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# 1 Experimental and Numerical Investigation of the Uplift Capacity of Plate 2 Anchors in Geocell-Reinforced Sand

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14 **Abstract:** Plate anchors are frequently used to provide resistance against uplift forces. This paper describes the reinforcing  
15 effects of a geocell-reinforced soil layer on uplift behavior of anchor plates. The uplift tests were conducted in a test pit  
16 at near full-scale on anchor plates with widths between 150 and 300 mm with embedment depths of 1.5 to 3 times the  
17 anchor width for both unreinforced and geocell-reinforced backfill. A single geocell layer with pocket size 110 mm×110  
18 mm and height 100 mm, fabricated from non-perforated and nonwoven geotextile, was used. The results show that the peak  
19 and residual uplift capacities of anchor models were highest when the geocell layer over the anchor was used, but with  
20 increasing anchor size and embedment depth, the benefit of the geocell reinforcement decreases. Peak loads between 130%  
21 and 155% of unreinforced conditions were observed when geocell reinforcement was present. Residual loading increased  
22 from 75% to 225% that of the unreinforced scenario. The reinforced anchor system could undergo larger upward  
23 displacements before peak loading occurred. These improvements may be attributed to the geocell reinforcement  
24 distributing stress to a wider area than the unreinforced case during uplift. The breakout factor increases with embedment  
25 depth and decreased with increasing anchor width for both unreinforced and reinforced conditions, the latter yielding larger  
26 breakout factors. Calibrated numerical modelling demonstrated favorable agreement with experimental observations,  
27 providing insight into detailed behavior of the system. For example, surface heave decreased by over 80% when geocell  
28 was present because of a much more efficient stress distribution imparted by the presence of the geocell layer.

29 **Keywords:** *Geosynthetics, Plate anchor, Geocell layer, Uplift load, Upward displacements, Numerical analysis*

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## 1. Introduction

In recent years, geosynthetics have become increasingly common due to their cost-efficiency in reinforcement applications. Geosynthetics are commonly manufactured in planar form (geotextiles, geogrids, geonets, geomembranes, strips), but three-dimensional (3D) reinforcements, such as geocells, are increasingly being adopted for soil reinforcement applications (Koerner, 2012). Geocells have demonstrated particular utility for foundation support, embankment protection, subgrade stabilization and earth retention (e.g. Tanyu et al., 2013; Moghaddas Tafreshi et al., 2013; Hegde and Sitharam, 2015; Biabani et al., 2016) but there is limited research towards assessing the efficacy of geocells towards increasing uplift resistance of earth anchors (e.g. Choudhary and Dash, 2013, Moghaddas Tafreshi et al., 2014). There is promise in such an application, however, as geocells increase soil strength by confinement, reducing lateral displacement and causing the confined composite to act as a stiffer mattress-like composite (Zhang et al., 2010).

Various structures are subject to loading that require the uplift resistance of anchors, including free-standing towers, wind turbines, submerged pipelines, chimneys, suspension bridges, and roofs (Ilamparuthi et al., 2002). In these applications, anchors are commonly embedded within nearby soil to provide stability and transmit tensile forces to a competent medium (Krishnaswamy and Parashar, 1994; Ghosh and Bera, 2010; Rangari et al., 2013). Anchors are the typical means of resisting these loads, commonly found in the form of plate anchors, helical anchors, deadman anchors, pile anchors, and drag anchors (Sabatini et al., 1999). The uplift capacity of a buried anchor typically comprises of the weight of soil within the failure zone as well as frictional and/or cohesive resistance along the realized failure surface. The required uplift capacity of these systems can be enhanced by increasing the size and embedment depth of the anchor or improving backfill strength and density (Choudhury and Subba Rao, 2005; Kumar and Bhoi, 2009; Song et al., 2009; Vishwas and Kumar, 2011; Liu et al., 2012; Wang and O'Loughlin, 2014; Tian et al., 2014; Bhattacharya and Kumar, 2014, 2015; Ganesh and Sahoo, 2016; Khan et al., 2017; Moayedi and Mosallanezhad, 2017; Shin et al., 2016).

Extensive research has been performed to improve assessment of anchor uplift behavior within unreinforced soil, comprising of experimental, analytical and numerical studies. Early research on anchor uplift capacity was performed under 1G conditions in the context of stabilizing transmission towers and was primarily limited to scaled laboratory experiments to demonstrate the effects of shape, embedment, soil conditions and soil types on anchor resistance (Meyerhof and Adams, 1968; Das and Seeley, 1975; Murray and Geddes, 1987; Frydman and Shaham, 1989; Ilamparuthi et al., 2002; Merifield and Sloan, 2006; Sakai and Tanaka, 2007; Song et al., 2008; Kouzer and Kumar, 2009; Khatri and Kumar, 2009; Deskmukh et al., 2010; Horpibulsuk and

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62 [Niramitkorburee, 2010; Honda et al., 2011](#)). To better capture realistic, scaled gravitational conditions,  
63 centrifuge-based laboratory experiments have been employed in assessing uplift capacity ([Dickin, 1988;](#)  
64 [Tagaya et al., 1988; Dickin and Leung, 1990](#)). Theoretical uplift solutions have been developed by using cavity  
65 expansion theory ([Vesic 1971](#)), limit equilibrium theory ([Meyerhof and Adams, 1968, Murray and Geddes,](#)  
66 [1987, Ghaly and Hanna, 1994; Sahoo and Khuntia, 2017](#)), reverse hopper theory ([Lee et al. 2014](#)), and elasto-  
67 plastic continuum analyses ([Rowe and Davis, 1982, Tagaya et al., 1988](#)). However, there is very little research  
68 studying the effect of geosynthetic reinforcement in realizing uplift capacity. Extensive experimental research  
69 has been performed on assessing the mechanism and uplift capacity of plate anchors in dry, cohesionless sand.  
70 [Dickin \(1988\)](#) investigated the uplift behavior of square plate anchors through use of a centrifuge and 1G  
71 experiments, demonstrating that anchor geometry has a notable influence on the breakout factor and failure  
72 mechanism. In consideration of possibly ~~unconservative~~ non-conservative scale effects, [Dickin \(1988\)](#)  
73 proposed an alternative set of breakout factors derived from [Meyerhof and Adams \(1968\)](#) and [Murray and](#)  
74 [Geddes \(1987\)](#) for different plate sizes with similar embedment ratios. The solution demonstrates good  
75 agreement with the experiments, but overestimates the small scale centrifuge results for embedment ratios (i.e.  
76 depth of embedment,  $D$ , divided by anchor width,  $B$ ) exceeding  $D/B > 4$ .

77 Employing large or deeply embedded anchors may not always be economical or practical means of  
78 obtaining the required anchor capacity. An alternative approach is to use smaller and/or less embedded anchors  
79 beneath geosynthetic reinforcements ([Krishnaswamy and Parashar, 1994; Ilamparuthi and Dickin, 2001, Ghosh](#)  
80 [and Bera, 2010; Keskin, 2015](#)). There is some insight into the load-bearing behavior of soil reinforced by  
81 geogrids and geotextiles ([Binquet and Lee, 1975; Yetimoglu et al, 1994; Karpurapu and Bathurst, 1995; Dash](#)  
82 [et al, 2003; Moghaddas Tafreshi and Rahimi, 2012; Tran et al., 2013; Vahedifard et al., 2016; Ouria and](#)  
83 [Mahmoudi, 2018, Dawson and Lee, 1988; Jones et al, 1991](#)). Three-dimensional cellular reinforcement has  
84 also been employed in this way ([Yoon et al., 2008; Leshchinsky and Ling, 2013; Moghaddas Tafreshi et al.,](#)  
85 [2014; Hegde and Sitharam, 2015; Guo et al., 2015; Indraratna et al., 2015; Biabani et al., 2016; Trung Ngo et](#)  
86 [al., 2016; Moghaddas Tafreshi et al., 2016; Oliaei and Kouzegaran, 2017; Song et al., 2017](#)). However, there  
87 is limited research improved anchor uplift capacity from geosynthetics - and that is almost entirely limited to  
88 the use of planar inclusions, such as geotextiles and geogrids, in dry sand. [Krishnaswamy and Parashar \(1994\)](#)  
89 investigated the uplift capacity of small-scale anchor plate embedded in dry sand with and without  
90 geosynthetics, finding that reinforcement can increase uplift capacity significantly. [Ilamparuthi and Dickin](#)  
91 [\(2001\)](#) investigated the behavior of small-scale belled piles embedded in sand, finding increased uplift

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92 resistance when reinforced with geogrids and geocells. Ghosh and Bera (2010) reported the results of  
 93 experimental investigations on the effect of geotextile ties on uplift capacity of anchors embedded in sand.

94 Probably, use of geosynthetics with anchors will only be a practical and economic technique when the soil  
 95 is compacted in layers after the anchor has been placed. Such use is likely to be less suitable when an anchor  
 96 is to be installed in pre-existing soil strata as, otherwise, excavation and replacement of the covering soil would  
 97 then be needed. In these latter circumstances, granular pile anchor foundations (GPAFs) may be used (Kumar  
 98 and Rao (2000); Phani Kumar et al (2004)). These comprise an anchor plate, placed at the bottom of a hole  
 99 that is backfilled with granular soil, connected by cable or rod to foundation above. These GPAFs~~Granular pile~~  
 100 ~~anchors~~ are frequently used in expansive soils to resist the uplift forces mobilized ~~in the foundations~~ due to the  
 101 swelling behaviour of soils. Kumar and Rao (2000) and Rao and Phanikumar (2000) established that the pullout  
 102 capacity of such granular pile anchors ~~isare~~ increased ~~from the presence of base~~ when geosynthetics are used at  
 103 the base, above the anchor plate, mainly owing to increased frictional resistance between the reinforcement  
 104 and the confining medium. ~~kumar~~-Kumar (2016) similarly reported that geogrid reinforcement increases the  
 105 uplift capacity of granular pile-anchor in expansive clay beds. Choudhary and Dash (2013) and Moghaddas  
 106 Tafreshi et al. (2014) studied the effects of geocell reinforcement on enhancing the uplift capacity of anchors  
 107 and belled piles, both demonstrating significant improvement when the reinforcement was present. However,  
 108 there is limited analysis of anchor behavior in geocell-reinforced backfill and extrapolation to geometric  
 109 configurations. Thus, this study expands on prior contributions by introducing the results of a comprehensive  
 110 testing program on near full-scale anchors performed on a laboratory pit in unreinforced- and geocell-  
 111 reinforced backfill.

## 112 2. Experimental Series

113 A series of near full-scale tests (a total of 22 independent tests plus 28 repeated tests) on horizontal square  
 114 plate anchor installed in unreinforced soil and geocell-reinforced soil was performed to:

- 115 a) evaluate the influence of geocell confinement above plate anchors subject to uplift loading,
- 116 b) investigate the influence of embedment depth and plate size on uplift capacity, and
- 117 c) ~~and~~-calibrate numerical analyses that simulate the uplift response of the plate anchor and provide  
 118 insight into internal behavior of both the geocell and backfill.

119 Only one type of geocell, one height ( $h$ ) and pocket size ( $d$ ) of geocell, and one type of soil were used in  
 120 this study. Thus,  $d/B$  and  $h/B$  ratios adopted might not be the optimum values and a change in  $d/B$  and  $h/B$   
 121 might change the results. Other soils might change the benefit and/or the optimum geometrical arrangements.

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122 Nonetheless, the results still inform general trends that may be expected from use of geocell reinforcement in  
123 anchoring applications.

### 124 3. Test Materials

#### 125 3.1. Soil Properties

126 The soil for both backfill and infill used in the experimental series was consistent throughout all of the  
127 physical experiments – well-graded sand (SW in the Unified Soil Classification System, [ASTM D 2487-11](#),  
128  $G_s=2.66$ ). There is a significant quantity of fine gravel (46%) and little fines (<1%), as shown in the grain size  
129 distribution ([Fig. 1](#)). From modified proctor compaction testing ([ASTM D 1557-12](#)), the maximum dry unit  
130 weight of this soil was determined about 20.42 kN/m<sup>3</sup> with an optimum moisture content of approximately  
131 5.1%. The angle of internal friction ( $\phi$ ) of the soil, obtained by consolidated undrained triaxial compression  
132 tests at a wet density of 19.72 kN/m<sup>3</sup> (92% relative compaction with moisture content of 5%, similar to the  
133 compacted density of the backfill soil layers - see [Table 2](#)) of specimens was 40.5°.

#### 134 3.2. Geocell Properties

135 The geocell used in the tests had a pocket size ( $d$ ) and height ( $h$ ) of 110 mm × 110 mm and 100 mm,  
136 respectively. [Fig. 2](#) shows an isometric view of the geocell placed over the bottom soil layer and plate anchor.  
137 The geocell used in testing was fabricated from a type of a non-woven polymeric geotextile that was thermo-  
138 welded to form a ‘non-perforated geocell’. The engineering properties of this geotextile, as listed by the  
139 manufacturer, are presented in [Table 1](#). According to the manufacturer ([Treff, 2011](#)), the tensile strength and  
140 stiffness of the geocell joint is higher than, or similar to, that of the geocell wall material (i.e. geotextile)  
141 preventing seam rupture ([Moghaddas Tafreshi and Dawson, 2012](#)).

### 142 4. Test Pit and Loading System

#### 143 4.1. Test Pit

144 Testing was performed in an vertical indoor test pit, measuring 2200 mm × 2200 mm in plan and 1000 mm  
145 in depth, wherein the soil, anchor, geocell layer and instrumentation (i.e. load cell, LVDT and pressure cells)  
146 was installed (see [Fig. 3](#)). As the width and depth of the test pit were respectively more than seven and three  
147 times bigger than the maximum width of the anchor dimensions ( $B = 150, 225$  and 300 mm), the boundary  
148 effects were not considered significant ([Consoli et al., 2012a; b](#)). During anchor uplift, it was observed that the  
149 surface heave above the anchor was less than three times of the anchor width, corroborating the aforementioned  
150 assumption. [Fig. 3a](#) illustrates a photograph of equipment installation prior to loading. A typical schematic of  
151 the test set-up is shown in [Fig. 3b](#).

#### 152 4.2. Loading and Data Acquisition Systems

153 The loading system (Fig. 3) included a loading frame, hydraulic actuator, and a controlling unit. The frame  
154 consisted of two heavy steel columns fixed into a strong floor and spanning the width of the test pit, supporting  
155 the hydraulic actuator. The hydraulic actuator and control unit may produce monotonic or repeated loading  
156 with the capability of applying a stepwise, controlled load with a maximum capacity of 100 kN. The data  
157 acquisition system recorded uplift load, upward displacement and in-situ soil pressure. A S-shaped load cell  
158 with the accuracy of  $\pm 0.01\%$  for a full-scale capacity of 100 kN was placed between the loading shaft and a  
159 rod attached to the plate anchor (see Fig. 3). A stiff 40 mm diameter rod was employed so that the deflection  
160 measured externally would be sensibly the same as that of the plate anchor. To measure the displacement of  
161 the plate anchor during the loading, a linear variable differential transducer (LVDT) with the accuracy of 0.01%  
162 of full range (100 mm) was attached to the loading shaft and the supporting beam as shown in Fig. 3. Vertical  
163 stress within the backfill was monitored with two soil pressure cells (abbreviated to SPC, 50 mm diameter with  
164 an accuracy of 0.01% of full range of 1000 kPa). The left and right soil pressure cells (abbreviated to "L.SPC"  
165 and "R.SPC", respectively) are located at 40 and 200 mm away from the center of anchor, approximately at a  
166 depth of 100 mm above the anchor (Fig. 3b) for both unreinforced and geocell-reinforced tests. To ensure an  
167 accurate reading, all of the devices were calibrated prior to each test series.

#### 168 4.3. Preparation of Test Pit and Experimental Procedure

169 In order to ensure consistent soil density within the test pit, both unreinforced and geocell-reinforced soils  
170 were compacted with a handheld vibrating plate compactor, 450 mm in width. According to the embedment  
171 depth of anchor, the unreinforced soil layers were prepared and compacted at thicknesses of either 50, 75 or  
172 100 mm with, respectively, one, two or three passes of compactor to achieve the required density (i.e. dry unit  
173 weight of  $\approx 18.76 \text{ kN/m}^3$  in Table 2). To achieve the required density of soil in the pockets of the geocell layer  
174 (shown in Table 2), it was compacted with four passes of compactor. This amount of compactive effort was  
175 maintained throughout all tests. The depth of influence of the compactor is specified as 50-100 mm, diffusing  
176 any added compaction in deeper layers. Sand cone tests (ASTM D1556-07) were conducted to measure the  
177 densities of compacted soil and geocell infill, ensuring compliance to a relative compaction levels that remained  
178 within 91-93% (average moisture content between 4.8% and 5.2%). Table 2 shows the average measured dry  
179 unit weights of unreinforced soil and geocell infill after compaction of each layers. The anchor plate, with the  
180 rod of desired length attached, was placed in the center of the test pit on the compacted soil layer surface after  
181 the first 100mm of soil was placed. Thereafter, the geocell reinforcement panel was extended above the anchor.

182 The cell pockets were filled with backfill soil to include about 10 mm thickness of extra soil over the geocell,  
183 after which compaction of infilled was continued until appropriate density was achieved. Thereafter, two soil  
184 pressure cells were installed (see Fig. 3b) and the load cell was connected between the actuator and plate anchor  
185 along with an LVDT. When the system was ready for testing, tensile uplift loading was applied monotonically  
186 at an equivalent pressure increase of 1.5 kPa per second while upward displacement, uplift force and soil  
187 pressure were monitored and recorded using LVDT, load cell and soil pressure cells (“L.SPC” and “R.SPC”),  
188 respectively. Testing was stopped when failure (a peak load) was observed. In the absence of a distinct failure  
189 peak, the uplift was stopped at an upward displacement of 20 mm.

## 190 5. Testing Program

191 The geometry of the test configurations for the anchor plate embedded in unreinforced and geocell-  
192 reinforced backfill is as shown in Fig. 3b. Three sizes of steel anchor plates (B=150, 225, 300 mm, 25.4 mm  
193 in thickness) with four embedment depth ratios (D/B=1.5, 2, 2.5, 3) in both unreinforced and geocell-reinforced  
194 backfill were examined under static loads (Table 3). Choudhary and Dash (2013) discussed that geocell width  
195 may influence the performance of plate anchors, observing decreasing gains in improvement of uplift carrying  
196 capacity when geocell width increasing beyond 2 times the anchor width ( $b=2B$ ). Thus, to achieve the  
197 maximum performance of geocell reinforcement, the width of the geocell layer (dimension b) was selected to  
198 be approximately three times the plate width ( $b/B\approx 3$ )—i.e. with the geocell widths of about 450 mm, 675 mm  
199 and 900 mm, respectively for anchor widths of 150 mm, 225 mm and 300 mm. The thickness of the geocell  
200 layer above the anchor plate was held constant in all the tests at 100 mm. Several replicate tests were performed  
201 for each configuration for so as to give confidence in the experimental results and anchor behavior. Anchor  
202 capacities determined for a given test configuration never demonstrated more than 8% difference indicating  
203 that the test results were, effectively, repeatable-reliable.

## 204 6. Experimental results

205 In this section, the results of the uplift tests are presented along with a discussion highlighting the effects  
206 of the anchor embedment depth, anchor width, and geocell reinforcement on uplift capacity and the pressure  
207 above the anchor.

### 208 6.1. Behavior of Unreinforced and Reinforced Beds

209 The monotonic uplift load-displacement relationship of unreinforced and geocell-reinforced systems are  
210 shown in Fig. 4. For all unreinforced anchor systems, the general trend of uplift load with displacement is  
211 consistent although there are key differences between the reinforced and unreinforced system's responses.

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212 When unreinforced, a distinct peak uplift load was observed at an outward displacement equal to 2-6 mm, and  
 213 thereafter there is a significant reduction until a sustained residual load is reached. In contrast, the geocell-  
 214 reinforced system demonstrates sustained uplift resistance after a peak load occurring at displacements between  
 215 5-11 mm. No clear post-peak reduction in load capacity is observed for these cases. At a given imposed load  
 216 level, the anchor embedded in a geocell-reinforced soil had a smaller outward displacement than the anchor  
 217 embedded in the equivalent unreinforced bed. Soil reinforced with geocell had a higher initial stiffness and  
 218 strength and ductility than an untreated system. Fig. 4 also shows that both the peak and the residual uplift load  
 219 increased with anchor width and embedment depth for both unreinforced and reinforced conditions. Peak  
 220 reinforcement loads are about 40% higher than the equivalent unreinforced peak loads.

221 In general, the uplift load-displacement response of unreinforced and reinforced systems are shown in Fig.  
 222 5. A three-stage behaviour illustrated in Fig. 5a, is observed in uplift tests on unreinforced system. They are:

223 *Stage 1) Pre-peak behaviour:* the uplift load rises rapidly with the displacement towards a peak value ( $P_{peak}$ ).

224 *Stage 2) Post-peak behaviour:* rapid reduction in the pullout load occurs as displacement occurs.

225 *Stage 3) Residual behaviour:* final, unchanging residual/sustained uplift load ( $P_{res.}$ ) at large displacements. For  
 226 the unreinforced response, a significant difference between peak and residual upward displacement is evident.

227 For the geocell-reinforced system, two-stage behaviour is mostly observed as shown in Fig. 5b. The  
 228 observed stages are:

229 *Stage 1) Pre-peak behaviour:* a rapid increase in uplift load with the displacement.

230 *Stage 2) Post-peak behaviour:* insignificant reduction from peak load ( $P_{peak}$ ) to a residual load ( $P_{res.}$ ) which  
 231 remains close to the peak uplift load.

232 The three-phase behaviour of unreinforced system is similar to the load-deflection behavior of dense bed  
 233 sand where material dilation under shear means that significant energy and displacement is needed to rearrange  
 234 particles into a fabric that can shear, after which much less energy is needed to continue the shearing. Hence  
 235 the residual strength is considerably less than the peak value. It is also similar to the response seen (in  
 236 compression) beneath shallow foundations undergoing 'general' failure, as defined by Vesic (1963). The low  
 237 confinement allows dilation to take place so that, once peak bearing capacity is reached, subsequent deflection  
 238 requires less load. (or shallow anchors) whereas

239 In contrast, the two-phase behavior of reinforced system is similar to the behavior of a medium dense sand  
 240 bed where the fabric allows peak strength to be reached without dilation (so there is no post-peak load reduction

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241 as deformation continues), or in contained punching failure (Vesic, 1963) where the surrounding stress prevents  
 242 dilation (or deep anchors).

243 This it appears that, at least in the arrangements tested here, the reinforced systems prevented dilation  
 244 around the anchor and, thus, lead to a response without a post-peak load capacity reduction. The geocell layer  
 245 thus performs a potentially critical role in providing a more reliable load capacity should large deflections  
 246 occur.

## 247 6.2. Uplift Capacity and Upward Displacement of Anchor

248 The variation of peak and residual uplift loads of anchors as a function of embedment depth are presented  
 249 in Figs. 6a and 6b for unreinforced and reinforced systems respectively. Both peak and residual uplift loads of  
 250 unreinforced and reinforced beds increase approximately linearly with anchor embedment depth. For instance,  
 251 an anchor width of 300 mm in reinforced soil showed peak uplift loads for embedment depth of 1.5, 2, 2.5 and  
 252 3.0 of 8.88, 14.57, 20.54 and 25.74 kN, respectively. For these tests, the corresponding uplift displacements  
 253 were found to be about 5-11 mm (Fig. 4c and Table 4).

254 This figure also demonstrates that for the larger widths (B=225 and 300 mm) of anchor, the variation of  
 255 both the peak and residual uplift loads with embedment depth is significant where it is not insignificant for  
 256 the smallest width (B=150 mm) of anchor. It may be noted that small-scale models may not always give reliable  
 257 assessments but, more significantly, that if large-scale models or full-size plate anchors are allowed to be  
 258 displaced they can generate significant load capacities – especially if the latter is covered in a geocell-reinforced  
 259 soil layer. Fig. 6 also shows that the values of both peak and residual uplift loads increase with anchor width,  
 260 irrespective of embedment depth (ratio of D/B). The rate of increase in peak uplift capacity with anchor width  
 261 between 225 and 300 mm was about 1.75 times that for anchor widths between 150 and 225 mm.

262 For the purpose of this paper, the improvement in peak and residual uplift loads due to the presence of  
 263 geocell reinforcement are represented using two non-dimensional improvement factors:

- 264 (1) Improvement in peak uplift load of anchor ( $IF_{peak}$ ) which compares the peak uplift load of the geocell-  
 265 reinforced system to that of the unreinforced system, defined as:

$$IF_{peak} = \frac{(P_{peak})_{rein.}}{(P_{peak})_{unrein.}} \quad (1)$$

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(2) Improvement in residual uplift load of anchor ( $IF_{res.}$ ) of the geocell-reinforced system to that of the unreinforced system, defined as:

$$IF_{res.} = \frac{(P_{res.})_{rein.}}{(P_{res.})_{unrein.}} \quad (2)$$

where  $(P_{peak})_{rein.}$  and  $(P_{peak})_{unrein.}$  are the values of peak uplift load of the geocell-reinforced and unreinforced systems, respectively and  $(P_{res.})_{rein.}$  and  $(P_{res.})_{unrein.}$  are the values of residual uplift load of the geocell-reinforced and unreinforced systems corresponding to 20 mm of upward displacement of anchor, respectively. It should be noted that, if the anchor embedded in unreinforced or geocell-reinforced system reaches its residual uplift capacity at a displacement larger than 20 mm (not shown in Fig. 4), the residual uplift capacity at 20 mm upward displacement was taken as the residual value.

Together, Figs. 4 and Figs. 6 show that geocell reinforcement exhibits increased load capacity at all embedments, all displacements and all anchor widths when compared to the corresponding unreinforced geometry. The variation of value of the improvement factors ( $IF_{peak}$  and  $IF_{res.}$ ) are shown for varying anchor embedments and widths in Fig. 7a. Generally, the improvement in residual uplift load ( $IF_{res.}$ ) - i.e. the reinforcing efficacy - decreases with increase in the embedment depth and anchor width. Moreover, the results show that despite a significant decrease in  $IF_{res.}$  with increase in embedment depth and anchor width; however, the variation of  $IF_{peak}$  between tests is not significant. It can be also seen that  $IF_{res.}$  values are larger than the values of  $IF_{peak}$ , irrespective of the embedment depth and anchor width. Hence, beneficial effect of geocell is more pronounced when the design of anchor plate is based on the residual uplift capacity of anchor.

Fig. 7b depicts the variation of  $P_{res.}/P_{peak}$  with embedment depth of anchor (D/B) for different anchor widths. It shows that the use of geocell reinforcement leads to stabilizing post-peak behavior with a maximum reduction of less than 10% from the peak load to a residual load ( $P_{res.}/P_{peak} > 90\%$ ), whereas unreinforced installations demonstrate more than a 45-55% reduction from peak load to the residual for anchor widths of 150 and 225 mm and about 20-40% for an anchor widths of 300 mm. The differences in IF values and in  $P_{res.}/P_{peak}$  (Fig. 7b) ratios for reinforced conditions are attributable to the geocell layer preventing narrower, localized shear failure within the overburden soil. Generally, geocell reinforcement provide a stronger, more ductile anchoring system than unreinforced plate anchors. This behavior is attributable to wider mobilization of soil shear strength and overburden as well as added tensile resistance of the geocell mattress. The slab-like behavior of the geocell provides higher residual uplift resistance. Similar observations have been made for uplift resistance of reinforced, small scale belled piles (Ilamparuthi and Dickin 2001 and Moghaddas Tafreshi et al. 2014).

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295 **Table 4** shows the upward displacement at peak uplift resistance (abbreviated to  $u_{peak}$ ) for both unreinforced  
 296 and reinforced systems. For a given embedment depth and anchor width of,  $u_{peak}$  is greater in the reinforced  
 297 system compared to that in unreinforced system. However, it should be noted that use of geocell reinforcement  
 298 provides significantly larger resistance than the unreinforced case at moderately small displacements (i.e. 1-  
 299 5mm). Generally, the unreinforced and reinforced systems provided a similar load-displacement response at  
 300 small displacements (i.e. 0-2 mm) as geosynthetic reinforcement requires strain or displacement to mobilize  
 301 resistance. The results in **Table 4** also reveal that for both unreinforced and geocell-reinforced systems,  $u_{peak}$   
 302 increases with embedment depth and anchor width, attributable to increased overburden resistance. To make  
 303 direct comparisons of the upward displacement of anchors in reinforced and unreinforced systems, a non-  
 304 dimensional parameter of  $(Iu)_{peak}$  is defined as:

$$(Iu)_{peak} = \frac{(u_{peak})_{rein.}}{(u_{peak})_{unrein.}} \quad (3)$$

305 where  $(u_{peak})_{rein.}$  is the displacement corresponding to the peak uplift load in the reinforced system, and  
 306  $(u_{peak})_{unrein.}$  that of the unreinforced systems.  $(Iu)_{peak}$  decreases with increase in the embedment depth of anchor  
 307 for all anchor widths (e.g. from 2.79 to 1.98 as embedment depth increases from 1B to 3B for the 225 mm wide  
 308 anchor, **Table 4**).  $(Iu)_{peak}$  also decreases with increasing anchor width for all the embedments (e.g. from 4.03  
 309 to 1.56 as anchor width increases from 150 mm to 300 mm, for the 2.5B embedment). This may be attributable  
 310 to the load dispersion geometry occurring due to shear transfer in the geocell system. This would suggest that  
 311 geocell reinforcement would be most efficient when placed perpendicular and nearby to the reinforcement  
 312 layer. That is, reinforcement is most effective when a concentrated loading occurs close to a geosynthetic  
 313 system as it provides maximum interaction, ~~greater-provides~~ localized ~~resistance to~~ shear displacements; and  
 314 increased load ~~dispersion-spreading~~ – an observation made for reinforced foundation systems (Binquet and Lee,  
 315 1975; Dawson and Lee, 1988; Yetimoglu et al, 1994; Karpurapu and Bathurst, 1995; Dash et al, 2003;  
 316 Moghaddas Tafreshi and Dawson, 2012; Thakur et al., 2012; Tran et al., 2013; Moghaddas Tafreshi et al.,  
 317 2013). Similarly, mobilization of reinforcement loading tends to be restricted to only part of a flexible  
 318 geosynthetic system; hence, the extent of the reinforcement geometry should be considered in design.

### 319 6.3. Breakout Factors

320 The *breakout factor* ( $N_q$ ) is commonly used to define uplift capacity (Bowles, 1996; Goel et al., 2006).  
 321 The breakout factor is defined from the results of tests, in a dimensionless form as:

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$$N_q = \frac{P_{peak}}{W} = \frac{P_{peak}}{\gamma AD} \quad (4)$$

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Where  $N_q$  is anchor breakout factor,  $P_{peak}$  is the anchor ultimate uplift capacity,  $W$  is the soil weight above the anchor,  $\gamma$  is the unit weight of soil,  $D$  is the embedment depth of the anchor and  $A$  is the anchor area which in this paper defines as  $B^2$  for a square anchor. Fig. 8 shows breakout factors as a function of embedment depth and anchor width of anchor for both unreinforced and geocell-reinforced systems. This figure shows that the breakout factor increases with embedment depth and decreases with increase in the width of anchor, whether unreinforced or reinforced, agreeing with the findings of Ravichandran et al. (2008). For all embedment depths and widths of anchor, the geocell-reinforced system delivers a larger breakout factor than unreinforced conditions.

#### 6.4. Soil Pressures over the Anchor

In order to demonstrate how geocell reinforcement distributes uplift pressures, the variation of measured stress with upward displacement of anchor is plotted in Fig. 9 for an anchor width of 300 mm and an embedment depth of 2.5 and 3 ( $D/B=2.5$  and 3) for both unreinforced and geocell-reinforced systems. The stress plotted is that inside the soil medium at a point 100 mm above the anchor plate, 40 and 200 mm away from the center of anchor (i.e. at the location of the pressure cells “L.SPC” and “R.SPC”) demonstrated in Fig. 9. The pressure readings demonstrate that vertical pressure increases with upward anchor displacement. The pressure measured by the left soil pressure cell (“L.SPC”), 40 mm away from the center of anchor, shows a greater pressure increase compared to that of the right pressure cell anchor (“R.SPC”), 200 mm away from the center of anchor. The ratio of the measured maximum pressure by “R.SPC” to that measured by “L.SPC” is about 0.6-0.7 for both unreinforced and geocell-reinforced system, irrespective of embedment depth. The pressure measured 100 mm above the anchor plate is significantly less in the geocell-reinforced system than in the unreinforced system. For example, for the anchor embedded at a depth of 3B, the maximum pressure recorded by “L.SPC”, is 182.4 and 134.4 kPa and by “R.SPC” is 106.4 and 95.2 kPa, for unreinforced and the geocell-reinforced system respectively – reductions of 26% and 10.5%, respectively.

To more clearly demonstrate the effect of geocell reinforcement on uplift pressure dispersion, the soil pressures measured by “L.SPC” and “R.SPC”, corresponding to the peak load obtained in the unreinforced system for the anchor width of 300 mm, are shown in Table 5. The maximum uplift pressure in Table 5 was calculated by dividing the maximum uplift load by the area of the anchor plate. To evaluate the ratio,  $P$ , of soil pressure in the reinforced system to that in the unreinforced system, two specific ratios are introduced:

$$P_L = \frac{(L.SPC)_{rein.}}{(L.SPC)_{unrein.}} \quad (5)$$

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$$P_R = \frac{(R.SPC)_{rein.}}{(R.SPC)_{unrein.}} \quad (6)$$

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350 In which  $(L.SPC)_{rein.}$  and  $(L.SPC)_{unrein.}$  are the pressures measured in the reinforced and unreinforced  
 351 systems, respectively, by the left pressure cells (Eq. 5); while Eq. 6 takes the same approach for the right  
 352 pressure cell readings. In all cases the values of soil pressure are those measured when the anchor force equals  
 353 the maximum obtained in the corresponding unreinforced installation. In this way,  $P_L$  and  $P_R$  values less than  
 354 unity (as given in [Table 5](#)) indirectly show how the same anchor force must act over a larger area of soil when  
 355 geocell reinforcement is present – delivering a stress reduction of between 25% and 41%. This implies a wider  
 356 tributary area of overburden soil mobilized for uplift resistance. In order to assess these tributary areas, a simple  
 357 analysis that defined average pressures above the anchor plate ( $\sigma_{un.}$  and  $\sigma_{re.}$  for unreinforced and reinforced  
 358 soil, respectively) was used, defined as:

$$\sigma_{re.} = \sigma_{max} \times \frac{B^2}{B_{re.}^2} \quad \& \quad \sigma_{un.} = \sigma_{max} \times \frac{B^2}{B_{un.}^2} \quad (7)$$

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359 Where  $\sigma_{max} = (P_{peak})_{un}/B^2$  and  $B_{re.}$  and  $B_{un.}$  are the dimension of back-calculated reinforced and unreinforced  
 360 tributary area 100 mm above the anchor, defined by a relationship between the dispersion angle,  $\alpha_{re}$  and  $\alpha_{un}$ :

$$B_{re.} = B + 2h \tan \alpha_{re.} \quad \& \quad B_{un.} = B + 2h \tan \alpha_{un.} \quad (8)$$

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361 Where the parameter  $h$  is the height of geocell layer (100 mm in this case). According to the soil pressure  
 362 results given in [Table 5](#) for anchor width of 300 mm and Eq. (7), the average value of  $B_{un.}$  and  $B_{re.}$  for  
 363 unreinforced and reinforced systems can be calculated as, respectively, about 370 mm and 460 mm. Hence, the  
 364 mean value of pressure distribution angle,  $\alpha_{un.}$  and  $\alpha_{re.}$  for unreinforced and reinforced systems respectively,  
 365 was calculated using Eq. (8) as about 19.3 and 24.7 degrees, respectively. This demonstrates enhanced stress  
 366 dispersion provided by geocell reinforcement. These results do not directly reveal the mechanism by which  
 367 this more effective load-distribution is achieved but it may be inferred that the cellular structure confines cell  
 368 infill and mobilizes greater soil area ([Thakur et al., 2012](#); [Moghaddas Tafreshi et al. 2014](#)). Other authors have  
 369 also attributed this to improved anchorage ([Thakur et al., 2012](#); [Tavakoli et al., 2012](#)) so that frictional,  
 370 “blanketing” effect is achieved by the geocell-soil reinforced layer. Numerical modeling provides better insight  
 371 into these internal mechanisms that are difficult to observe in physical experiments.

## 372 7. Numerical Analysis

373 Numerical studies serve as a cost-effective means of building upon experimental results without the added  
374 expense and labor required for large-scale testing. There is extensive research using numerical techniques to  
375 assess unreinforced soil resistance (Merifield and Sloan, 2006; Dickin and Laman, 2007), but to the authors'  
376 knowledge, there is no numerical study on uplift capacity of reinforced soil. Furthermore, there is limited  
377 research into the complex 3D stress conditions and failure mechanisms associated with buried anchors and  
378 geosynthetic inclusions. To better characterize these internal mechanisms, finite element (FE) modeling was  
379 performed using a three-dimensional model of soil and geocell based on the large-scale experimental results.

### 380 7.1. Finite Element Analysis

381 Similar to the experiments, only one layer of geocell of fixed aperture width and cell height was modeled.  
382 Simulations were performed on three different plate sizes ( $B=150, 225, 300$  mm), four embedment depth ratios  
383 ( $D/B=1.5$  to 3) and one reinforcement width to plate anchor width ratio ( $b/B=3$ ). For this study, twenty-two  
384 simulations were performed, consisting of both unreinforced and reinforced cases. For direct comparison with  
385 experimental results, 20 mm of upward, vertical displacement was applied rigidly at a location representative  
386 of the anchor plate. The computed load was used to evaluate the uplift capacity. The analysis was run in two  
387 phases – first a gravity stage where gravity was slowly applied over 100 seconds of virtual time and a loading  
388 stage where 20 mm of displacement was imposed over a virtual 1000 second timeframe. Thus, upward  
389 movement was applied under displacement control conditions at a rate of 1.2 mm/min (=20 mm/1000 sec.).  
390 Over these periods, stresses, displacements, strains and reaction forces were output through use of ABAQUS  
391 version 6.12 Explicit, a solver used to analyze large deformation geotechnical problems. Load control  
392 conditions may be used in FE modeling, but can lead to numerical difficulties when a user is attempting to  
393 determine the ultimate limit state conditions.

394 **Fig. 10a** shows the analyzed configurations where  $D$ ,  $B$  and  $b$  are as previously defined (see **Fig. 3**). Since  
395 the anchor, geocell and the loading were symmetrical, the model replicated only half the physical test  
396 arrangements for reduced computational expense as shown in **Fig. 10a**. All points on the vertical  $x$ - $z$  plane  
397 passing through the center of the anchor plate were constrained from lateral displacement in the  $y$ -direction  
398 and from rotation around  $x$  and  $z$  axes (**Figs. 10a**). **Fig. 10a** also shows the other boundary conditions used. All  
399 the vertical, external walls could displace vertically, but not horizontally. The base of the model was restricted  
400 from downward displacement during the application of the gravity step, but could translate vertically with any  
401 uplift movements. This boundary contains a plate-sized gap in the center of the model (**Fig. 10a**). This gap,

402 with a thickness of 25.4 mm, was the location where displacement boundary conditions of 20 mm were applied  
403 during the loading stage and reaction forces were extracted concurrently. The geocell inclusion was placed  
404 within the soil using *Embedded Region* conditions in ABAQUS, which mitigates the challenges of mesh  
405 congruence at the expense of treating the geocell as a tied material - the case in other numerical studies  
406 (Leshchinsky and Ling, 2013). The *Embedded Region* constraint is essentially a tie constraint that determines  
407 the spatial relationship of nodes of a given embedded shell/membrane/surface element (i.e. the geocell) with  
408 respect to the nodes of a given “host” region (in this case, the soil). For this constraint, the translational degrees  
409 of freedom for the embedded nodes that define the elements of the geocell shell elements are constrained to  
410 interpolated values of the corresponding degrees of freedom of the host element (Hibbit et al. 2017). The  
411 unreinforced models maintained the same boundary and loading conditions, but had no embedded geocell. To  
412 avoid computational issues due to large differential stiffness between the steel plate and the surrounding soil,  
413 uplift movements were applied directly to soil beneath the geocell, omitting actual modeling of the anchor  
414 plate.

#### 415 7.2. Material Properties and Meshing

416 The granular backfill soil was modeled as a non-associative elastic-plastic material, obeying [the 3D](#)  
417 Drucker-Prager (D-P) yield criterion (Leshchinsky and Ling, 2013). Although more complex constitutive  
418 models are available, the D-P model was deemed appropriate as its strength and yield properties are dependent  
419 on volumetric strain and stress levels that may play a role in the observed uplift behaviour. Furthermore, the  
420 [D-P constitutive laws](#) have been demonstrated to be effective in the modelling of granular materials in various  
421 geosynthetic applications (Yoo and Kim , 2008; Leshchinsky and Ling, 2013, Ambauen et al. 2015). The  
422 deformation and strength properties of the backfill soil were calibrated to match data from triaxial compression  
423 tests (i.e stress-strain responses under three confining pressures), so as to demonstrate no more than 10%-15%  
424 difference between the numerical results and the triaxial test results. The soil properties used in the analysis  
425 are summarized in [Table 6](#). A Poisson’s ratio of 0.3 and a Young’s Modulus of 70 MPa were determined from  
426 an appropriate capture of the load-displacement response of the reinforced and unreinforced anchoring systems.  
427 A comparison to past literature demonstrates that these values were found to be very reasonable for sand ( $\nu=0.3$   
428 to 0.45,  $E_s=5$  MPa to 180 MPa, [Bowles 1983](#)).

429 A small value of cohesion (1 kPa) was assigned to the backfill soil in order to improve numerical stability  
430 and to avoid modeling difficulties, such as localization issues at or near singularities. The geocell was modeled  
431 as a purely elastic material since the soil tends to demonstrate large strains and collapse before significant

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432 plasticity occurs in the relatively extensible geocell materials. The geocell pockets were modeled with a  
433 hexahedron shape (Fig. 10a) as opposed to the actual pseudo-sinusoidal shape used in the experiments as it  
434 simplifies meshing and benefits model convergence - an assumption made in prior FE modeling of geocell  
435 (Yang, 2010; Leshchinsky and Ling, 2012). The Young's modulus of the geotextile material (HDPE, obtained  
436 from Tension test according to ASTM D4632-08) used in the analysis and its Poisson's ratio are considered  
437 800 MPa and 0.33, respectively.

438 The unreinforced model consisted of approximately 45,000 elements and 50,000 nodes for the unreinforced  
439 case and approximately 65,000 elements and 70,000 nodes for the reinforced case (Fig. 10b). A majority of  
440 these elements were placed near the anchor plate, as its behavior was of most interest and it is the location  
441 where deformation was expected to be concentrated. The soil is represented with tetrahedral 8-noded elements  
442 with reduced integration (C3D8R), while the geocell was modeled as a shell meshed with 4-noded quadrilateral  
443 reduced integration elements (S4R). A sensitivity analysis was performed to ensure that the meshing employed  
444 for each type of model was adequate. These results demonstrate that the use of 40,000 and 60,000 elements for  
445 unreinforced and reinforced cases, respectively, were appropriate for solution accuracy.

#### 446 7.3. Comparison between results from ABAQUS analyses and physical tests

448 Comparison between the near full-scale experiments and numerical modeling load-displacement curves  
449 considering embedment ratios of 1.5, 2, 2.5 and 3 with and without geocell reinforcement are shown in Fig.  
450 11. Although analyses of the 150 mm plate anchors show agreement of peak loads for the unreinforced case,  
451 rather large overestimates of peak load were obtained for the reinforced cases with some post-peak instability  
452 observed in the estimated load - perhaps attributable similarity in the plate and geocell pocket size. For these  
453 reasons the 150 mm data are not presented here. The selected constitutive model does not capture the post-peak  
454 softening well, a common limitation in FE modeling. For smaller plate anchor sizes (225×225 mm), numerical  
455 perturbations arise due to the explicit solver maintaining stability under large deformations, particularly with  
456 small overburden. However, the maximum observed uplift load and the initial load-displacement response are  
457 satisfactorily captured for all cases.

#### 458 7.4. Soil Displacement under Uplift Loading

459 The plate size, the embedment ratio, and the presence of geocell affected the uplift mechanism observed in  
460 the soil. For example, the presence of geocell results in a larger region that must deform to allow yield (Fig.  
461 12). The presence of the confined soil within the geocell mattress results in mobilization of tensile stress in the



462 geocell, passive resistance of the confined soil, and a wider distribution of stress displacements that must occur  
463 with uplift. The increased uplift capacity can be attributed to this load-spreading phenomenon. As seen in Fig.  
464 12, the displacement contours for the reinforced case begin further from the plate, a distinct difference from  
465 the unreinforced case, where a rather narrow column of soil above is displaced directly from the edges of the  
466 plate. In Fig. 13, this phenomenon is further demonstrated by comparing the locus of maximum plastic shear  
467 within the soil. The angle between this inferred shear surface and the vertical ( $\theta$ ) is approximately  $19.5^\circ$  for  
468 both unreinforced and reinforced cases. This corroborates observations about uplift failure surfaces oriented  
469  $\phi/2$  from the vertical in the literature (Meyerhof and Adams, 1968). However, as opposed to the unreinforced  
470 case, which exhibits the onset of shear originating a distance of  $B/2$  from the centerline, the presence of geocell  
471 results in almost double the distance from the centerline to the point at which plastic strain occurs during uplift  
472 (Fig. 13).

473 This reinforcing phenomenon of the geocell is further demonstrated by comparing soil heave, as shown in  
474 Fig. 14. In this plot, the black lines represent the vertical displacement computed at the surface, corresponding  
475 to plate displacement of 20 mm for the unreinforced and reinforced cases; while the red lines represent the  
476 vertical displacements measured at the surface for the reinforced cases corresponding to the peak/ultimate uplift  
477 loads for the unreinforced cases of similar configuration. This plot shows that when the geocell is present (red  
478 lines), the heave is less than 10% of that experienced with the unreinforced installation (black lines) for the  
479 same load. However, when comparing heave profiles at the end of the numerical analysis (plate displacement  
480 of 20 mm), the geocell-reinforced soil demonstrates a significantly wider region of displacement  
481 (approximately 30-50% wider), indicating a larger zone in which the uplift resistance is gained due to the  
482 geocell's presence (Fig. 14). As expected, increasingly wide plates exhibit wider surface displacements, a  
483 behavior that is more pronounced with reinforcement. Furthermore, increasing embedment depth resulted in a  
484 decrease in surface heave as the deformation is dispersed within more material before reaching the surface.  
485 The heave realized at the surface displayed a relatively circular shape for both reinforced and unreinforced  
486 conditions, particularly with increasing embedment depth. The redistribution of stresses due to the geocell  
487 exaggerates this behavior.

488 Table 7 lists the maximum distance from the center of plate at which heave is discernable (although the  
489 affected zone is only approximately circular the term 'maximum surface heave radius' is used). Values as  
490 measured in the experiments and in the numerical models for different arrangements are given for a plate

491 displacement of 20 mm (the end of analysis). This table indicates good agreement between computed and  
492 measured results.

#### 493 **7.5. Geocell Deformations and Strains**

494 As plate uplift occurs, part of the overlying geocell deforms, providing tensile resistance and developing  
495 frictional forces along the top and bottom boundaries of the displacing mattress (Fig. 15). As vertical uplift  
496 increases, the relative mobilization width of geocell confinement ( $b'$ ) increases. With excessive displacement,  
497 stiffer geocell material, or more ductile soil, it is possible that the mobilized geocell width would be equivalent  
498 to the entire width of the geocell (i.e.  $b=b'$ ), but that was never the case for the values of the parameters studied  
499 here. For the cases investigated, the mobilized geocell width is compared by means of longitudinal strain in  
500 geocell mattress (Fig. 16). The longitudinal strain remains around 0.4% in the center of geocell for all cases,  
501 while reaching a maximum value of approximately 2.5-3.5% at the edge of anchor plate, eventually decreasing  
502 to zero at some distance from the edge of the plate. Approximately 50% of the geocell width undergoes enough  
503 strain to develop frictional forces between the geocell surfaces and the surrounding soil in the cases studied.  
504 As the geocell becomes stiffer, soil more ductile or uplift displacements greater, it is possible that the mobilized  
505 geocell width may approach the width of the reinforcements, but one must be careful to prevent excessive  
506 displacement during uplift so as to prevent failure.

#### 507 **8. Summary and Conclusions**

508 The presented study demonstrates the results of a series of near full-scale experiments and numerical  
509 models performed on plate anchors embedded in sand with and without geocell reinforcement. The parameters  
510 studied in the testing program and numerical analyses include geocell reinforcement, and anchor width and  
511 embedment depth. Conclusions include:

- 512 • The presence of the geocell layer increased the plate anchor capacity significantly, a phenomenon that  
513 can be attributed to a wider region of mobilized, vertically-displacing overburden soil. It also resulted  
514 in sustained uplift resistance at larger displacements, different from the distinct softening  
515 behavior observed for post-peak conditions in unreinforced systems. The wider mobilization of  
516 overburden soil is highlighted by an observed pressure reduction of between 28% and 41% when a  
517 geocell layer was present. Similarly, the dispersion angle (relative to the vertical) was measured to be  
518 about 19.3° and 24.7° for unreinforced and reinforced systems, respectively, indicating the greater  
519 load distribution achieved from the presence of a geocell layer.

- Both the peak and residual uplift loads of unreinforced and reinforced systems increase approximately linearly with anchor embedment depth, irrespective of the anchor width. For the larger width anchors (225 and 300 mm), the rate of increase in both the peak and residual uplift loads with embedment depth is significantly greater than for small anchors (150 mm width), whether reinforced or not, seemingly indicating some kind of transition in load dispersion–spreading behavior from that experienced with punching shear failure (small anchors) to that associated with general failure (terms as per Vesic, 1963). There is significant difference between the upward displacements corresponding to the maximum uplift load and the residual loads of unreinforced system.
- As expected, the breakout factor increases with embedment depth and decreases with increasing anchor width for both reinforced and unreinforced conditions. It is higher for geocell-reinforced conditions than unreinforced conditions, irrespective of embedment depth and width of anchor.
- Calibrated FE simulations were performed to replicate physical testing, demonstrating reasonable agreement with experimental observations. These numerical models captured the performance of the reinforced soil reasonably well, demonstrating mobilized reinforcement tributary area, lowered uplift stresses, shear occurring in overburden soil, and reduced heave from the presence of the geocell, but could not sufficiently capture the characteristic post-peak softening behavior observed in the physical unreinforced tests. Future work could include more complex constitutive models that capture this important behavior.
- Corroborating prior work, it is demonstrated that there is a scale effect that should be considered for square plate anchors – specifically, increasing the plate dimensions for fixed embedment ratios will result in lower breakout factors.

The experiments and numeric results were obtained for only one type of soil, one type of geocell characteristics and one size of geocell (i.e. height and pocket). In spite of these limitations, the uplift plate anchor tests and the matching numerical simulations carried out in the present study provide considerable encouragement for the use of geocell reinforcement, in improving the behavior of anchor plate. However, future studies could extend the presented numerical techniques to assess relevant design parameters, such as soil type, plate size, embedment depth, anchor and reinforcement geometric configuration, and stiffness of geosynthetic materials towards establishing more robust design criteria for geocell-reinforced anchoring, accounting for the influence of geocell-infill interaction properties, and the influence of varying geocell specifications (i.e roughness, shape, and presence of perforations). This study, however, highlights the

mechanisms that one must consider when extending this concept further. Future work could also parameterize the effects of these material properties on mobilization of geocell tensions.

#### Acknowledgment

The authors thank DuPont de Nemours, Luxembourg, and their UK agents, TDP Limited, for providing the geocell reinforcement used in this test program.

#### References

American Society for Testing and Materials, 2007. *Standard Test Method for Density and Unit Weight of Soil in Place by the Sand-Cone Method*. ASTM International, D1556.

American Society for Testing and Materials, 2008. *Standard Test Method for Grab Breaking Load and Elongation of Geotextiles*. ASTM International, D4632.

American Society for Testing and Materials, 2011. *Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)*. ASTM International, D 2487-11.

American Society for Testing and Materials, 2012. *Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort*. ASTM, D 1557-12.

Ambauen, S., Leshchinsky, B., Xie, Y., & Rayamajhi, D. (2015). Service-state behavior of reinforced soil walls supporting spread footings: a parametric study using finite-element analysis. *Geosynth. Int'l. Geosynth. Int'l.*, 23(3), 156-170.

Biabani, M. M., Indraratna, B., Trung Ngo, N., 2016. Modelling of geocell-reinforced subballast subjected to cyclic loading. *Geotextiles and Geomembranes*, 44 (March), 489–503.

Binquet, J. and Lee, K.L., 1975. Bearing capacity tests on reinforced earth slabs. *J Geotech. Eng'g Div.*, ASCE, 101 (GT12), 1241-1255.

Bhattacharya, P., Kumar, J., 2014. Pullout capacity of inclined plate anchors embedded in sand. *Canadian Geotech. Journal*, 51(11), 1365-1370.

Bhattacharya, P., Kumar, J., 2015. Uplift Capacity of Strip and Circular Anchors in Soft Clay with an Overlay of Sand Layer. *Geotechnical and Geological Engineering*, 33(6), 1475-1488.

Bowles, J.E., 1996. *Foundation Analysis and Design*. 5th edn., McGraw-Hill, New York, 1175pp.

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- 576 Choudhury, D., Subba Rao, K. S., 2005. Seismic uplift capacity of inclined strip anchors. *Canadian Geotech. J.*, *Canadian Geotechnical Journal*, 42(1), 263-271.
- 577
- 578 Choudhary, A. K., Dash, S. K., 2013. Uplift behaviour of horizontal plate anchors embedded in geocell-  
579 reinforced sand. *Proceedings Proc. of Indian Geotechnical Geotech. Conference Conf.*, December 22-24,  
580 Roorkee.
- 581 Consoli, N. C., Thomé, A., Girardello, V., Ruver, C. A., 2012a. Uplift behavior of plates embedded in fiber-  
582 reinforced cement stabilized backfill. *Geotext. & Geomem.*, 35 (December), 107–111
- 583 Consoli, N. C., Ruver, C.A., Girardello, V., Festugato, L., Thomé, A., 2012b. Effect of polypropylene fibers  
584 on the uplift behavior of model footings embedded in sand. *Geosynth. Int.* *Geosynthetics International*,  
585 19(1), 79-84
- 586 Das, B., Seeley, G. 1975. Breakout resistance of shallow horizontal anchors, *Journal of the Geotechnica. l*  
587 *Engineering Eng'g*, ASCE, 101(9), 999-1003
- 588 Dash S.K., Sireesh, S., Sitharam, T.G., 2003. Model studies on circular footing supported on geocell reinforced  
589 sand underlain by soft clay. *Geotext. & Geomem., Geotextiles and Geomembranes*, 21 (4), 197–219
- 590 Dawson, A.R., Lee, R.G., 1988, Full scale foundation trials on grid-reinforced clay, *Geosynthetics for Soil*  
591 *Improvement*, Ed. Holtz R, ASCE *Geotechnical-Geotech. Special Publication Pub'n*, 18, 27-147.
- 592 Deskmukh, V.B., Dewaikar, D.M., Deepankar Choudhury., 2010. Computations of uplift capacity of pile  
593 anchors in cohesionless soil. *Acta Geotechnica*, 5 (2), 87 – 94.
- 594 Dickin, E., 1988. Uplift behavior of horizontal anchor plates in sand, *J Geotech. Eng'g*, *Journal of geotechnical*  
595 *engineering*, ASCE. 114(11), 1300-17.
- 596 Dickin, E., Laman, M., 2007. Uplift response of strip anchors in cohesionless soil', *Advances in Engineering*  
597 *Eng'g* Software, 38 (8–9), 618–25.
- 598 Dickin, E.A., Leung, C.F., 1990. Performance of piles with enlarged bases subjected to uplift forces. *Canadian*  
599 *Geotech. J., Canadian Geotechnical Journal*, 27(5), 546–556.
- 600 Frydman, S., Shaham, I., 1989. Pullout capacity of slab anchors in sand, *Canadian Geotech. J., Canadian*  
601 *Geotechnical Journal*, 26(3), 385–400.

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- 602 Ganesh, R., Sahoo, J. P., 2016. Uplift capacity of horizontal strip plate anchors adjacent to slopes considering  
603 seismic loadings. *Soils and Foundations*, 56(6), 998-1007.
- 604 Ghaly, A., Hanna, A., 1994. Model investigation of the performance of single anchors and groups of anchors,  
605 *Canadian Geotech. J., Canadian Geotechnical Journal*, 31(2), 273-284
- 606 Ghosh, A., Bera, A. K., 2010. Effect of Geotextile Ties on Uplift Capacity of Anchors Embedded in Sand,  
607 *Geotech. & Geolog. Eng'g. Geotechnical and Geological Engineering*, 28(5), 567-77.
- 608 Goel, S., Shalini., Patra, N.R., 2006. Break out resistance of inclined anchors in sand, *Geotech. & Geolog.*  
609 *Eng'g., Geotech-Geol-Eng-24* (6), 1511-1525.
- 610 Guo, J., Han, J., Schrock, S.D., Parsons, R.L., 2015. Field evaluation of vegetation growth in geocell-reinforced  
611 unpaved Shoulders, *Geotext. & Geomem., Geotextiles and Geomembranes*, 43(5), 403-411.
- 612 Hibbett, Karlsson, & Sorensen (2017). *ABAQUS/explicit: User's manual* (Vol. 1). Hibbett, Karlsson &  
613 Sorensen.
- 614 Hegde, A., Sitharam, T. G., 2015. 3-Dimensional numerical modelling of geocell reinforced sand beds,  
615 *Geotext. & Geomem., Geotextiles and Geomembranes*, 43(2), 171-81.
- 616 Honda, T., Hirai, Y., Sato, E., 2011. Uplift capacity of belled and multi-belled piles in dense sand. *Soils and &*  
617 *Foundations*, 51 (3), 483-496.
- 618 Horpibulsuk, S., Niramitkoree, A., 2010. Pullout resistance of bearing reinforcement embedded in sand.  
619 *Soils and Foundations*, 50 (2), 215-228.
- 620 Ilamparuthi, K., Dickin, E. A., 2001. The influence of soil reinforcement on the uplift behaviour of belled piles  
621 embedded in sand, *Geotext. & Geomem., Geotextiles and Geomembranes*, 19(1), 1-22.
- 622 Ilamparuthi, K., Dickin, E. A., Muthukrisnaiah, K., 2002. Experimental investigation of the uplift behaviour  
623 of circular plate anchors embedded in sand, *Canadian Geotech. J., Canadian Geotechnical Journal*, 39 (3)  
624 648-664.
- 625 Indraratna, B., Biabani, M.M., Nimbalkar, S., 2015. Behavior of Geocell-Reinforced Subballast Subjected to  
626 Cyclic Loading in Plane-Strain Condition. *Journal of Geotechnical and Geoenvironmental Engineering J.*  
627 *Geotech. & Geoenviron. Eng'g., ASCE*. 141(1), 16pp.

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- 628 Jones, R.H., Lee, R.G. and Dawson A.R., 1991. Full-scale trials of grid reinforced soil foundations on alluvium,  
 629 *Quaternary Engineering Geology*, Eng. Geol. Sp. Publ. No. 7, eds. Forster, A, Culshaw M G, Cripps S  
 630 C, Little J A and Moon C F, Geol. Soc., London, pp.643-649.
- 631 Karpurapu, R., Bathurst, R. J., 1995. Behaviour of geosynthetic reinforced soil retaining walls using the finite  
 632 element method. *Computers & Geotech., Computers and Geotechnics*, 17(3), 279-299
- 633 Keskin, M. S., 2015. Model studies of uplift capacity behavior of square plate anchors in geogrid-reinforced  
 634 sand. *Geomechanics-Geomech. and Engineering Eng'g.*, 8(4), 595-613.
- 635 Khan, A. J., Mostofa, G., Jadid, R., 2017. Pullout resistance of concrete anchor block embedded in cohesionless  
 636 soil. *Geomech. & Eng'g., Geomechanics and Engineering*, 12(4), 675-688.
- 637 Khatri, V.N., Kumar, J., 2009. Vertical uplift resistance of circular plate anchors in clays under undrained  
 638 condition. *Computers & Geotech., Computers and Geotechnics*, 36 (8), 1352–1359. Koerner, R. M. (2012).  
 639 Designing with geosynthetics (Vol. 1). Xlibris Corporation.
- 640 Kouzer, K., Kumar, J., 2009. Vertical uplift capacity of two interfering horizontal anchors in sand using an  
 641 upper bound limit analysis, *Computers and Geotechnics Geotech.*, 36 (6), 1084–1089.
- 642 Krishnaswamy, N. R., Parashar, S. P., 1994. Uplift behaviour of plate anchors with geosynthetics, *Geotext. &*  
 643 *Geomem., Geotextiles and Geomembranes*, 13(2), 67–89.
- 644 Kumar, J., Bhoi, M. K., 2009. Vertical uplift capacity of equally spaced multiple strip anchors in sand, *Geotech.*  
 645 *& Geolog. Eng'g., Geotechnical and Geological Engineering*, 27(3), 461–72.
- 646 Kumar, B. R. P., & Rao, N. R. (2000). Increasing pull-out capacity of granular pile anchors in expansive soils  
 647 using base geosynthetics. *Canadian Geotech. J., Canadian Geotechnical Journal*, 37(4), 870-881.
- 648 Kumar, B. R. P., 2016. Influence of Geogrid Reinforcement on Pullout Response of Granular Pile-Anchors  
 649 (GPAs) in Expansive Soils. *Indian Geotechnical Journal*, 46 (4), 437–444.
- 650 Lee, K. F., Davidson, J. F., Akroyd, J., Kraft, M., 2014. Lifting a buried object: Reverse hopper theory,  
 651 *Chemical-Chem. Engineering-Eng'g Science Sci.*, 105, 198–207.
- 652 Leshchinsky, B., Ling, H., 2012. Effects of geocell confinement on strength and deformation behavior of  
 653 gravel. *J. Geotech. & Geoenviron. Eng'g., ASCE. Journal of Geotechnical and Geoenvironmental*  
 654 *Engineering, ASCE*, 139(2), 340-352.

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- 655 Leshchinsky, B., Ling, H. I., 2013. Numerical modeling of behavior of railway ballasted structure with geocell  
 656 confinement, *Geotext. & Geomem., Geotextiles and Geomembranes*, 36, 33–43.
- 657 Liu, J., Liu, M., Zhu, Z., 2012. Sand Deformation around an Uplift Plate Anchor. *J. Geotech. & Geoenviron.*  
 658 *Eng'g., ASCE, Journal of Geotechnical and Geoenvironmental Engineering*, 138(6), 728-737.
- 659 Merifield, R. S., Sloan, S. W., 2006. The ultimate pullout capacity of anchors in frictional soils, *Canadian*  
 660 *Geotech. J., Canadian Geotechnical Journal*, 43(8), 852–68.
- 661 Meyerhof, G. G., Adams, J. I., 1968. The Ultimate Uplift Capacity of Foundations, *Canadian Geotech. J.,*  
 662 *Canadian Geotechnical Journal*, 5(4), 225–44.
- 663 Moayedi, H., Mosallanezhad, M., 2017. Uplift Resistance of Belled and Multi-Belled Piles in Loose Sand.  
 664 *Measurement*, 109(October), 346-353
- 665 Moghaddas Tafreshi, S.N., Rahimi M., 2012. A simplified pseudo-dynamic method of reinforced retaining  
 666 wall subjected to seismic loads. *Materialy 15 WCEE*, Lisboa.
- 667 Moghaddas Tafreshi, S.N., Dawson, A.R., 2012. A comparison of static and cyclic loading responses of  
 668 foundations on geocell-reinforced sand. *Geotext. & Geomem., Geotextiles and Geomembranes* 32(June),  
 669 55-68.
- 670 Moghaddas Tafreshi, S.N., Khalaj, O., Dawson, A.R., 2013. Pilot-scale load tests of a combined multi-layered  
 671 geocell and rubber-reinforced foundation. *Geosynth. Int'l, Geosynth. Int.* 20 (3), 143-161.
- 672 Moghaddas Tafreshi, S. N., Javadi, S., Dawson, A.R., 2014. Influence of geocell reinforcement on uplift  
 673 response of belled piles, *Acta Geotechnica*, 9(3), 513–28.
- 674 Moghaddas Tafreshi, S.N., Sharifi, P., Dawson, A.R., 2016. Performance of circular footings on sand by use  
 675 of multiple-geocell or-planar geotextile reinforcing layers, *Soils & Foundations, Soils and Foundations* 56  
 676 (6), 984-997.
- 677 Murray, E., Geddes, J., 1987. Uplift of anchor plates in sand. *J. Geotech. Eng'g., ASCE, Journal of geotechnical*  
 678 *engineering, ASCE*, 113(3), 202-215.
- 679 Oliaei, M., Kouzegaran, S., 2017. Efficiency of cellular geosynthetics for foundation reinforcement. *Geotext.*  
 680 *& Geomem., Geotextiles and Geomembranes*, 45(2), 11-22.

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- 681 Ouria, A., Mahmoudi, A., 2018. Laboratory and numerical modeling of strip footing on geotextile-reinforced  
 682 sand with cement-treated interface. *Geotext. & Geomem., Geotextiles and Geomembranes*, 46(1), 29-39
- 683 O'Shaughnessy, V., Garga, V.K., 2000. Tire-reinforced earthfill. Part 2: Pull-out behaviour and reinforced  
 684 slope design, *Canadian Geotech. J., Canadian Geotechnical Journal*, 37(1), 97-116.
- 685 Phani Kumar, B.R., Sharma, R.S., Srirama Rao, A., Madhav, M.R., 2004. Granular Pile – Anchor Foundation  
 686 (GPAF) System for Improving the Engineering Behaviour of Expansive Clay Beds. *Geotech. Testing J.,*  
 687 *ASTM*, 27, (3), 279-287.
- 688 Rangari, S. M., Choudhury, D., Dewaikar, D. M., 2013. Computations of Seismic Passive Resistance and Uplift  
 689 Capacity of Horizontal Strip Anchors in Sand, *Geotech. & Geolog. Eng'g., Geotechnical and Geological*  
 690 *Engineering*, 31(2), 569–80.
- 691 Rao, A. S., Phani Kumar, B. R., Increasing pull-out capacity of granular pile anchors in expansive soils using  
 692 base geosynthetics, *Canadian Geotech. J.*, 37, 870-881
- 693 Ravichandran, P. T., Ilamparuthi, K., Touffeq, M. M., 2008. Investigations on Uplift Behaviour of Plate Anchor  
 694 in Reinforced Sand Bed. *Electronic Journal of Geotechnical-Geotech. Engineering Eng'g.*, 13, 1-8.
- 695 Rowe, R. K., Davis, E. H., 1982. The behaviour of anchor plates in sand, *Geotechnique*, 32(1), 25–41.
- 696 Sabatini, P. J., Pass, D. G., Bachus, R. C., 1999. *Geotechnical engineering circular no. 4: ground anchors and*  
 697 *anchored systems* (No. FHWA-IF-99-015).
- 698 Sakai, T., Tanaka, T., 2007. Experimental and Numerical Study of Uplift Behavior of Shallow Circular Anchor  
 699 in Two-Layered Sand, *J. Geotech. & Geoenviron. Eng'g., ASCE. Journal of Geotechnical and*  
 700 *Geoenvironmental Engineering*, 133(4), 469–477.
- 701 Sahoo, J. P., Khuntia, S., 2017. Lower bound solutions for uplift capacity of strip anchors adjacent to sloping  
 702 ground in clay. *Marine Georesources and Geotechnology* (In Press)
- 703 Shin, J., Kim, J., Chang, H. J. 2016. Anchor plate effect on the breakout capacity in tension for thin-walled  
 704 concrete panels. *Engineering Structures*, 106, (1) 147-153.
- 705 Song, Z., Hu, Y., Randolph, M.F., 2008. Numerical simulation of vertical pullout of plate anchors in clay. *J.*  
 706 *Geotech. & Geoenviron. Eng'g., ASCE. J Geotech. Geoenviron. Eng., ASCE*, 134 (6), 866–887.

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- 707 Song, Z., Hu, Y., O'Loughlin, C., Randolph, M.F., 2009. Loss in Anchor Embedment during Plate Anchor  
 708 Keying in Clay. *J. Geotech. & Geoenviron. Eng'g., ASCE, Journal of Geotechnical and Geoenvironmental*  
 709 *Engineering*, 135(10), 1475–1485.
- 710 Song, F., Liu, H., Chai, H., Chen, J., 2017. Stability analysis of geocell-reinforced retaining walls. *Geosynth.*  
 711 *Int'l, Geosynthetics International*, 24(5), 442–450.
- 712 Tagaya, K., Scott, R. F., Aboshi, H., 1988. Pullout resistance of buried anchor in sand. *Soils and &*  
 713 *Foundations*, 28(3), 114–30.
- 714 Tavakoli Mehrjardi, G. h., Moghaddas Tafreshi, S. N., Dawson, A. R., 2012. Combined use of geocell  
 715 reinforcement and rubber–soil mixtures to improve performance of buried pipes. *Geotext. & Geomem.,*  
 716 *Geotextiles and Geomembranes*, 34 (October), 116–130.
- 717 Tanyu, B.F., Aydilek, A.H., Lau, A.W., Edil, T.B., Benson, C.H., 2013. Laboratory evaluation of geocell-  
 718 reinforced gravel subbase over poor subgrades. *Geosynth. Int'l, Geosynth. Int.* 20 (2), 47-61.
- 719 Thakur, J. K., Han, J., Pokharel, S. K. Parsons, R. L., 2012. Performance of geocell-reinforced recycled asphalt  
 720 pavement (RAP) bases over weak subgrade under cyclic plate loading. *Geotext. & Geomem., Geotextiles*  
 721 *and Geomembranes*, 35(December), 14–24.
- 722 Tian, Y., Gaudin, C., Cassidy, M.J., 2014. Improving Plate Anchor Design with a Keying Flap. *Geotech. &*  
 723 *Geolog. Eng'g., Journal of Geotechnical and Geoenvironmental Engineering*, 140(5), 13pp.
- 724 Tran, V. D. H., Meguid, M. a., Chouinard, L. E. (2013). A finite-discrete element framework for the 3D  
 725 modeling of geogrid-soil interaction under pullout loading conditions, *Geotext. & Geomem., Geotextiles*  
 726 *and Geomembranes*, 37: 1–9.
- 727 Treff, A., 2011. Private Communication with Albert Treff of DuPont de Nemours, Luxembourg.
- 728 Trung Ngo. N., Indraratna, B., Rujikiatkamjorn, C., Biabani, M. M., 2016. Experimental and Discrete Element  
 729 Modeling of Geocell-Stabilized Subballast Subjected to Cyclic Loading. *J. Geotech. & Geoenviron.*  
 730 *Eng'g., ASCE, Journal of Geotechnical and Geoenvironmental Engineering*, 142(4), 14pp
- 731 Vahedifard, F., Shahrokhbadi, S., Leshchinsky, D., 2016. Geosynthetic-reinforced soil structures with concave  
 732 facing profile. *Geotext. & Geomem., Geotextiles and Geomembranes*, 44 (3), 358-365.

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- 733 Vesic, A. S., 1963. Bearing capacity of deep foundations in sand, *Highway Research Record*, No. 39, 112–  
 734 153.
- 735 Vesic, A. S., 1971. Breakout resistance of objects embedded in ocean bottom, *Journal of the Soil Mechanics*  
 736 *and Foundations Division*, ASCE, 97(9): 1183–205.
- 737 Vishwas, N. K., Kumar, J., 2011. Effect of anchor width on pullout capacity of strip anchors in sand  
 738 *Canadian Geotech. J., Canadian Geotechnical Journal*, 48(3), 511-517.
- 739 Wang, D., O'Loughlin, C.D., 2014. Numerical study of pull-out capacities of dynamically embedded  
 740 plateanchors. *Canadian Geotech. J., Canadian Geotechnical Journal*, 51(11), 1263-1272.
- 741 Yetimoglu, T., Wu, J.T., Saglamer, A., 1994, Bearing capacity of rectangular footings on geogrid-reinforced  
 742 sand. *J. Geotech. Eng'g.*, ASCE, 120(12), 2083-2099.
- 743 Yang, X., 2010. *Numerical Analyses of Geocell-Reinforced Granular Soils under Static and Repeated Loads.*  
 744 PhD Thesis. University of Kansas, USA.
- 745 Yoo, C., & Kim, S. B. (2008). Performance of a two-tier geosynthetic reinforced segmental retaining wall  
 746 under a surcharge load: Full-scale load test and 3D finite element analysis. *Geotextiles and*  
 747 *Geomembranes*, 26(6), 460-472. Yoon, Y.W., Heo, S.B., Kim, S.K., 2008. Geotechnical performance of  
 748 waste tires for soil reinforcement from chamber tests. *Geotext. & Geomem., Geotextiles and*  
 749 *Geomembranes*-26 (1), 100-107.
- 750 Zhang, L., Zhao, M., Shi, C., Zhao, H., 2010. Bearing capacity of geocell reinforcement in embankment  
 751 engineering, *Geotext. & Geomem., Geotextiles and Geomembranes*, 28(5), 475–82.

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**Nomenclature**

<i>A</i>	anchor area
<i>B</i>	width of anchor plate
<i>b</i>	width of geocell mattress

$B_{un.}, B_{re.}$	dimension of back-calculated reinforced and unreinforced tributary area 100 mm above the anchor
$D$	embedment depth of anchor plate
$d$	geocell pocket size
$E_{gc}$	geocell Young's modulus
$E_s$	soil Young's modulus
$G_s$	specific gravity
$h$	height of geocell
$IF_{peak}$	improvement in peak uplift load
$IF_{res}$	improvement in residual uplift load
$L.SPC$	left soil pressure cell
$N_q$	<i>breakout factor</i>
$P_L$	ratio of pressure measured in the reinforced case to that in the unreinforced case for the left soil pressure cell
$P_{peak}$	peak uplift load
$P_R$	ratio of pressure measured in the reinforced case to that in the unreinforced case for the right soil pressure cell
$P_{res}$	residual uplift load
$R.SPC$	right soil pressure cell
$u_{peak}$	peak upward displacement
$W$	soil weight above the anchor
$\alpha_{un.}, \alpha_{re.}$	average value of pressure distribution dispersion angle through unreinforced and reinforced soil
$\gamma$	soil unit weight
$\nu$	Poisson's ratio
$\sigma_{max}$	maximum uplift pressure on top surface of anchor embedded in unreinforced soil
$\sigma_{un.}, \sigma_{re.}$	average pressure within soil for unreinforced and reinforced soil 100 mm above anchor
$\phi$	soil angle of internal friction
$\psi$	Angle of dilation

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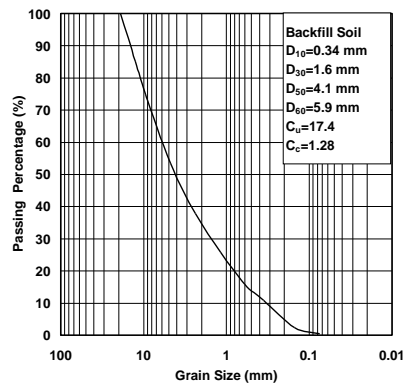


Fig. 1. Grain size distribution curve for backfill soil (as per ASTM D 2487-11).

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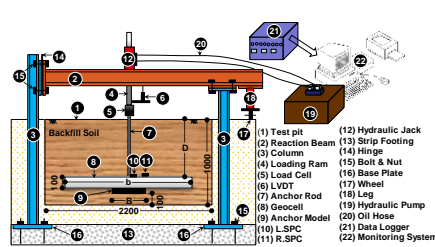
Fig. 2. A view of geocell (TDP Limited) spread over anchor plate in the test pit.

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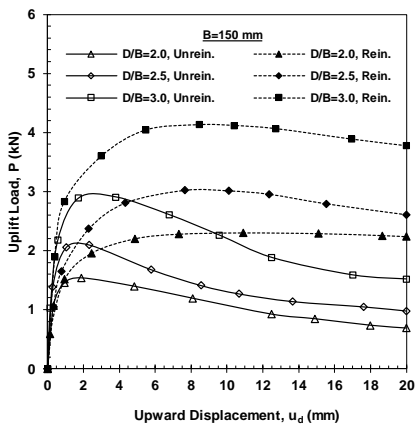
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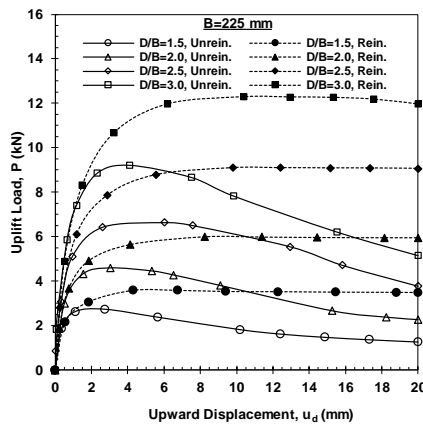
(b)

Fig. 3. Test installation prior to loading (a) actual physical model and (b) Schematic representation (units in mm).

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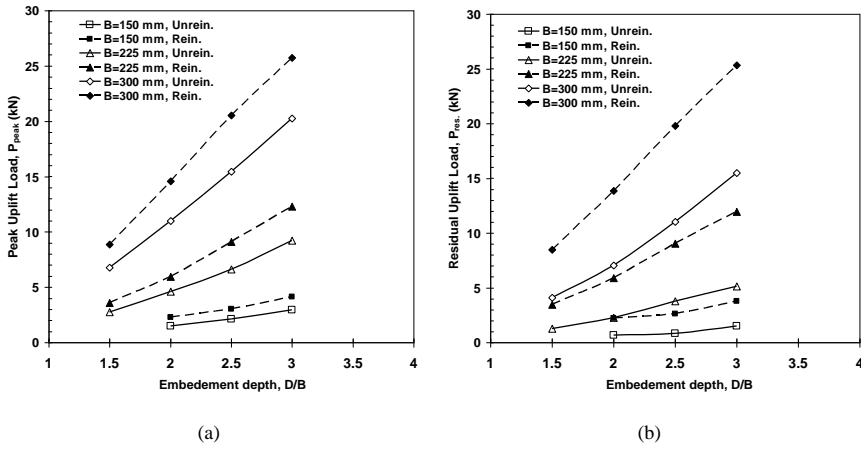


Fig. 6. Variation of peak and residual uplift loads of unreinforced and reinforced bed with embedment depth (D/B) of anchor for different anchor width, (a) peak uplift load (b) residual uplift loads.

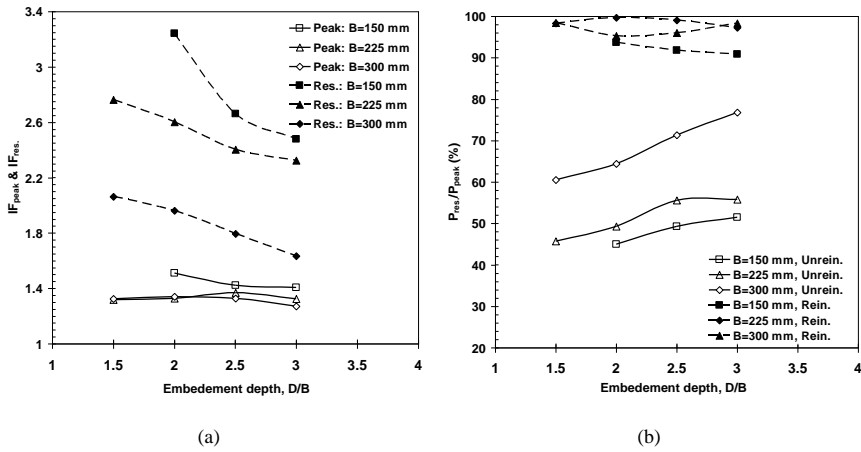


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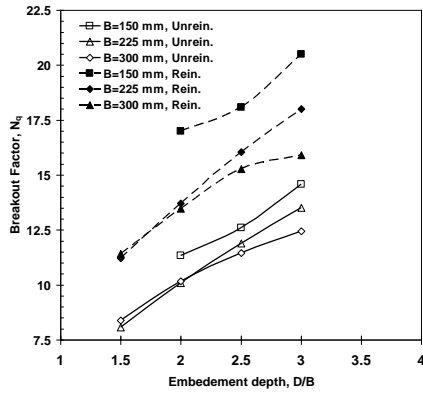


Fig. 8. Variation of breakout factor,  $N_q$  of unreinforced and reinforced beds with embedment depth ( $D/B$ ) of anchor for different anchor width.

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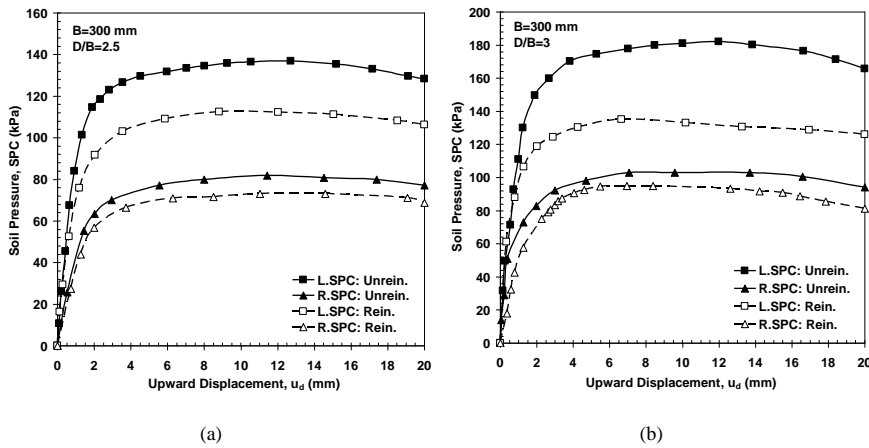


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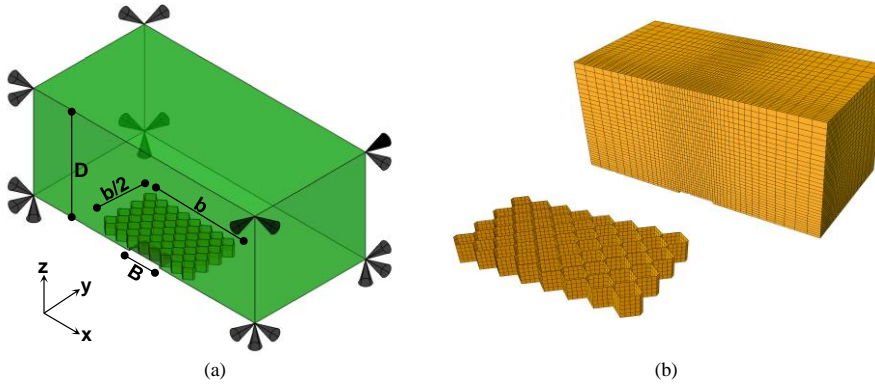
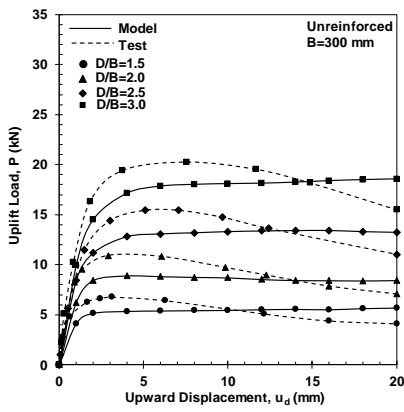
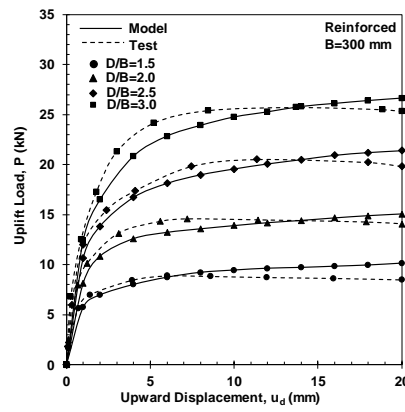


Fig. 10. (a) Model geometry and boundary conditions and (b) sample mesh of soil and geocell layer.



(a)



(b)

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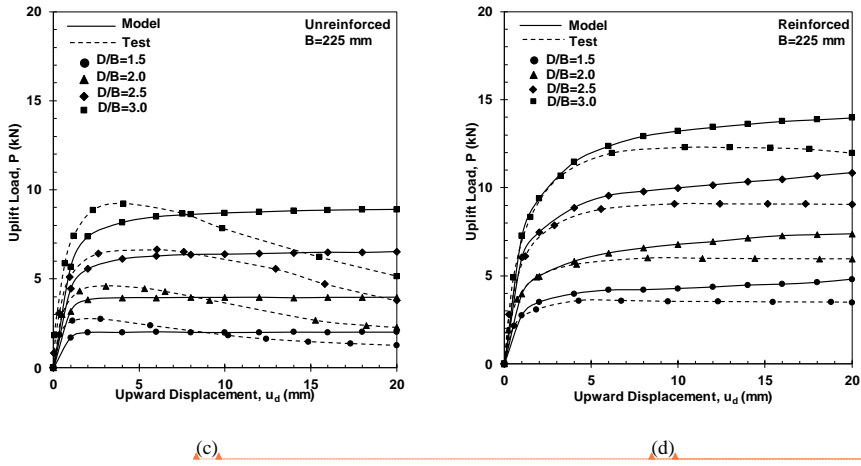


Fig. 11. Comparison between experimental and numerical modeling load-displacement curves (a) unreinforced (for B=300 mm), (b) reinforced (B=300 mm), (c) unreinforced (B=225 mm) and (d) reinforced (B=225 mm)

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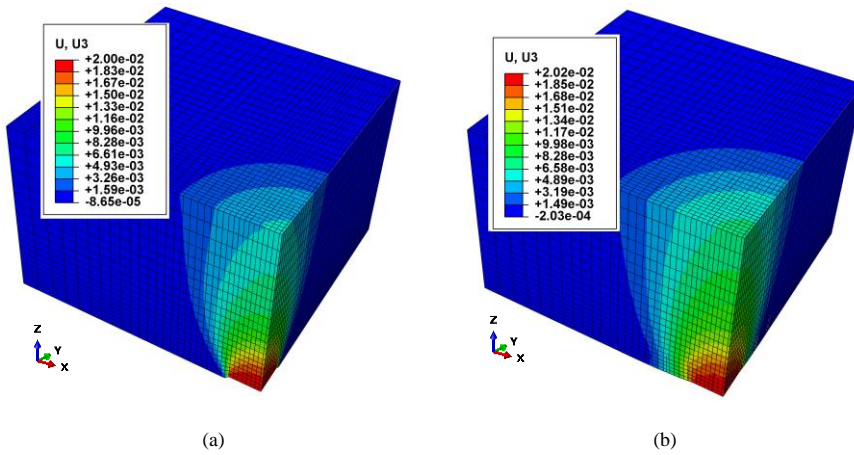


Fig. 12. Example displacement contours for B=300 mm and D/B=3, at the end of analysis (plate displacement of 20 mm) (a) unreinforced and (b) reinforced conditions.

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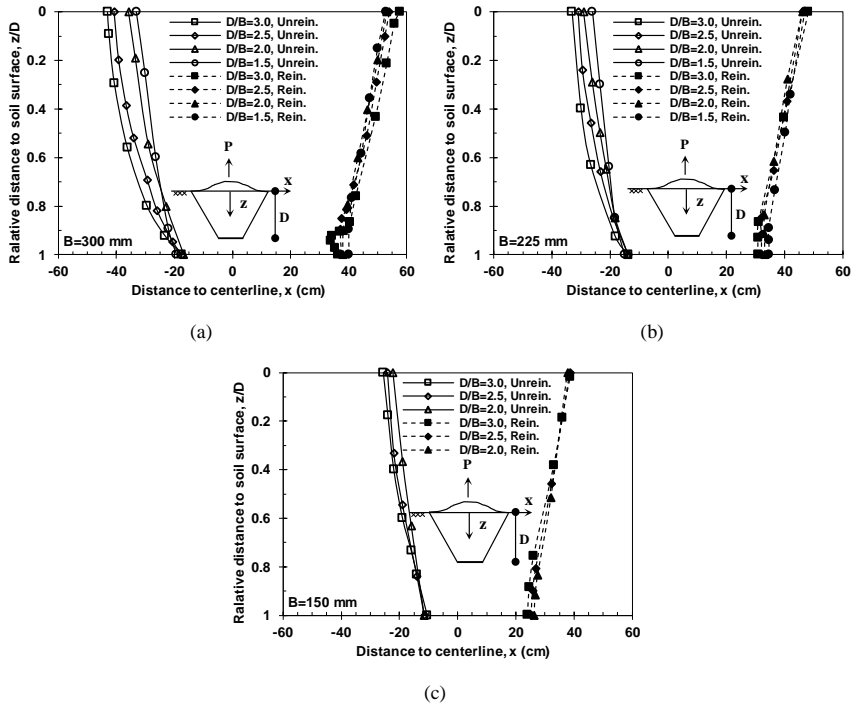
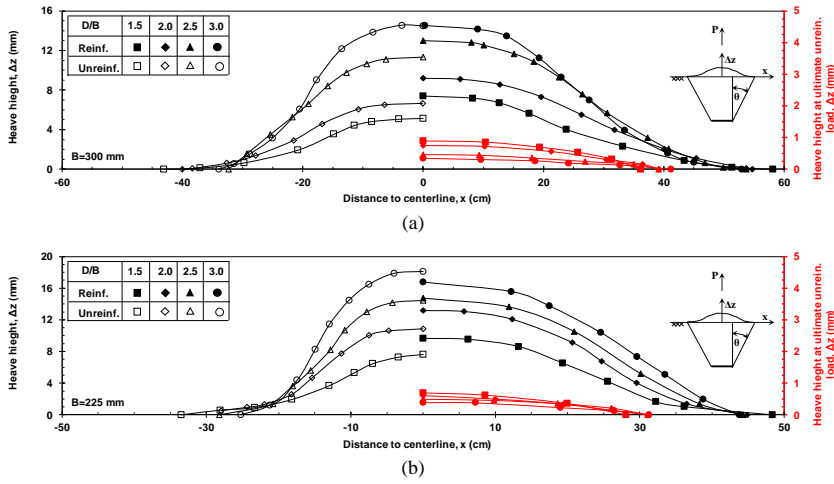


Fig. 13. Recorded zones of concentrated plastic shear strain, at the end of analysis (plate displacement of 20 mm) for unreinforced and reinforced systems (a) B=300 mm, (b) B=225 mm, (c) B=150 mm.

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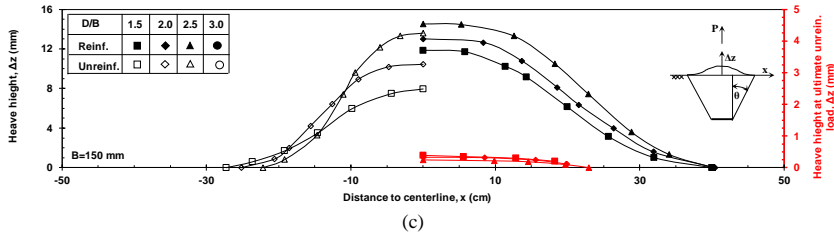


Fig. 14. Surface heave for different configuration of anchor model (a) B=300 mm, (b) B=225 mm, (c) B=150 mm (the black lines represent the surface heave at the end of analysis (plate displacement of 20 mm) of the unreinforced and reinforced cases and the red lines represent surface heave for a reinforced case with load corresponding to the ultimate, unreinforced, uplift capacity).

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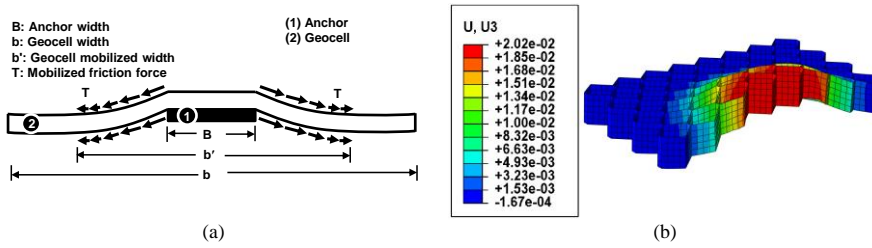


Fig. 15. (a) Idealized geocell deformations and (b) observed deformations from FE modeling.

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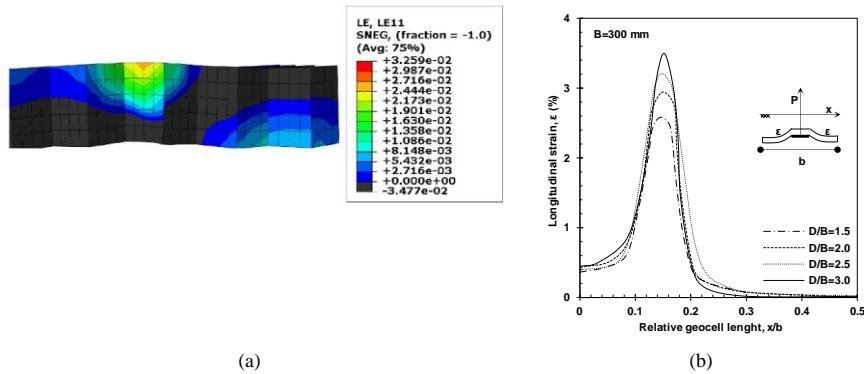


Fig. 16. (a) Contours and (b) plot of tensile strain on the top surface of the geocell.

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**Table 1.** The engineering properties of the geotextile used in the tests

Description	Value
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Type of geotextile	Non-woven
Material	Polypropylene
Area weight (gr/m <sup>2</sup> )	190
Thickness under 2 kN/m <sup>2</sup> (mm)	0.57
Thickness under 200 kN/m <sup>2</sup> (mm)	0.47
Tensile strength (kN/m)	13.1
Strength at 5% (kN/m)	5.7
Effective opening size (mm)	0.08

**Table 2.** Densities of soil for unreinforced and geocell-reinforced layers after compaction (ASTM D 1557-12).

Type of layer	Average dry density (kN/m <sup>3</sup> )
Unreinforced soil layer	≈18.76*
Geocell-reinforced layer	Between 18.2 and 18.4

\*approximately 92% of maximum dry density – see Sec. 3.1

**Table 3.** Scheme of the uplift tests on anchor in unreinforced and geocell-reinforced backfills (h=100 mm, b/B=3)

test series	type of test	anchor width, B (mm)	embedment depth ratio, D/B	No. of Tests	purpose of the tests
1	unreinforced	150	2, 2.5, 3	3+4*	Provide baseline estimates regarding uplift capacity
		225, 300	1.5, 2, 2.5, 3	8+10*	
2	geocell-reinforced	150	2, 2.5, 3	3+4*	Highlight the effect of the geocell reinforcement on uplift capacity
		225, 300	1.5, 2, 2.5, 3	8+10*	

\*The tests which were performed two or three times to verify the repeatability of the test data. For example, in test Series 2 on anchor plate with width of 150 mm. 7 tests were performed: 3 independent tests plus 4 replicates.

**Table 4.** Comparison of upward displacement corresponding to maximum uplift load in reinforced and unreinforced system (displacement in mm)

D/B	B=150 mm			B=225 mm			B=300 mm		
	(u <sub>peak</sub> ) <sub>unrein.</sub>	(u <sub>peak</sub> ) <sub>rein.</sub>	Iu <sub>peak</sub>	(u <sub>peak</sub> ) <sub>unrein.</sub>	(u <sub>peak</sub> ) <sub>rein.</sub>	Iu <sub>peak</sub>	(u <sub>peak</sub> ) <sub>unrein.</sub>	(u <sub>peak</sub> ) <sub>rein.</sub>	Iu <sub>peak</sub>
1.5	--	--	--	1.54	4.3	2.79	3.11	6.03	1.94

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2	1.28	5.82	4.54	2.32	6.05	2.32	4.15	7.22	1.74
2.5	1.55	6.25	4.03	3.42	7.42	2.17	5.59	8.75	1.56
3	2.84	7.24	2.54	4.1	8.1	1.98	7.57	10.85	1.43

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**Table 5.** Comparison of measured soil pressure in unreinforced and geocell-reinforced systems corresponding to peak uplift load of unreinforced system

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		Soil pressure corresponding to maximum uplift load of unreinforced system						
B (mm)	D/B	Unreinforced			Reinforced		Ratio of soil pressure in reinforced system to unreinforced system (P)	
		Maximum uplift pressure, $\sigma_{max}$ (kPa)	L.SP C (kPa)	R.SP C (kPa)	L.SPC (kPa)	R.SPC (kPa)	P <sub>L</sub>	P <sub>R</sub>
300	1.5	75.6	67.2	39.2	43.20	23.20	0.64	0.59
	2	123.3	89.6	53.2	64.20	36.10	0.72	0.68
	2.5	172.2	137.3	82.4	95.40	61.80	0.69	0.75
	3	224.4	182.4	106.4	121.20	75.80	0.66	0.71

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**Table 6.** Backfill soil properties used in Finite element analysis

Description	value
Internal angle of friction, $\phi$ (°)	40.5°
Angle of dilation, $\psi$ (°)	5°
Young's modulus, $E_s$ (MPa)	70
Poisson's ratio, $\nu$	0.3
Mass Density, $\gamma$ (kN/m <sup>3</sup> )	19.72

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**Table 7.** Comparison of the maximum surface heave radius for physical tests and numerical models, corresponding to a plate displacement of 20 mm

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B (mm)	D/B	Maximum surface heave radius (cm)			
		Unreinforced		Reinforced	
		Test	Model	Test	Model
300	3	47.3	43.8	63.4	58.9
	2.5	42.4	40.8	59.3	55.7
	2	33.3	32.5	55.2	53.8
	1.5	32.8	32.4	52.1	51.7
225	3	37.2	34.8	49.1	49.6
	2.5	34.2	32.9	45.2	45.6
	2	29.4	28.6	43.3	44.6
	1.5	25.8	25.4	41.2	43.1
150	3	30.1	27.8	40.4	40.8
	2.5	27.3	25.2	38.2	39.3
	2	23.4	22.5	37.5	38.1

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