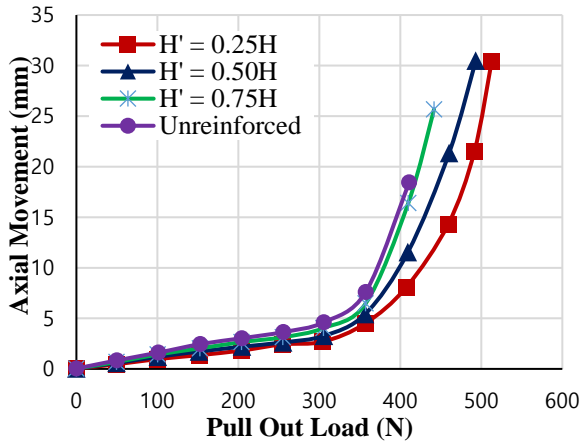
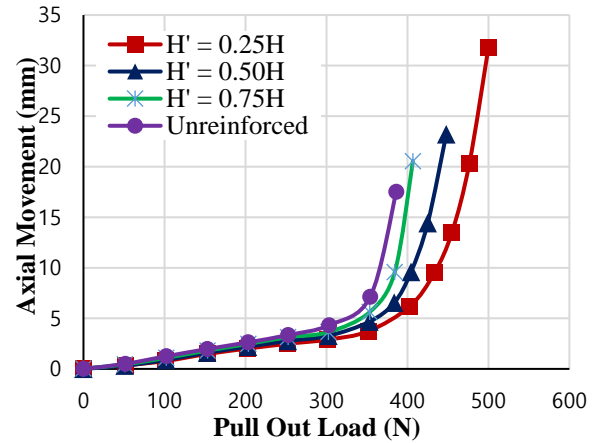
(e) $H/B = 6$ (f) $H/B = 8$

Fig. 4 Continued-

load increment of 20 N or 40 N. Next higher loads were applied where the rate of upward movement was less than .05 mm/hr or less. The load increments were decided by carrying out on few pilot tests earlier. Under each increment of load, the upward movement of the anchor plate was recorded with the help of 25 mm dial gauge placed on the steel plate attached to the anchor shaft. Pulling of anchor plates was continued till failure. The load and anchor movement at different loading stages were recorded. Load vs. axial movement curves were then plotted to obtain the ultimate pull out capacity. In this way all the anchor tests were done to complete the experimental investigation of the present study.

4. Results and discussion

4.1 Pullout load vs. axial movement

Axial movements of anchor plates have been plotted against applied pullout load for all shapes and sizes of anchors both in reinforced and unreinforced soil. Three sample typical results for square ($L/B=1$), rectangular ($L/B=2$) and strip ($L/B=8$) plate anchor have been presented here. Figs. 4(a) to 4(f) present results of axial movement vs load for 50×50 plate size with different H/B . From these figures it may be seen that the load displacement/movement response of the anchors in both reinforced and unreinforced soil are similar in nature exhibiting nonlinear behavior. Plots (Figs. 4(a)-4(f)) also indicate that the pullout load increased linearly in the initial stages and later it eventually became continuously curvilinear except for a short portion at the end without any definite yield point and the displacement at any stage of loading is less in reinforced soil compared to unreinforced soil. Another two sample results have been presented in Figs. 5 and 6 for plate size 50×100 and 50×400 respectively.

Considering the nature of the curves, the ultimate pullout loads have, therefore, been estimated by double tangent method and tabulated in Tables 5 and 6. In addition

to this, the axial displacements ' δ_u ' corresponding to the ultimate pullout loads ' P_u ' are also shown in these tables.

From the figures (Figs. 4 to 6), it is quite evident that compared to unreinforced soil, the curvilinear part shifts to the right indicating higher pullout load with increasing displacement in case of reinforced soil. Thus, the ultimate pullout load is higher in reinforced soil compared to unreinforced soil for all depths of embedment and positions of reinforcement as shown in Tables 5 and 6.

The maximum increase in pullout load due to inclusion of reinforcement is found to be 56 to 63% for square anchors, 47 to 57% for rectangular and 36% for strip anchor of $L/B = 8$. Moreover, it is also noted from the table that maximum increase in pullout load was obtained when the reinforcement was placed at the height of 0.25H above the anchor plate where H is the depth of embedment, and the pullout load decreased when the reinforcement position was shifted further upward from the plate.

Such behavior may be attributed to the fact that in case of proximity of reinforcement to the plate, contribution of frictional force from the reinforcement is more because of large overburden pressure and also the contact area of reinforcement with soil, beyond the failure zone is more. Similar behavior was also reported by Saran and Rao (2002) where maximum increase in uplift resistance was obtained for the position of reinforcement at the top of the plate compared to other positions above the plate. Some other previous studies also reported similar enhancement of pullout load due to inclusion of reinforcement (Kingshri *et al.* (2005), Ravichandran *et al.* (2008), Banerjee and Mahadevuni (2017), Dash and Choudhary (2019).

The anchor displacement at ultimate pullout load shown in Tables 5 and 6 suggests that the ultimate displacement increases with increasing embedment depth in both reinforced and un-reinforced soil. However, for a particular depth of embedment, in comparison to unreinforced soil, such displacement was found to be higher which is indicative of the fact that a large anchor movement is required to mobilize the friction between the reinforcing material (geotextile) and the soil. In case of reinforced soil,

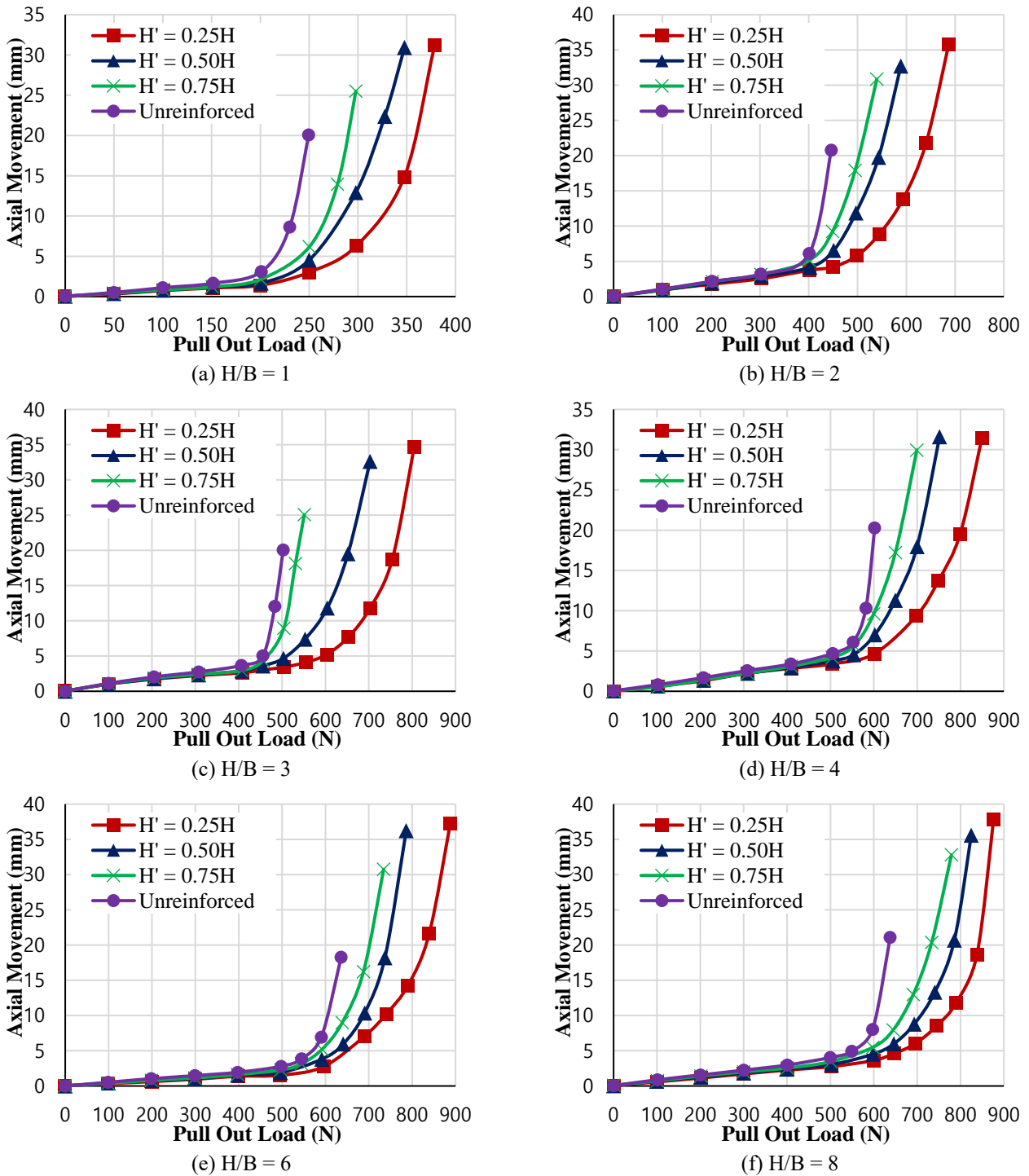


Fig. 5 Axial movement vs load plot for 50×100 plate size with different H/B

it was found that the failure pullout load occurred at a relative failure displacement of 16 to 28% compared to 10 to 13% in unreinforced soil. The relative failure displacement of anchor has been defined here as the ratio of failure displacement ‘ δ_u ’ to the least dimension (B) of anchor.

4.2 Soil flow mechanism during pull-out

During the pullout of the anchors with different

embedment depths in reinforced and unreinforced soil at different depths, an attempt has been made to observe the soil movement at failure by taking photographs as shown in Fig. 7 for a typical 50 × 50 mm anchor plate for different embedded depths for unreinforced soil. At the failure load, tension cracks develop with associated upheaval of soil surface, maximum being near the shaft was observed for anchors with a $H/B \leq 4$ for unreinforced soil as shown in Figs. 7(a) and 7(b). On the other hand, for anchors at higher depths (for $H/B > 4$), as observed in Fig. 7(c) neither

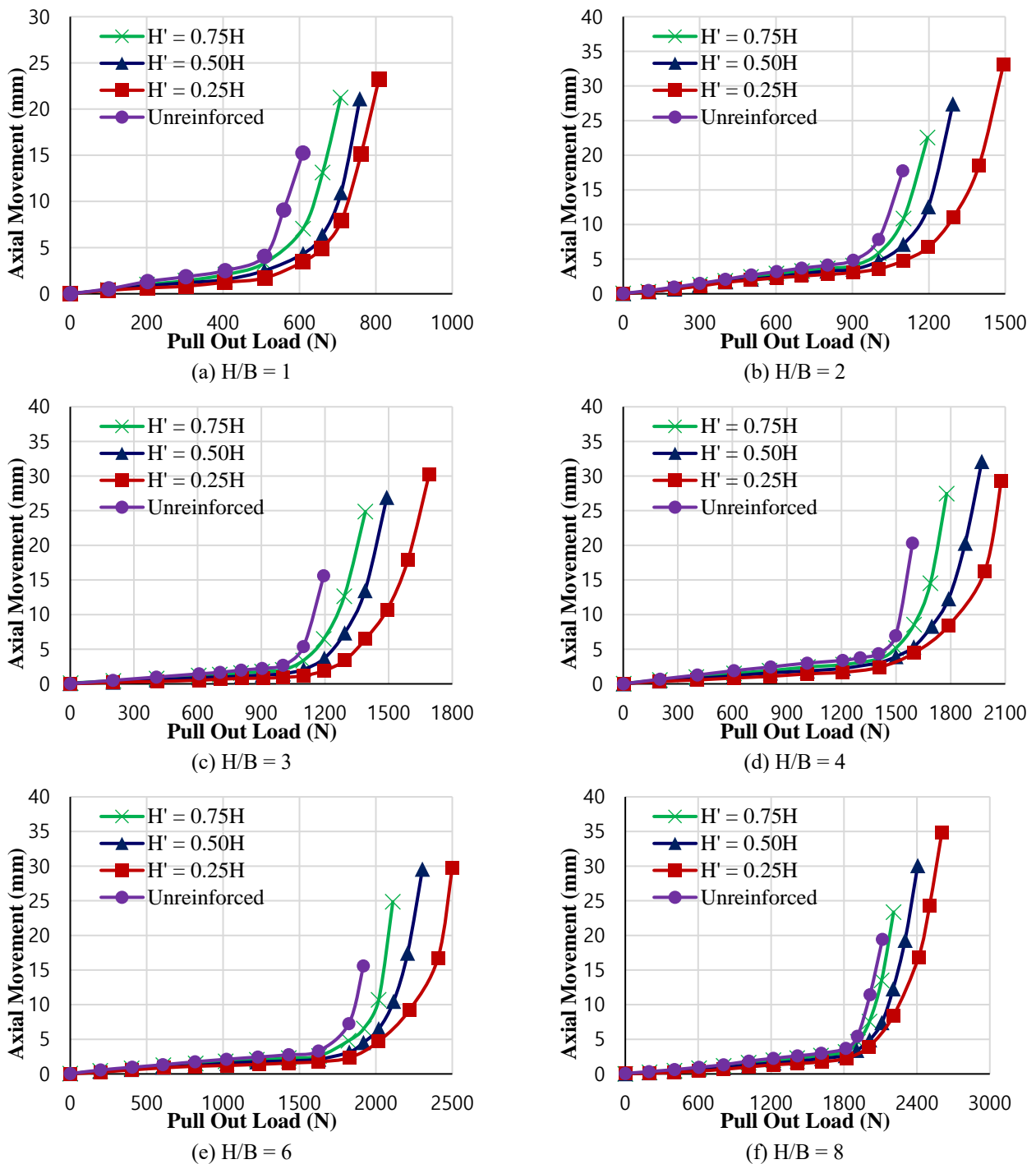


Fig. 6 Axial movement vs load plot for 50×400 plate size with different H/B

upheaval nor the tension cracks were observed. In case of reinforced soil, as shown in Figs. 8(a) to 8(d), similar upheaval of the surface was noticed but unlike in unreinforced soil such upheaval was also observed even beyond H/B value of 4 at an H/B = 6 as shown in Fig. 8(c). However, anchor embedment in reinforced soil beyond H/B value of 6 no upheaval was observed as shown in Fig. 8(d).

In addition to this, for all the tests on anchor for H/B ≤ 4 in reinforced and unreinforced soil as seen from these figures [7a & b & 8a and b] there was no noticeable plastic

flow is observed around the anchor excepting a cavity created by the upward movement of the anchor, extent of which was almost equal to the size of anchor. However, in case of anchor embedded with a H/B > 4 for un-reinforced soil and H/B > 6 for reinforced soil, a noticeable flow of soil around the anchor plate together with cavitations at anchor bottom was observed, as shown in Figs. 7(c) and 8(d), with no upheaval of soil at the surface indicating local failure of the soil around the anchor. Now according to Singh *et al.* (2007), such behavior in plate anchors in soft clay has been

Table 5 Ultimate Pullout Load and Corresponding Displacement for H/B ratio 1, 2 and 3

Plate size (mm)	H/B = 1				H/B = 2				H/B = 3				
	H'/H	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75
50 × 50	P_u, P_{ur} (KN)	0.135	0.210	0.175	0.160	0.230	0.350	0.310	0.270	0.300	0.410	0.350	0.320
	δ_u (mm)	5.5	10.5	9.0	8.0	6.0	12.0	10.0	9.0	6.0	13.0	11.0	10.0
75 × 75	H'/H	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75
	P_u, P_{ur} (KN)	0.295	0.465	0.420	0.350	0.505	0.750	0.690	0.600	0.650	0.910	0.790	0.708
100 × 100	δ_u (mm)	5.0	11.0	10.0	9.5	6.0	11.5	11.0	10.0	6.0	12.0	11.5	9.5
	H'/H	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75
50 × 100	P_u, P_{ur} (KN)	0.550	0.995	0.870	0.785	0.930	1.40	1.36	1.25	1.13	1.59	1.40	1.30
	δ_u (mm)	6.0	11.0	10.0	9.0	6.0	12.0	11.0	9.5	6.5	13	11.5	10.0
50 × 200	H'/H	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75
	P_u, P_{ur} (KN)	0.210	0.330	0.280	0.260	0.400	0.590	0.500	0.460	0.458	0.600	0.540	0.490
50 × 300	δ_u (mm)	5.0	10.0	9.5	8.5	5.5	11.0	1.0	10.0	6.5	12.0	11.0	10.5
	H'/H	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75
50 × 400	P_u, P_{ur} (KN)	0.330	0.485	0.440	0.390	0.620	0.880	0.760	0.700	0.815	1.125	0.970	0.900
	δ_u (mm)	6	10	9	8	6.5	11.0	9.5	9.0	7.0	11.5	10	9.5
50 × 300	H'/H	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75
	P_u, P_{ur} (KN)	0.420	0.580	0.530	0.500	0.820	1.10	0.970	0.920	1.1	1.46	1.35	1.23
50 × 400	δ_u (mm)	5.5	10.5	9.5	9.0	6.5	11.5	10	9.5	7	12	11	10
	H'/H	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75
50 × 400	P_u, P_{ur} (KN)	0.515	0.700	0.660	0.590	0.960	1.3	1.15	1.07	1.10	1.50	1.35	1.25
	δ_u (mm)	5.5	8.0	7.5	7.0	5.5	10.5	9.0	8.0	6	11	10.5	10

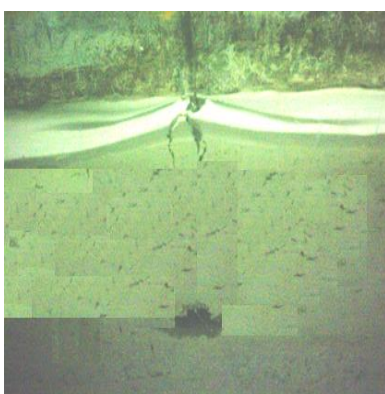
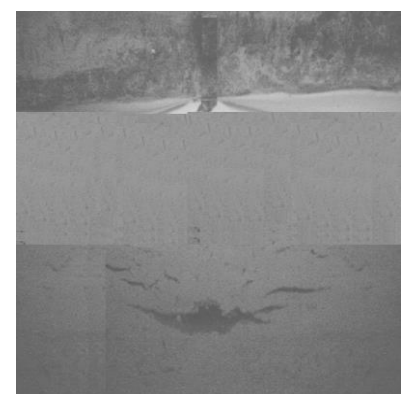
(a) $H/B = 2$ (b) $H/B = 4$ (c) $H/B = 6$

Fig. 7 Soil flow mechanism for 50×50mm anchor plate in unreinforced soil

attributed as deep anchor behavior with local failure of the soil around the anchor. So, all such above behavior exhibits a critical embedment depth below which the anchor behaves as a shallow anchor and beyond that the behavior results that of deep anchor. So compared to unreinforced soil this deep anchor behavior occurs at higher depth of embedment

in reinforced soil due to the inclusion of reinforcement resulting an increase in the effective area of anchorage which changes the failure pattern from local type to general type and failure surface reaches the ground surface. Such behavior was also reported by Krishnaswamy and Parashar (1994) from the experimental study of anchors in reinforced clay.

Table 6 Ultimate Pullout Load and Corresponding Displacement for H/B ratio 4, 6 and 8

Plate size (mm)	H/B = 4					H/B = 6					H/B = 8		
	H'/H	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75
50 × 50	P_u, P_{ur} (KN)	0.330	0.428	0.375	0.350	0.340	0.440	0.395	0.360	0.345	0.450	0.400	0.375
	δ_u (mm)	6.0	13.5	11.5	10.5	7.5	14.0	12.0	11.0	7.5	14.5	12.5	11.5
75 × 75	H'/H	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75
	P_u, P_{ur} (KN)	0.730	0.960	0.825	0.770	0.768	0.975	0.875	0.800	0.785	1.000	0.880	0.845
	δ_u (mm)	6.0	12.5	12	10.5	6.5	13.0	12.5	10.5	7.0	14.0	13.0	11.0
100 × 100	H'/H	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75
	P_u, P_{ur} (KN)	1.30	1.67	1.45	1.35	1.35	1.70	1.55	1.45	1.40	1.72	1.58	1.47
	δ_u (mm)	6.5	13.0	12.0	10.0	6.5	13.5	12.5	11.5	7	14	13	12
50 × 100	H'/H	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75
	P_u, P_{ur} (KN)	0.560	0.750	0.660	0.610	0.585	0.800	0.720	0.670	0.590	0.820	0.755	0.700
	δ_u (mm)	6.5	13.0	12.5	11.0	7.0	13.5	13	11.5	7.0	14.0	13.5	12.0
50 × 200	H'/H	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75
	P_u, P_{ur} (KN)	0.950	1.255	1.15	1.05	1.02	1.42	1.29	1.20	1.05	1.44	1.35	1.25
	δ_u (mm)	7	12.5	10.5	10	7.0	13	11	10	6.0	13.5	11.4	11.0
50 × 300	H'/H	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75
	P_u, P_{ur} (KN)	1.27	1.65	1.52	1.39	1.4	1.82	1.68	1.58	1.48	1.85	1.72	1.65
	δ_u (mm)	7	13	12	10.5	7.5	14.0	13	12.0	7.5	14.5	13.5	12.5
50 × 400	H'/H	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75
	P_u, P_{ur} (KN)	1.5	1.90	1.78	1.65	1.80	2.28	2.10	2.00	1.90	2.32	2.30	2.08
	δ_u (mm)	6.5	11.0	10.5	10.0	7.5	12	11.5	10.5	5.0	12.0	11.5	10.5

4.3 Effect of shape and size of anchor on pullout load

Influence of anchor size on the ultimate pullout load in reinforced and unreinforced soil may be observed from the test results of square anchors (Tables 3 and 4) for varying sizes of 50 mm, 75 mm & 100 mm used in the present investigation. From this table it may be seen that for the same depth of embedment namely 200 mm corresponding to H/B of 4, 3 & 2 for 50 mm, 75 mm & 100 mm wide square anchors respectively, the ultimate pullout load varied significantly and increased with the increase in L/B . Similar observations are also found for other depths of embedment. But a comparison between the pullout loads of square and rectangular anchors shows that square anchor has more unit capacity (obtained by dividing the ultimate pull out capacity by the area of anchor) than the rectangular anchor and is more efficient in carrying pullout load. In other words, the anchors with lower L/B ratio gives higher unit capacity.

The reason for this may be that the percentage contribution of shear resistance from the side wedges formed on both sides decreases in comparison to the total

resistance as stated by Dickin and Leung (1983). The effect of shape of anchor on the uplift load has been shown in Figs. 9(a) to 9(c) for 50 mm anchor in reinforced soil with reinforcement at 0.25, 0.50 & 0.75H above the plate for square, rectangular and strip ($L/B = 8$). In these figures it may be seen that at all embedded depths a substantial increase in uplift load occurred with increasing L/B of the anchor. Similar observations were also reported from the experimental results of Krishnaswamy and Parashar (1994).

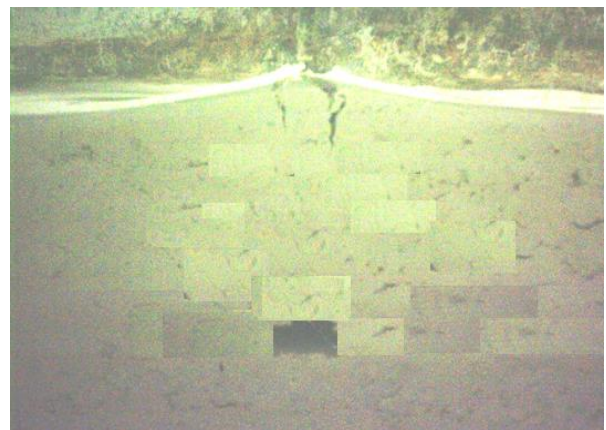
A table (Table 7) has been prepared to quantify the increase in ultimate pullout load when shape changes from square to rectangular with respect to a square anchor of size 50×50 mm for a particular relative depth of reinforcement (H'/H), i.e., 0.25. From the table it is observed that as the shape changes from square to rectangle, there is a substantial increase in ultimate pullout load. With respect to the square anchor of size 50×50, an increase of 55.6% and 281.5% are observed for rectangular anchors of size 5×100 and 50×400, respectively for unreinforced soil with $H/B = 1$. Similar behavior is also observed for the reinforced soil. In case of reinforced soil, an increase of 57.1% and 233.3%

Table 7 Increase in ultimate Pullout load due to shape changes from square to rectangular with respect to anchor plate 50×50

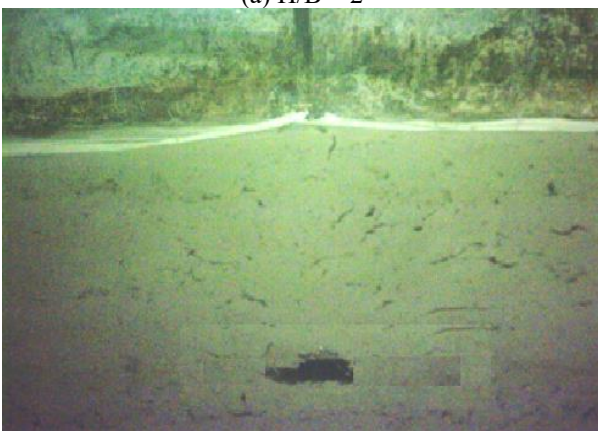
Plate Size	$H'/H = 0.25$											
	Unreinforced						Reinforced					
	H/B						H/B					
	1	2	3	4	6	8	1	2	3	4	6	8
50×100	55.6	73.9	52.7	69.7	72.1	71.0	57.1	68.6	46.3	75.2	81.8	82.2
50×200	144.4	169.6	171.7	187.9	200.0	204.3	131.0	151.4	174.4	193.2	222.7	220.0
50×300	211.1	256.5	266.7	284.8	311.8	329.0	176.2	214.3	256.1	285.5	313.6	311.1
50×400	281.5	317.4	266.7	354.5	429.4	450.7	233.3	271.4	265.9	343.9	418.2	415.6



(a) H/B = 2



(b) H/B = 4



(c) H/B = 6



(d) H/B = 8

Fig. 8 Soil flow mechanism for 50×50mm anchor plate in reinforced soil

are observed for rectangular anchors of size 5×100 and 50×400, respectively with $H/B = 1$. This is so because as the shape changes from square to rectangle larger area of soil gets involved in the failure and contribute to the ultimate pullout load.

4.4 Non-dimensional parameters

4.4.1 Influence of H'/H , H/B and L/B on normalized form of pullout load

Various governing parameters influencing the ultimate pullout load of anchors in reinforced soil have been expressed in the normalized forms: embedment ratio (H/B), relative depth of reinforcement (H'/H), size of plate (L/B),

and relative ultimate displacement (δ_u/B). Their variation with normalized ultimate pullout load ' $\frac{P_{ur}}{\gamma A H}$ ', has been

presented in Figs. 10 to 12. From all these figures, in general, it may be observed that $\frac{P_{ur}}{\gamma A H}$ decreases with the

increase in H/B , H'/H and the δ_u/B . However, among these figures, on close observation of Figs 10(a) to 10(c) it may be seen that such decrease of pullout capacity factor beyond $H/B = 4$ for rectangular anchors with $L/B = 4$ and 6 and strip anchor (for $L/B = 8$) are marginal compared to square anchor ($L/B = 1$) as is revealed by the slope of the

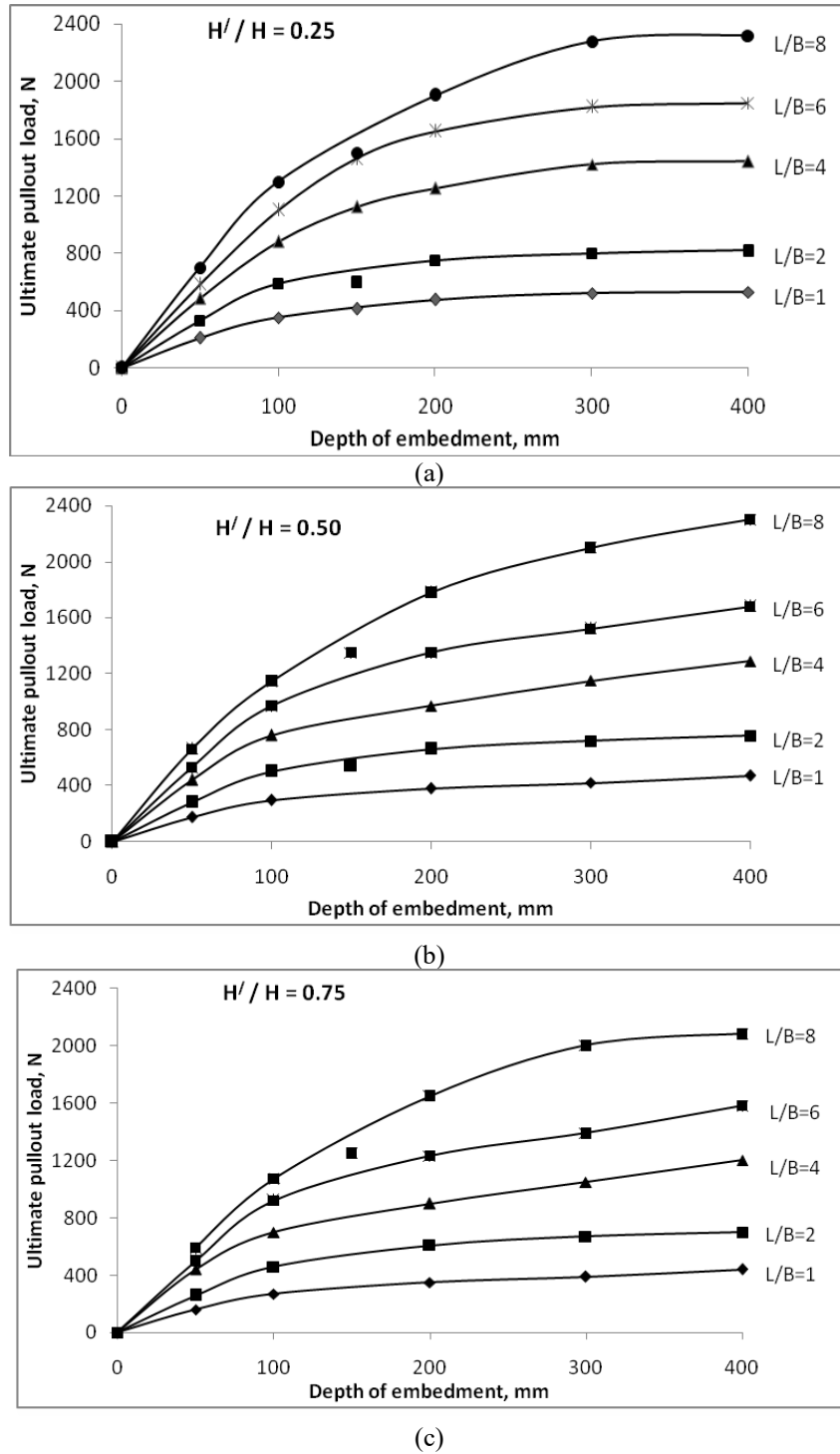


Fig. 9 Ultimate Pullout load vs. depth of embedment for different geometry of 50 mm anchor in reinforced soil (a) $H'/H = 0.25$ (b) $H'/H = 0.5$ and (c) $H'/H = 0.75$

corresponding curves. The effect of size of anchor is quite evident and is quantified with different L/B of plate anchors. The smaller size anchor appears to exhibit higher normalized pullout load at a particular H/B ratio. This observation is in complete agreement with Dickin and Laman (2007) and Tilak and Samadhiya (2021).

Variation of the ultimate pullout load with the failure displacements has been conveniently expressed in non-dimensional ultimate load as pullout capacity factor with

normalized form of displacement as relative failure displacement (δ_u/B) as shown in Fig. 12 for the anchors of different L/B in reinforced soil for H'/H as 0.25. It is found from the Figure 12 that in general with decreasing value of $\frac{P_{ur}}{\gamma AH}$, the relative displacement increases and approaches to a nearly limiting value. Such behavior may be analyzed based on the findings of uplift capacity factor and the

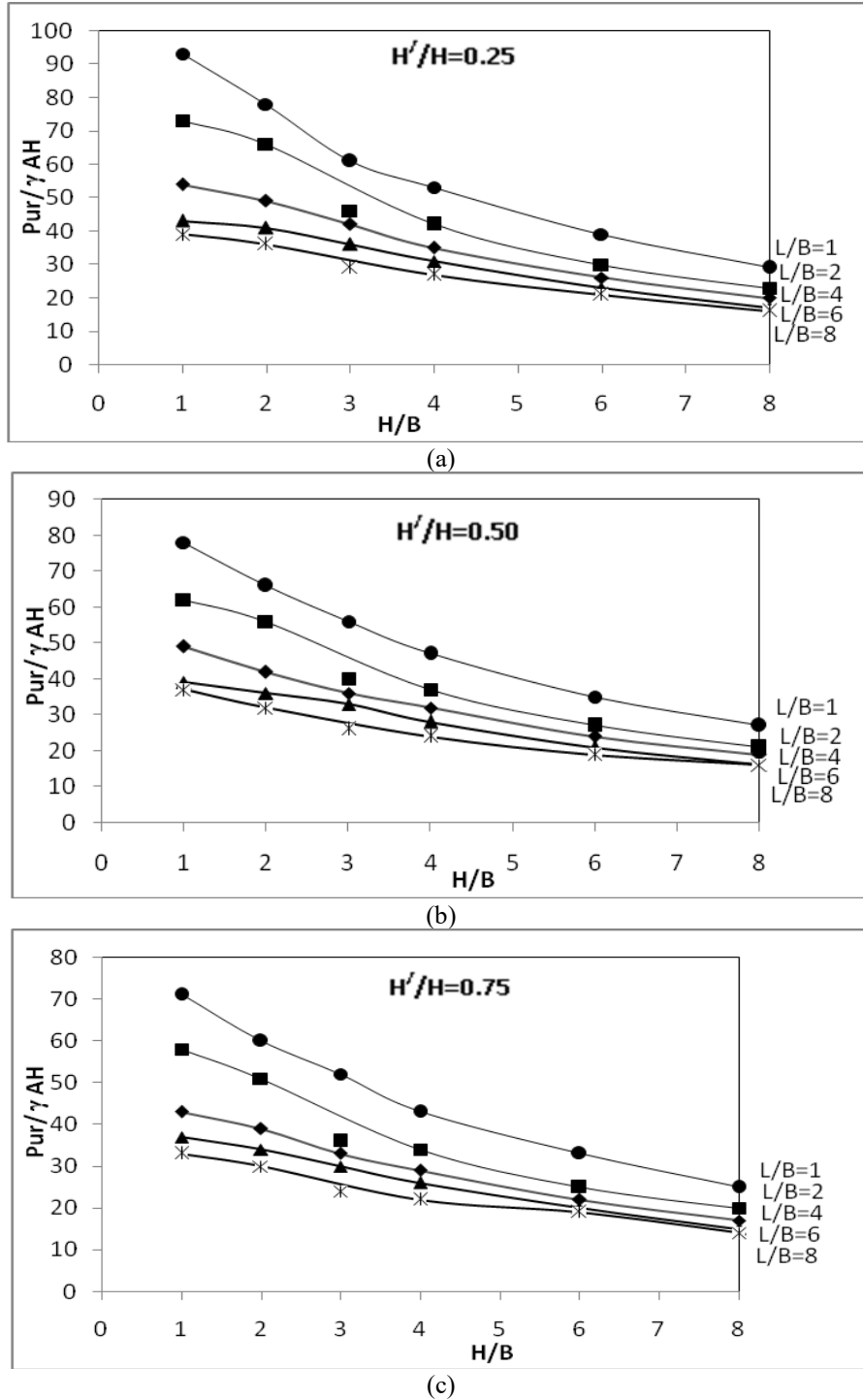


Fig. 10 Variation of normalized pull out load with H/B for (a) $H'/H = 0.25$ (b) $H'/H = 0.5$ and (c) $H'/H = 0.75$

displacement with increasing embedment depth. Previously it has been found that with increasing embedment depth for a particular size of anchor the pullout capacity factor decreases as shown in Fig. 10. But on the other hand, the displacement δ_u increases with H/B because of involvement of more volume of soil and hence the relative displacement δ_u/B increases with H/B for that particular anchor. But this displacement becomes limited at certain depth of embedment which indicates the transition from shallow to deep anchor with localized failure of soil.

4.4.2 Influence of relative displacement $\frac{\delta_u}{B}$ on H'/H and H/B

In order to study the aspect of axial movement at ultimate load of the anchors in reinforced soil, the axial movement with respect to the least size of the anchor have been calculated as $\frac{\delta_u}{B}$ and plotted against H/B for particular position of reinforcement ($H'/H = 0.25$) as shown in Fig. 13. It may be seen from the figure, that the relative displacement increases sharply from $H/B = 1$ to 4 and

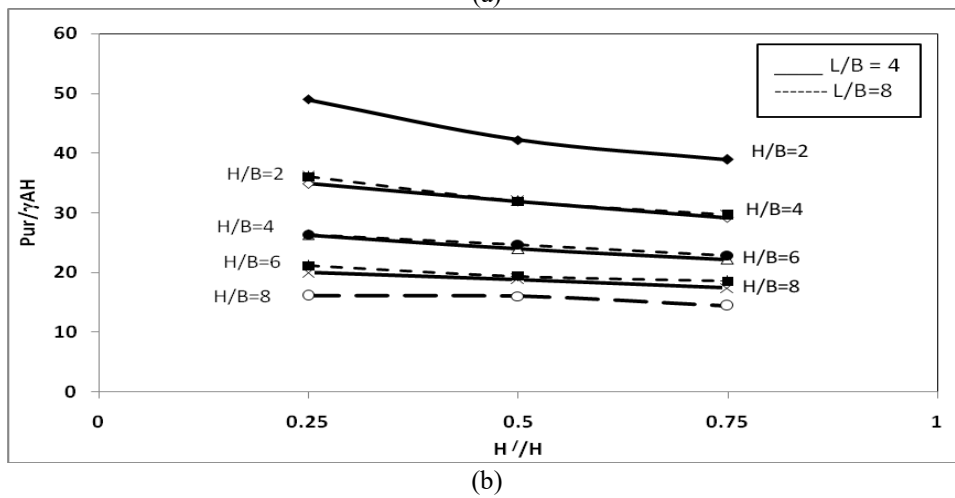
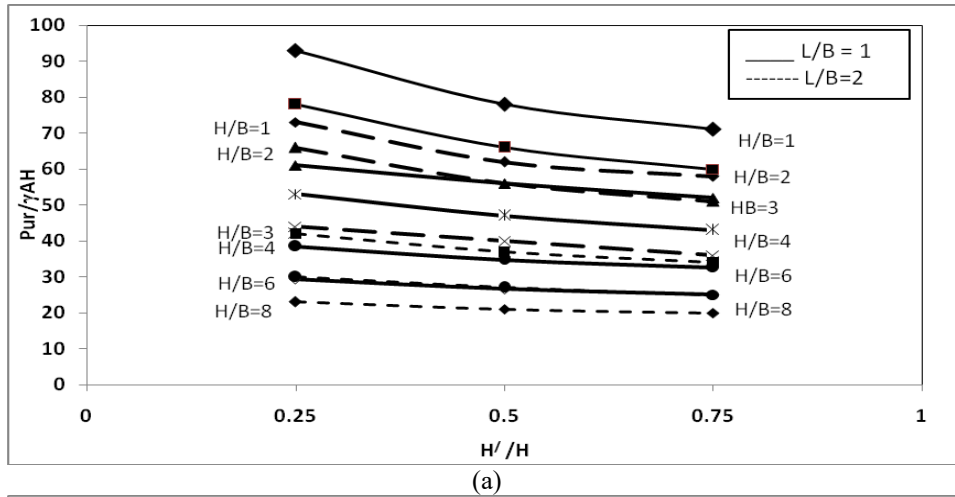


Fig. 11 Variation of pullout capacity factor with H'/H

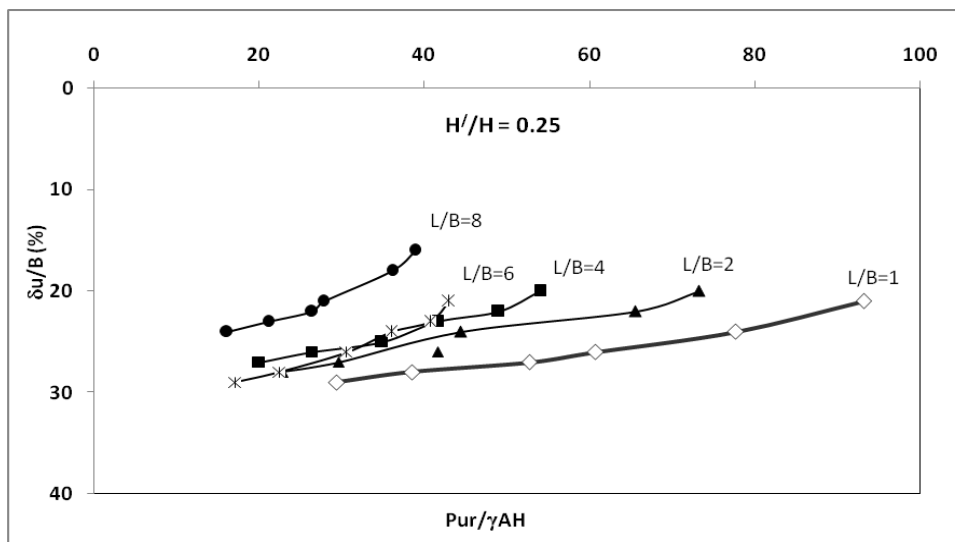


Fig. 12 Variation of δ_u/B with pullout capacity factor

thereafter it becomes almost asymptotic beyond $H/B = 6$. This may be due to the fact that displacement increases up to $H/B \leq 6$ because of shallow anchor behavior within this depth and deep anchor behavior begins at this depth. In addition to this, it is also found from the figure that for a

particular value of H/B , the ultimate displacement is less in case of strip anchor $L/B = 8$ compared to square or rectangular anchor $L/B = 1$ and 2 , $L/B = 2$ and 4 . Such finding is well expected as the soils around the former get subjected to plane-strain conditions, whereas, in the case of

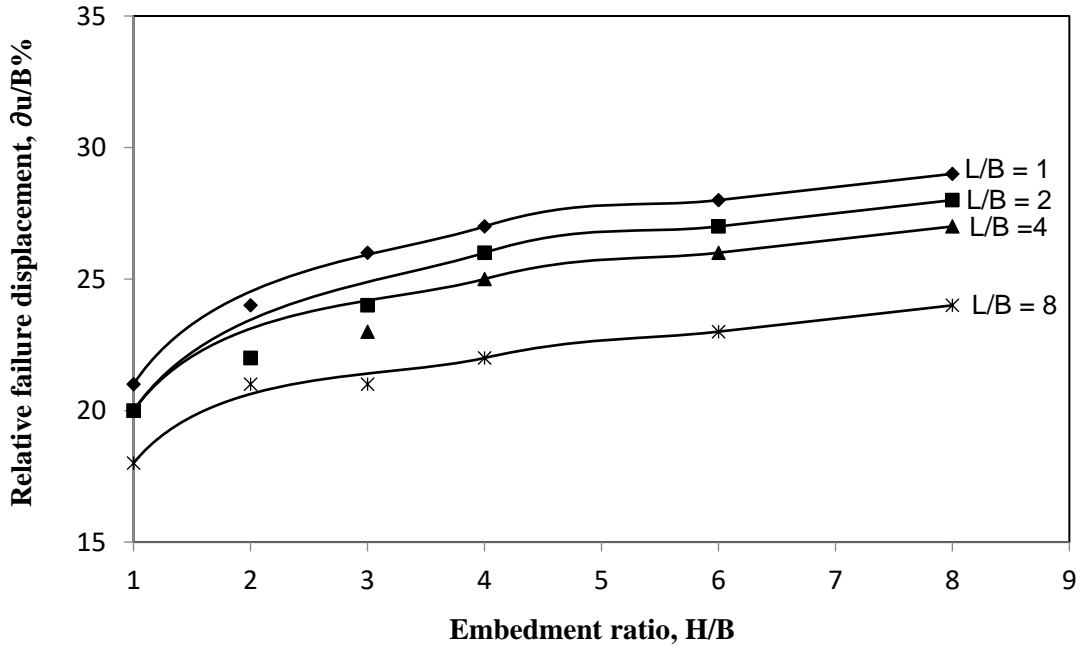
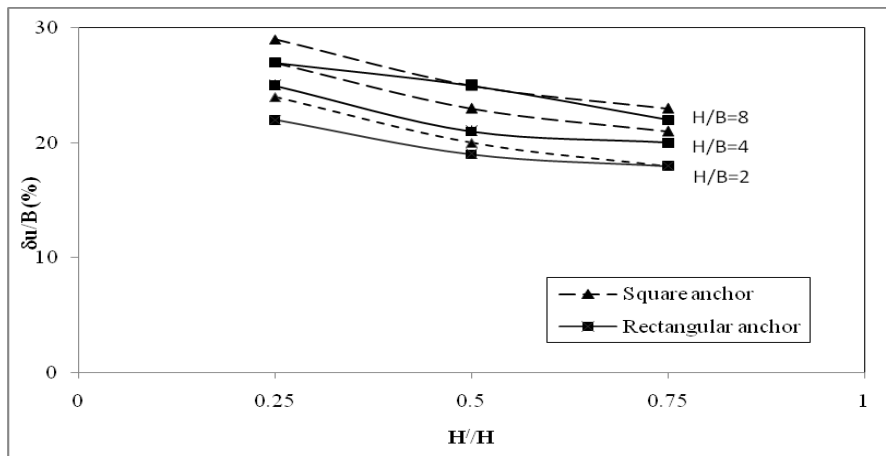
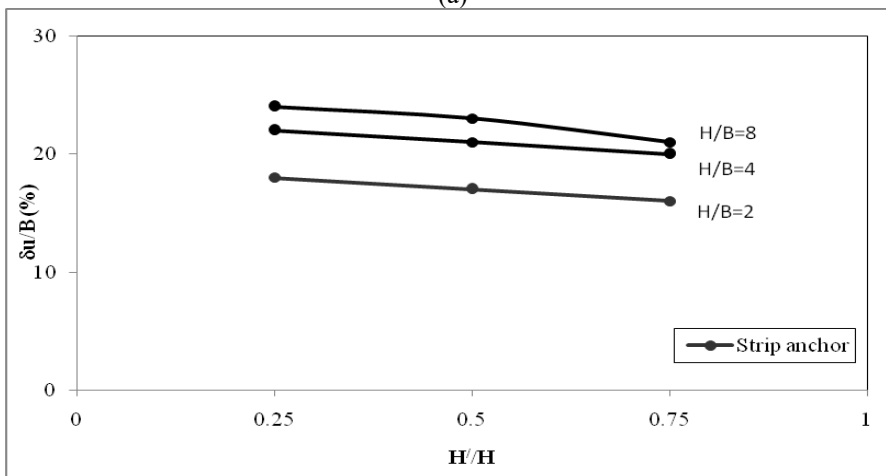


Fig. 13 Variation of ultimate relative displacement with H/B



(a)



(b)

Fig. 14 Variation of ultimate relative displacement with H'/H

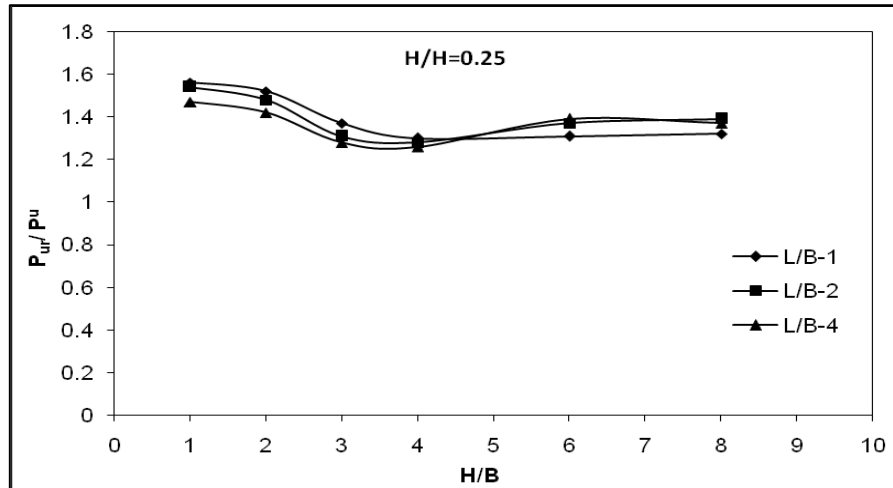


Fig. 15 Pullout improvement factor of anchor for different H/B

Table 8 Break Out Factors of Plate Anchors

Plate Size (mm)		H/B = 1.0			H/B = 2.0			H/B = 3.0					
50 × 50	H'/H	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75
	N _c	3.6	5.6	4.7	4.3	6.1	9.3	8.3	7.2	8.0	10.9	9.1	8.5
75 × 75	H'/H	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75
	N _c	3.5	5.5	5.0	4.1	6.0	8.9	8.2	7.1	7.8	10.8	9.4	8.4
100 × 100	H'/H	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75
	N _c	3.7	5.6	5.1	4.2	6.2	9.3	8.4	7.3	7.6	10.6	9.3	8.7
50 × 100	H'/H	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75
	N _c	2.8	4.4	3.7	3.5	5.3	7.9	6.7	6.1	6.10	9.4	8.0	6.5
50 × 200	H'/H	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75
	N _c	2.2	3.2	2.9	2.6	4.1	5.9	5.1	4.7	5.4	7.5	6.5	6.0
50 × 300	H'/H	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75
	N _c	1.9	2.6	2.4	2.2	3.6	4.9	4.3	4.1	4.9	6.5	6.0	5.5
50 × 400	H'/H	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75
	N _c	1.7	2.3	2.2	2.0	3.2	4.3	3.8	3.6	3.7	5.0	4.5	4.2

later one it is subjected to a conditions quite similar to that of triaxial compression. It has been well established earlier that deformations in plane strain become generally smaller than in triaxial compression (Dickin 1988).

4.5 Break out factor

The ultimate anchor pullout capacity in undrained clay is usually expressed as a function of the undrained shear strength as given by Merifield *et al.* (2003) in the following form.

$$q_u = C_u N_c \tag{1}$$

where $q_u = \frac{Q_u}{A_p}$ in which Q_u is the ultimate pullout load and A_p is area of anchor plate.

Now for a homogeneous soil profile, the breakout factor as given by Merifield *et al.* (2003) is

$$N_c = \left(\frac{q_u}{C_u} \right)_{\gamma \neq 0} = N_{co} + \frac{\gamma H}{C_u} \tag{2}$$

Where γ is the unit wt. of soil, H is the depth of embedment and N_{co} is defined as breakout factor in

weightless soil which is expressed as $\left(\frac{q_u}{C_u} \right)_{\gamma = 0}$.

In the present investigation from model test as the term $\frac{\gamma H}{C_u}$ is very small, the breakout factor has

$$\text{been estimated as } N_c = N_{co} = \frac{q_u}{C_u} \tag{3}$$

Considering the above formulation, the breakout factors for model anchors of different sizes embedded at different depths have been obtained from the ultimate pullout loads for both reinforced and unreinforced soil and the same has been tabulated in Tables 8 and 9.

From the results, it is observed that at a particular H/B , the breakout factor (N_c) decreases with increasing L/B . And it is further observed that with the increase in H'/H , N_c decreases at a particular H/B . The breakout factor for anchors in reinforced cohesive soil increases with H/B and attains an almost constant value at an H/B of 6 and same occurs at H/B approximately equals to 5 in un-reinforced soil. Similar variation of pullout bearing capacity coefficient was reported in previous studies. Feng *et al.*

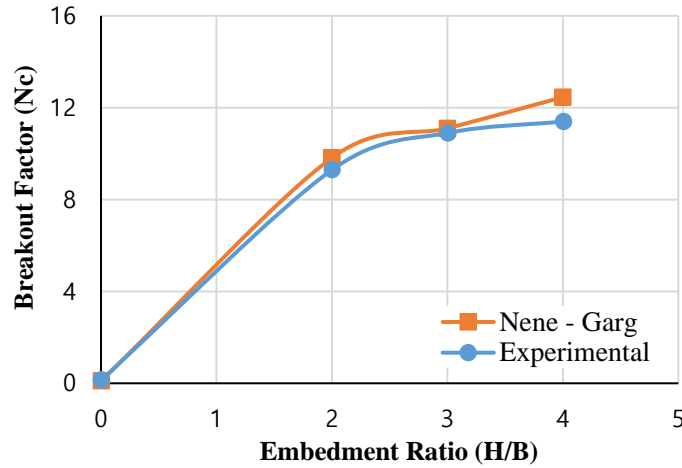


Fig. 16 Comparison of breakout factor with depth of embedment with Nene-Garg (1991)

Table 9 Break Out Factors of Plate Anchors

Plate Size (mm)	H/B = 4.0						H/B = 6.0						H/B = 8.0					
	H'/H	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75	
50 × 50	H'/H	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75	
	N_c	8.8	11.4	10.0	9.4	9.1	11.8	10.5	9.7	9.2	12.0	10.7	10.0					
75 × 75	H'/H	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75					
	N_c	8.7	11.4	9.8	9.1	9.1	11.6	10	9.5	9.3	11.9	10.4	10.0					
100 × 100	H'/H	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75					
	N_c	8.8	11.1	9.7	9.0	9.0	11.5	10.3	9.7	9.2	11.7	10.5	9.8					
50 × 100	H'/H	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75					
	N_c	7.5	10.0	8.8	8.2	7.8	10.7	9.6	8.9	7.9	10.9	10.0	9.3					
50 × 200	H'/H	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75					
	N_c	6.3	8.4	7.7	7.0	6.8	9.5	8.6	8.0	7.0	9.6	9.0	8.3					
50 × 300	H'/H	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75					
	N_c	5.6	7.3	6.8	6.2	6.5	8.1	7.5	7.0	6.6	8.2	7.6	7.3					
50 × 400	H'/H	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75	UR	0.25	0.5	0.75					
	N_c	5.0	6.3	5.9	5.5	6.0	7.6	7.0	6.7	6.3	7.7	7.6	6.9					

(2020) also observed that bearing capacity coefficient becomes stable when H/B crosses a value of 5. The Fig. 16 shows a comparison of breakout factor (P_{ur}/C_u) for anchor size 50 × 50 with a $H'/H = 0.25$. The comparison exhibits an excellent agreement with Nene-Garg (1991).

4.6 Multiple regression model for breakout factor

Based on 126 numbers of experimental data, the following generalized equation for breakout factor has been developed for anchors in reinforced soil from multiple regression analysis

$$N_c = a_0 + a_1 (L/B) + a_2 (H/B) + a_3 (H'/H) \quad (4)$$

in which N_c = Nondimensional breakout factor
 L/B = Aspect ratio of plate anchor
 H/B = Embedment ratio
 H'/H = Relative depth of reinforcement in embedded soil
 a_0, a_1, a_2 and a_3 = Multiple regression coefficients

Table 10 Values of multiple regression coefficients and t-statistics of different parameters of the model (Eq. (4))

Parameters	Coefficients	Standard Error
Intercept	$a_0 = 7.98$	0.3848
Aspect ratio (L/B)	$a_1 = -0.540$	0.04248
Embedment ratio (H/B)	$a_2 = 0.73$	0.04571
Relative depth of reinforcement (H'/H)	$a_3 = -2.6533$	0.53305

Values of multiple regression coefficients (a_0, a_1, a_2 and a_3) and the standard error (E_s) of the above equation have been found out and tabulated in Table 10. Calculated values of multiple coefficients of determination (R^2) and adjusted multiple coefficient (R^2_{adj}) of the above model are 0.8404 & 0.8348 respectively.

The paper studies the pullout behavior of plate anchor in reinforced cohesive soil using extensive laboratory model tests. The effect of different sizes of plate anchors, their embedment and different position of reinforcement on the pullout behavior have been studied. The work can be

extended for inclined anchors with different inclinations and sizes. It would also be interesting to investigate the pullout behavior for layered soil. The type of reinforcement can be varied to obtain the influence of reinforcement type. In this regard, geocell reinforcement can be used to see the effectiveness of such type of reinforcement. The present work considers only single plate anchor for a particular combination, which can be extended to multiple plate anchors in a combination with the above-mentioned other variations.

5. Conclusions

The study examines the behavior of plate anchors in reinforced and unreinforced clay under pullout load extensively. Different sizes of plate anchors, their embedment and different position of reinforcement on the pullout behavior have been studied. From the entire study following conclusions can be drawn:

- Higher pullout load with higher displacement is observed in reinforced soil in comparison with unreinforced soil. The maximum increase due to reinforcement is found to be 56 to 63% for square, 47 to 57% for rectangular and 36% for strip anchor. Maximum pullout load was obtained when the reinforcement was placed at the height of $0.25H$ above the anchor plate. At the failure load, tension cracks associated with upheaval of soil surface and no noticeable plastic flow around the anchor was observed for anchors at $H/B \leq 4$ for unreinforced and $H/B \leq 6$ for reinforced soil. However, in case of $H/B > 4$ for unreinforced soil and $H/B > 6$ for reinforced soil, a noticeable flow of soil around the anchor plate together with cavitations at anchor bottom was observed with no upheaval of soil at the surface indicating local failure of the soil around the anchor.
- Normalized pullout load ($P_{ur}/\gamma AH$) is found to decrease with the increase in H/B , H'/H and the δ_v/B . Relative displacement is observed to increase sharply from $H/B = 1$ to 4 due to shallow anchor behavior and thereafter it becomes almost asymptotic beyond $H/B = 6$ which signify the beginning of deep anchor behavior. Relative displacement decreases with the increase in H'/H due to lesser confinement and such decrease is significant for H'/H from 0.25 to 0.5 in case of square and rectangular anchors whereas for strip anchor the decrease is marginal.
- The improvement ratio is found to decrease with H/B up to 4 and thereafter it further increases up to 6 and does not vary with H/B appreciably beyond $H/B = 6$. The initial decrease is due to the shallow embedment ($H/B < 4$) and the contribution of embedment dominates than the reinforcement. For H/B value 4 to 6 both H/B and reinforcement both are influencing the pullout capacity positively to the increase in the improvement ratio. At $H/B > 6$, improvement ratio becomes constant due to deep anchor behavior and there is no impact of reinforcement.
- For a particular value of H/B , the breakout factor decreases with increasing L/B and also with increasing H'/H . An equation for breakout factor of anchors in reinforced soil has been obtained through regression

analysis of the model test results and tested with theoretical results. All the parameters governing the breakout factor viz. H/B , L/B of anchors and the H'/H are included as predictors in this equation.

References

- Adams, J.I. and Meyerhoff, G.G. (1968), "The uplift capacity of foundations", *Can. Geotech. J.*, **5**(4), 225-244.
- Banerjee, S. and Mahadevuni, N. (2017), "Pull-out behaviour of square anchor plates in reinforced soft clay", *Int. J. Geosynth. Ground Eng.*, **3**(3). <https://doi.org/10.1007/s40891-017-0101-y>.
- Bhattacharya, P. and Kumar, J. (2014a), "Pullout capacity of inclined plate anchors embedded in sand", *Can. Geotech. J.*, **51**(11), 1365-1370. <https://doi.org/10.1139/cgj-2014-0114>
- Bhattacharya, P. and Kumar, J. (2014b), "Vertical pullout capacity of horizontal anchor plates in the presence of seismic and seepage forces", *Geomech. Geoeng.*, **9**(4), 294-302. <https://doi.org/10.1080/17486025.2014.902116>.
- Bhattacharya, P. and Sahoo, S. (2017), "Uplift capacity of horizontal anchor plate embedded near to the cohesionless slope by limit analysis", *Geomech. Eng.*, **13**(4), 701-714. <https://doi.org/10.12989/gae.2017.13.4.701>.
- Biradar, J., Banerjee, S., Shankar, R., Ghosh, P., Mukherjee, S. and Fatahi, B. (2019), "Response of square anchor plates embedded in reinforced soft clay subjected to cyclic loading", *Geomech. Eng.*, **17**(2), 165-173. <https://doi.org/10.12989/gae.2019.17.2.165>.
- Choudhury, D. and Rao, K.S.S. (2004), "Seismic uplift capacity of strip anchors in soil", *Geotech. Geol. Eng.*, **22**(1), 59-72.
- Dash, S.K. and Choudhary, A.K. (2019), "Pullout behavior of geocell-reinforced vertical plate anchors under lateral Loading", *Int. J. Geomech.*, **19**(8), 04019082-1-04019082-13. [https://doi.org/10.1061/\(ASCE\)GM.1943-5622.0001452](https://doi.org/10.1061/(ASCE)GM.1943-5622.0001452).
- Dickin, E.A. (1988), "Uplift behavior of horizontal anchor plates in sand", *J. Geotech. Rng.*, **114**(11), 1300-1317. [https://doi.org/10.1061/\(ASCE\)0733-9410\(1988\)114:11\(1300\)](https://doi.org/10.1061/(ASCE)0733-9410(1988)114:11(1300)).
- Dickin, E.A. and Leung, C.F. (1983), "Centrifuge model tests on vertical anchor plates", *J. Geotech. Eng.*, **109**(12), 1503-1525. [https://doi.org/10.1061/\(ASCE\)0733-9410\(1983\)109:12\(1503\)](https://doi.org/10.1061/(ASCE)0733-9410(1983)109:12(1503)).
- Dickin, E.A. and Laman, M. (2007), "Uplift response of the strip anchors in cohesionless soil", *Adv Eng Softw.*, **38**(8-9), 618-625.
- Feng, T., Zong, J., Jiang, W., Zhang J. and Song, J. (2020), "Ultimate pullout capacity of a square plate anchor in clay with an interbedded stiff layer", *Adv. Civil Eng.*, **2020**, 8867678. <https://doi.org/10.1155/2020/8867678>.
- Ghosh, A. and Bera, A.K. (2010), "Effect of geotextile ties on uplift capacity of anchors embedded in sand", *Geotech. Geol. Eng.*, **28**(5), 567-577. <https://doi.org/10.1007/s10706-010-9313-9>.
- Ilamparuthi, K., Dickin, E.A. and Muthukrisnaiah, K. (2002), "Experimental investigation of the uplift behaviour of circular plate anchors embedded in sand", *Can. Geotech. J.*, **39**, 648-664. <https://doi.org/10.1139/t02-005>.
- Ilamparuthi K., Ravichandran, P.T. and Mohammed Toufeeq, M. (2008), "Study on uplift behaviour of plate anchor in geogrid reinforced sand bed", *Geotech. Earthq. Eng. Soil Dynam. IV Congress, ASCE*, 1-10. [https://doi.org/10.1061/40975\(318\)116](https://doi.org/10.1061/40975(318)116).
- Jadid, R., Abedin, Z., Shahriar, A.R. and Arif, M.Z.U. (2018), "Analytical model for pullout capacity of a vertical concrete anchor block embedded at shallow depth in cohesionless soil", *Int. J. Geo. Mech.*, **18**(7), 1-8. [https://doi.org/10.1061/\(ASCE\)GM.1943-5622.0001212](https://doi.org/10.1061/(ASCE)GM.1943-5622.0001212).
- Jadid, R., Shahriar, A.R., Rahman, M.R. and Imtiaz, T. (2019), "Evaluation of theoretical models to predict the pullout capacity of a vertical anchor embedded in cohesionless soil", *Geotech.*

- Geol. Eng.*, **37**(5), 3567-3586. <https://doi.org/10.1007/s10706-019-00870-9>.
- Kingshri, A., Ilamparuthi, K. and Ravichandran, P.T. (2005), "Enhancement of uplift capacity of anchors with Geocomposite", *Proceeding of the National Symposium on Geotechnical prediction methods (Geopredict 2005)*, IIT Madras, Chennai.
- Krishnaswamy, N.R. and Parashar, S.P. (1994), "Uplift behavior of plate anchors with geosynthetics", *Geotext. Geomembranes*, **13**(2), 67-89. [https://doi.org/10.1016/0266-1144\(94\)90040-X](https://doi.org/10.1016/0266-1144(94)90040-X).
- Kumar, J. (2003), "Uplift resistance of strip and circular anchors in a two layered sand", *Soils Found.*, **43**(1), 101-107. <https://doi.org/10.3208/sandf.43.101>.
- Nene, A.S. and Garg, S. (1991), "Behaviour of shallow plate anchors in reinforced cohesive soils", *Indian Geotech. J.*, **21**(4), 327-336.
- Park, S.H. and Lee, J.K. (2021), "Ultimate uplift resistance of circular plate anchors in undrained two-layer clays", *Geomech. Eng.*, **27**(3), 213-221. <https://doi.org/10.12989/gae.2021.27.3.213>
- Ponniiah, D.A. and Finlay, T.W. (2011), "Cyclic behaviour of plate anchors", *Can. Geotech. J.*, **25**(2), 374-381. <https://doi.org/10.1139/t88-038>.
- Rahimi, M., Leshchinsky, B. and Tafreshi, S.N.M. (2018a), "Assessing the ultimate uplift capacity of plate anchors in geocell-reinforced sand", *Geosynth. Int.*, **25**(6), 612-629. <https://doi.org/10.1680/jgein.18.00029>.
- Rahimi, M., Tafreshi, S.N.M., Leshchinsky, B. and Dawson, A.R. (2018b), "Experimental and numerical investigation of the uplift capacity of plate anchors in geocell-reinforced sand", *Geotext. Geomembranes*, **46**(6), 801-816. <https://doi.org/10.1016/j.geotextmem.2018.07.010>.
- Rowe, R.K. and Davis, E.H. (1982), "The behaviour of anchor plates in sand", *Geotechnique*, **32**(1), 25-41. <https://doi.org/10.1680/geot.1982.32.1.25>.
- Merifield, R.S., Sloan, S.W. and Yu, H.S. (2001), "Stability of plate anchors in undrained clay", *Geotechnique*, **51**(2), 114-153. <https://doi.org/10.1680/geot.2001.51.2.141>.
- Merifield, R.S., Lyamin, A.V., Sloan, S.W. and Yu, H.S. (2003), "Three-dimensional lower bound solutions for stability of plate anchors in clay", *J. Geotech. Geo-environ. Eng.*, **129**(3), 243-253. [https://doi.org/10.1061/\(ASCE\)1090-0241\(2003\)129:3\(243\)](https://doi.org/10.1061/(ASCE)1090-0241(2003)129:3(243)).
- Nene, A.S. and Garg, S. (1991), "Behaviour of plate anchors in reinforced cohesive soils", *Indian Geotech. J.*, **21**(4).
- Ravichandran, P.T., Ilamparuthi, K. and Toufeeq, M.M. (2008), "Study on uplift behavior of plate anchors under monotonic and cyclic loading", *Proceeding of the 12th international conference of IACMAG*, 1-6 October, Goa India.
- Ravishankar, S., Banerjee, S., Sarvesh and Mukherjee, S. (2022), "Static, cyclic, and post-cyclic pullout response of horizontal plate anchors in reinforced soft clay", *Int. J. Geosynth. Ground Eng.*, **3**. <https://doi.org/10.1007/s40891-022-00381-3>
- Saran, S. and Rao, P.P. (2002), "Uplift behaviour of horizontal plate anchors with geosynthetics", *Indian Geotech. J.*, **32**(2), 329-338.
- Shahirar, A.R., Islam, M.S. and Jadid, R. (2020), "Ultimate pullout capacity of vertical anchors in frictional soils", *Int. J. Geo. Mech.*, **20**(2), 1-19. [https://doi.org/10.1061/\(ASCE\)GM.1943-5622.0001576](https://doi.org/10.1061/(ASCE)GM.1943-5622.0001576).
- Shiau, J., Nguyen, T. and Ly-Khuong, D. (2024), "Unraveling seismic uplift behavior of plate anchors in frictional-cohesive soils: A comprehensive analysis through stability factors and machine learning", *Ocean Eng.*, **297**, 116987. <https://doi.org/10.1016/j.oceaneng.2024.116987>.
- Singh S.P., Tripathy, D.K. and Ramaswamy, S.V. (2020), "Estimation of uplift capacity of rapidly loaded plate anchors in soft clay", *Mar. Georesour. Geotec.*, **25**(3-4), 237-249. <https://doi.org/10.1080/10641190701699376>.
- Tilak, V.B. and Samadhiya, N.K. (2021), "Pullout capacity of multi-plate horizontal anchors in sand: an experimental study", *Acta Geotechnica*, **16**, 2851-2875. <https://doi.org/10.1007/s11440-021-01173-1>.
- Tilak, V.B. and Samadhiya, N.K. (2022), "Pullout capacity of circular multi-plate vertical anchors in sand – An experimental study", *Ocean Eng.*, **258**. <https://doi.org/10.1016/j.oceaneng.2022.111779>.
- Yunkul, K., Usluogullari, O.F. and Gurbuz, A. (2021), "Numerical analysis of geocell reinforced square shallow horizontal plate anchor", *Geotech. Geol. Eng.*, **39**(4), 3081-3099. <https://doi.org/10.1007/s10706-021-01679-1>
- Zhou, Z., Conleth, D., White, D.J. and Stainer, S.A. (2020), "Improvements in plate anchor capacity due to cyclic and maintained loads combined with consolidation", *Geotechnique*, **70**(8), 732-749. <https://doi.org/10.1680/jgeot.19.TI.028>.
- Zhuang, P., Yue, H., Song, X., Yang, H., Zhang, H. and Yu, H. (2022), "Pullout behavior of inclined shallow plate anchors in sand", *Can. Geotech. J.*, **59**, 239-253. <https://doi.org/10.1139/cgj-2020-0495>.

IC