Load-Settlement Behaviour of Geotextile-Based Geocell Reinforced Sand Bed

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ABSTRACT: The potential of application of geotextile-based geocells in improvement of performance of sand foundations is investigated in this study. Model plate load tests conducted on unreinforced and geocell-reinforced sand beds have shown that the use of geocell reinforcement improved the performance of reinforced sand bed, both in terms of bearing capacity and settlement. The bearing capacity of sand bed is found to increase with an increase in reinforcement width (b); however, the benefit is observed marginal for $b > 4B$ (B = width of footing). The results also show a maximum Improvement Factor of about 3.5 for the relative density of 35%, and about 2.4 and 1.9 for the relative density of 70% and 90%, respectively, at s/B = 10%, b/B = 3 (s = settlement of footing). Further, it is found that provision of geocell reinforcement almost arrests the surface heaving of soil, irrespective of the relative density of sand bed.

KEYWORDS: Geocell reinforcement, Relative density, Bearing capacity, Improvement factor, Surface heaving.

1. INTRODUCTION

Geosynthetics are being widely used for soil reinforcement. Geocell, a type of geosynthetics, consists of three dimensional interconnected cells, and is used for improving the performance of foundations of unpaved roads, earth embankment, liquid storage tanks and oil exploration platforms (Webster and Alford, 1978; Bathurst et al., 1993; Mandal et al., 1994; Krishnaswamy et al., 2000; Dash et al., 2001, 2003; Sitharam et al., 2005; Madhavi Latha and Murthy, 2007; Zhou et al., 2008; Madhavi Latha and Somwanshi, 2009; Pokharel et al., 2010; Tafreshi et al., 2012; Hedge and Sitharam, 2013; Biswas et al., 2013, 2016; Karger et al., 2017). The literature reveals that the provision of geocell reinforcement in soil increases the load-bearing capacity by about 2 to 8 times and reduces the settlement by about 20-50% (Dash et al. 2001a, 2003; Tafreshi et al., 2010; Hedge and Sitharam, 2013; Biswas et al., 2013). In the recent past many model studies were conducted to investigate the optimum and effective application of geocell system with reference to several parameters, such as geocell geometry, depth of placement of geocell, density of infill materials, types of infill materials, stiffness and strength of geocell materials, etc. (Dash et al., 2001, 2003, 2010; Hedge and Sitharam, 2013; Kargar et al., 2017). However, most of the past studies were carried out on geocell made from geogrids or factory-made geocell of polymeric material. Only very limited study on geotextile-based geocells is available in the literature (Tafreshi et al., 2010; Kargar et al., 2017; Doley et al. 2019). Furthermore, the influence of geocell reinforcement width and the effect of relative density of soil on the performance of geocell-reinforced foundation system have not been investigated systematically. These key practical aspects have been investigated in this research by conducting a series of model footing load tests in the laboratory.

2. LABORATORY MODEL TESTS

2.1 Test Tank and Footing

The internal dimensions of the steel tank fabricated for the experimental study were 1200 mm × 980 mm × 1010 mm (L×B×H). Structural steel angle sections were welded to connect the test tank side plates to achieve negligible lateral deformation. A reaction steel frame, designed to support a 100-kN hydraulic jack, was attached to the steel tank. A square steel plate of size 150 mm ×150 mm × 20 mm was placed as the model footing. A thin layer of sand was pasted to the bottom face of the steel plate to make it rough. The model footing was subjected to a reaction load applied vertically through a steel ball. The reaction load applied through the hydraulic jack to the square footing was controlled manually and was measured with a proving ring. The loading arrangement is illustrated in Figure 1. The settlements of the footing were measured with two dial gauges placed on the model footing diagonally opposite to each other. The surface deformations (heave) were measured by using four dial gauges placed on the foundation soil at distances 1.5B and 3B from the centre on either side of the footing.

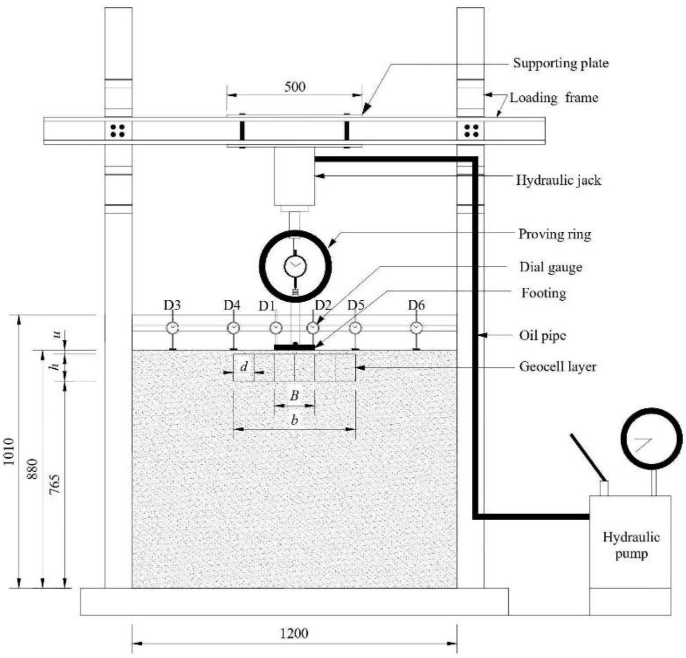


Figure 1 Test setup scheme (Note: All dimensions are in mm)

2.2 Test Materials

2.2.1 Sand

River sand was used for the experimental program. It was made free from roots, organic matter, etc. by washing and cleaning. The sample was then air dried (water content ≈ 1%) in the laboratory before it was used in the experimental work. The specific gravity of the sand was determined as 2.66. The density in the densest state was found to be 1730 kg/m^3 and that in the loosest state was 1510 kg/m^3. The angle of friction of the sand at relative densities 35, 70 and 90% were determined from standard direct shear tests. The particle size distribution curve obtained from the sieve analysis is shown in Figure 2. The physical properties of sand are given in Table 1. The sand is classified as poorly graded sand (SP) as per the Unified Soil Classification System (USCS). The peak friction angles determined in this study (Table 1) were found comparable to the values reported by Dash et al. (2010) and Mamo et al. (2015) for a similar type of sand under different relative densities.

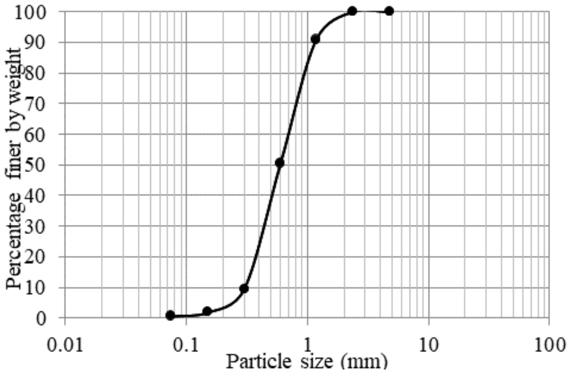


Figure 2 Particle size distribution of the river sand used

Table 1 Properties of the river sand used

Material property	Values
Effective size, D_{10} (mm)	0.30
Coefficient of uniformity (C_u)	2.33
Coefficient of curvature (C_c)	0.84
Maximum dry unit weight ($\gamma_{d,max}$) (kN/m^3)	16.95
Minimum dry unit weight ($\gamma_{d,min}$) (kN/m^3)	14.52
Peak angle of friction (φ^o) at D_r = 35%	38.8^0
Peak angle of friction (φ^o) at D_r = 70%	40.5^0
Peak angle of friction (φ^o) at D_r = 90%	41.5^0

2.2.2 Geocell Reinforcement

The geocell was prepared in the laboratory by stitching polyester woven geotextile. This material is abundantly available in the form of common office curtain blinds. In order to fabricate the geocell of desired dimension, the paper templates were first made. The geotextile was then cut and stitched with nylon thread as per the template. Tensile stress-strain behavior of the geotextile used for geocell is shown in Figure 3. The material properties of the geotextile used were tested in the laboratory and the results are shown in Table 2. The prepared geocell seam was also tested and was found to be as strong as the parent material. A photographic view of geotextile, stitching process to form geocell, one dimension of geocell pocket and complete form of the geocell reinforcement are shown in Figures 4(a) - 4(d).

Table 2 Properties of the geotextile used to make the geocell

Parameter	Description
Geocell material type	Geotextile
Polymer	Polyester
Thickness, t (mm)	0.8
Ultimate tensile strength, T_u (kN/m)	24
Failure strain (%)	7.0

2.3 Preparation of Test Setup and Procedure

The model footing tests were performed by loading the footing over the sand bed of 880 mm thickness. The pluviation procedure (raining of sand through air) was adopted to prepare the uniform test sand bed of desired relative density value of 35, 70 and 90%. The density obtained through rainfall technique depends on the height through which the sand was allowed to fall. The system was calibrated by measuring the respective density achieved for different preset heights of fall during a pluviation test series. The height of fall required to maintain relative densities of 35, 70 and 90% of the sand in the test tank was read from the calibration curve (Figure 5). By this technique, less than $\pm 2\%$ variation was observed in the measured densities at different locations of the sand bed. In literature (Dash et al., 2001; Tafreshi et al., 2010) it was found that the optimum placement depth of geocell would be 0.1B (B = footing width) below the bottom of the footing. Therefore, after achieving the desired level of sand bed by pluviation procedure, the geocell of intended size was placed at the depth of 0.1B below the footing. The same river sand was used to fill the geocell pockets by pluviation technique to maintain the uniform relative density. Once the geocells were filled up, the fill surface was levelled with great care to avoid the change in the relative density of the top surface.

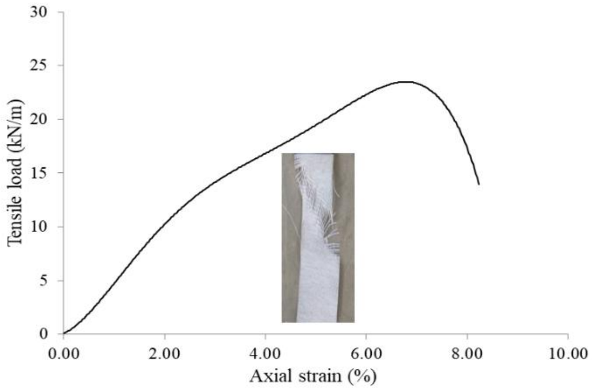


Figure 3 Tensile stress vs. strain response of the geotextile used for geocell

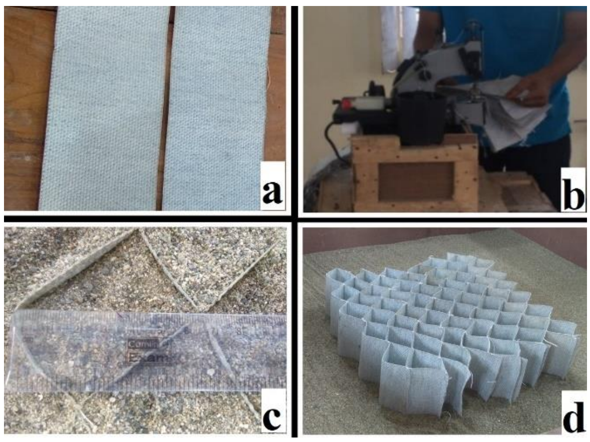


Figure 4 Photographic view of: (a) the geotextile, (b) stitching of geotextile, (c) one dimension of geocell pocket, and (d) geotextile-based geocell after complete stitching

The footing was then placed at the top of the bed exactly at the centre of the test tank. The average of settlements recorded by the two dial gauges touching the opposite edges of the steel plate were taken as the footing settlement (s), whereas the surface deformations (heave) recorded by four dial gauges placed on the foundation soil at distances 1.5B and 3B from the centre on either side of the footing were taken as the surface heave (δ). The parameters such as footing settlement (s) and surface deformation (δ) of the ground were normalized with width of the footing (B) to express them in a non-dimensional form as s/B (%) and δ/B (%), respectively.

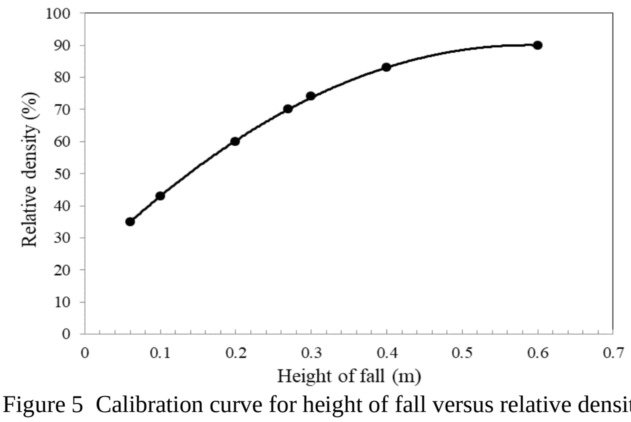


Figure 5 Calibration curve for height of fall versus relative density

3. RESULTS AND DISCUSSION

The schedule of model footing tests is described in Table 3. The test series (A-B) were carried out on unreinforced and geocell-reinforced sand bed to quantify the improvement of geocell-reinforced foundation system with various relative densities of sand bases. The test series C was conducted to quantify the effect of geocell reinforcement width for different relative densities of sand bases.

Table 3 Schedule of model scale tests

Test series	**Parameters**	
	Constant	**Variable**
A	Unreinforced sand	D_r =35%, 70% & 90%
B	Reinforced sand, d/B = 0.5, h/B = 0.66, b/B = 3, u/B = 0.1	D_r =35%, 70% & 90%
C	Reinforced sand, d/B = 0.50, h/B = 0.66, u/B = 0.1	b/B = 1, 2, 3, 4, 5 and 6 D_r =35%, 70% & 90%

In this study, to investigate the performance of geocell-reinforced sand foundations, the improvement in bearing capacity for each model test was analyzed in the form of an Improvement Factor (I_f), defined as:

$$I_f = q_R/q_U \tag{1}$$

where, q_R is the bearing capacity of a geocell-reinforced sand foundation and q_U is the bearing capacity of unreinforced sand foundation at the same level of settlement.

In literature (Cerato et al., 2007; Boiko et al., 2013), it is found that the ultimate bearing pressure of unreinforced soil is generally at settlement ratio of 5% to 10% of the footing width. Therefore, in this study the I_f due to inclusion of reinforcement has been considered at s/B = 10%.

3.1 Bearing Pressure-Settlement Responses

3.1.1 Unreinforced Sand Foundation System

The pressure-settlement behaviour of uniform sand foundations having different relative densities (D_r = 35, 70 and 90%) are presented in Figure 6. It can be seen from the curve that the ultimate load-carrying capacity is about 58 kPa for D_r = 35% and about 128 kPa for D_r = 90% at measured settlement s/B = 10%. In general, the results presented in Figure 6 indicate a higher bearing pressure response against footing settlement for sand beds having higher relative density. It can be seen that the bearing capacity failure for dense sand (D_r = 90%) has taken place at a settlement equal to 12% of footing width. Tafreshi and Dawson (2012) have also observed the same range of settlement ratio, *i.e.* s/B = 12% for the bearing capacity failure of unreinforced sand bed. The curves for unreinforced sand foundations also clearly indicate the punching shear failure, local shear failure and general shear failure for relative density of 35, 70 and 90%, respectively. A similar trend of observation was also reported by Vesic (1973) for a model footing supported on unreinforced sand bed. Moreover, it can be observed that the variations of bearing pressure with footing settlements are non-linear and well-defined failure surfaces are seen for all the three sand beds within the range of settlements tested (up to s/B = 22%). The results also revealed that at normalized settlement of 2%, the load-carrying capacity for loose sand bed (D_r = 35%) is 23 kPa, whereas it is 51 kPa for the dense sand (D_r = 90%). The corresponding values for 12% settlements were 64 kPa and 137 kPa, respectively.

3.1.2 Geocell-reinforced sand foundation system

The bearing pressure settlement response of geocell-reinforced sand bed with geocell geometry with d/B = 0.5, b/B = 3, u/B = 0.1 & h/B = 0.66, for three different relative densities (D_r = 35, 70, and 90%) of sand beds are also presented in Figure 6. The results show that use of geocell reinforcement increases the load-bearing capacity and decreases the settlement of the footing. The curves depict a higher bearing pressure for densest sand bed (D_r); however, the foundation responses indicated reduction in beneficial effect (in terms of Improvement Factor, *i.e.* I_f) with the increase in relative density of sand bed (D_r) (Figure 7). A maximum Improvement Factor (I_f) of about 3.5 was seen for loose sand (D_r = 35%), whereas it was about 2.4 for D_r = 70% and about 1.9 for D_r = 90% at s/B = 10%. The reduction in improvement is attributed to the fact that the denseness of sand beds provides greater resistance against possible deformation, and hence, reduces the strain induced sand-geocell interactions. It can also be seen from Figure 6 that even for sand bed having relative density of 35%, the load-carrying capacity increases to about 307 kPa (at s/B = 18%). Furthermore, in case of geocell-reinforced sand bed, no clear failure was observed in the pressure-settlement curve even up to the large settlement at s/B = 22%. In the past studies, Dash et al. (2003) have reported an Improvement Factor (I_f) in the range of 1.4 to 3.4 for s/B = 1% to 15%, whereas Hegde and Sitharam (2013) have reported an I_f in the range of 1.1 to 1.8 for s/B = 2% to 18% in a geocell-reinforced soil. In the present study, the results show an intermediate I_f of 1.6 to 3.0 for s/B = 2% to 18%.

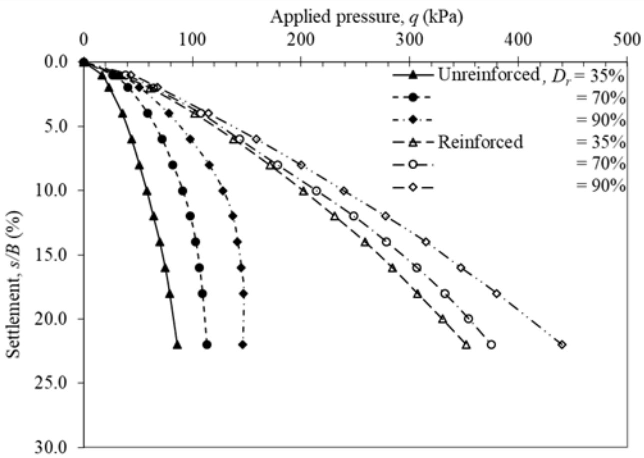


Figure 6 Variation of footing settlement with bearing pressure for unreinforced and geocell-reinforced sand beds

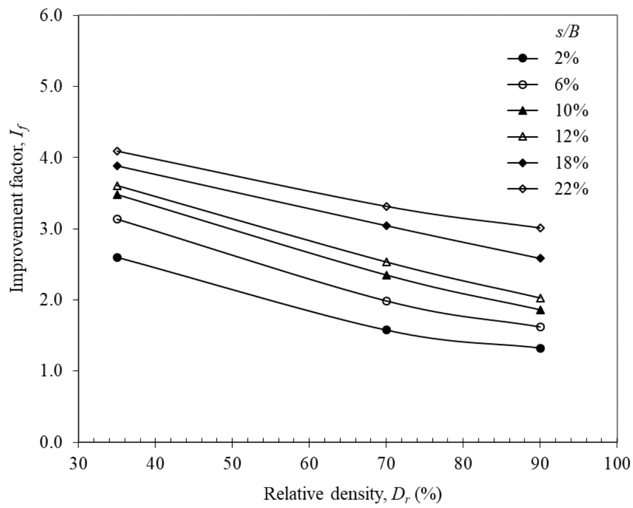


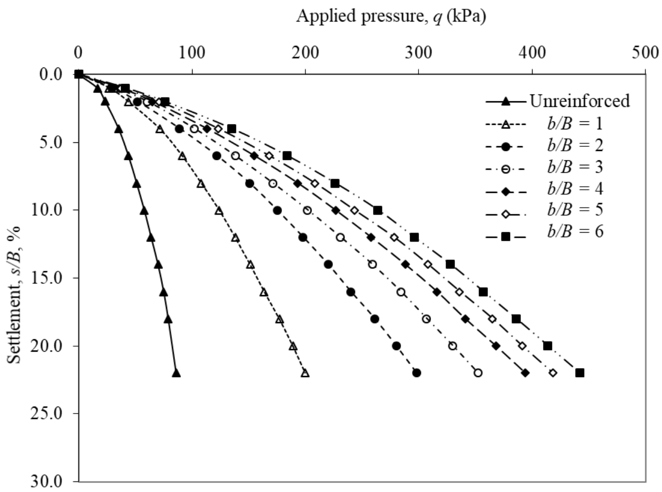
Figure 7 Variation of Improvement factor (I_f) for different s/B and varying D_r of sand beds

3.1.3 Effect of Reinforcement Width and Relative Density of Sand

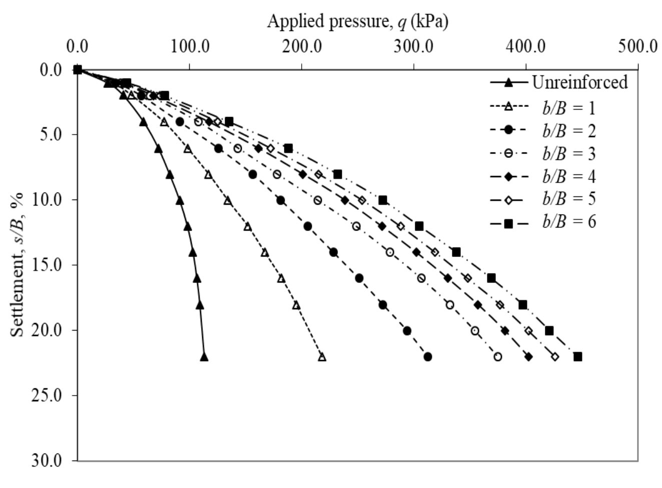
Figures 8(a) - 8(c) illustrate the effect of the geocell reinforcement on the load-settlement behaviour of reinforced models corresponding to the relative densities of sand (D_r) and the geocell reinforcement width. As can be seen, bearing-capacity generally increases as *b/B* values increase, but did not follow a linear trend with a rise in D_r. For instance, at *s/B* = 12%, *b/B* = 3, bearing-capacity Improvement Factor (I_f) for D_r = 35% is 3.6, whereas the values are 2.5 and 2 for the reinforced models of D_r = 70 and 90%, respectively. The tests data also reveal that the performance of geocell-reinforced foundation system, both in terms of bearing capacity and settlement, increases with an increase in geocell reinforcement width. For instance, the bearing capacity Improvement Factor was about 2.1 and 2.5 for reinforcement width, $b = 2B$ and $b = 3B$, respectively, at *s/B* = 12%, D_r = 70%. However, when geocell width reaches an optimum value (4*B*), the effect of improvements becomes negligible (Figure 9).

The variation of surface deformation with footing settlement for unreinforced and geocell-reinforced sand foundation, at a distance *B* from the centre of the footing, are presented in Figures 10(a) - 10 (f). In general, heaving was predominant for the unreinforced case with D_r = 70 and 90%. It can be seen that the surface heaving (δ/B) increases from 1.3 to 2.7 for unreinforced sand with D_r = 90%, when footing settles down from 6 to 10% of footing width, *B*.

A similar trend was also observed for the unreinforced foundation soils with D_r = 70%. But, in this case the surface heaving (δ/B) was 1.24 to 2.0 in the measured settlement ratio 6 to 10% of footing width. It is also to be noted that since a punching shear failure has taken place in unreinforced soil with D_r = 35% (Figure 6), therefore, the surface heaving at *s/B* = 10% was about 0.2% only. However, heaving was found to have reduced in the geocell-reinforced foundations with D_r = 70 and 90%. The surface heaving of unreinforced sand with D_r = 90% at 18% of footing settlement was observed to be about 3.6%, whereas it reduced to about 0.8% with geocell reinforcement.



(a)



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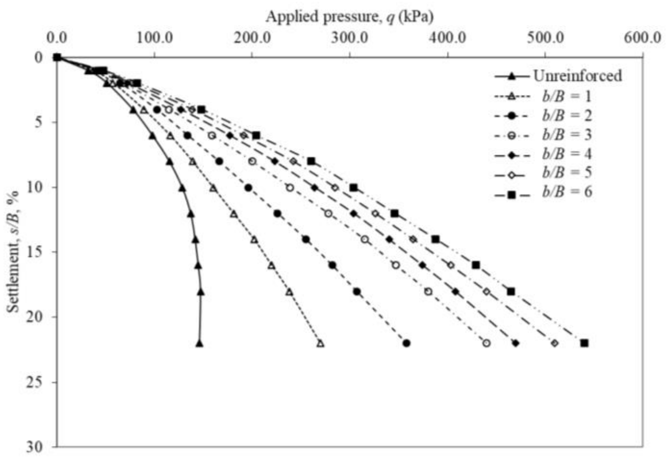


(c)

Figure 8 Variation of footing settlement with bearing pressure for unreinforced and geocell-reinforced sand beds: (a) D_r = 35%, (b) D_r = 70%, and (c) D_r = 90%

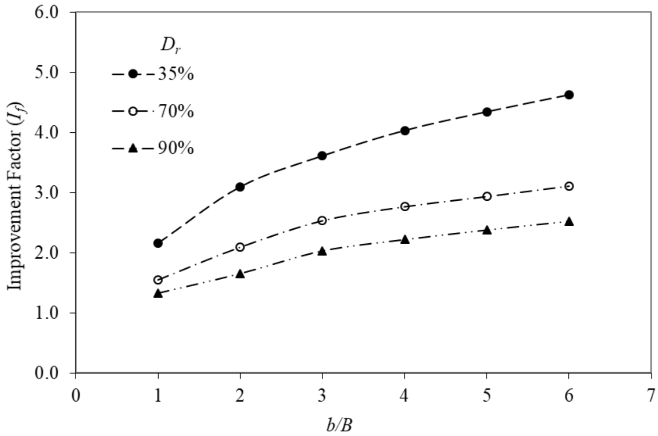
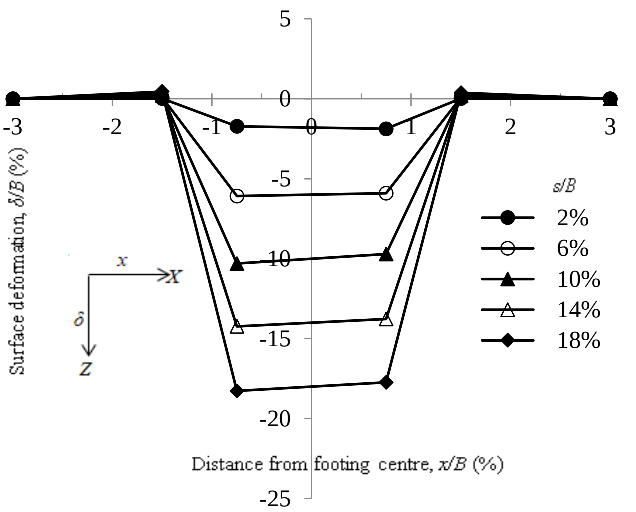


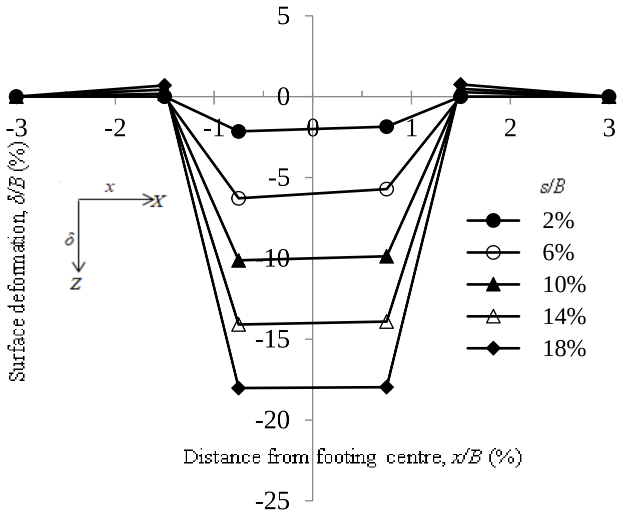
Figure 9 Variation of Improvement factor for different *b/B* at measured settlement *s/B* = 12%

The increased surface heaving for the unreinforced sand beds with D_r = 70 and 90% is due to the effect of dilatant behavior of dense sand. In case of geocell-reinforced foundations with D_r = 70 and 90% due to increase in stiffness of geocell-reinforced sand layer, the footing loads distribute over a wider area and thus the underneath soil experiences a lower pressure. In contrary, the surface heaving of geocell-reinforced sand with D_r = 35% is observed to increase from 0.4% to 1% at *s/B* = 18%. This may be due to the fact that the geocell mattress act as a raft foundation and the failure envelope shifted to the edge of the geocell reinforcement instead of the edge of the square footing.

Figure 11 shows the variation of the surface heaving and settlement of unreinforced and geocell-reinforced sand for different subgrade relative densities at equal load intensity of 79 kPa, which is the load-carrying capacity of unreinforced sand with D_r = 35% at *s/B* = 18%. The result clearly indicates a reduction of footing settlement with the provision of geocell reinforcement. A better load-carrying capacity of geocell-reinforced sand bed is also observed as compared to the unreinforced sand. It is also observed that the depressions are greater at the centre and reduces towards the edge of the test tank which might be due to bending of the geocell-sand mattress, as shown in Figures 12(a) - 12(b). Furthermore, the maximum depth of depressions at the centre is found to reduce as the subgrade relative density increases. Similar deformation responses of reinforced foundation system have also been reported by Dash et al. (2001a, 2003a), Sireesh et al. (2009a) and Biswas et al. (2013) when geocells made from geogrids were used.



(a)



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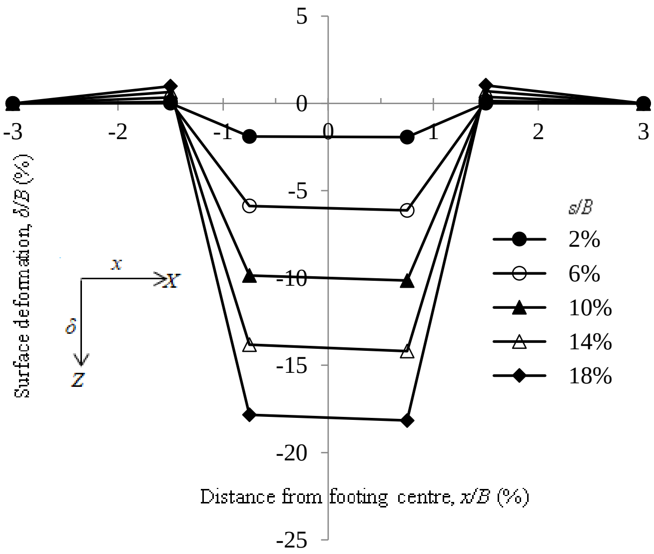

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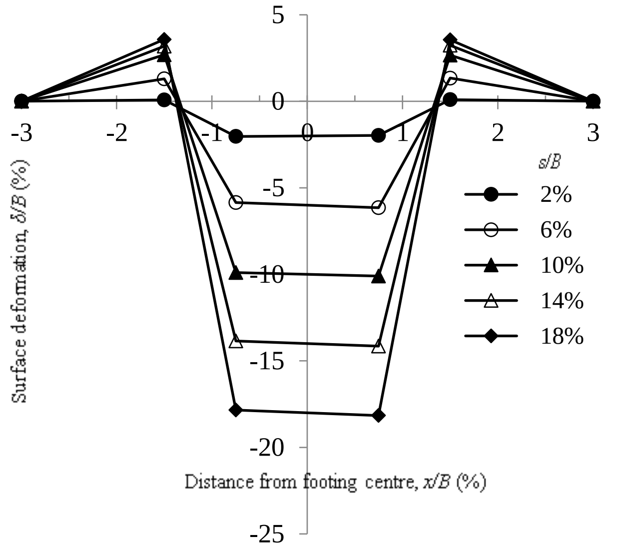

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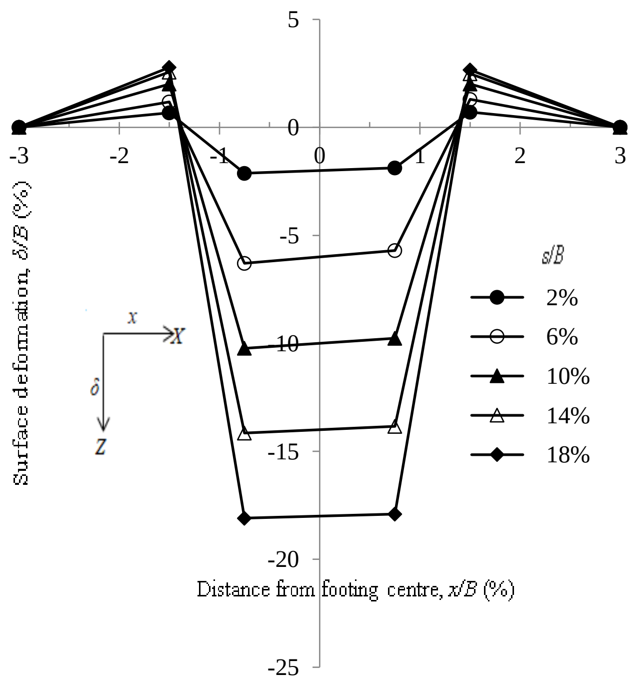

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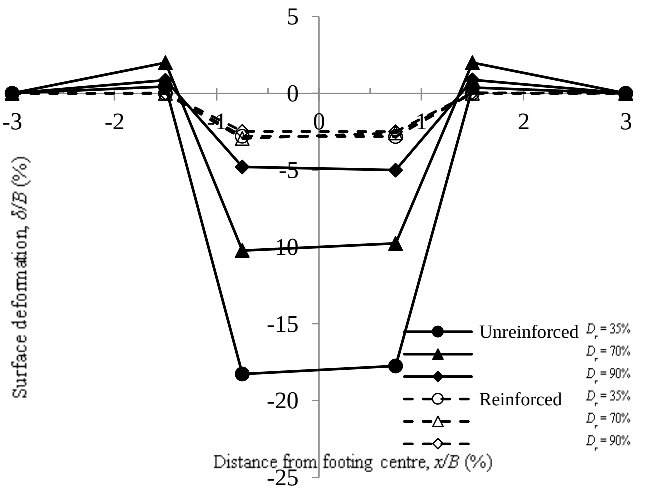


(f)

Figure 10 Surface heaving with footing settlement for unreinforced and geocell-reinforced sand beds: (a) unreinforced, D_r = 35%, (b) geocell-reinforced bed, d/B = 0.5, h/B = 0.66, u/B = 0.1, b/B = 3, D_r = 35%, (c) unreinforced, D_r = 70%, (d) geocell-reinforced bed, d/B = 0.5, h/B = 0.66, u/B = 0.1, b/B = 3, D_r = 70%, (e) unreinforced, D_r = 90%, and (f) geocell-reinforced bed, d/B = 0.5, h/B = 0.66, u/B = 0.1, b/B = 3, D_r = 90%

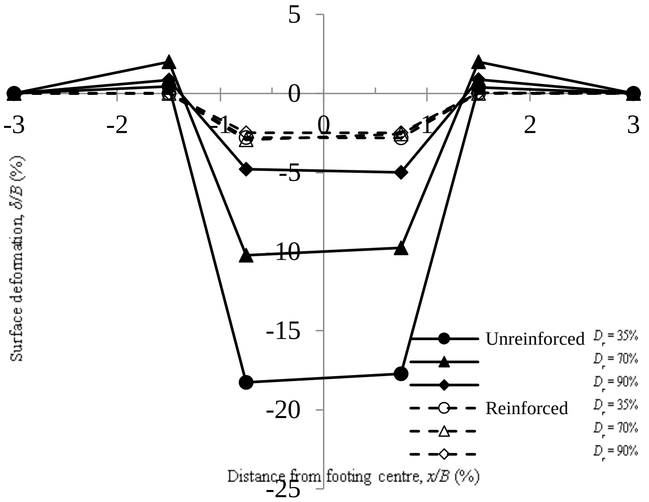
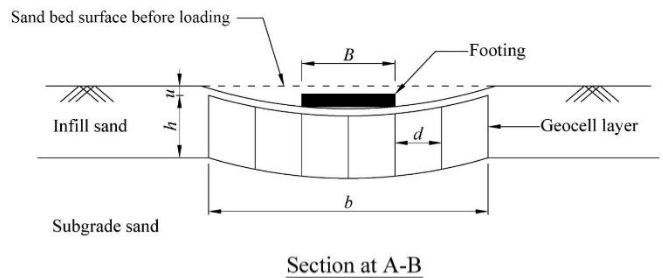


Figure 11 Variation of surface heaving and settlement for unreinforced and geocell-reinforced sand beds at an equal intesity of load for different subgrade relative density, D_r = 35%, 70% and 90%

(a)



(b)

Figure 12 Photographic view of footing settlement for: (a) geocell-reinforced foundations (d/B = 0.5, h/B = 0.66, u/B = 0.1, b/B = 3 and D_r = 70%) and (b) Schematic diagram of settlement of geocell-reinforced foundation system along section A-B

4. CONCLUSIONS

This paper presents the results of the experimental studies conducted to investigate the geotextile-based geocell reinforcement on the performance of geocell-reinforced foundation system. Based on the results obtained, the following conclusions can be made:

1. The geotextile-based geocell reinforcement can be effectively utilized in the enhancement of bearing capacity and settlement of sandy soil.
2. The load-settlement behavior of geocell-reinforced foundation system improves with an increase in geotextile-based geocell-reinforcement width. With the geocell reinforcement width, b = 2B, the bearing capacity improvement (as compared to unreinforced bed) was found about 2.5 times, whereas with the b = 3B, it was 3 times at s/B = 18%, D_r = 70%. However, when reinforcement width reaches an optimum value (4B), the effect of improvements becomes only marginal.
3. The improvement in bearing capacity decreases with an increase in denseness of sand bed. In the case of geocell-reinforced foundation system with low density sand bed (D_r = 35%), maximum improvement was found about 3.5 times, whereas it was only 1.9 times for high density sand bed (D_r = 90%) at s/B = 10%. Thus, it can be concluded that the geotextile-based geocell contribution in improving the load-carrying capacity is very significant for low relative density sand bed.
4. Furthermore, the use of geotextile-based geocell reinforcement almost arrests the surface heaving of soil irrespective of which relative density of sand bed the footing has been rested.
5. The plate load tests have been carried out at different relative densities of sand and the data will be very useful for developing analytical solution for footings resting on geocell-reinforced sandy soils.

5. ACKNOWLEDGEMENTS

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