Cyclic and Post-Cycling Anchor Response in Geocell-Reinforced Sand

S.N. Moghaddas Tafreshi1,* (Corresponding Author), M. Rahimi2, A.R. Dawson3, B. Leshchinsky4

1, *Corresponding Author. Department of Civil Engineering, K.N. Toosi University of Technology, Valiasr St., Mirdamad Cr., Tehran, Iran. Tel: +982188779473; Fax: +982188779476; E-mail address: nas_moghaddas@kntu.ac.ir

2Department of Civil Engineering, K.N. Toosi University of Technology, Valiasr St., Mirdamad Cr., Tehran, Iran. Tel: +982188779473; Fax: +982188779476; E-mail address: my.rahimi@mail.kntu.ac.ir

3Nottingham Transportation Engineering Centre, University of Nottingham, Nottingham, UK. Tel: +441159513902; Fax: +441159513909; E-mail address: andrew.dawson@nottingham.ac.uk

4Forest Engineering, Resources and Management Department, College of Forestry, Oregon State University, 280 Peavy Hall, Corvallis, Oregon 97331, USA. Tel: +1541-737-8873; E-mail address: ben.leshchinsky@oregonstate.edu
Abstract:

Plate anchors are commonly used to resist static, cyclic and monotonic after cyclic-loading uplift loads. Under cyclic loading, progressive sudden failure may occur, characterized by accumulated displacement – even under loads significantly less than the static capacity. Despite extensive usage of geocell for increasing the cyclic resilience, the influence of geocell reinforcements on cyclic uplift capacity is not well-understood. In this study, a series of near-full scale, experimental tests with and without geocell are presented. Results show that the unreinforced system fails cyclically under a load that is almost 70% of its static capacity ($P_u$), but use of geocell enables stable cyclic resistance of over 100%$P_u$. For the given soil and configurations, a cyclic displacement rate that reaches less than 0.05 mm/cycle tends to highlight a likely stable response. Evaluation of the soil’s response to cyclic loading demonstrates that, with increasing loading cycles, the loading is increasingly transmitted through the soil close to the anchor in the unreinforced case, but that the reinforced case is less prone to this phenomenon. The monotonic post-cycling capacity of both reinforced and unreinforced anchors decreases after application of cyclic loading; however, the unreinforced scenario demonstrates larger decreases in capacity, particularly in the residual capacity.

Keywords: Anchor, Uplift, Geocell, Cyclic Loading, Post-cycling Behavior, Large-Scale Testing
1. Introduction

The stability of various structures (e.g. masts, wind turbines, rock-fall protection fences, etc.) may directly depend on anchoring that may resist static and cyclic uplift loadings. Under cyclic uplift loading of anchoring systems, cumulative displacements may occur, resulting in the onset of failure over time (Andreadis and Harvey, 1981; Schiavon et al., 2017). The onset of progressive anchoring failure is often a function of the magnitude of static and cyclic loading, soil type, and anchoring system. Hence, the primary design requirement for many anchoring systems is to obtain sufficient resistance to static and cyclic load while keeping the cyclic displacement behavior compatible with structural mooring requirements. Thus, it is accepted that both ultimate and service limit states be considered in the design of anchoring. Due to the complexity of soil behavior under repeated loading, the design of anchors under cyclic loading is generally conservative – reliant on a high factor of safety applied to the static load capacity. However, design for static conditions may still neglect potential instability due to progressive anchor displacement. Hence, it is critical to arrest cumulative cyclic anchor displacements to sustain both short-term and long-term stability. One viable means of mitigating progressive deformation of soil under cyclic loading is the application of geosynthetic reinforcement. Although commonly used to inhibit cyclic deformation and “ratcheting” under compressive loading (Mengelt et al., 2006; Indraratna et al., 2014; Ngo et al., 2015; Basack et al. 2015; Thakur et al., 2016; Suku et al. 2016, Koshi and Unnikrishnan, 2016; Satyal et al., 2018; Kargar and Hosseini, 2018; Dash and Choudhary, 2018 and Wang et al. 2018), the application of geosynthetics are promising for resisting uplift loads as well. Of particular promise are three-dimensional (3D) geocells reinforcements (Koerner, 1998), which provide three mechanisms of lateral resistance effect, vertical stress dispersion and membrane mechanism for increasing the load bearing capacity and improving the performance of pavement (Koerner, 1998; Zhang et al., 2010; Sitharam and Hegde, 2013; Hegde, 2017).

The cyclic uplift behavior of anchors is complex, and often a function of soil, anchor dimensions, loading magnitude, and loading pattern. Ponniah and Finlay (1988), Datta et al.(1990), Prasad and Rao (1994), Singh and Ramaswamy (2008, 2010) and Yu et. al. (2015) used scaled experiments to observe the cyclic behavior of plate anchors in cohesive soils, observing that anchor systems may exhibit different cyclic response based on soil compressibility, shear strength, and embedment. Similar observations were made about cyclic uplift behavior being influenced by embedment, cyclic loading pattern and relative density in granular materials (Andreadis and Harvey,
1979, 1981; Petereit, 1987; Byrne 2000; Choudhury and Subba Rao, 2005; Wang and O’Loughlin, 2014; Schiavon 2016; Stuyts et al. 2016; Schiavon et al., 2017 and Pérez et al., 2018).

However, there is limited research focusing on the beneficial role that geosynthetics may play in enhancing cyclic resistance of anchoring systems. Ravichandran et. al. (2008) studied the behavior of plate anchors buried in geogrid-reinforced sand under monotonic and repeated loading – for the limited set of tests, it was observed that the geosynthetic systems helped increase uplift capacity. Moghadas Tafreshi et al. (2014a) investigated the influence of geocell reinforcement on improving cyclic uplift resistance of belled piles, demonstrating significant improvement when the reinforcement was present. However, the available studies are either limited in scale or in breadth of design factors considered.

The objective of this study is to better assess the role of geosynthetics reinforcement in the vertical cyclic uplift load response and in the monotonic load response after a period of cyclic loading (the ‘post-cycling’ uplift behavior) of plate anchors, particularly when using geocell reinforcement. To achieve this, a series of near full-scale physical tests (a total of 27 independent tests plus extra repeated tests) were performed on a horizontal square plate anchor installed in unreinforced and geocell-reinforced soil. During testing, the load – displacement behavior of geocell-reinforced system was compared to an unreinforced control scenario. The influence of embedment depth and cyclic load amplitude ($P_c$) on the plate anchor’s uplift response was observed.

2. Materials and Experimental Setup

2.1. Soil Properties

A well-graded sand (SW, ASTM D2487-11) with specific gravity of 2.66 ($G_s$=2.66) was used to fill the geocell pockets and backfill soil in the testing program. There is a significant quantity of fine gravel (46%) and little fines (<1%), as shown in the grain size distribution (Fig. 1). Based on the modified proctor compaction (ASTM D1557-12), the maximum dry density and optimum moisture content of this soil were approximately 20.42 kN/m$^3$ and 5.1%, respectively. The angle of internal friction ($\phi$) of the soil, obtained from consolidated drained triaxial compression tests was 40.5° at a moist density of 19.73 kN/m$^3$ (corresponding to relative compaction of 92%, similar to the compacted density of the backfill soil layers in test pit) and a moisture content of 5%. As the test pit material was
partially saturated, suction stresses were present, but were considered negligible for the material used (0.1-1kPa for gravelly sand, Fredlund 2006).

2.2. Geocell Properties

Each cell in the geocell used is 110 mm long and wide ($d$) and 100 mm high ($h$). Fig. 2 shows an isometric view of the geocell spread over the bottom soil layer and the plate anchor. This geocell was manufactured from a nonwoven polymeric geotextile that was thermo-welded without internal perforations within each pocket. The engineering properties of this geotextile, as listed by the manufacturer, are presented in Table 1. In all tests, the ratio of the geocell pocket size ($d$) to width of anchor plate ($B=300$ mm) were kept constant. However, the $d/B$ ratio adopted is not necessarily the optimum value and a change in this ratio might increase or decrease the resistance encountered. Future research could investigate optimal dimensions of geocell anchoring.

2.3. Experimental Setup

To investigate the uplift capacity and upward displacement of plate anchors supported by geocell layers, large-scale testing on a square steel anchor plate with width of 300 mm and 2.54 mm thickness attached to an anchor rod with diameter of 50 mm was conducted in an indoor test pit. The test pit, measuring 2200 mm × 2200 mm in plan and 1000 mm in depth, contained the soil, anchor, geocell reinforcement and instrumentation (i.e. load cell, LVDTs and pressure cells). The four sides of the test pit were vertical (Fig. 3). Because the width and depth of the test pit were respectively more than seven and three times bigger than the width of the anchor, the boundary effects during testing were not considered to be significant (Consoli et al., 2012).

The loading system (Fig. 3) consisted of a loading frame, hydraulic actuator, and a controlling unit. The loading frame is comprised of two heavy steel columns fixed in the ground and a horizontal strong reaction beam spanning the width of the test pit that supports a hydraulic actuator. The hydraulic actuator and control unit may produce monotonic or cyclic loads with the capability of applying a stepwise controlled load with a maximum tensile capacity of 100 kN. The loading frequency of the loading system was in the range of 0.05 Hz to 0.5 Hz, but the best performance was at the 0.1 Hz which is desirable to simulate the low frequency of the wind loads (Herrmann, 1981; Rao and Prasad, 1991; Singh and Ramaswamy, 2008).

A custom data acquisition system was developed to read and record applied uplift loading, displacements and soil pressures at a frequency of 100 Hz. A load cell with the accuracy of ±0.01% and a full-scale capacity of 100 kN was
placed between the loading shaft and a rod attached to the plate anchor (Fig. 3a). To measure the displacement of the plate anchor during the loading, a Linear Variable Differential Transducer (LVDT) with the accuracy of 0.01% of full range (100 mm) was attached to the loading shaft and the supporting beam (as shown in Fig. 3). In some tests, two soil pressure cells (“SPC”) monitored the soil pressure at a depth of 100mm above the anchor (the depth of the upper edge of the geocell) (Fig. 3b). The pressure cells had a capacity of 1000 kPa and an accuracy of 0.01% (0.1kPa), small enough to not significantly influence measurements. To prevent stress concentrations from asperities on soil grains located adjacent to the pressure cell, each cell was placed in a small bag filled with clay for consistent transferring of stress to the pressure cells. The suffixes “i” and “o” are used to indicate the inner and outer positions 50 and 150 mm away from the center of anchor, respectively. All output data streams (load cell, LVDT and pressure cells) were recorded continuously using a data acquisition system within internal processor. To ensure an accurate reading, all of the devices were calibrated prior to each test series. Fig. 3a illustrates the test installation prior to loading. A schematic cross-section of the experimental set-up containing the test pit, loading system and data measurement system, geocell layer, and the anchor is shown in Fig. 3b.

2.4. Preparation of Test Pit and Experimental Procedure

In order to compact the unreinforced layers and geocell-reinforced layer in the test pit (Fig. 3), a handheld vibrating plate compactor was used. In all the tests, depending on the embedment depth of anchor the unreinforced soil layers were prepared and compacted at thicknesses of either 50 or 100 mm with respectively one or three passes of the compactor to achieve the required density (i.e. dry density of ≈18.78 kN/m$^3$ in Table 2). As the same the soil filled the pockets of geocell layer was compacted with four passes of compactor to achieve the required density of soil layer (shown in Table 2). This amount of compactive effort was maintained throughout the testing series. The density of the both unreinforced and reinforced layers were checked for compaction specifications through sand cone testing (ASTM D1556-07), performed at least three times per lift. A maximum difference of approximately 1-2% was observed between the measured and desired density of compacted layer. The materials used were compacted at an optimum moisture content of 5%, but the average measured (recovered) moisture content of the layers was between 4.8% and 5.2%. The exposed backfill material was covered with a waterproof paper to limit possible moisture loss.

To prepare the backfill in the test pit, a 100 mm thick unreinforced soil layer was compacted first. Then, the anchor plate was placed in the center of the test pit on the surface of compacted soil layer, with the correct connected
Thereafter, the geocell reinforcement (in the reinforced case) was spread above the anchor and cell pockets were filled and compacted (dry density of 18.2-18.4 kN/m$^3$) with backfill soil with about 10 mm extra thickness of soil over the geocell. Two soil pressure cells were then installed. The desired level of the soil surface/embedment depth was achieved, after the compaction of unreinforced soil layers above the geocell layer (average dry density of 18.78 kN/m$^3$). When the installation was prepared for testing, a desired loading pattern including initial monotonic and subsequent cyclic load (see section 2.5.) was applied to the anchor plate, while upward displacement, uplift force and soil pressure were recorded using the aforementioned LVDT, load cell and soil pressure cells (SPCi and SPCo), respectively.

2.5. Experimental Series and Loading Pattern

Increased embedment depth of anchors results in enhanced anchor capacity. Therefore, three embedment depth ratios ($D/B=1.5, 2, 2.5$) were assessed for both unreinforced and geocell-reinforced backfills under monotonic and cyclic loading. The geocell width in all the monotonic and cyclic reinforced tests was selected to be three times the width of the geocell layer ($b/B=3$ or $b=900$ mm) since the influence of more extensive soil reinforcement on uplift capacity decreases outside this range (Choudhary and Dash, 2013; Rahimi et al., 2018a). The thickness of the geocell layer above the anchor plate was held constant in all tests at 100 mm. The details of the test program are given in Table 3. Six monotonic uplift tests (series 1-2) at three embedment depth ratios ($D/B=1.5, 2, 2.5$) were conducted to obtain the ultimate uplift resistance of unreinforced ($P_u$) and reinforced ($P_r$) beds, respectively. Monotonic loading was continued until softening behavior had occurred in the load-displacement response or the maximum stroke of the actuator (20 mm) had been reached. The monotonic ultimate uplift capacity obtained from Test Series 1 and 2 are used to compare with post-cycling uplift capacity (see Section 3.7.). Furthermore, the unreinforced capacity ($P_u$) determined in testing (Test Series 1) was then used to determine cyclic load ratios in Test Series 3 (cyclic loading, unreinforced) and Test Series 4 (cyclic loading, geocell-reinforced). Another object of Test Series 3 and 4 is determination of the anchor’s post-cycling uplift resistance.

Typically, anchors endure sustained loads, but additional cyclic loading may occur in addition to static loading (e.g. winds, wave loading, and vibrations), which may influence anchor performance for a short time period. Furthermore, anchor serviceability under monotonic post-cycling loading after cyclic load application may have great...
importance. Therefore, the loading pattern for cyclically-loaded tests were divided into three phases as shown in Fig. 4:

i) **Monotonic loading**: The ratio of applied initial sustained load ($P_s$) to monotonic ultimate uplift capacity of unreinforced installation ($P_u$) is expressed as $SLR = \frac{P_s}{P_u}$. A fixed and constant $SLR$ value of 30% ($SLR = \frac{P_s}{P_u} = 0.3$) was applied for each respective embedment depth, as the typical factor of safety for design is approximately three. In all the tests, the initial sustained load ($P_s$) was applied with a rate of 1.5 kPa per second to the both unreinforced and reinforced system (Fig. 4). After reaching the predefined $P_s$, the load is kept constant for approximately 120 seconds as to stabilize anchor movement before applying cyclic loading. To control the rate of 1.5 kPa per second (i.e. the rate of 0.135 kN per second) during monotonic loading, the predefined $P_s$ was applied at a fixed duration which was operated by an automated load control system.

ii) **Cyclic loading**: After the sustained load is reached, 250 sinusoidal loading cycles of amplitude $P_c$ and 10 sec. period (0.1 Hz frequency) are applied to the anchor (Fig. 4). Typically, the actual frequency of wind load, simulated herein, is no greater than 0.1 Hz (Herrmann, 1981). A 10 sec. period has been commonly applied in the physical modeling of cyclically-loaded anchor plates which are exposed to the low frequency loads of the wind storms (Ponniah and Finlay, 1988; Rao and Prasad, 1991; Singh and Ramaswamy, 2008). For each cycle of loading and unloading, the load in the anchor was varied from sustained load ($P_s$) to the desired cyclic load ($P_s + P_c$), where ($P_c$) was amplitude of cyclic loading (Fig. 4). Three cyclic load ratios ($CLR = \frac{P_c}{P_u} = 20, 30$ and 40%) were assessed for unreinforced conditions and four cyclic load ratios ($CLR = 40, 50, 60$ and 70 %) were assessed for reinforced conditions. It is worth noting that 30% of the static uplift capacity of the reinforced system is greater than the corresponding value for the unreinforced case, thus, a higher CLR was selected for cyclic loading under reinforced conditions as to bring the anchoring system closer to failure. However, a CLR of 40% was presented for both reinforced and unreinforced systems for direct comparison. Cyclic loading was continued until 250 loading cycles were completed, when 20 mm of uplift had reached, or cyclic failure occurred. For this preliminary study, 250 loading cycles deemed reasonable to assess general anchor behavior as this range exhibited displacement accumulation rates that were small enough for low amplitude loading ($CLR < 40\%$).
and large for high amplitude cyclic loading (CLR≥40%), which is often short in duration for well-designed anchor systems (Schiavon et al., 2017).

iii) Post-cycling loading: If cyclic failure had not occurred after the completion of 250 loading cycles, a monotonic load was applied once more at a rate of 1.5 kPa per second to evaluate the post-cycling capacity of plate anchor.

Several replicate installations were performed to confirm the repeatability of the loading behavior, instrumentation and loading control. The results obtained showed a close match between results of the repeated tests: the maximum difference between the results was about 6-8%, so the results were considered reliable.

3. Results

In this section, the results of the monotonic and cyclic uplift tests are presented for varying embedment, cyclic loading amplitude (CLR), and reinforcement conditions. Cyclic uplift displacement, rate of anchor displacement, soil pressure above the anchor (in a few tests- Section 3.6) and post cycling uplift capacity of anchor plate were evaluated.

3.1. Ultimate Capacity of Reinforced and Unreinforced Anchors under Monotonic Loading

To define the sustained load ratio (SLR) and cyclic load ratio (CLR) to be used in the subsequent cyclic loading tests, the ultimate uplift capacity was determined in six monotonic uplift tests performed at three different embedment depth (D/B=1.5, 2.0 and 2.5) for unreinforced and geocell-reinforced conditions. Fig. 5 shows the load-displacement behavior of unreinforced and reinforced cases at different embedment depth ratios. In general, the uplift load-displacement response demonstrated for unreinforced conditions was characterized by a relatively rapid increase in loading until a peak was reached, followed by a distinct softening behavior with continued displacement. For geocell-reinforced conditions, peak resistance was sustained over a range of upward displacement with no distinct softening behavior occurring for the given range of displacement evaluated in the tests. In both cases, the inferred peak loads for the unreinforced case was used to determine \( P_u \). More details about static results are available in Rahimi et al., (2018b).
3.2. Overall Cyclic Behavior of Unreinforced and Geocell Reinforced Anchor Systems

Both the unreinforced and reinforced installations were tested with a fixed static load ratio (SLR=30%) and varying cyclic load ratios (CLR) as shown in Table 3. Two general types of load-displacement behavior were observed under the application of loading cycles, characterized as behavior (1) where no failure occurs under cumulative cyclic displacement (stable condition), or (2) where a certain CLR may result in the eventual failure under large cumulative displacement (unstable condition).

Stable conditions were observed for lower cyclic loading magnitudes (CLR≤30%) in unreinforced conditions and for all reinforced scenarios (except for D/B=1.5 with CLR=70%). An example of typical cyclic behavior under stable conditions is presented in Fig. 6a for first 1500 sec. of loading. This figure shows that at the first phase of loading (monotonic loading) anchor displacement increases linearly with time. After initial monotonic loading, anchor displacement increases nonlinearly under the application of cyclic loading, reducing with each loading cycle and even reaching a relatively stable state where displacements are primarily elastic. This characteristic may be defined as “plastic shakedown” (Werkmeister et al., 2007), whereas stress states that are less than that required for progressive failure result in long-term, steady-state response where no collapse is observed. Fig. 6b shows the load hysteresis derived from the same test. In most of the tests, a large proportion of total anchor uplift displacement (between 15% to 55% of total displacement) occurs in the first cycle, reaching an eventual stable state under applied cyclic loading. With increased load cycles, the hysteresis loops become more symmetric and loading and unloading paths become closer, implying that the load-displacement response is acting under increasingly elastic conditions.

Unstable behavior was observed for unreinforced conditions when CLR was greater than 40% and for geocell reinforced conditions when CLR=70% at embedment depth of D/B=1.5 as shown typically in Fig. 6c-d. For unreinforced conditions, the stable trend of reduced anchor upward displacement was sustained unless a cyclic load ratio exceeded a critical magnitude that led to eventual cumulative displacement and catastrophic failure, defined as the critical cyclic load ratio (CLR). Thus in the unreinforced system, all the tests performed with SLR=30% and CLR less than 40% of the monotonic uplift capacity delivers a stable response, but when CLR exceeds 40% (CLR=40%), the unreinforced system is no longer stable under the applied cyclic load, exhibiting cumulative plastic, cyclic displacements. Use of reinforcement may attenuate some of the progressive displacements that occur under cyclic loading. The reinforced system can distribute load to a wider area and prevent shear localization, consequently
inhibiting strain localizations and progressive failure mechanisms. **Fig. 6c-d** shows typical unstable behavior under cyclic loading. As seen in **Fig. 6c**, displacements continue to increase with loading cycles, ultimately realizing a catastrophic failure after definite cycles of loading. **Fig. 6d** shows the load-displacement hysteresis of the unstable behavior. With increasing load cycles, the system cannot maintain the desired load level, gradually reaching failure conditions where permanent displacements increase with each loading cycle.

### 3.3. Cyclic Loading of Unreinforced Anchors

**Fig. 7** shows the cumulative displacements measured at the peak of each loading cycle for unreinforced conditions under cyclic load ratios of \(\text{CLR}=20\%\), 30\% and 40\% at \(D/B\) of 1.5, 2 and 2.5 and **Fig. 8** shows the displacement accumulation rate during cyclic loading. As cyclic load ratio increases, cumulative displacement increases either for all embedment depths, although the rate of increase of displacement is higher for more shallowly-embedded anchors (e.g. \(D/B=1.5\)). As \(\text{CLR}\) exceeds 40\%, the system fails progressively under cumulative displacement. Thus \(\text{CLR}=40\%\) is a critical cyclic load amplitude that is the threshold between a stable and unstable response of the unreinforced bed. As the embedment depth increases, the number of loading cycles required to reach the critical cyclic load ratio increase commensurately. For example, the number of cycles to failure for \(\text{CLR}\) of 40\% and \(D/B\) of 1.5, 2.0 and 2.5 was 31, 72 and 148 number of cycles, respectively. However, failure may occur with a different number of loading cycles between \(\text{CLR}\) of 30\% and 40\%, but would exceed the cycles required for failure for \(\text{CLR}=40\%\).

As expected, an increase in the amplitude of cyclic load (CLR) causes the progressive anchor displacement to increase. For example, the anchor displacement for the unreinforced bed with embedment depth ratio, \(D/B=1.5\), at the end of the cyclic loading are 1.90 and 2.89 mm for the cyclic load with CLR=20\% and 30\%, respectively. However, anchor displacement under cyclic loading is greater for smaller embedment depths. As the embedment depth increases, shakedown occurs more rapidly and the maximum displacement at the end of cyclic loading decreases. For example, as the embedment depth increases from \(D/B=1.5\) to 2.5, the maximum displacement decreases from 1.90 to 0.77 mm and 2.89 to 1.44 mm for \(\text{CLR} = 20\%\) and 30\%, respectively. This behavior may be attributed to the increased stiffness due to the greater confining stress and probably extension of shear zone provided by the increased overburden. When a non-stabilizing response is observed as a consequence of excessive displacement, significant heave at the surface
may be observed. This mechanism suggests that the unreinforced soil, when subjected to cyclic loading may eventually fail after excessive displacements occur in the soil around and above the anchor.

**Fig. 8** shows the cumulative displacements rate with the number of load cycles for unreinforced conditions under cyclic load ratios of $CLR=20\%$, $30\%$ and $40\%$ at $D/B$ of 1.5, 2 and 2.5. This figure indicates that for $CLR=20\%$ and $30\%$, the displacement accumulation rate decreases rapidly after the first 10 loading cycles, reaching a small and relatively constant value. This rate increases with loading amplitude. Accumulated displacement rate is about 0.05 mm/cycle for $CLR=20\%$ and $30\%$ after 10 loading cycles, but it is always more than 0.05 mm/cycle for $CLR=40\%$ and, after some cycles of loading, the displacement accumulation rate begins to rise rapidly and stabilization does not occur. As one might expect, the lower the rate of cyclic displacement after initial shakedown, the more likely that stable cyclic behavior will be sustained throughout cyclic loading as obtained for $CLR=20\%$ and $30\%$. Schiavon (2016) reported the same trend about helical piles under cyclic uplift load, for which a displacement accumulation rate of less than 0.1 mm/cycles was a sign of stable behavior.

### 3.4. Comparison of Cyclic Response of Unreinforced and Geocell-Reinforced Anchors

As observed for unreinforced conditions, a threshold cyclic load ratio may demonstrate a transition from a stable to an unstable condition – use of soil reinforcement may mitigate this phenomenon. **Fig. 9** compares the behavior for unreinforced and reinforced conditions for $CLR=40\%$. Unlike the unreinforced case, the reinforced case shows a stable response for $CLR=40\%$. As seen in **Fig. 9a**, the cumulative displacements for the reinforced installation is well below the corresponding value in unreinforced condition at same cyclic load ratio. The hysteresis loops for the anchor, shown in **Fig. 9b**, are derived from the unreinforced and reinforced tests. The hysteresis loop of the unreinforced installation shows excessive deformation and subsequently unstable behaviour whereas, in the geocell-reinforced installation, a steady response condition was achieved with the load-displacement path forming a closed hysteresis loop.

**Fig. 10a** shows the variation of unreinforced and reinforced displacements for $CLR=40\%$ for three different embedment depth ratios. As seen, in all cases the reinforced installation exhibits a well stabilized response compared with the non-stabilized response of the unreinforced case. The effect of soil reinforcement is that it enables a stable response under cyclic loading as the confined, stiff behavior of the reinforced composite diminishes the upward
displacement through mobilization of the reinforcement’s tensile resistance and a greater distribution of uplift stresses.

**Fig. 10b** shows the displacement accumulation rate for unreinforced and reinforced tests; the rate is well below 0.05 mm/cycle after first 10 loading cycles for the reinforced case, a sign of stabilized response, whereas the unreinforced installation all develop instability – taking more cycles for a greater embedment.

**Fig. 11** shows the surface heave at the end of cyclic loading with CLR=40% for unreinforced and reinforced beds. As seen in **Fig. 11a**, with application of cyclic load to the unreinforced bed, the soil located above the anchor locally displaced upward and cracks propagated though the soil, leading to a reduction of soil resistance and finally to failure of soil-anchor system. On the other hand as seen in **Fig. 11b** the embedded geocell prevents local displacement of soil and cracks are not observed on the soil surface. In this case, a wider mass of soil was evenly displaced upward, without localized shear displacement. Thus, the combined soil-geocell exhibits a greater resistance against cyclic loading and has limited upward displacement. **Fig. 12** compares the measured surface heave heights at the end of the cyclic loading. These are measured at failure in the unreinforced case (20 mm anchor displacement) and the response after loading cycle number 250 for the reinforced case (failure has not occurred). As seen, in the unreinforced case the anchor causes surface displacements close to the centerline whereas, in the reinforced case, a wider region of soil is displaced. The increased width of the area of surface heave for reinforced versus unreinforced conditions is suggestive of a change in the geometry of the shear failure mechanism. Unfortunately, the actual shape of the failure geometry was not explicitly observed or measured in these experiments. Future work could better describe this mechanism, best captured through numerical modeling. Even though the maximum unreinforced centerline heave is around 7 times greater than in the reinforced case, at a radial distance of 30-35mm (~twice the anchor plate radius) the surface heave is the same. Thus, the geocell layer acts to prevent upward ‘punching’ failure.

### 3.5. Response of Geocell-Reinforced Anchors under Heavy Cyclic Load

In order to evaluate the reinforced bed’s performance under higher cyclic loading, additional tests were performed under cyclic load ratios of CLR of 50%, 60% and 70% for \( D/B \) of 1.5, 2.0 and 2.5. **Fig. 13** shows the load-displacement hysteretic behavior for different cyclic load ratios at \( D/B \) of 2.0. Increasing the cyclic load ratio results in greater magnitudes of cumulative displacement. Measured displacements after 250 loading cycles were 4.15, 5.02 and 9.84
mm for CLR=50%, 60% and 70%, respectively. There is, thus, non-linearity in the deformation response to loading suggesting that punching failure might occur at very large cyclic load ratios (CLRs).

**Fig. 14** illustrated the load displacement loop at load cycles of 1, 10, 100 and 200 for the different cyclic load ratios and D/B of 2.0. The plastic displacement at the end of first cycle is much larger than subsequent cycles, meaning that the system’s response is stabilizing even at these high loads. The load displacement hysteresis of later cycles tend to approach a constant hysteretical shape that is closed, implying that the load-displacement response is largely elastic (although at a somewhat reduced modulus value by the end of cycling in the CLR=70% case). Modulus is also seen to reduce as CLR increases, indicating a likely transition with some of the load that was carried by the overburden soil now being carried by the geocell reinforcement.

**Fig. 15** shows the variation of the uplifting displacement of anchor buried in geocell-reinforced bed with cyclic loading for CLR=50%, 60% and 70% at different embedment depth ratios. The reinforced system may sustain large cyclic loading without reaching an unstable state with the exception of shallow anchor embedment, D/B=1.5, where the anchor displacement reached the maximum actuator stroke of 20 mm after 57 load cycles. One important advantage of the reinforced system over the unreinforced system is that the reinforced system be able to accommodate a cyclic load representative of the ultimate monotonic uplifting capacity of the unreinforced system (e.g. CLR=70% or $P_u + P_c = 100\% P_u$) without the loss of function. In this case, the cyclic portion of the load pattern is double the sustained static load (e.g. $P_c > 2P_s$), implying that a reinforced system could easily resist heavy cyclic loading. This behavior likely owes to the slab-like behavior of the geocell-soil composite, effectively distributing uplifting loading more effectively and mobilizing tensile resistance within the reinforcement structure. Because of the three-dimensional structure of the geocell, the confined cells of soil displace laterally after application of uplifting loading, increasing the shear strength of the composite system (Moghaddas Tafreshi and Dawson, 2010; Thakur et al., 2012; 2016; Rahimi et al., 2018a). The confined soil-geocell structure has relatively high flexural stiffness to resist out-of-plane loads. Therefore, the load distribution area increases and upward displacement diminishes, which helps the overall stability of composite layer against static and cyclic loads.

**Fig. 16** shows the displacement accumulation rate for different cyclic loads and embedment depth ratios. As discussed before, the displacement accumulation rate in the initial cycles (especially in first 10 cycles) is an important surrogate for describing the long-term stability of anchor cyclic behavior. As seen in **Fig. 16**, as cyclic load ratio
increases, the rate of upward displacement increases too. However, after the first 10 cycles (except $D/B=1.5$ and $CLR=70\%$) it decreases rapidly beneath a rate of 0.05 mm/cycle, which as seen in previous sections leading to a stable response for the given soil type and anchor dimensions. *Schiavon* (2016) reported the same finding for helical piles under cyclic uplift load. Furthermore, after 250 load cycles, the rate of upward displacement decreases to less than 0.01 mm/cycle (except $D/B=1.5$ at $CLR=70\%$), implying stability in the short term for cyclic loading and adequacy of 250 load cycles for recognition of anchor behavior type (whether stable or unstable behavior). It is observed that the reinforced system tends to experience large displacement prior to reaching a distinct yield within the given displacement limits. This implies that such a system is less prone to catastrophic failure and, if failure were to occur, it would be by progressive accumulation of displacements and serviceability failure.

Generally, when a non-stabilizing response is observed (commonly for the unreinforced case at $D/B=1.5$, 2, 2.5 under $CLR=40\%$ and uncommonly for the reinforced case at $D/B=1.5$ under $CLR=70\%$), due to excessive anchor upward displacement, significant heave of the soil surface starts. This, in these unreinforced and reinforced cases, local ruptures in the region above and around the anchor (punching failure), permit large displacements.

### 3.6. Soil pressures over the anchor

In order to demonstrate how soil pressure changes over the anchor during cyclic loading, in selected tests soil pressure was measured through the two soil pressure cells (SPCi and SPCo). *Fig. 17* shows the variation of measured stress with time or loading cycle for an anchor with the embedment depth ratio of 2 ($D/B=2$) in both the unreinforced and reinforced case. *Fig. 17a-b* illustrates the typical variation of change in soil pressures due to uplift loading, at a point 100 mm above the anchor plate, 50 and 150 mm away from the center of anchor. As seen at the first, static, phase of loading (approximately 0-25s), soil pressure within both pressure cells linearly increase to reach an approximately constant value as the uplift load develops in the soil. It then remained constant (25-145s) until the second phase of loading commenced (cyclic loading). In this cyclic load stage, the soil pressure near the center of anchor (i.e. SPCi) increased with increasing cycle number. On the other hand, the soil pressure decreased at the location of the outer pressure cell. Thus, with application of cyclic loading, load spreading becomes less effective with stress becoming more concentrated in the zone where, for other installations, punching failure would occur. While
shear dislocation has not developed, it is clear that cyclic loading is beginning to redistribute the stresses in such a way that dislocation might, eventually, be achieved.

Fig. 17c-d compare the inner and outer soil pressure peaks of each loading cycles for an anchor with the embedment depth ratio of 2 (D/B=2) in the unreinforced and reinforced cases at different cyclic load ratios. In both cases the local increase of soil pressure on the top of anchor center increases as CLR increases (causing failure of the unreinforced case at CLR=40% and soil pressure of 115 kPa) while the soil pressure away from the anchor decreases (after a small increase in the first few cycles of loading of the reinforced soil). Soil pressure in all reinforced cases is less than in the unreinforced cases regardless of the fact that the cyclic load ratio in all cases is higher for the reinforced system. Evidently, the reinforced system can distribute load over a larger area and this helps to generate a more even and consistent distribution of uplift stress in the overlying soil. As the cyclic load ratio increases, the soil pressure measured by the outer soil pressure cell (SPCo) decreases more rapidly with number of cycles. Another observation is that, as CLR increases, the stress distributed outwards from the anchor centerline remains high when the installation is reinforced. Thus, reinforcement benefit is increased at high load ratios and at more cycles – eventually the installation is adjusting to the loading with more stress being transferred to the geocell layer.

To more clearly demonstrate the effect of geocell reinforcement on uplift pressure dispersion, the net soil pressures change due to cyclic uplift load measured by SPCi and SPCo at the peak of the first and last loading cyclic for D/B=2 and different cyclic load ratios, are shown in Table 4. To evaluate the efficiency of reinforcement on distribution of uplift pressure over a larger area, two specific ratios, \( \chi_{\text{unrein.}} \) and \( \chi_{\text{rein.}} \) are introduced:

\[
\chi_{\text{unrein.}} = \frac{( \text{SPCo} )_{\text{unrein.}}}{( \text{SPCi} )_{\text{unrein.}}} \quad (1)
\]

\[
\chi_{\text{rein.}} = \frac{( \text{SPCo} )_{\text{rein.}}}{( \text{SPCi} )_{\text{rein.}}} \quad (2)
\]

in which \(( \text{SPCo} )_{\text{unrein.}} \) and \(( \text{SPCi} )_{\text{unrein.}} \) are the pressures measured in the unreinforced systems by the outer and inner pressure cells, respectively (Eq. 1); while Eq. 2 takes the same approach for the reinforced conditions. In all cases, the values of soil pressure measured by outer pressure cell are less than those measured by the inner pressure cell. In this way, \( \chi_{\text{unrein.}} \) and \( \chi_{\text{rein.}} \) values less than unity (as given in Table 4) indirectly show that soil pressure decreases away from the center of the anchor, but in all cases more reduction occurs for unreinforced case. Initial values of \( \chi_{\text{unrein.}} \) and \( \chi_{\text{rein.}} \) (i.e 1st in Table 4) are approximately 0.4 and 0.6 for unreinforced and reinforced case, respectively. Thus, even
at first cycling loop, more even distribution is achieved by the reinforced installation. The change of the \( \chi \) value on cycling is more pronounced at lower load ratio values than at higher ones, although reinforcement makes the reduction due to cycling less significant, i.e. stress concentration due to cyclic load adaptation is more readily avoided by reinforced soil.

3.7. Post-cycling Monotonic Behavior of Unreinforced and Reinforced Anchor Systems

After stable cyclic loading, monotonic loading was applied to the anchor until failure occurred, highlighting the influence of cyclic loading on the degradation or increase of the ultimate capacity of anchor systems. Fig. 18 shows the load-displacement curve for initial monotonic loading, cyclic loading and post-cycling monotonic loading for \( D/B=2.0 \) and CLR of 30% and 60% for unreinforced and reinforced beds, respectively. Rao and Prasad (1991) reported a slight increase in post-cyclic loading capacity (i.e. the capacity of anchors subjected to the monotonic loading after a period of cyclic loading) under low amplitude cyclic loading (CLR less than 20%) and a reduction in the post-cycling uplift capacity with increase of CLR. Furthermore, the reinforced case shows more consistent post-peak ductile response, undergoing considerable displacement without significant loss of strength. On the other hand, there is a large reduction observing in the residual capacity (i.e. observation of increasing displacement with little change in loading or achieving an upward displacement of 20 mm) for the unreinforced case.

For unreinforced conditions, post-cycling loading was only applied at two different load levels - CLR of 20% and 30%. For reinforced conditions, post-cycling loads were applied at CLR of 40%, 50%, 60% and 70%. Fig. 19 compares the post-cycling monotonic uplift loads following different cyclic load levels for both unreinforced and reinforced conditions at \( D/B \) of 2. The general trend of uplift load versus upward displacement for post-cycling static load (Fig. 19) is same as for the purely static loading (c.f. Fig. 5), but there are some key differences. A distinct peak uplift load was observed for unreinforced conditions whereas no distinct peak was observed for reinforced conditions as shown in Fig. 19. This is also evident for the monotonic-only results (Fig. 5). The geocell-reinforced systems exhibited a stiffer response than the unreinforced system (Rahimi et al., 2018b). Post-cycling monotonic loading, even at small CLR, show a non-negligible reduction in both unreinforced peak and residual loads with the largest cyclic loads resulting in the greatest reduction in subsequent monotonic load capacity.
Table 5 shows a detailed summary of post-cycling monotonic loading at different embedment depths and cyclic load levels. Less than a 5% reduction is observed in the uplift capacity of the reinforced bed at the failure load level of the unreinforced case (CLR=40%), i.e. hardly any damage has been caused to the reinforced system under cyclic loading. This advantage is more significant in comparison to the equivalent reduction for the unreinforced installation, which is about 8% but at a much lower cyclic load level. At higher cyclic load levels there is a 15% reduction in both the peak and residual loads for the reinforced bed with CLR=40-70% whereas a 20% reduction occurs for peak and a 20-30% reduction for residual loads in the unreinforced bed at CLR=20 and 30%, respectively. This reduction in strength may be attributed to the progression of plastic deformation in the overburden material, which in the case of dense materials, may result in some level of softening. The presence of the reinforcement may reduce this accumulation of plastic strain within the overlying material during cyclic loading while also providing mechanical resistance against uplift when brought to failure, demonstrating less pronounced post-cyclic loss of anchor capacity in comparison to unreinforced conditions. It should be noted that this behavior may not applicable to loose, cohesionless materials. For example, Rao and Prasad (1991) reported up to 4% increase in post-cycling uplift capacity for low amplitude cyclic loading (SLR+CLR≤50%) in loose soils, likely owing to localized densification. On the other hand, they reported up to 20% decrease in post-cycling uplift capacity for heavily cyclic loaded condition due to the onset of strain localization and plastic deformation in the soil. That is, the same phenomenon that may densify loose soils may also loosen dense soils, subsequently decreasing post-cycling anchor uplift capacity (Schivan et al., 2017). This phenomenon illustrates the importance of considering both the peak and residual conditions when assessing ultimate anchor capacity in design. Overall, the reinforced bed has two main advantages in comparison to the unreinforced system (1) resistance against high cyclic loads and (2) post-cycling behavior without loss of peak and residual uplift capacity, which are very useful for long-term application of anchor to the environments that are prone to frequent cyclic loading.

4. Summary and Conclusions

This study presents the results of a set of experiments on the behavior of unreinforced and geocell-reinforced anchor plates placed in sand and subject to both monotonic and cyclic uplift loading. The cyclic and monotonic post-cycling responses of plate anchor buried in three different embedment depths in soil were evaluated. The experimental tests were performed with a fixed sustained load (ratio being 30% of the monotonic ultimate static uplift capacity of
the unreinforced bed) followed by cyclic load testing at various amplitudes for ≤250 cycles. The findings described below are valid for plate anchors of similar conditions of geometry, embedment depth, soil density, soil moisture, soil grain sizes and cyclic loading parameters. Key conclusions are as follows:

- Two general types of load-displacement behavior were observed under cyclic loading – a stable or unstable response. A stable response, characterized by decreasing rates of uplift displacement accumulation and by hysteresis loops of reducing area, was observed in most reinforced tests and in unreinforced cases subject to lower levels of loading. For unreinforced conditions, a CLR of 40% was identified as the threshold between a stable and unstable response.

- Accumulated displacement increases with cyclic load ratio and decreases with embedment depth ratio. The rate of accumulated displacement reaches a constant value after about 10 loading cycles. For the given geometry and materials, sustained displacement rates of more than 0.05 mm/cycle were indicative of likely progressive failure under excessive accumulated displacement.

- Where large cumulative displacements and unstable conditions occurred in unreinforced anchoring configurations (\(D/B=1.5, 2, 2.5\) under \(CLR=40\%\)) geocell reinforcement prevented excessive displacements. The maximum anchor upward displacement is decreased relative to the unreinforced scenario for all cyclic load ratios. The reinforced system exhibited a stable response under high amplitude cyclic loading. With the exception of one test (\(D/B=1.5\) under \(CLR=70\%\)), failure was not observed for reinforced conditions subject to \(CLR\) of 40, 50, 60 and 70%.

- For the unstable response (unreinforced case at \(D/B=1.5, 2, 2.5\) under \(CLR=40\%\) and reinforced case at \(D/B=1.5\) under \(CLR=70\%\)), the excessive anchor upward displacement causes significant heave of the soil surface local to the anchor rod.

- With an increasing number of loading cycles, the uplift pressure increases dramatically in the zone near to the axis of anchor, and diminishes at the edge of anchor, particularly in the unreinforced case. Comparison of soil pressure measured by inner and outer pressure cells (i.e. SPCI and SPCo) reveals that, under cyclic loading, stresses tend to be concentrated around the soil near the anchor rod, while the presence of reinforcement tends to distribute stresses over a larger area, preventing or delaying shear localization and improving anchor stability.
The post-cycling anchor load capacity of both the reinforced and unreinforced systems was less than their respective original static load capacities. The greatest reduction from initial to final monotonic load capacities was found in those installations that had received the largest magnitude of cyclic load amplitude. At the same cyclic stress level, more damage was observed (by means of the reduction from initial to final monotonic – peak and residual – load capacities) in the unreinforced than in the reinforced installations.

The experimental 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 tests provide insight into the possible use of geocell reinforcement in anchoring applications. Added testing on other soils, reinforcement types and full-scale conditions would further support its use in field application. Although the results provide an improved understanding of cyclic uplift behavior considering geocell reinforcements, it is critical that alternative configurations be scaled appropriately. This study, however, is insightful to represent near full-scale conditions and could be helpful in designing large-scale anchor model tests and their simulation by numerical models and methods. The presented results could possibly be generalized to different cyclic conditions, but this would require careful consideration of scale, particularly relating to larger anchor plate sizes, different soil properties (density and strength) and different geocell material properties. Although the general mechanisms and behavior observed in the model tests could be reproduced in real applications, further tests with large-scale model anchor plates should be conducted to validate the present findings at larger scales to determine the associated scale effects. Dimensional analyses may provide scaling laws that enable conversion of design parameters from model tests to more realistic dimensions used in design (e.g. scaling by a factor of \( \lambda \), representative of the ratio of width of prototype anchor plate to width of model anchor plate). By using the scaling law proposed by Langhaar (1951) and dimensional analysis of Buckingham (1914), it was deduced that the reinforcement used at full-scale requires a stiffness \( \lambda^2 \) times that of reinforcements used in the model tests to attain similar results, while the geometric should be increased by \( \lambda \). However, such conclusions should be validated in full-scale tests.

However, future work could extend the presented study to assess relevant design parameters, such as density and mechanical properties of soil, plate size, embedment depth, anchor type, reinforcement geometric configuration, and stiffness of geosynthetic materials. Future work could also consider the influence of geocell-infill interaction properties such as roughness and shape, type and stiffness of geosynthetic materials and presence...
of perforations to take into account the influence of varying geocell specification. In addition, different patterns
of cyclic loading and loading frequency can be considered in future studies.

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**Nomenclature**

- **B**: width of anchor plate
- **b**: width of geocell mattress
- **CLR**: cyclic load ratio (CLR=\(P_c/P_u\))
- **CLR\(_{cr}\)**: critical cyclic load ratio
- **d**: geocell pocket size
- **D**: embedment depth of anchor plate
- **G\(_s\)**: specific gravity
- **h**: height of geocell
- **\(P_c\)**: ratio of cyclic load amplitude to monotonic ultimate uplift capacity of unreinforced installation
- **\(P_r\)**: ultimate uplift capacity of reinforced installation
- **\(P_s\)**: ratio of applied initial sustained load to monotonic ultimate uplift capacity of unreinforced installation
- **\(P_u\)**: ultimate uplift capacity of unreinforced installation
- **SLR**: sustained load ratio (CLR=\(P_s/P_u\))
- **SPCi**: inner soil pressure cell
- **SPCo**: outer soil pressure cell
- **\(u_d\)**: anchor upward displacement
- **\(\gamma\)**: soil unit weight
- **\(\lambda\)**: the ratio of width of prototype anchor plate to width of model anchor plate
- **\(\phi\)**: soil angle of internal friction
- **\(\chi_{rein}\)**: ratio of outer pressure cell (SPCo) to the inner pressure cell (SPCi) at reinforced condition
- **\(\chi_{unrein.}\)**: ratio of outer pressure cell (SPCo) to the inner pressure cell (SPCi) at unreinforced condition

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| Fig. 18 | Variation of the uplift load with anchor movement (a) unreinforced case, D/B=2.0 and CLR= 30% (b) reinforced, D/B=2.0 and CLR= 60% |
| Fig. 19 | Post-cycling behavior of anchor plate at D/B=2 and different cyclic load ratio, CLR (a) unreinforced case (b) reinforced case |
**Table 1.** Engineering properties of the geotextile used in the tests

| Description                          | Value     |
|--------------------------------------|-----------|
| Type of geotextile                   | Nonwoven  |
| Material                             | Polypropylene |
| Area weight (gr/m²)                  | 190       |
| Thickness under 2 kN/m² (mm)         | 0.57      |
| Thickness under 200 kN/m² (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

| Type of layer                        | Average dry density (kN/m³) |
|--------------------------------------|-----------------------------|
| Unreinforced soil layer              | ≈18.78*                     |
| Geocell-reinforced layer             | Between 18.2 and 18.4      |

*approximately 92% of maximum dry density – see Sec. 2.1.

**Table 3.** Scheme of the uplift tests on anchor in unreinforced and geocell-reinforced backfills (h=100 mm, b/B=3, SLR=30%)

| Test Series | Type of Test              | Cyclic Load Ratio, CLR (%) | Embedment Depth Ratio, D/B | No. of Tests | Purpose of the Tests |
|-------------|---------------------------|----------------------------|-----------------------------|--------------|----------------------|
| 1           | Monotonic unreinforced    | -                          | -                           | 3            | Obtain the ultimate unreinforced capacity, performed first and comparison with post-cycling capacity. |
| 2           | Monotonic geocell-reinforced | -                          | 1.5, 2, 2.5                | 3            | Quantify additional capacity from reinforcement and comparison with post-cycling capacity. |
| 3           | Cyclic unreinforced       | 20, 30, 40                 |                             | 9            | Understand cyclic behavior of loaded anchor systems. |
| 4           | Cyclic geocell-reinforced | 40, 50, 60, 70             |                             | 12           | Quantify improvement of anchoring under cyclic loading. |
Table 4. Comparison of measured net soil pressure change due to cyclic uplift load in unreinforced and geocell-reinforced systems corresponding to peak of first (1st) and last (250th) lading cycles.

| D/B | CLR (%) | Unreinforced | 1st | 250th | 1st | 250th | Reinforced | 1st | 250th |
|-----|---------|--------------|-----|-------|-----|-------|------------|-----|-------|
|     |         | SPCi | SPCo | $\chi$ | SPCi | SPCo | $\chi$ | SPCi | SPCo | $\chi$ |
| 2   | 20      | 64   | 101  | 26   | 8    | 0.41 | 0.08 | --- | --- | --- |
|     | 30      | 76   | 113  | 31   | 8    | 0.41 | 0.08 | --- | --- | --- |
|     | 40      | 82   | 115  | 35   | 31   | 0.43 | 0.27 | 47  | 83   | 27   | 14   | 0.57 | 0.17 |
|     | 50      | ---  | ---  | ---  | ---  | ---  | ---  | 53  | 86   | 31   | 16   | 0.58 | 0.19 |
|     | 60      | ---  | ---  | ---  | ---  | ---  | ---  | 58  | 91   | 33   | 28   | 0.57 | 0.31 |
|     | 70      | ---  | ---  | ---  | ---  | ---  | ---  | 62  | 102  | 36   | 40   | 0.58 | 0.40 |

* Corresponding to pre-failure condition

Table 5: Static post cyclic capacity comparison with ultimate static capacity.

| CLR (%) | D/B=1.5 | P_{post-cycling}/P_{static} (%) | D/B=2.0 | D/B=2.5 |
|---------|---------|---------------------------------|---------|---------|
|         | Peak | Res. | Peak | Res. | Peak | Res. | Peak | Res. |
| Unrein. | Rein. | Unrein. | Rein. | Unrein. | Rein. | Unrein. | Rein. | Unrein. | Rein. |
| 20      | 91   | *    | 77   | *    | 93   | *    | 80   | *    | 92   | *    | 81   | *    |
| 30      | 82   | *    | 69   | *    | 83   | *    | 71   | *    | 84   | *    | 71   | *    |
| 40      | Fail | 95   | Fail | 97   | Fail | 96   | Fail | 98   | Fail | 96   | Fail | 96   |
| 50      | *    | 89   | *    | 92   | *    | 92   | *    | 92   | *    | 92   | *    | 88   |
| 60      | *    | 85   | *    | 85   | *    | 90   | *    | 85   | *    | 89   | *    | 87   |
| 70      | *    | Fail | *    | Fail | *    | 87   | *    | 84   | *    | 86   | *    | 85   |

* Test was not performed in these cases
Fig. 1. Grain size distribution curves for backfill soil

Fig. 2. A view of geocell spread over the anchor plate in the test pit
Fig. 3. Test installation prior to loading (a) actual physical model and (b) Schematic representation (units in mm)
Fig. 4. Schematic diagram of loading pattern

Fig. 5. Load-displacement behavior of anchor plate (a) unreinforced case (b) reinforced case
Fig. 6. Typical trend response (a) stable anchor upward movement with time (b) stable load-displacement hysteresis (c) unstable anchor upward movement with time (d) unstable load-displacement hysteresis
Fig. 7. Variation of the anchor uplift displacements with cyclic loading for the unreinforced case under different cyclic load ratio for (a) D/B = 1.5 (b) D/B = 2.0 and (c) D/B = 2.5
Fig. 8. Variation of the rate of upward displacement per cycle for the unreinforced case under different cyclic load ratio for (a) D/B=1.5 (b) D/B=2.0 and (c) D/B=2.5
Fig. 9. Anchor response at CLR$_{cr}$=40% and D/B=2.0 for unreinforced and reinforced case (a) upward displacement variation (b) load hysteresis.

Fig. 10. Anchor response at CLR$_{cr}$=40% for reinforced and unreinforced (repeated) at different embedment depth ratios (a) variation of anchor movement (b) accumulated displacement rate.
Fig. 11. Heave of soil surface at the end of the cyclic loading for CLR=40% and D/B=2 (a) unreinforced bed (b) reinforced bed.

Fig. 12. Heave height at soil surface respect to anchor centerline at the end of the cyclic loading with CLR=40% for unreinforced bed (20 mm anchor displacement) and reinforced bed (after 250 loading cycles).
Fig. 13. Load displacement hysteresis for reinforced case at $D/B=2$ for different cyclic load ratios (a) CLR=50%, (b) CLR=60% and (c) CLR=70%
Fig. 14. Load displacement loop at 1st, 10th, 100th and 200th cycle for reinforced case at D/B=2 for different cyclic load ratios (a) CLR=50%, (b) CLR=60% and (c) CLR=70%
**Fig. 15.** Variation of the anchor upward movement with number of load cycles for the reinforced case under different cyclic load ratio for (a) $D/B=1.5$ (b) $D/B=2.0$ and (c) $D/B=2.5$
Fig. 16. Variation of the rate of upward displacement per cycle for the reinforced case under different cyclic load ratio for (a) $D/B=1.5$ (b) $D/B=2.0$ and (c) $D/B=2.5$
Fig. 17. Typical trend of soil pressure at location of (a) $SP_{Ci}$ (b) $SP_{Co}$, and soil pressure measured at $D/B=2$ under different CLR for (c) unreinforced bed (d) reinforced bed.
Fig. 18. Variation of the uplift load with anchor movement (a) unreinforced case, $D/B=2.0$ and $CLR=30\%$ (b) reinforced, $D/B=2.0$ and $CLR=60\%$.

Fig. 19. Post-cycling behavior of anchor plate at $D/B=2$ and different cyclic load ratio, $CLR$ (a) unreinforced case (b) reinforced case.