Cyclic Response of Footing with Embedment Depth on Multi-Layered Geocell-Reinforced Bed

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Abstract. In order to investigate the effect of embedment depth on settlement of footing supported by geocell-reinforced bed, a series of cyclic plate loading at a diameter of 300 mm supported by layers of geocell in a test pit of 2000*2000 mm in plane and 700 mm in depth, were performed. The results show that installation of the geocell layers in the foundation bed toward embedded footing supported by one layer geocell has more effect on increasing the resilient behaviour in addition to reduction of accumulated plastic and total settlement of system. The study also compares the embedment depth ratio of one layer geocell reinforcement with two and three layer geocell reinforcement bed with no embedment depth.

1. Introduction
Geosynthetic-reinforced soil offers economy, ease of installation, performance and reliability in many areas of geotechnical engineering. In recent decades, geosynthetic inclusions in the form of two-dimensional reinforcement (e.g., geotextile and geogrid) and three-dimensional reinforcement (e.g., geocell) have been increasingly used in geotechnical engineering applications for, e.g., road construction layers, stable embankments, slope and earth stabilization, and construction of footings over soft soil e.g., Hufenus et al [1]; Kim et al [2]; El Sawwaf [3]; Bathurst et al [4]; Moghaddas Tafreshi and Dawson [5]; Moghaddas Tafreshi et al [6]; Madhavi Latha [7]; Leshchinsky and Ling [8]. Although, in addition to planar reinforcements, several investigations have also highlighted the beneficial use of geocell reinforcement in the construction of embankments and footing over soft soil under static and repeated loads e.g. Sireesh et al., [9]; Moghaddas Tafreshi and Dawson, [10]; Yang et al., [11]; Moghaddas Tafreshi and Dawson, [12]; Chen et al., [13]. The three dimensional geometry of geocell i.e., the superior confinement offered by the geocells in all directions, allows the soil in the cells to develop a passive resistance that increases the soil’s bearing capacity and decreases the settlement of the foundation bed. All of these studies on geocell reinforcement have been conducted for surface footings, despite the fact that embedded footings are more common in practice. At present, very limited experimental work is reported that assesses the effect of embedment depth of footing on planar reinforced footings under static loads (Sitharam and Sireesh, [15]; Patra et al., [16]; Sitharam and Sireesh, [17]).

In the current research, the overall goal is to demonstrate the benefits of introducing geocell reinforcement to address embedment depth effect. Cyclic loading conditions were selected as these are
of particular concern for pavement and machine foundation problems where localized soil reinforcement might be appropriate. Thus a series of cyclic plate load tests of a foundation supported on unreinforced soil or soil reinforced with geocell with different ratio of embedment depth were performed in a test pit with 2000×2000 mm in plan and 700 mm in depth using a 300 mm diameter rigid steel plate. The parameters studied in this testing program include the number of geocell layers and the embedment depth ratio of footing supported by single layer geocell reinforcement on settlements of loading plate subjected to incremental cyclic loading.

2. Test Materials

2.1. Soil
Granular soil passing through the 38 mm sieve with a specific gravity of 2.68 (G_s=2.68) was used as backfill soil in the testing program. It was sourced from a local quarry and satisfies the criteria and limitations recommended in [17]. The grading of this soil is presented graphically in Figure 1a, [18]. According to the Unified Soil Classification System [19], the soil is classified as well-graded gravel with sand. According to the modified proctor compaction tests [20], the maximum dry density was about 22.82 kN/m³, which corresponds to an optimum moisture content of 6.7% (see Figure 1b). The angle of internal friction (φ) of soil obtained through triaxial compression tests at a wet density of 19.35 kN/m³ (corresponding to 90% of maximum dry density) was 39.5°. This soil was used to fill the geocell.

2.2. Geocell
The geocells used in this study was formed of a non-woven polymeric geotextile. Table 1. shows the properties of the geotextile. The geocell has the height and pocket size of 100 mm and 110x110 mm², respectively. In this study, the ratio of the geocell pocket size (d=110 mm) to loading plate diameter (D=300 mm) is 0.37 (d/D=0.37).
Table 1. Engineering properties of the geotextile

| Description                          | Value |
|--------------------------------------|-------|
| Area weight (g/m²)                   | 290   |
| Thickness under 2 kN/m² (mm)         | 0.75  |
| Thickness under 200 kN/m² (mm)       | 0.62  |
| Tensile strength (kN/m)              | 21.30 |
| Strength at 5% (kN/m)                | 9.30  |

3. Test Setup
To investigate the bearing capacity and the settlement of shallow footings supported by geocell, an experimental program was conducted using a standard plate load. All plate load tests were conducted in an outdoor test pit. The test pit, measuring 2000 mm × 2000 mm in plan, and 700 mm in depth, was excavated in natural ground to construct the geocell layer. The four sides of the test pit were only approximately vertical due to the natural ground’s characteristics. The schematic cross-section of the test set-up of the foundation bed containing geocell layers, the loading plate model, loading system and data measurement system (dial gauges) and the geometry of the test configurations, is shown in Figure 2.

Figure 2. Schematic cross-section of the test set-up (not to scale)

Loading, unloading and reloading were imposed at the surface of loading plate using a hand operated hydraulic jack, with the capacity up to 200 kN. The steel rigid plate of 300 mm in diameter and 30 mm in thickness was placed on the surface at the centre of the installation. The diameter and thickness of the loading plate are selected according to the ASTM D1195-09, [22]. Hence, in order to simulate the cyclic loading, unloading and reloading 5 cyclic loading with different amplitude were imposed through the plate at a rate of 1.5 kPa per second. The maximum applied pressure was 850 kPa (See Figure 3). The low rate of loading used to collect the data with no automatic system. Since the soil used in the backfill is granulated soil with low water content, therefore it would be expected the rate of loading has no significant effect on the shear strength of backfill. It is in line with the findings of Huy et al [23], which reported an increase in the internal friction angle of the dry granulated soil about 0.5 degree at 65% of relative density and up to 2 degrees at 83% of relative density when the loading changes from static loading to dynamic loading with loading velocity from 0.2 m/s up to 0.595 m/s.
In order to compact the layer of foundation bed including the unreinforced soil and geocell-reinforced layer, a walk-behind vibrating plate compactor, 450 mm in width, was used. In all the tests, the compactor passed over the backfill at nine levels being 0, 60, 160, 220, 320, 380, 480, 540, 640, and 700 mm from the level of the base of the loading plate. To achieve the required density of soil that filled the geocell pockets, more passes of the compactor were needed compared to the unreinforced layer. The unreinforced layer and geocell reinforced layer being compacted with one and two of compactor, respectively, so that the compaction effort, and consequently compaction energy, was kept the same for all passes of the compactor. To have a better assessment of the layer' compaction, in some installations and after layer compaction, three sand cone tests in accordance with ASTM [21] were conducted to measure the densities of compacted soil layer and the density of the soil filled into the geocell pockets. The densities measured revealed a close match between density values of the three cone tests with maximum differences in results of around 1-1.5%. This difference seems to be small for geotechnical applications. It should be noted that the different layers of materials used were compacted at an optimum moisture content of 6.7%, but the average measured (recovered) moisture content of the layers was between 6.1% and 6.8% (See Figure 1b).

4. Test Parameters and Testing Program
The details of all the test series done in this study are given in Table 2. The width of the geocell layer (b) and the depth of the geocell layer below the footing (u) are expressed in non-dimensional form with respect to footing width (D=300 mm) as, b/D and u/D, whereas the height of geocell layer (h_g) is expressed in dimensional form equal to 100 mm. The parameters of b/D and u/D were held constant in all the tests at b/D=5 and u/D =0.2 [12, 24-26].

To assess the accuracy of the measurements and the reliability of the results, many of the tests were repeated. The results obtained revealed a close match between results of the two or three repeated tests (e.g. maximum difference 6-8%). 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 geotechnical testing apparatuses.
Table 2. Scheme of the plate load tests for footing on unreinforced and geocell-reinforced bed

| Test Series | Type of test     | N  | D/D | No. of Tests | Purpose of the tests                                                                 |
|-------------|------------------|----|-----|--------------|--------------------------------------------------------------------------------------|
| 1           | Unreinforced     | 0  | 0, 0.25, 0.75 | 3+2*        | To investigate the effect of embedment depth                                           |
| 2           | Geocell reinforced| 1  | 0.25, 0.75 | 3+3*        | To investigate the effect of footing embedment depth and number of geocell layers    |
| 3           | Geocell reinforced| 2, 3 | 0   | 2+2*        |                                                                                      |

*The tests which were performed two or three times to verify the repeatability of the test data

5. Results and Discussions

5.1. The effect of the number of geocell layers

The variation of the loading plate deformation with the number of load cycles for the unreinforced system and the multi-layered geocell reinforced system with one, two and three layers of geocell (Ng=1, 2, 3), when the layers of geocell were placed at the optimum values of u/D=h/D=0.2, is shown in Figure 4a. Also, the residual plastic deformation of the unreinforced and reinforced bases with the number of loading cycles is shown in Figure 4b. This figure shows that as the number of geocell layers increases (i.e., the increase in the depth of the reinforced zone), both stiffness and bearing pressure at a specified settlement of total deformation and plastic deformation increase substantially. Moreover, it can be seen that the total and residual deformations of the unreinforced foundation tend to increase with the amplitude of cyclic loads. There is a non-stabilizing response; eventually leading to plastic failure, particularly at higher levels of cyclic loads (i.e., 740 kPa). The authors note that a large deformation in these tests is not the primary means of judging unsuitability of the arrangements under test but, rather, a non-stabilizing response. Large deformations could largely be dealt with in practice by compaction, whereas instability responses are destructive.

Figure 4 Variation of (a) loading plate deformation, and (b) residual deformation with applied cyclic load for the unreinforced and geocell reinforced systems with one, two and three layers of geocell
For the reinforced bed, regardless of the number of geocell layers, the rate of change of both total and the residual deformation of the loaded surface reduces as the number of load cycles increases, particularly for the reinforced bed with three layers of geocell. The performance of geocell reinforcement in decreasing the deformations may be attributed to the superior confinement offered by the geocell layers in all directions. Thus the multi-cell geometry allows the soil in the cells to develop a passive resistance that increases the soil’s bearing capacity and decreases the deformations within the foundation bed. This behaviour is a consequence of the shakedown process as the granular structure of the sand becomes arranged into a progressively more stable arrangement better able to behave resiliently without undergoing plastic deformation.

It implies that the reinforced system as compared with unreinforced system is storing energy (and releasing it in resilient recovery) rather than the energy being used to cause further damage. This stabilizing response suggests that the early process of reorientation of particles inside the geocell layers, which causes local fill stiffening, ceases relative rapidly and the system then reaches a “plastic shakedown” condition, in which subsequent deformation is fully recovered in each cycle.

5.2. The effect of embedment depth

Figure 5a compares the variation of the loading plate deformation with the applied cyclic load for the geocell reinforced bed with different embedment depth ratios. To more clearly demonstrate the performance of the embedment depth, only the residual plastic deformation, is shown in Figure 5b. It can clearly be observed that increasing embedment depth ratio considerably decreases both the total and residual plastic deformations of the loading plate, compared with the response of the surface reinforced bed.

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For a more quantitative comparison, the values of maximum and residual plastic deformations at applied load of 680 kPa, the total settlement values are about 25, 18, and 14 mm and the plastic settlement values 22.5, 15, 11 mm for geocell reinforced bed with embedment depth ratio of 0, 0.25 and 0.75, respectively. Figure 6 shows the variation of the resilient settlement of loading plate with the applied cyclic load for the geocell reinforced bed with embedment depth ratios of 0, 0.25 and 0.75. This figure depicts clearly that increasing the embedment depth ratio increases the resilient settlement of loading
plate. For example, at applied cyclic load of 850 kPa the values of resilient settlement are about 2.01, 2.19 and 3.05 mm for embedment depth ratio of 0, 0.25 and 0.75, respectively.

Figure 6. Variation of applied cyclic load with resilient settlement for single layer of geocell reinforced bed with embedment depth ratio (0, 0.25 and 0.75)

6. Summary and Conclusion
A series of cyclic plate load tests was conducted to assess the concept of embedment depth of geocell-reinforced foundation bed as potential foundation improvement technique. Based on the results of the test program described in this paper, the following conclusions can be made:

- Installation of the geocell layers in the foundation bed increases the resilient behaviour in addition to the reduction of the accumulated plastic and total settlement of the foundation due, in part, to better load spreading of the composite system and to better energy absorbance properties of geocell.

- Footing supported on one layer geocell reinforced beds is almost linear up to a settlement range of 25-30% of the footing width, even at a settlement equal to about 50% of the footing width, clear signs of failure were not evident in the case of geocell-reinforced foundations.

- A comparison between number of layers and embedment depth ratio, under the same amplitude load shows that, the total settlement value for footing supported by three layers geocell reinforcement is less than those obtained for footing with embedment ratio of 0.75 supported by one layer geocell reinforcement. For example, at bearing capacity value of 680 kPa, total settlement of footing supported by three layers geocell reinforcement is 21% less than one layer geocell reinforced footing with embedment ratio of 0.75.

- Resilient deformation forms a greater proportion of the total deformation as the number of geocell layers increases. Nevertheless, for one layer geocell reinforced bed by increasing the embedment depth ratio, significant effect on resilient deformation has not been observed.

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