Performance of circular footings on sand by use of multiple-geocell or -planar geotextile reinforcing layers

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Abstract: This paper describes a series of reduced scale tests, at unit gravity, performed on circular footings supported by reinforced sand. Reinforcement by multiple layers of geocell was investigated and performance of the footing was compared to one on the same sandy soil containing multi-layered planar geotextile reinforcement. The comparison used geocell and geotextile layers formed from the same parent geosynthetic material having the same characteristics but with less mass of geocell. Results show that the reinforcements' efficiency (described in terms of the load carrying and subgrade modulus enhancement) decreased as the number of layers increased. In tests at moderate and low footing settlements, significant improvements in bearing capacity and subgrade modulus were obtained with the application of three layers of geocell. On the whole, multi-layered geocell-reinforced soil provides a more effective and much stiffer system that can deliver greater foundation loads and subgrade modulus, as compared to the multi-layered planar-reinforced soil, even when less parent geosynthetic material is used in the multi-layered geocell arrangement. Furthermore, reinforcement benefit is achievable at settlements as small as 0.2-0.4% of footing diameter for the geocell installations whereas settlements 4 to 5 times larger are needed before benefit is gained from a comparable planar geotextile system. To achieve comparable performances, the multi-layered geocell requires 1/4 to 1/2 the mass of geosynthetic material as needed in the form of a multi-layered planar geotextile reinforcement (depending on the settlement allowable). The multi-layered geocell reinforcement needs considerably less parent geosynthetic (reducing transport and, perhaps supply costs) and reduces the size of reinforcement zone required, consequently reducing excavation and the amount of backfill required.

Keywords: Multi-layered geocell; Multi-layered geotextile; Bearing pressure; subgrade modulus; Circular footing

1. Introduction

Geosynthetic materials have been increasingly used in a variety of geotechnical engineering applications including ground stabilization beneath embankments, pavements, and shallow strip footings (e.g., Raymond 2002; Giroud and Han, 2004a;b; Zhou and Wen, 2008; Thakur et al., 2012; Tanyu et al., 2013). Numerous studies have examined the benefits of multiple layers of planar reinforcement for the bearing capacity and settlement of foundations (e.g., Sharma et al., 2009; Alamshahi and Hataf, 2009; Madhavi Latha and Somwanshi, 2009; Sadoglu et al., 2009; Lovisa et al., 2010; Moghaddas Tafreshi et al., 2011; El Sawwaf and Nazir, 2012; Nair and Madhavi Latha, 2014; Asakereh et al., 2013; Abu-Farsakh et al., 2013; Chakraborty and Kumar, 2014; Chen and Abu-Farsakh, 2015).

The majority of studies have focused on planar geotextiles and geogrids; however, several investigations have also highlighted the beneficial use of single layer of geocell reinforcement in the construction of foundations and embankments over soft soil (Krishnaswamy et al., 2000; Madhavi Latha et al., 2006; Sireesh et al., 2009; Pokharel et al, 2010; Dash, 2010; Moghaddas Tafreshi and Dawson, 2010a,b; Boushehrian et al., 2011; Han et al., 2011; Yang et al., 2012; Chen et al., 2013; Moghaddas Tafreshi et al., 2013; 2014; Indraratna et al., 2015). Dash et al. (2003) reported the beneficial ability of geocell constructions to improve the bearing capacity of circular footings supported on geocell-reinforced sand overlying soft clay.

Sireesh et al. (2009) carried out a series of laboratory scale model tests on a rigid circular footing with diameter of 150 mm, supported by geocell-reinforced sand layers overlying a clay bed that contained a cylindrical void with diameter of 95 mm and length of 900 mm to simulate a micro-tunnel or similar. The soil beds were prepared in a test tank with inside dimensions of 900×900×900 mm. Substantial improvement in performance was obtained by the provision of a geocell mattress, of adequate size, specifically when the geocell mattress spread beyond the void, a distance at least equal to the diameter of the void. The vertical distance between the geocell mattress and the void, beyond which there is insignificant influence of the void on the performance of the footing, is about 1.8 times the diameter of the footing. Han et al., (2011) conducted full-scale accelerated pavement tests to evaluate the effect of one layer of geocell reinforcement on recycled asphalt pavement base courses over weak subgrades. They reported the benefits of geocell reinforcement in terms of reduced rut depths for a defined number of passes of the wheel loads. Together, these previous works, by a variety of authors, have delivered a better understanding of the behaviour of foundations supported by multiple layers of planar reinforcement and by single geocell layers. Although the present authors have contributed to the understanding of the behaviour of foundation beds reinforced by single geocell layers under static and repeated loads (Moghaddas Tafreshi and Dawson, 2010a,b), yet there remains a lack of study into the behaviour of foundations supported by multi-layered geocell reinforcing layers and it is this aspect on which the present paper places emphasis.

Geosynthetic inclusions will be most effective if used in the zone significantly stressed by the footing because it is there that the strains are largest and, hence, the geosynthetic has greatest opportunity to modify the strain pattern in the soil. Although the extent of the highly stressed zone beneath the footing base depends on soil and geosynthetic properties, according to Boussinesq's stress field in a semi-infinite medium (Boussinesq, 1885), the vertical stress reduces to about 28% of the applied surface vertical stress at 1 diameter and to about 15% at a depth of 1.5 diameters. Thus the benefit of geosynthetic inclusions can be expected to become minimal at depths greater than these.

Footings where geosynthetic reinforcement may be beneficial include outrigger pads for cranes and similar plant, as foundations at the corners of demountable seating banks, as pad foundations of low-rise housing that is raised off the ground for reasons of ventilation or flood-damage avoidance, from corner loads imposed by container stacks at docks, etc. Since most manufacturers of geocell produce them only at heights less than or equal to 200 mm (typically at 25-200mm), the use of a single layer of geocell as thick as 1.5 m beneath the footing is impossible. Even if a very thick geocell were available, such a thick geocell layer would likely make compaction of cell-fill extremely difficult (as reported by Han et al., (2011) and as observed by the authors), probably negating any reinforcement benefit. Hence, the use of several layers of geocell (e.g. 3 or 4), each with a thickness ≤200 mm, spaced at regular vertical intervals in the zone significantly stressed by the footing is a practical alternative and could be a beneficial means of reinforcing the soil beneath a footing. For this reason, this article addresses the perceived deficiency in the number of studies investigating the performance of multi-layered geocell reinforcement.

2. Aims

Given the potential of geosynthetic reinforcement to provide improved foundations in the way described in the previous section, a series of reduced scale tests were performed to:

a) evaluate the performance of such circular footings when supported by soil reinforced with multi-layered geocell (fabricated from a geotextile),

b) demonstrate the relative benefits of multi-layered geocell reinforcement systems as compared with planar reinforcement systems that used a lower mass of the same type of geotextile material.

The parameters varied in the study include the vertical spacing between reinforcement layers and the number of reinforcement layers below the footing.

3. Model Tests

A physical test was used to provide close-to realistic test conditions (i.e. realistic geosynthetic and soil materials at near full (field)-scale). The schematic representation of the physical test setup and its attachments comprising a testing tank, loading system and data measurement system, is shown in Fig. 1.

3.1. Testing tank

The test tank is a rigid box with plan dimensions of 1000 mm × 1000 mm, and 1000 mm depth. The back and side faces of the tank consist of smooth MDF sheets of 20 mm thickness. The front face of the tank is made of 20 mm thick plexiglass. This permits observation and measurement below surface in plane-strain tests, although the test conditions of the experiments described in this paper obviated the need to take measurements in this way. To prevent undesirable movement of the four sides of the tank, the rigidity of the tank has been stiffened using steel section (U-100) on four sides of the tank. Under a maximum applied loading of 1000 kPa on the footing model, the measured deflections of the sides of the tank, using four dial gauges installed perpendicular to the four sides of the tanks were very small, demonstrating that there would be negligible displacement at the stress levels applied in the main test program described below. This confirmed the suitability of the test tank for the work described here.

All tests were performed using a rigid steel plate of 112.8 mm diameter (*D)* and 20 mm thickness, being a scaled circular footing. The footing was placed at the centre of the soil surface on the backfill. The width and depth of the test tank is thus about nine times as large as the footing diameter, so the boundary effect on the test results was considered to be small. This assumption was verified in some of the tests reported here (both reinforced and unreinforced tests), by horizontal observations through the plexiglass and by vertical measurement. In these tests it was observed, using a straight edge to determine the location of soil unaffected by heave, that the soil surface showed no visible bulging beyond 5, 4 and 3 radii from the loading axis for unreinforcrd, geotextile-reinforced and geocell-reinforced soil beds, respectively. For reinforced soils, the limit of the affected soil was always within the extent of the reinforced zone. These observations give confidence, for all tests, that the boundary effect of the testing tank walls on the results was insignificant, even at the largest settlements. Slip line interpretation of this heave would mean that any rupture planes were in a zone less than ¼ of the box depth and less than 40-50% of the box width. Furthermore, the results to be presented later in this paper show the benefit of multi-layer geocell and geotextile reinforcements in reducing settlement and, hence, significant stress changes and associated strains will, likely, be local to the model footing.

The zone of significant stress increase due to the footing would, of course, extend somewhat further than ¼ of the box depth and 40-50% of the box width but, typically, stress gradients beyond rupture planes are very steep indicating that, once the test box boundary is reached, the stresses will have changed insignificantly (e.g. Panagiotidou et al. (2010)). Furthermore, the results to be presented later in this paper show that the greatest benefit of multi-layer geocell reinforcement is likely to be when settlements are small and, hence, significant stress changes and associated strains will be local to the footing. Taken together, these factors indicate that the boundary effect on the tests is likely to be insignificant.

3.2. Loading system

The loading system includes a loading frame, a hydraulic cylinder, and a controlling unit. The loading frame consists of two stiff and heavy steel columns and a horizontal beam that support the hydraulic actuator. The actuator may produce monotonic or repeated loads with a maximum capacity of 20 kN. In all tests, load was applied monotonically at a rate of 1.0 kPa per second.

3.3. Instrumentation

The instrumentation system was developed to read both load and settlement automatically. An S-shaped load cell with an accuracy of ±0.01% and a full-scale capacity of 20 kN was placed between the loading shaft and the footing to precisely measure the applied load. Although, no significant differential settlement across the diameter of the footing (loading plate) was observed, nevertheless the average settlement of the footing(s) was monitored during loading by two linear variable differential transducers (*LVDTs*) with an accuracy of 0.01% of full range (100 mm), located on diametrally opposite edges of the footing. All of the devices were calibrated prior to each series of tests.

4. Material properties

4.1. Geocell and geotextile reinforcements

The geocell used in the current research was commercially fabricated from the same type of a non-woven polymeric fabric as used to make the planar geotextile used in the present experiments. Although planar layers of non-woven geotextile have rarely been used in practice for reinforcement, their importance here is as a reference to which the use of the same parent fabric manufactured as geocells may be compared. The geocell comprises geotextile strips that had been thermo-welded into a cellular system providing confinement chambers for aggregate infill. The high tensile strength of both the weld and geotextile provides an ideal structure that prevents infill from spreading thus reducing subsidence (of foundations) and rutting (of medium to light trafficked surfaces). The authors recognize that the particular planar geotextile and geocell materials selected for the experiments do not provide a precise, scaled, replica (in terms of stiffness or geometry) of the materials available at full-scale. This issue is discussed in more detail in Sections 8 and 9. Nevertheless, the emphasis of this paper is the *relative* behaviour of the geocell- and geotextile-reinforced systems (for which any scaling limitations should be similar), and for these there should be a high comparative reliability.

The geocell pocket has a non-circular shape (see Fig. 2), thus the pocket size (d) of the geocell is taken as the diameter of an equivalent circular area, with the pocket opening area being as shown in Fig. 2. The pocket size of the geocell used was kept constant (d=50 mm), while the geocell was used at a constant thickness (H_g) of 25 mm in this testing program. The ratio of the geocell pocket size (d) to diameter of circular footing ($D=112.8\ mm$) is, thus, 0.45

(d/D=0.45). Dash et al. (2001) in their studies on strip footings supported by geocell-reinforced sand, reported that the bearing capacity of footings increases with decrease in pocket size, due to the overall increase in confinement effect of geocell pockets and rigidity of the mattress. As the pocket size increases, the confinement reduces and hence the soil moves more freely out of the pockets leading to smaller load carrying capacity. Rajagopal et al. (1999) also observed a similar influence of the pocket size on the behaviour of geocell-reinforced sands. It should be noted that for the small footing diameter relative to the size of the geocell pocket, local effects might be created by the position of the cell walls relative to the footing. Therefore an increase in d/D (bigger pockets/smaller footings) might reduce any reinforcement benefit as discussed further in Section 9.

Fig. 2 shows an isometric view of the type of geocell used in the investigations. The non-woven geotextile used as planar reinforcement was also used as the material forming the geocell. Both were made and supplied by the same company. The engineering properties of the geotextile (and, thus, of the geocell walls) are presented in Table 1. The strength and stiffness of the geocell joints are reported by the manufacturer to be equal or greater than the geotextile strength (Treff, 2011).

4.2. Soil

The soil used is a relatively uniform silica sand of rounded grain sizes between 0.85 and 2.18 mm. The specific gravity of this soil was measured in laboratory as 2.68 (G_s=2.68) in accordance with ASTM D 854. The grain size distribution of this sand is also shown in Fig. 3. The properties of the sand, which is classified as SP in the unified soil classification system (ASTM D 2478), are given in Table 2.

5. Test preparation and procedure

The schematic layout of the geocell and geotextile reinforcement is shown in Figs. 4 and 5, respectively. In this study, the backfill layers were prepared by compaction of soil into the testing tank in both unreinforced and reinforced systems using static loading, to a target relative density of 85%. Density was assessed using sand cone tests in accordance with ASTM D1556-07. Due to hole instability during assessment, it is conceivable that the assessed density was not a valid reflection of the true value. However, the difference between the mean assessed density, as measured several times by the cone tests, and the target density value was 3% or less. This difference seems to be small for geotechnical applications and indicates a reliable, repeatable method even if the true density may be systematically offset from the desired 85% relative density target. Unfortunately, there was no means of checking available to the authors. The close match in the pressure-settlement variation of two or three repeated tests under the same test conditions (See Table 3) also strongly implies that the density was consistent.

Compaction was achieved by means of a hydraulic cylinder (using the same hydraulic cylinder as later applied the static load during each test). This applies a constant pressure on a stiff wooden plate (990 mm × 990 mm in plan dimension). Thus a 5 mm wide gap was provided on each side of the tank to prevent contact between the wooden plate and the sides of the tank. The applied stress and number of compaction repetitions for the different thicknesses of soil layers and for the geocell layer with thicknesses of 25 cm were manipulated to achieve the same assessed soil density for both unreinforced and reinforced installations in all tests. The target density was obtained for the thickness of unreinforced layers (about 15, 20 and 25 mm) by using a fixed pressure of 15 kPa applied on the surface of soil layer, (one, two and three times, respectively). For the geocell-reinforced layer 25 cm thick, the same assessed density was achieved by using a fixed pressure of 20 kPa, applied once.

In the case of the unreinforced foundation, the soil was compacted in 25 mm thick layers until the soil reached the footing level. In the case of the planar and geocell reinforcement, the unreinforced soil was compacted in 25 mm thick layers until the soil reached the first reinforcement level. Thereafter the first layer of planar or geocell reinforcement was placed on the surface of the soil, after which the soil compaction was continued until the desired level for the second layer of reinforcement was achieved. Cell pockets in the geocell were filled with soil so as to include 1 cm thickness of extra soil over the geocell and thereafter the compaction was continued. The preparation of the reinforced soil, using one to four layers of reinforcement, was continued up to the footing level.

The base of the circular footing was made rough by covering it with epoxy glue and rolling it in sand. The footing was placed at the centre of the soil surface backfill. The load cell was placed on the loading shaft, via a hemi-spherical connection designed to maintain vertical loading alignment, so as to record the applied loads, and the LVDTs were connected (see Section 3.3). Load was applied monotonically at a rate of 1.0 kPa per second until peak load or a settlement of s/D=25% had been reached. In the absence of a peak load capacity being observed, such a large settlement indicates that serviceability failure for a footing has been substantially exceeded and relates to Vesic's (1973) assertion that an approximately constant value or steady, but low, rate of increase in applied stress represents failure. For practical use of footings, much lower settlement ratios would be tolerable, so it is the load capacity at these lower settlements that is of real importance and will be investigated further in this paper.

6. Test parameters and testing program

In addition to the information as shown in Figs. 4 and 5, the details of the both geocell and planar-reinforced tests are given in Table 3. In the case of geocell-reinforced soil, three series of tests (Test series 2, 3 and 4) were conducted by varying the number of geocell layers (N_g) and the vertical spacing of geocell layers below the footing (h_g). Likewise, in the case of the geotextile-reinforced soil, three series of tests (Test series 5, 6 and 7) were conducted by varying the number of geotextile layers (N_p) and the vertical spacing of the geotextile layers below the footing (h_p). Tests Series 1 was performed on unreinforced sand to quantify the improvements due to reinforcement.

The assessment of performance was undertaken for ‘twinned’ arrangements: each pair has one ‘twin’ containing one or more planar sheets while the other ‘twin’ contains the same number of layers of geocell reinforcement. The dimensions of each ‘twin’ in the pair was derived from earlier experiments (Moghaddas Tafreshi and Dawson, 2010a, 2012) in which the same mass of geosynthetic had been used in each ‘twin’ (i.e. the same area of raw geosynthetic material had been used in each member of the pair although in the case of the geocell, it had been cut, folded and bonded to form the geocell which then had a smaller plan area in the ground than did its planar ‘twin’). The width of the geocell and geotextile layers (b_g for geocell and b_p for geotextile) and the depth to the top of the first geocell and geotextile layer below the footing (u_g for geocell and u_p for geotextile) are expressed in non-dimensional form with respect to footing diameter (D).

However, there are two important differences between the study described in the present paper and the earlier study by Moghaddas Tafreshi and Dawson, (2010a, 2012). Firstly, the earlier study used a strip footing (i.e. plane-strain conditions applied) and secondly the loaded area was smaller – the footing in earlier study had a width of 75 mm and a length of 148 mm – i.e. an area approximately 10% smaller than provided by the circular footing used in the test program described in this paper. Moghaddas Tafreshi and Dawson, (2010a, 2012) recommended values of the above parameters as b_g/D= 3.2, b_p/D= 4.1, u_g/D=0.1 and u_p/D=0.32 because further reduction in settlement began to require excessive additional reinforcement mass. The ratio b_p/b_g in that earlier study was, thus, 4.1/3.2 = 1.28 which represents the ratio of the masses per unit area of a geocell:planar ‘pair’, i.e. in Moghaddas Tafreshi and Dawson’s study the same mass of reinforcement was used in both members of the ‘pair’.

The same b_g, b_p, u_g and u_p values were used and kept constant in the axisymmetrically loaded tests described here. It means that the mass of the geosynthetic material in the geocell will now be less than in its planar geotextile 'twin' by a factor of approximately 1.28, because the geocell is now shorter in 2 directions, not just one (i.e. the area covered by the planar geotextile is now 1.28^2 larger than that covered by the geocell, but the geocell mass/m^2 is only 1.28 times greater than the mass/m^2 of the planar geotextile). As the results will show, later in this paper, the performance of the geocell 'twin' always exceeded that of the planar 'twin' so the geocell's reduced relative mass is not a hindrance to the objective of the paper to make a comparative study of the efficiency of the two types of reinforcement and only serves to further emphasize the geocell's superiority.

The adopted b_g, b_p, u_g and u_p values may, therefore, be sub-optimal for the axisymmetric case, but in the absence of a detailed study, the authors note that Terzaghi's shape factor for bearing capacity suggests only a 32% ultimate load difference between strip and circular arrangements (based on assumptions of matching loaded area). This suggests that the preferred geometric arrangements should not change significantly from plane-strain to axisymmetric cases.

Two variable parameters, h_g and h_p, expressed non-dimensionally as a function of footing diameter (D) as h_g/D and h_p/D, are used to describe the vertical spacing of the reinforcement between the bottom of the previous layer and the top of the next layer.

Many of the tests were repeated to examine the performance of the apparatus, the accuracy of the measurements, the repeatability of the system, reliability of the results and finally to verify the consistency of the test data. The pressure-settlement variation of two or three repeated tests having the same test conditions, gave a close match with a maximum difference in results of around 8-10%. This difference was considered to be small and is subsequently neglected. It demonstrates that the procedure and technique adopted can produce repeatable tests within the bounds that may be expected from similar geotechnical testing apparatuses. The tests were repeated two or three times as specified by "*" and "**" in Table 2, respectively.

7. Results and discussions

The performance improvement due to the provision of reinforcement is represented using a non-dimensional improvement factor which compares the subgrade modulus (i.e., coefficient of subgrade reaction, k) of the footing on the planar geotextile (subscript 'p') or geocell (subscript 'g') reinforced soil to that of the unreinforced (subscript 'un') soil at a given settlement, s. The subgrade modulus k, is the secant modulus (i.e. the slope of the line joining the point on the stress-settlement curve, at a given settlement, to the origin) calculated at different footing settlements. Thus, the subgrade modulus improvement factor (Ik) at different footing settlements is defined as $Ik_p = k_p/k_{un}$ *for the planar reinforcement* and as $Ik_g = k_g/k_{un}$ for the geocell reinforcement (where $k_{un.}$, k_p and k_g are the subgrade modulus values of the unreinforced bed, the planar-reinforced bed and the geocell-reinforced bed at a given settlement, respectively).

7.1. Determination of the optimum value of h_g/D **and** *h_p/D ratios*

For the geocell reinforcement case, the optimum value of vertical layer spacing, as defined by the non-dimensional ratio h_g/D, was obtained from Test Series 3 (Table 3). Using two layers of geocell (N_g=2), Fig. 6 shows that the subgrade modulus improvement factor (Ik_g), initially, slightly increases as h_g/D increases from 0 to about 0.36, but that, thereafter, the value of Ik_g decreases with further increase in vertical distance between two geocell layers (h_g/D). Yoon et al. (2008), in their studies on a circular plate of diameter of 350 mm resting on sand reinforced with multiple layers of 'Tirecell' (made from treads of waste tires), reported that the effectiveness of their 'Tirecell' reinforcement was highest for a vertical spacing of reinforcement layers of 0.2 times the plate diameter. The present study on the effect of vertical spacing between reinforcement layers (h_g/D) gives a greater optimal spacing than that reported by Yoon et al. (2008), probably due to differences in the footing size, the soil properties, types of 3D reinforcement (geocell reinforcement fabricated from a type of a geotextile in this paper compared to the 'Tirecell' made of waste auto-tires in Yoon et al., 2008) and the geometric dimensions of the reinforcement.

For the geotextile reinforcement case, the subgrade modulus improvement factor (Ik_p) with h_p/D, for two layers of geotextile (N_p=2), at different values of settlement, is depicted in Fig. 7 (Test Series 6 in Table 3). Both Figs. 6 and 7 reveal optimum values of h_g/D and h_p/D, approximately 0.36 and 0.4, respectively. As anticipated, regardless of spacing of geocell or geotextile, the subgrade modulus is always greater than in the unreinforced case (i.e. the values of Ik_p and Ik_g are always greater than one) and this reinforcement effect increases with settlement.

Extensive earlier studies (e.g. Bathurst et al., 1986; Yetimoglu et al., 1994) showed that the optimum depth of a single geosynthetics sheet is at around 0.25*D* to 0.4*D*, because, at this depth, the largest value of outward shear is induced in the soil beneath the footing and the tensile load capacity of the geosynthetics is thereby mobilized and reinforcement achieved. In the present experiments the depth to the top geotextile layer, u_p, is 0.32*D* so is likely to be in, approximately, the optimum position. If other layers are added below this layer, then they can only be expected to contribute benefit if h_g/D (or h_p/D) is small enough for the interaction between layers to be significant, otherwise the lower layers will be too deep to interact with the stresses imposed by the footing and the system will behave as though it were reinforced with a single layer of reinforcement at a depth of u_g (or u_p) (note: desirable u_g and u_p values are likely to be partly a function of the soil friction; u_p is small, so there is little opportunity for this to change significantly, but u_g is larger and might not be close to 0.32*D* for other soils). Therefore the lines in Figs. 6 and 7 must be asymptotic to such a condition: i.e. indicative of the reinforcement that would be achieved by a single layer of reinforcement.

However, the composite system comprised of soil with multiple layers of geocell can clearly deliver reinforcement that is much greater than that provided by a single geocell layer at the same depth. This is demonstrated by comparing the value of Ik_g in Fig. 6, at a (close) geocell layer spacing value of h_g/D = 0.36, with its asymptotic value at high h_g/D when the lower layers are certain to be contributing little or nothing to the reinforcing effect. All the lines on Fig. 6 show reinforcement benefit, revealing that reinforcement is realised even at low settlement values, *s/D.*

On the other hand, Fig. 7 demonstrates that extra geotextile reinforcing layers at the optimum spacing of 0.4D only begin to have a significant benefit once there is large displacement (perhaps greater than about 6% of footing diameter) when significant strains can be expected deeper into the soil, reaching lower layers. Hence, it is possible to conclude that a multi-layer geocell acts differently from a multi-layer geotextile. It may be surmised that (when vertical geocell spacing is small) the first layer of geocell acts to pass the stress field imposed by the foundation deeper into the soil where the second layer of reinforcement provides some of the tensile capacity to oppose the outward shear even under low settlements. This response may be contrasted with that of the geotextile installation at similar vertical spacing where the second layer appears to have little or no effect until the upper layer's reinforcing potential has been fully exploited. Although, definitive confirmation that the different layers of reinforcement act compositely would require contemporaneous measurement of reinforcement strain within each layer (or the results of a calibrated numerical model) which could be investigated in future study, the results do show that, at appropriate spacing, the upper and lower geocell sheets act at the same time to resist loading whereas the two geotextile layers provide a more sequential resistance to loading.

Hence, to make a comparative study between multi-layered geotextile and multi-layered geocell-reinforced soils, the spacing ratios h_g/D = 0.36 and h_p/D = 0.40 (i.e. the previously identified preferred values) were subsequently used for all layers, except where noted otherwise.

7.2. The general behaviour of the multi-layered geocell and multi-layered planar reinforcement

Fig. 8 presents the bearing pressure-settlement behaviour of geocell- and planar-reinforced foundations when the layers of geocell and geotextile were placed at (u_g/D=0.1 and h_g/D=0.36) and (u_p/D=0.32 and h_p/D=0.4), respectively. For any matching pair of geocell and planar reinforcement (N_g = N_p=1; *etc*.), the width of geocell and geotextile reinforcement are kept constant (as before, at b_g/D= 3.2, b_p/D= 4.1, respectively) and the mass of geosynthetic material in the geocell will be 1.28 times less than that in its 'twinned' planar geotextile installation. It may be observed that, with increasing the layers of reinforcement (increase in the mass of the geocell and geotextile reinforcement and consequently the increase in the depth of the reinforced zone; Z_R) both stiffness and bearing pressure (bearing pressure at a specified settlement) increase considerably. In the case of the unreinforced soil, it is apparent from Fig. 8 that the peak bearing pressure has taken place at a footing settlement equal to approximately 13% of footing diameter while in case of both the geocell- and geotextile-reinforced soil, no clear failure point is evident.

For the reinforced soil, beyond a footing settlement level of s/D=8-14%, there is a noticeable reduction in the slope of the pressure-settlement curve (the ratio $\Delta q/\Delta(s/D)$ reduces). At this range of settlement, heave of the fill surface became observable by the naked eye in the form of distinct changes of gradient. At the end of the test, exhumation revealed that his heave was attributable to the soil-reinforcement composite material rupturing locally close to the footing, because of the latter's large displacement. Beyond this stage, the slopes of the pressure-settlement curves for the moderately- and heavily-reinforced cases remain almost constant while the footing bearing pressure increases continuously, but gradually, as further mobilization of reinforcement and anchorage is exploited.

7.3. Relative performance due to multi-layered geocell and multi-layered geotextile reinforcement

Fig. 9 shows the variation of the subgrade modulus with number of reinforcement layers at three levels of settlement (s/D=4%, 8% and 12%) when the layers of geocell and geotextile were placed at h_g/D=0.36 and h_p/D=0.4, respectively. From this figure, it can be seen that for the multi-layered geocell, the increase in the modulus with increase in the number of geocell layers is significant up to three layers (N_g=3), whereas for greater N_g the benefit is marginal. In contrast, Fig. 9 shows that the performance improvement in modulus due to the provision of planar reinforcement, might continue beyond 4 layers (N_p>4). The results shown as Fig. 9 also indicate that, at the same number of layers of reinforcement, the geocell system delivers a better performance than does the geotextile system. The subgrade modulus also decreases with settlement ratio, although at all settlements the comparable geocell installations remain stiffer than the planar installations, probably for the reasons alluded to in Section 7.1.

In order to investigate clearly the performance of the geocell reinforcement and planar reinforcement in increasing the subgrade modulus of a reinforced bed due to increase in the number of the geocell layers (N_g), or in the number of layers of the planar reinforcement (N_p), compared to the unreinforced one, the variation of the subgrade modulus improvement factor (Ik_g & Ik_p) with number of reinforcement layers is shown in Fig. 10. In all situations, the values of Ik_g and Ik_p are larger at greater footing settlement for both planar and geocell cases, with greater reinforcement as the footing penetrates further (attributable to greater mobilization of tensile strain in the reinforcement layers and to the confinement provided between layers by the reinforcement).

For the multi-layered geocell, no significant improvement in performance is achieved when the number of geocell layers is more than three ($N_g \geq 3$). Therefore, when three layers of geocell are located at h_g/D =0.36, the maximum zone of soil that can usefully be reinforced extends to a depth of approximately 1.48D (Z_R= 1.48D, see Table 4). In contrast, Fig. 10 shows that the performance improvement due to the provision of planar reinforcement may continue beyond 4 layers (N_p>4 with reinforcement zone of Z_R>1.52D, see Table 4). Fig. 10 also shows that improvement in subgrade modulus is greater for geocell reinforcement than for geotextile reinforcement, irrespective of settlement ratio of the footing. For example, for $N_g = N_p = 3$ and a settlement ratio of s/D = 4%, the geocell installation improves the subgrade modulus by 84% more than the compared to the planar installation.

The comparative investigations in Figs. 9 and 10 imply that in order to achieve a specified improvement in subgrade modulus, considerably less mass of geosynthetic material would be used in a geocell implementation compared to a planar one. Alternatively, by comparing, for example, the improvement due to two layers of geocell reinforcement (N_g=2) with the improvement due to four layers of planar reinforcement (N_p=4) at a settlement ratio of 4%, both are shown to have a similar subgrade modulus (Fig. 9) and, hence, a similar subgrade modulus improvement factor (Fig. 10), yet the geocell installation contains approximately 40% of the mass of geosynthetic material (i.e. 2/(4*1.28)≈0.4). If this type of calculation is repeated at other settlement ratios, values between about 0.25 and 0.5 are obtained. Also, Table 4 shows that the reinforcement zone depth beneath the footing (Z_R) for four layers of planar reinforcement (Z_R= 1.52D) is approximately 1.68 times larger than for two layers of geocell (Z_R= 0.9D).

Overall, the results show that the geocell system provides a better performance than does the geotextile system, so that the same or greater improvement in vertical stiffness and much shallower required zone of reinforcement can always be gained by significantly less geotextile material employed in an arrangement of geocell layers than in planar sheets (Table 4). Whether this is also associated with an economic benefit will depend on the fabrication costs of the geocell material, the reinforcement zone depth beneath the footing (i.e., excavation and backfilling) and on any difference in soil backfill material and procedure.

7.4. Relative performance of multi-layered geocell system and multi-layered geotextile systems for footing settlement ratios, s/D, of less than 2%

For most practical purposes, performance of reinforced systems at low footing settlement ratios, s/D (say, less than 2%) is critical, hence footing performance at such low settlements is made the subject of Fig. 11. The layers of geocell and geotextile were again placed at their preferred positions beneath the footing (u_g/D=0.1, u_p/D=0.32, h_g/D=0.36, and h_p/D=0.4). Again, comparing the 'twinned' geocell and geotextile installations, the multi-layered geocell reinforcement system is both stiffer and more effective than the system with multi-layered planar reinforcement system. Furthermore, benefit of the geocell reinforcement is gained at very low settlement ratios (S/D = 0.4%) whereas, in the case of planar reinforcement, the benefit only appears at footing settlement ratios of around 1-1.5%. At low settlements, apparently before the planar geotextile has attracted loading to itself, planar installations may actually lead to a softer response than when unreinforced. The cause of this is uncertain but is probably indicative of a lower geotextile-soil interface friction than soil-soil friction at a point in the loading sequence before the geotextile has been tensioned and is able to deliver benefit. Similar results were observed in the pressure-settlement of geotextile and geogrid reinforcement (Madhavi Latha and Somwanshi, 2009) and of geocell reinforcement (Dash et al., 2001; 2003).

It is likely that the better performance at low settlement levels of the multi-layered geocell, compared with that of the multi-layered geotextile, is due to the geocell system gaining its resistance from the soil confinement that occurs when localized hoop stresses are developed in the walls of cells close (vertically and horizontally) to the footing. In a planar system, reinforcing action requires outward shear stress to be developed in the horizontal plane between the geotextile and soil throughout a zone whose size is controlled by the load spreading achieved in the soil between the footing and the uppermost geotextile layer. Such shear strains are not thought to be necessary in the geocell system, as localized compression alone will be sufficient to generate the hoop strain.

8. Scale effects

When conducting a model test at a reduced scale, the scale effects prevent direct comparison to a full-scale prototype. Thus, it is necessary to consider the scale effects to properly simulate material properties (e.g., soil and reinforcement) and to scale the geometrical dimensions of each effective factor. The scale effects associated with a model may be elucidated through dimensional analysis, as has been investigated by several researchers in geotechnical engineering (e.g., Fakher and Jones, 1996, El-Emam and Bathurst, 2007; Sireesh et al., 2009; Moghaddas Tafreshi et al., 2011). In addition, dimensional analysis provides scaling laws that can convert design parameters from a small model into design parameters for a large prototype, by considering the effect of scaling by a factor of λ (the ratio of diameter of prototype circular footing to diameter of model circular footing). In order to achieve this scaling, it is necessary to assume that the reinforcement acts axi-symmetrically. For this to be a reasonable assumption, the strains generated by loading must be largely within the reinforced plan area. With a rectangular geosynthetic installation, if strains were not largely within the reinforced plan area, there would be more reinforcement on some radii than on others and axisymmetry would not be satisfied.

Also, the geocell pockets must be assumed to be small compared to the footing otherwise, once again, equal response on all radii will not be achieved. If footing diameter were much smaller than the horizontal dimensions of a cell pocket, loading would be carried, primarily, by the aggregate contained within a pocket and the additional load-spreading achieved by the addition of a geocell layer would, necessarily be small. If the loading plate spans many cells, then the response must, necessarily, be the result of the aggregate and geocell acting together in some way.

For the models tested and described here, the load plate only spans a few pockets so the benefit of the reinforcement will lie somewhere between the two extreme cases just outlined. The greater load-carrying capacity provided by the aggregate and geocells acting together may not, therefore, have been fully achieved in the scale tests reported here, but should be much more nearly achieved as footing size increases. Therefore, in this respect, scaling on the basis of the laboratory tests is more likely to be conservative, with respect to load-carrying capacity, than not.

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 λ^2 times that of reinforcement used in the model tests, while the geometric parameters and the soil shear modulus should be increased by λ. Details of the scale effects analysis can be found in the works of Sireesh et al. (2009) and Moghaddas Tafreshi et al. (2011). Thus, full-scale performance improvements to the extent seen in the model tests would necessitate fabrication of geotextile and geocells formed of geosynthetic material that is λ^2 times stiffer. As the strength and stiffness of the geocell joints are equal or greater than the values of the strength and stiffness of the cell wall geosynthetic (Treff, 2011), the same increase in bond characteristics will probably be needed, as well. The use of small grain sizes (between 0.85 and 2.18 mm) of uniform silica sand at relative density of 85% might have delivered the relatively low stiffness of soil used in the model tests, whereas the increased soil stiffness required for dimensional similitude might be attained in practice using well-graded soil that contains particles of a wide range of sizes.

However, obtaining geosynthetic material that is λ^2 times stiffer may not always be readily achieved. As an example increasing from a model footing diameter of 112.8 mm to a full-scale footing diameter of 500 mm would require that the stiffness of the geosynthetic to be used at full-scale be $(500/112.8)^2$ = 19.6 times as great as in the model – about (19.6×13.1) = 260 kN/m – which is near the limit achievable by conventional geosynthetics. On the other hand, an increase to 1500 mm diameter would imply a required stiffness of about 2300 kN/m, which is significantly beyond the stiffness of conventional geosynthetics. The implications of this are discussed in the next section (Point 4).

9. Discussion on application

The following general observations are made in discussing the findings of this research study:

(1) Performance of a single layer of geocell to reinforce the soil beneath the footing, using laboratory small-scale model tests, has been investigated by several authors (e.g., Dash et al., 2003; Sitharam et al., 2005; Sireesh et al., 2009; Moghaddas Tafreshi and Dawson, 2010a;b). They reported an effective geocell-reinforcement zone beneath the footing around 1.5-2 times the footing width/diameter (similar to the result obtained in this study of Z_R = 1.48D). Thus, for example, for a circular footing with diameter of 500 mm (such as might be used in the application envisaged), with a single layer of geocell located at u_g/D=0.1, with an effective reinforcement zone beneath the footing, Z_R, of around 1.5 times the footing diameter, the thickness of geocell layer (H_g) should be about 700 mm. Since, the heights of commercially produced geocell are fixed and manufacturers in both the USA and Europe do not produce geocell with a height greater than 200 mm, the value of H_g=700 mm would be impossible for the field use.

In addition, a thicker, single, geocell layer would probably give rise to serious compaction difficulties within the cells of geocell layers, consequently decreasing performance. Instead, the use of multiple layers of geocell, each with a low thickness and vertically spaced at their preferred spacings, is likely to be a more practical and beneficial solution once geocell manufacture and soil compaction is taken into account. Therefore, for a circular footing with of 500 mm diameter, the thickness of geocell layers (with h_g/D=0.36) ought to be about 700, 260, 120 and 60 mm, for one, two, three, and four layers of geocell, respectively. The first, particularly, and second dimensions are, clearly, impracticable but the use of three or four layers of geocell appears to offer a practical and realistic solution bearing in mind the field issues just discussed. In the present study, the scaling is on the basis of λ=4.4, then a 25 mm thickness of geocell layers as used in the model becomes 110 mm in practical applications which is close and similar to the dimension of real geocells (100-200 mm high).

(2) Although Milligan et al. (1986) and Adams and Collin (1997), in their studies on large- and small-scale tests of the behavior of granular layers with geogrid reinforcement, showed that the general mechanisms and behavior observed in the small model tests could be reproduced in large-scale tests, further tests with large-scale model foundations and different characteristics (especially stiffness) and pocket sizes of the geocell under various conditions must be conducted to validate the present findings and to determine the existence of any scale effects.

(3) Although, only one type of geocell and planar reinforcement, one footing diameter and one type of soil were used, this study has provided insight into the basic mechanisms that establish the bearing pressure versus settlement response of the multi-layered geocell, and should be helpful in designing larger tests or in simulation through numerical models.

(4) The results should, therefore, assist with practical applications. Possibly, the results could have wider application for more general foundation use, but would need scaling and adjusting for larger footing size, different soil properties and different geosynthetic properties in such cases. Jones et al. (1991) noted both differences and similarities between small-scale

and full-scale reinforced foundation behaviors. Their observations might be exploited to extend the work reported in this paper to general foundation reinforcement, but such is beyond the scope of this paper.

The benefits of reinforcement predicted by the work described in this paper have employed an available geosynthetic material which, when scaled would require higher stiffness geocells (or, indeed, planar materials). This has two implications:

a) to limit settlements at full-scale to scaled values of those settlements experienced in these model tests, whether by geocells or planar reinforcement would require significant increases in the stiffnesses of both soil and geosynthetic materials. The scaling principle indicates that this would only be achievable by conventional geosynthetic products for footing diameters to around 0.5 m. Therefore higher stiffness products would probably need to be developed (e.g. including metallic or polyaramid elements) for larger footings. Of course, some benefit would likely be achievable by geosynthetics having a range of moduli and the value of the "benefit:modulus" ratio could be explored in the future.

b) use of even high stiffness conventional geosynthetic material, as geocells or as planar geotextile layers, would result in higher settlements than directly predicted by the model results described in this paper if used beneath footings much larger than 0.5 m in diameter. The degree of increase of settlements cannot be deduced from the experiments performed here, and might be considered for further study, perhaps by numerical methods.

Nevertheless, the benefit (in terms of mechanical performance and reduced geosynthetic mass) of geocell installations relative to their planar geotextile 'twins', as modelled in the study reported here, will be unchanged.

(5) Direct scaling would lead to the need for large cells that, in practice may not be feasible to manufacture or use. Thus the factor by which the mass of geotextile material has to be scaled might be greater than the scaling of the footing with consequential economic implications. Nevertheless, within the limits discussed at the end of Section 8, a larger ratio of plate to cell size would likely be beneficial as punching of the plate into cells would become more difficult. Filling and compaction issues would also need addressing. Regarding the soil to be used at full scale, its stiffness should increase by the scaling factor. Some increase will be relatively easy to achieve by better on-site compaction than that achieved in the laboratory and by selection of backfill with high modulus values. But there will be practical limits to the degree of modulus increase achievable. For these, and doubtless other, reasons, the results presented here cannot simply be scaled to much larger dimensions.

(6) Generally, in practice, geogrid may have better interface properties than nonwoven geotextiles and therefore, a better performance might be generated using geogrid. Thus, comparison of the performance of geogrid and geocell fabricated from the same type of geogrid should be investigated in future studies.

10. Summary and conclusions

A series of laboratory pilot scale tests was carried out with a circular footing on geocell- or geotextile-reinforced sand so as to compare the potential benefits of multi-layered geocell and multi-layered planar geotextile reinforcement that had the same basic material characteristics. Benefits were assessed in terms of increased subgrade modulus or bearing capacity and the depth of effective reinforcement zone beneath the footing when using layers of geocell and layers of geotextile. Based on the results obtained, the following conclusions can be derived:

(1) It is evident that geosynthetic material arranged into multiple layers of geocell provides soil reinforcement against footing loading much more effectively, than would an even greater mass of material arranged as multiple layers of planar reinforcement.

(2) The optimum vertical spacing of geocell reinforcement layers and planar geotextile reinforcement layers are approximately 0.36 and 0.4 times footing diameter, respectively.

(3) Use of the geosynthetic material as geocell layers at optimum positions in the sand is always more effective than as planar layers at their optimum positions, even though there is at least 30% more material in the comparable planar installation.

(4) The different shape of the load deflection curves suggest that different reinforcement mechanisms are at play. Because the curves for soil reinforced with increasing number of layers of planar geotextile only differ at higher deflection levels it is posited that the reinforcement action is progressive as each layer becomes significantly strained only following strain in the layer above. In contrast the load deflection curves of installations with differing numbers of geocell layers show different behaviour from very early in the loading sequence suggesting a reinforcement mechanism involving composite action of multiple layers of geocell.

(5) The rate of enhancement in load carrying capacity and/or subgrade modulus of the foundation bed were reduced with increase in the number of reinforcement layers. Improvement became almost insignificant beyond three geocell layers whereas improvement in reinforcement by geotextile continues, suggesting that further benefit might be obtained with further layers of planar geotextile.

(6) To provide useful reinforcement, geocell layers should be placed in the soil above a depth equal to 1.5 times footing diameter.

(7) When the layers of geocell and geotextile were located optimally, a specified improvement in bearing pressure and/or subgrade modulus could be achieved by a geocell installation with 1/4 to 1/2 of the quantity of material used in the multi-layered planar installation. In addition, the depth of reinforced sand is less. This has potential to deliver practical installation benefits.

(8) At low footing settlement ratios such as likely to be of practical application (i.e., lower than 2%), the multi-layered geocell-reinforced soil is very significantly more effective than the system with multi-layered geotextile-reinforced system. Performance benefit is seen at much lower settlement ratios (about 0.2-0.4 compared to around 1-1.5% for the multi-layered geotextile-reinforced installation).

(9) For larger footing dimensions, multiple layers of geocell would seem to provide a practical alternative to a single layer of geocell. Multiple geocell layers each with a low height and vertically spaced at their optimum distances, are a more practical and beneficial solution than a single, deep, geocell once geocell manufacture and soil compaction is taken into account. It is probable that the significantly improved performance at low settlement ratios, due to the geocell layers, would cover the additional costs of material and installation.

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Nomenclature

A_g	area of the pocket opening of geocell reinforcement
b_g	reinforcement width of the geocell layers
b_p	reinforcement width of the planar geotextile layers
d	pocket size of the geocell
D	diameter of footing
D_r	relative density of soil
h_g	vertical spacing between layers of geocell reinforcement
h_p	vertical spacing between layers of planar reinforcement
H_g	thickness of the geoecell layers
Ik	improvement factor in subgrade modulus (general)
Ik_g	improvement factor in subgrade modulus due to geocell reinforcement
Ik_p	improvement factor in subgrade modulus due to planar reinforcement
$k_{un.}$	subgrade modulus of the unreinforced sand at a given settlement to the origin
k_g	subgrade modulus of the geocell reinforced sand at a given settlement to the origin
k_p	subgrade modulus of the planar reinforced sand at a given settlement to the origin
N_g	number of layers of geocell reinforcement
N_p	number of layers of planar geotextile reinforcement
s	settlement of footing
u_g	depth of the first layer of geocell reinforcement beneath the footing
u_p	depth of the first layer of planar geotextile reinforcement beneath the footing
Z_R	depth of the reinforced zone

Table 1. The engineering properties of the geotextile used in the tests (manufacturer's data).

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

Table 2. Physical properties of soil.

Description	**Value**
Coefficient of uniformity, C_u	1.35
Coefficient of curvature, C_c	0.95
Effective grain size, D_{10} (mm)	1.2
D_{30} (mm)	1.36
Medium grain size, D_{50} (mm)	1.53
D_{60} (mm)	1.62
Maximum void ratio, e_{max}	0.82
Minimum void ratio, e_{min}	0.54
Moisture content (%)	0
Specific gravity, G_s	2.68
Friction angle, ϕ (degree) at 85% relative density using standard triaxial test at three confining pressure of 50, 100, and 150 kPa	38.5

Table 3. Scheme of the bearing capacity tests for unreinforced and reinforced (multi-layered geocell and multi-layered planar geotextile) soil.

Test Series	Type of reinforcement	N_g or N_p	h_g/D or h_p/D	No. of Tests	Purpose of the tests
1	Unreinforced	--------	-------	1+2 (repeated)	To quantify the improvements due to reinforcements
2	Geocell Reinforced	1	------	1+2 (repeated)	To arrive at the optimum values of h_g/D and to study the effect of the number of geocell layers
3		2	0.18*, 0.27*, 0.36**, 0.45*, 0.7, 1, 1.24	7+5 (repeated)	
4		3*, 4*	0.36	2+2 (repeated)	
5	Planar Reinforced	*1*	------	1+1 (repeated)	To arrive at the optimum values of h_p/D and to study the effect of the number of geotextile layers.
6		2	0.22*, 0.32*, 0.4**, 0.5*, 0.66*, 0.94, 1.28	7+5 (repeated)	
7		3*, 4*	0.4	2+2 (repeated)	

*To verify repeatability of results, tests marked * were performed twice and those marked ** were performed thrice*

Parameters Definitions:

N_g: Number of geocell reinforcement layers

N_p: Number of geotextile reinforcement layers

h_g: Vertical spacing of the geocell layers

h_p: Vertical spacing of the geotextile layers

D: Loading plate diameter

Table 4. Reinforcement zone depth beneath the footing (Z_R) for both multi-layered geocell and multi-layered planar reinforcement used in the testing program (left column, for u_p/D=0.32 and h_p/D=0.4, right column, for u_g/D=0.1, h_g/D=0.36 and H_g=25 mm).

Number of geocell and planar reinforced layers, N_g and N_p	Reinforced zone depth (Z_R) beneath the footing for multiple geotextile layers	Reinforced zone depth (Z_R) beneath the footing for multiple geocell layers
1	0.32*D*	0.32*D*
2	0.72*D*	0.9*D*
3	1.12*D*	1.48*D*
4	1.52*D*	2.06*D*

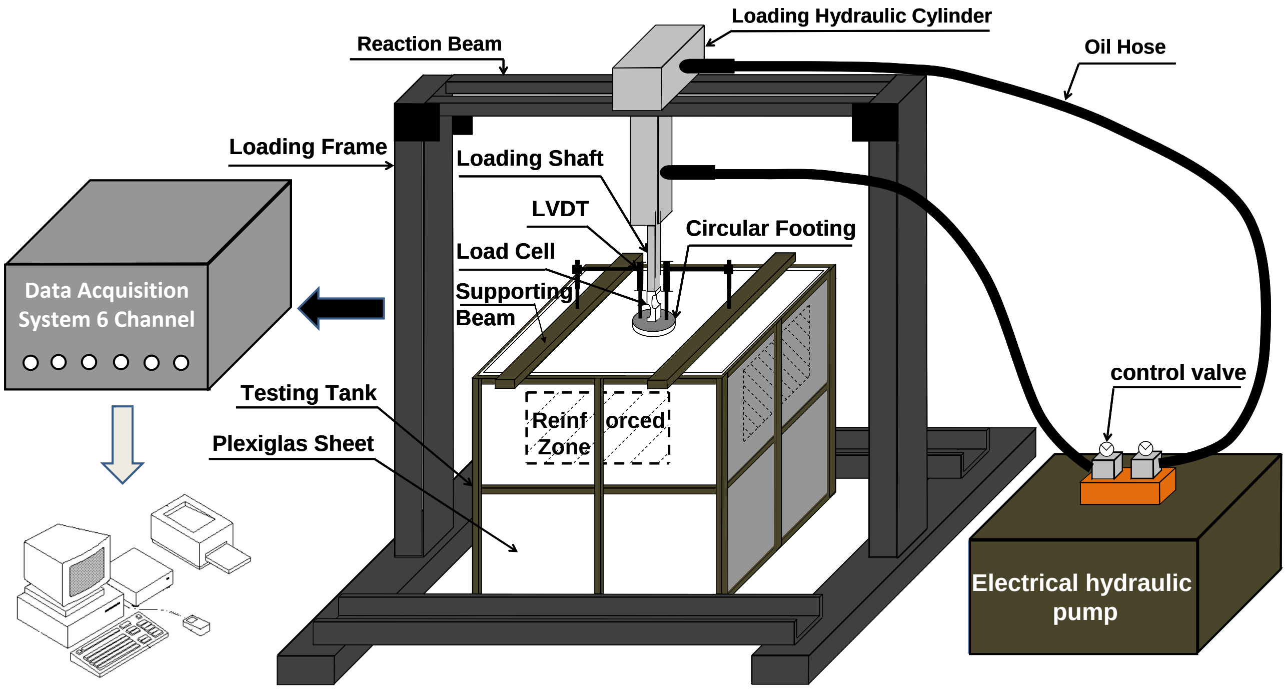

Fig. 1. Schematic representation of the test setup and layout of the trench

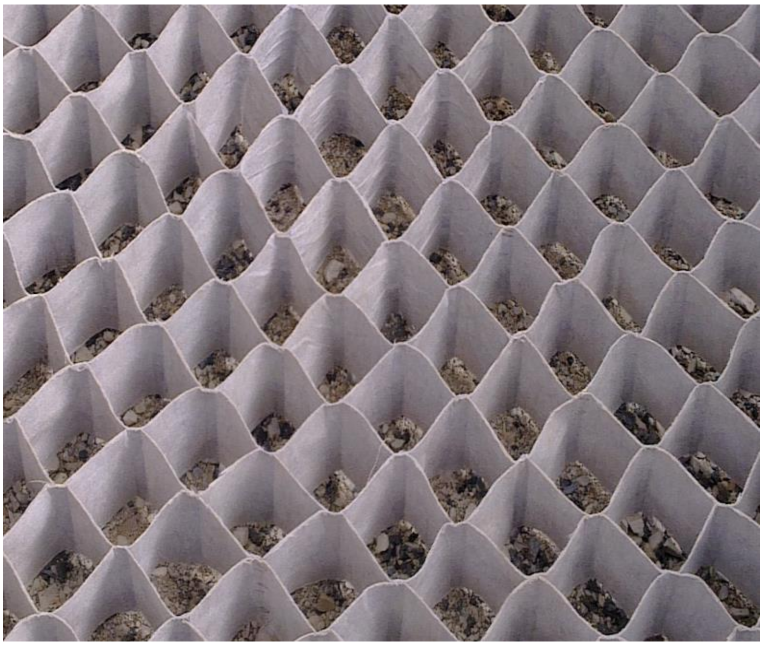

Fig. 2. Non-perforated flexible geocell (TDP Limited) used in this research

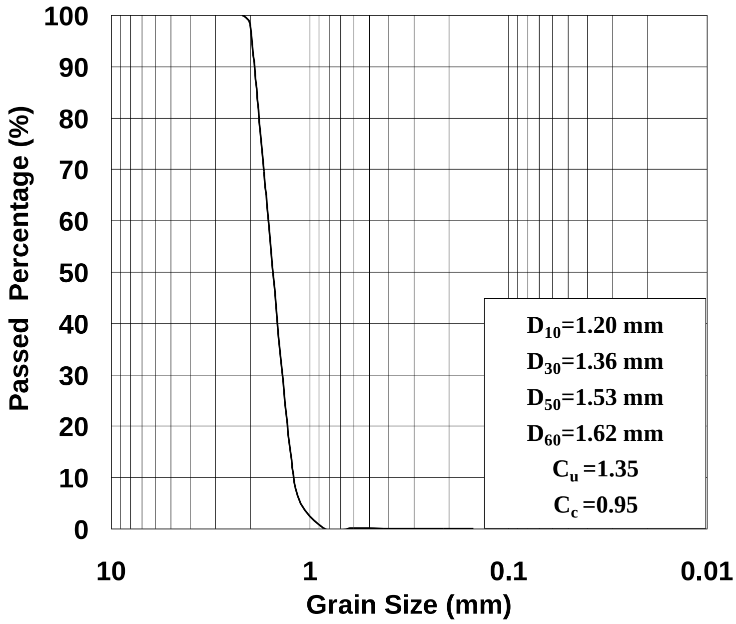

Fig. 3. Particle size distribution curve of the sand used beneath the footing.

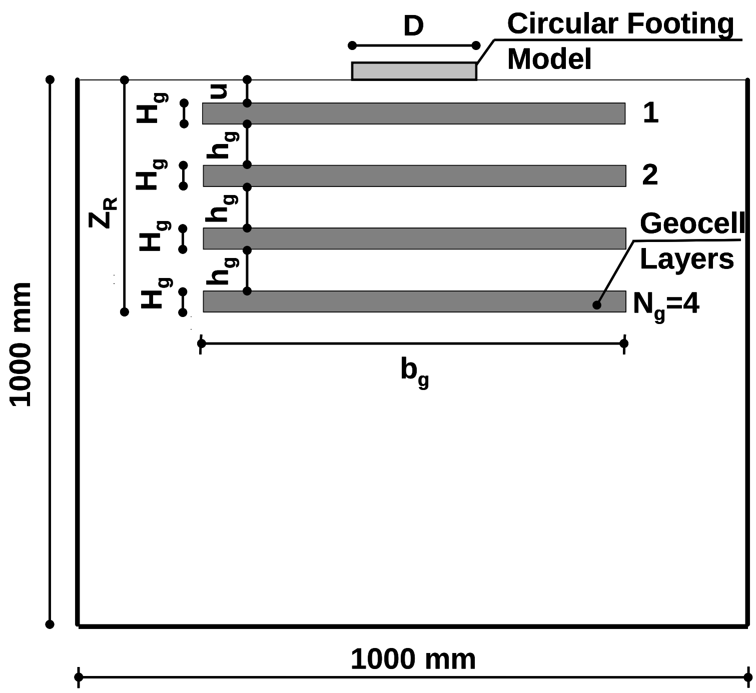

Fig. 4. Layout of the multi-layered geocell-reinforced installation.

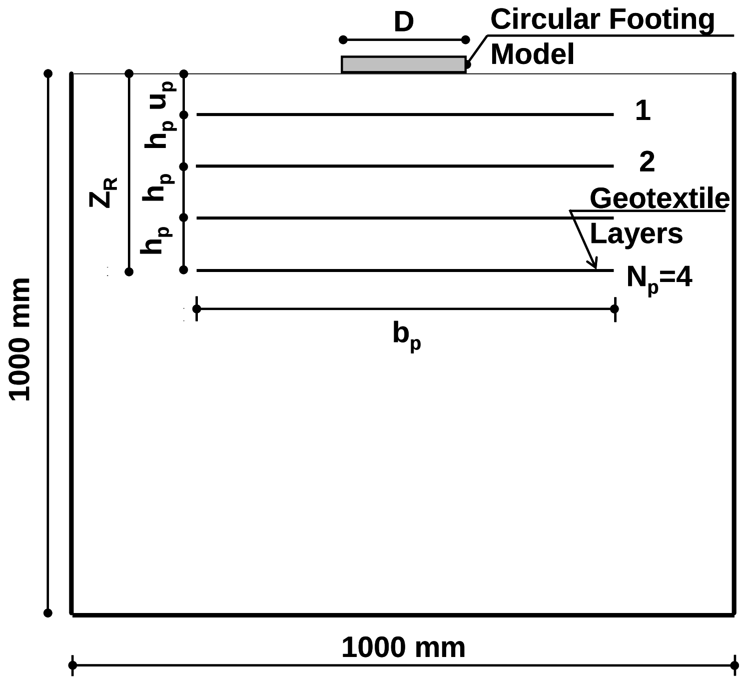

Fig. 5. Layout of the multi-layered planar geotextile-reinforced installation.

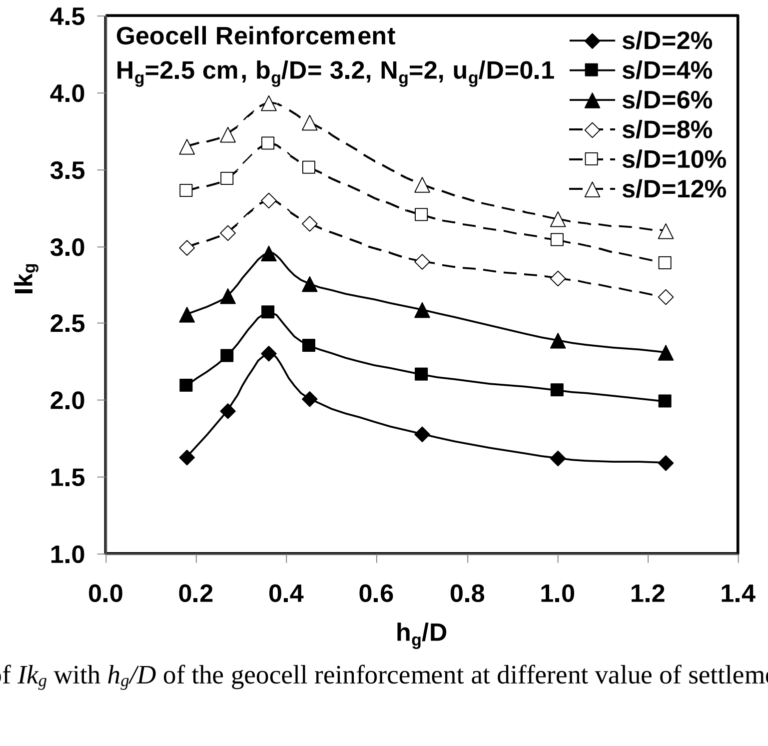

Fig. 6. Variation of Ik_g with h_g/D of the geocell reinforcement at different value of settlement.

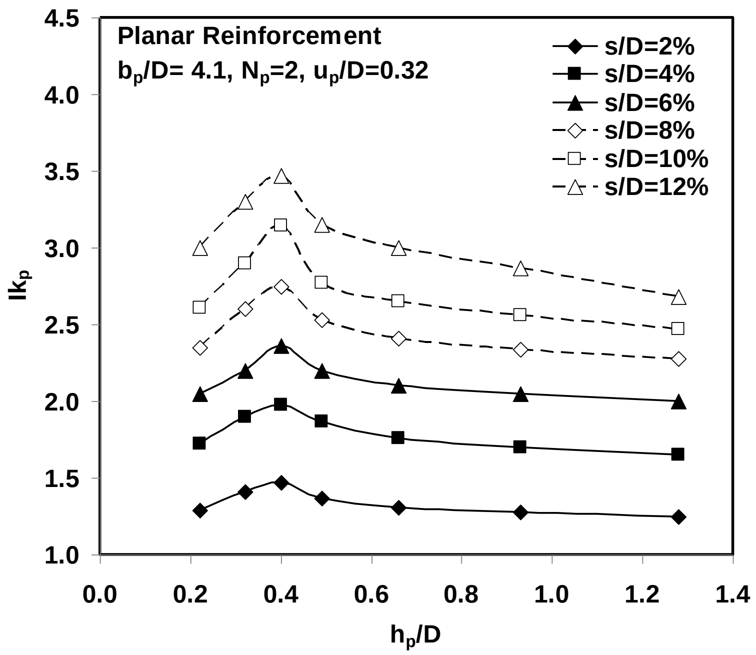

Fig. 7. Variation of Ik_p with h_p/D of planar reinforcement at different value of settlement.

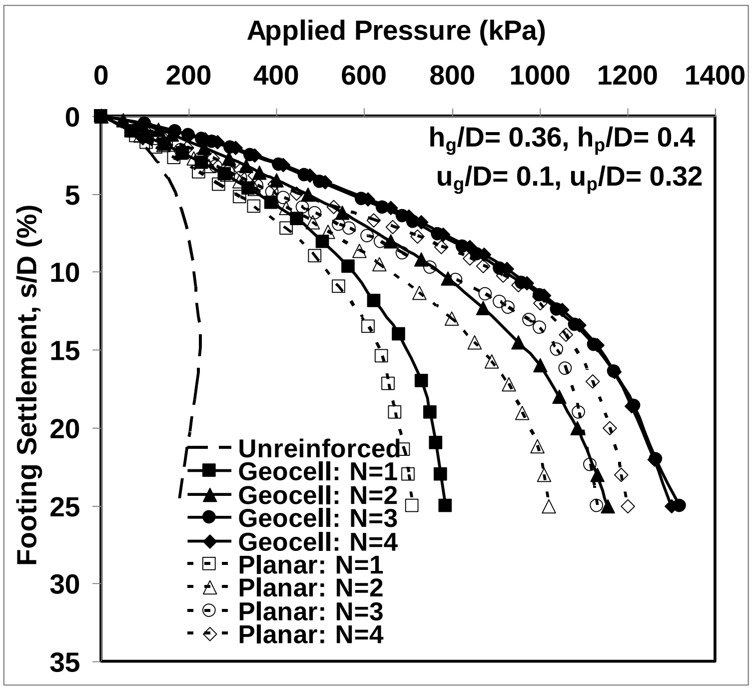

Fig. 8. Variation of bearing pressure with settlement for the geocell and planar reinforcement (h_g/D=0.36, h_p/D=0.4).

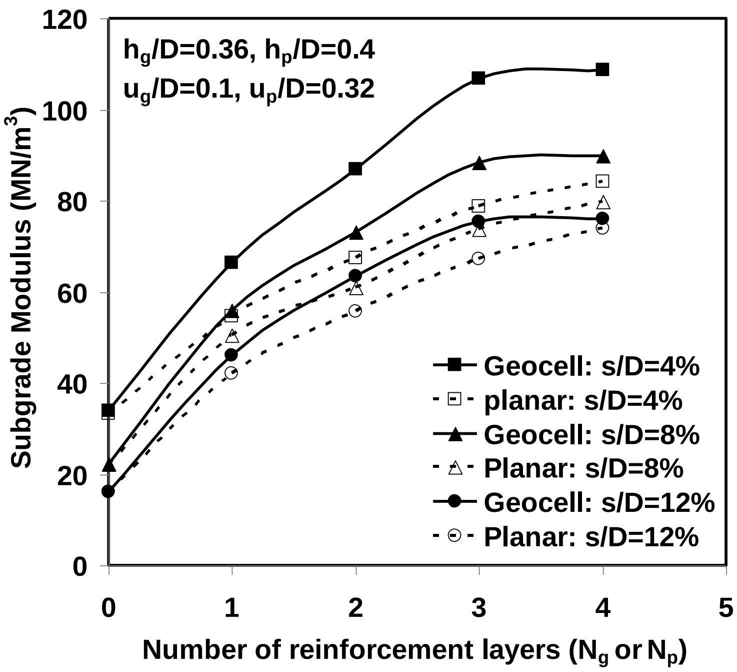

Fig. 9. Variation of Subgrade modulus with the number of geocell layers and planar geotextile layers (N_g & N_p) at different levels of settlement (s/D=4%, 8% and 12%) for h_g/D=0.36 & h_p/D=0.4.

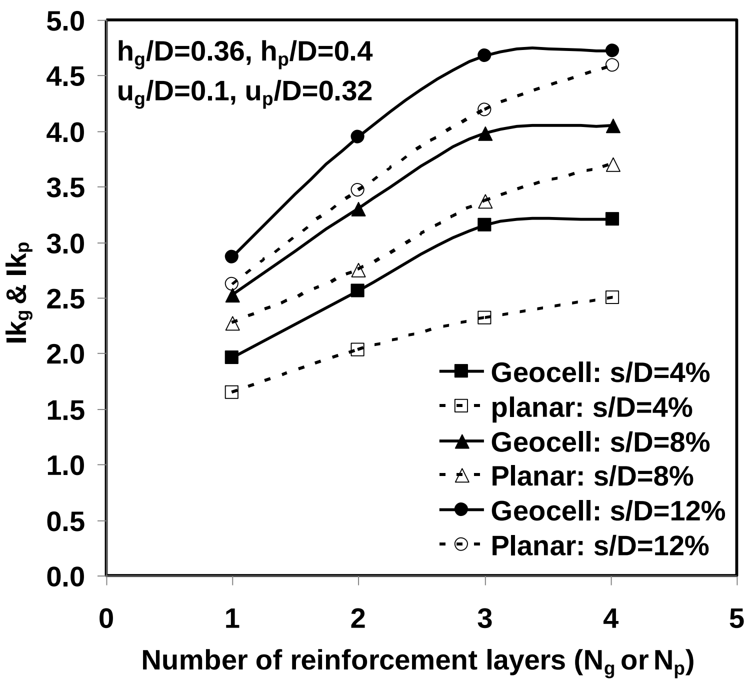

Fig. 10. Variation of Ik_g and Ik_p with the number of geocell layers and planar geotextile layers (N_g & N_p) at different levels of settlement (s/D=4%, 8% and 12%) for h_g/D=0.36 & h_p/D=0.4.

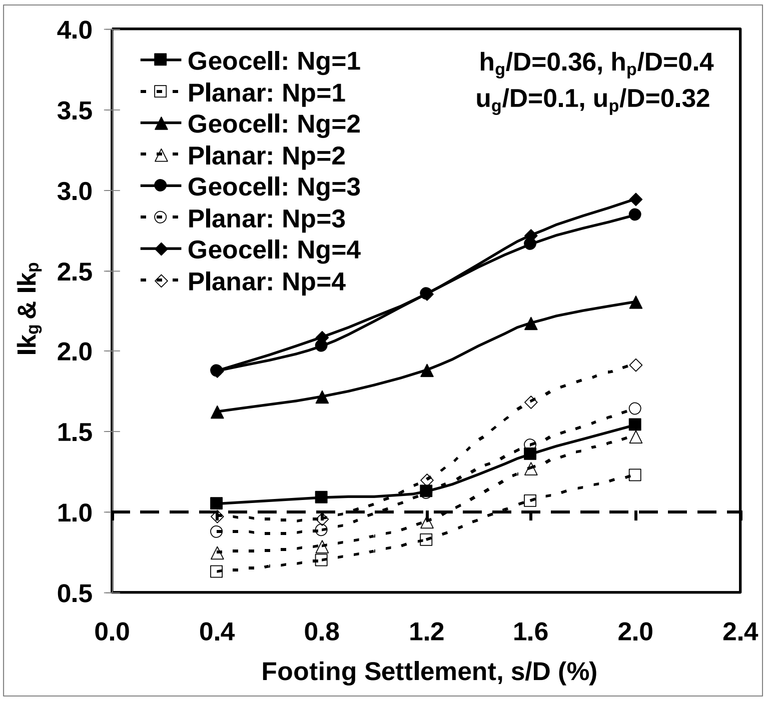

Fig. 11. Variation of Ik_g and I_p with low footing settlement (s/D) for different number of geocell layers and geotextile layers ($N_g = N_p$ =1, 2, 3, and 4) for h_g/D=0.36 & h_p/D=0.4.