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Comparison of bearing capacity of a strip footing on sand with geocell and with planar forms of geotextile reinforcement

S.N. Moghaddas Tafreshi [a,*], A.R. Dawson [b,1]

[a] Department of Civil Engineering, K.N. Toosi University of Technology, Valiasr St., Mirdamad Cr., Tehran, Iran
[b] Nottingham Transportation Engineering Centre, University of Nottingham, Nottingham, UK

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ABSTRACT

Comprehensive results from laboratory model tests on strip footings supported on the geocell and planar reinforced sand beds with the same characteristics of geotextile are presented. The various parameters studied in this testing program include the reinforcement width, the number of planar layers of geotextile and height of the geocell below the footing base. Contrary to other researches, the performance of the geocell and planar reinforcement is investigated at the range of low to medium settlement level, similar to those of interest in practice. The results show that the efficiency of reinforcement was decreased by increasing the number of the planar reinforcement layers, the height of the geocell reinforcement and the reinforcement width. For the same mass of geotextile material used in the tests at the settlement level of 4%, the maximum improvement in bearing capacity (IF) and percentage reduction in footing settlement (PRS) were obtained as 2.73 and 63% with the provision of geocell, respectively, while these values compare with 1.88 and 47% for the equivalent planar reinforcement. On the whole, the results indicate that, for the same quantity of geotextile material, the geocell reinforcement system behaves much stiffer and carries greater loading and settles less than does the equivalent planar reinforcement system. Therefore, a specified improvement in bearing pressure and footing settlement can be achieved using a lesser quantity of geocell material compared to planar geotextile.

1. Introduction

Geosynthetic materials have been widely used in geotechnical engineering applications for, e.g., longer-lasting road construction layers, stable embankments over soft soil and expedient access over soft ground. An additional, possible, use would be to improve the bearing capacity of footings, but, at present, this application is made difficult because of the limited knowledge on the load-settlement behaviour of footings on reinforced soils. To investigate such applications, researchers have undertaken many studies to investigate how best to arrange effective reinforcement. For example, Yoon et al. (2004), Ghosh et al. (2005), Patra et al. (2005, 2006) used model tests to study the influence of different types of reinforcement on the bearing capacity and settlement of the footing. They confirmed the beneficial effect of reinforcement on the enhancement of bearing capacity and reduction in settlement of footing. Hufenus et al. (2006) carried out full-scale field tests on a geosynthetic reinforced unpaved road to investigate the reinforcing effect on the bearing capacity and its performance on a soft subgrade. The various geosynthetics used for this reinforced unpaved road were found to have a relevant reinforcing effect only when used under a thin aggregated layer on a soft subgrade. El Sawwaf (2007) investigated the behaviour of strip footings on geogrid reinforced sand over a soft clay slope. Test results indicated that the inclusion of geogrid layers in the replaced sand not only significantly improves the footing performance but also leads to a great reduction in the depth of the reinforced sand layer that is required to achieve the allowable settlement. Moghaddas Tafreshi and Khalaj, (2008) performed an experimental study to investigate the beneficial effect of geogrid on the deformation of small diameter pipes and on the settlement of the soil surface when subjected to repeated loads that simulated vehicle loading. They reported that the percent of vertical diameter change and settlement of soil surface can be reduced significantly by using geogrid reinforcement.

Although planar geotextiles and geogrids have most often been studied, several investigations have also highlighted the beneficial use of geocell reinforcement in the construction of foundations and

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* Corresponding author. Tel.: +98 21 8877 9473; fax: +98 21 8877 9476.
E-mail addresses: nas_moghaddas@kntu.ac.ir (S.N. Moghaddas Tafreshi), andrew.dawson@nottingham.ac.uk (A.R. Dawson).
[1] Tel.: +44 115 951 3902; fax: +44 115 951 3909.

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Nomenclature

B	width of footing
b_p	reinforcement width of the planar reinforcement
u	depth of the first layer of planar reinforcement and embedded depth of the geocell reinforcement beneath the footing
h	vertical spacing between layers of planar reinforcement
N	number of layers of planar reinforcement
b_g	reinforcement width of the geocell reinforcement
H	height of the reinforced zone by the geocell reinforcement
d	pocket size of the geocell
Ag	area of the pocket opening of geocell reinforcement
D_r	relative density of soil
q_{unrein}	bearing pressure of footing on the unreinforced sand at a given settlement
q_{planar}	bearing pressure of footing on the planar reinforced sand at a given settlement
q_{geocell}	bearing pressure of footing on the geocell reinforced sand at a given settlement
IF	improvement factor in bearing pressure of footing (general)
IF_p	improvement factor in bearing pressure of footing due to planar reinforcement
IF_g	improvement factor in bearing pressure of footing due to geocell reinforcement
s_{unrein}	value of settlement of the unreinforced sand at a given bearing pressure
s_{planar}	value of settlement of the planar reinforced sand at a given bearing pressure corresponding to s_{unrein}
s_{geocell}	value of settlement of the geocell reinforced sand at a given bearing pressure corresponding to s_{unrein}
PRS	percentage reduction in footing settlement (general)
PRS_p	percentage reduction in footing settlement due to planar reinforcement
PRS_g	percentage reduction in footing settlement due to geocell reinforcement

embankments. Rea and Mitchell (1978) and Mitchell et al. (1979) carried out a series of small-scale laboratory tests on footings supported over sand beds reinforced with square shaped paper grid cells and observed different modes of failure. Shimizu and Inui (1990) carried out load tests on geotextile wall frames filled with sand overlying soft soil. Cowland and Wong (1993) reported a case study of the performance of an embankment supported on a geocell mattress over soft clay. Jenner et al. (1988), making use of slip line theory, have proposed a methodology to calculate the increase in bearing capacity due to the provision of geocell mattresses at the base of the embankment resting on soft soil. Krishnaswamy et al. (2000) carried out a series of laboratory model tests of earth embankments constructed on a geocell mattress supported over a soft clay bed. Dash et al. (2001a, b) investigated the reinforcing efficacy of the geocell mattress within a homogeneous sand bed supporting a strip footing. Dash et al. (2003, 2004) also reported load test results from a model circular footing supported on geocell reinforced sand overlying soft clay. In all of the above studies, the beneficial ability of geocell constructions to improve the bearing capacity of footings is reported. Madhavi Latha and Murthy (2007) through tri-axial compression tests have observed that geocell is a superior form of reinforcement than the planar one. Sireesh et al. (2009) carried out a series of laboratory scale model tests on a circular footing supported by geocell reinforced sand beds overlying clay bed with a continuous circular void. They reported that substantial improvement in performance can be obtained with the provision of geocell mattress, of adequate size, over the clay subgrade with void and beneficial effect could be obtained when the geocell mattress spread beyond the void at least a distance equal to the diameter of the void. Wesseloo et al. (2009) have studied the stress–strain behaviour of soil reinforced with single and multiple geocells. They reported geocell reinforcement owing to its three-dimensional configuration arrests the lateral spreading of the infill soil and creates a relatively stiffened mat that redistributes the footing pressure over wider area, on the underlying poor soil, thereby giving rise to enhanced load carrying capacity.

In most of these studies, researchers have reported the results of foundations supported by planar or three-dimensional geosynthetics (geocells) separately, whereas a comparison of planar and geocell reinforcement with regard to effectiveness and economy is likely to be more important in practice. At present, only a single experimental test has been reported in which a geocell (this type of geocell used was hand-made from geogrid) and a planar geogrid reinforcement arrangement were compared (Dash et al., 2003).

Hence, in the current research, and in order to develop a better understanding of the geocell reinforcement concept, a series of different laboratory, pilot scale tests were performed to evaluate the bearing pressure and settlement of a strip footing supported by reinforced relatively dense sand with either geocell (formed of geotextile) or with planar geotextile reinforcement. The overall goal was to demonstrate the benefits of geocell, with the detailed objective of this study being to compare the performance of geocell reinforcement systems and planar reinforcement systems that had the same characteristics and the same mass of geotextile reinforcing material (see Table 4). The various parameters studied in this testing program include the width of reinforcement, the number of planar layers and height of geocell reinforcement below the footing base, the details of which are presented in a later section. It should be noted that only one type of geocell and planar reinforcement, one footing width, and one type of sand were used in laboratory tests. It is recognized that the results of this study may be somewhat different to full-scale foundation behaviour in the field, although the general trend may be similar.

2. Laboratory model tests

A physical model test was conducted in a test bed-loading frame consisting of the testing tank, the loading system and the data acquisition system. The general arrangement of the laboratory test is shown in Fig. 1.

The testing tank is designed as a rigid box, 750 mm in length, 375 mm in height, and 150 mm in width, encompassing the reinforced soil and model foundation. The back and side faces of the tank consist of smooth ply-wood sheets of 17.5 mm thickness, which are permanently fixed to channel sections. To allow the visual observations of the sand reinforcement system, as well as photo scanning, the front face of the tank is made of a Plexiglas sheet, 15 mm in thickness. To prevent undesirable movement of the back and front sides of the tank (so as to maintain plane strain condition) the rigidity of the tank has been guaranteed by using two stiff steel sections of U-100 on the back face, with two stiff wedged blocks and a metallic spreader beam to retain the front face of the tank relative to the steel columns of the loading system. According to some preliminary test results (not further reported here), under a maximum applied loading stress of 1000 kPa on the soil surface, the measured deflection of the back and front faces of the tank were very small demonstrating that they would be negligible at the stress levels applied in the main test programme. The side wall friction effects on the model test results were reduced by coating the inside of the front and back walls with petroleum jelly. Also during the tests, no differential settlement between the two ends of the footing (loading plate) was observed. Taking these observations together demonstrates that plane strain conditions were achieved.

The loading system (Fig. 1) includes a loading frame, a hydraulic actuator and a controlling unit. The loading frame consists of four stiff and heavy steel columns and a horizontal crosshead that support the hydraulic actuator. The actuator may produce monotonic or repeated loads with maximum capacity of 10 kN.

The data acquisition system was developed in such a way so that both load and settlement could be read and recorded automatically. An S-shape load cell with an accuracy of ±0.01% full-scale was also used and placed between the loading shaft and footing to precisely measure the pattern of applied load. A linear variable differential transducer (LVDT) with an accuracy of 0.01% of full range (750 mm) was placed on the footing model to provide the value of footing settlement during the loading. To ensure an accurate reading, all of the devices were calibrated prior to each series of tests.

3. Materials

3.1. Sand

The soil used is a relatively uniform silica sand of grain sizes between 0.85 and 2.18 mm and specific gravity of 2.68 ($G_s = 2.68$). The grain size distribution of this sand is also shown in Fig. 2. The properties of the sand, which is classified as SP in the unified soil classification system, are tabulated in Table 1.

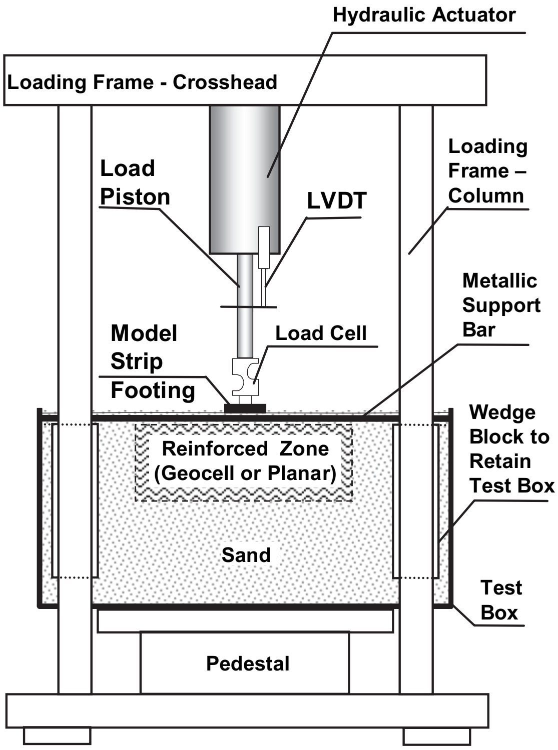

Fig. 1. General arrangements of test.

3.2. Reinforcements

Geosynthetics can be arranged into cellular structures that contain soil. These are termed “geocells” with the cell wall being manufactured from flexible, semi-flexible or strong geosynthetics such as geotextile, geogrids or even polymer sheets (punched or un-punched). In the reported researches (Bush et al., 1990; Krishnaswamy et al., 2000; Dash et al., 2003; Sitharam et al., 2007) geocell mattresses were prepared by cutting the geogrids to the required length and height from full rolls and placing them in transverse and diagonal directions, on the soil bed, with bodkin joints (plastic strips) inserted at the connections. This type of geocell is hand-made from geogrid and could be termed ‘geocells with perforations’.

In this current research, contrary to the above, the geocells used were made of a type of a planar geotextile thermo-welded to form a honeycomb structure with an open top and bottom – an innovative approach for use in ground stabilization. They could be termed ‘geocells without perforations’, being a form of ‘3D geotextile’. In this paper the abbreviated term “geocell” is used by the authors to describe this specific form of ‘geocell without perforations’. When the cells are filled with soil or other mineral material, it provides an ideal surface for construction projects such as foundations, slopes, driveways, etc. The high tensile strength of both the weld and geotextile provide an ideal structure with a high load capacity and prevents infill from spreading thus hindering subsidence. The pocket size (d) of the geocell is taken as the diameter of an equivalent circular area of the pocket opening (Ag), shown through hatch mark in Fig. 3 (i.e., $d^2 = (4/\pi) \times \mathrm{Ag}$). The pocket size ($d$) of the geocell used was kept constant ($d = 50$ mm), while it was used at thicknesses (H) of 25, 50, 75 and 100 mm in the testing program. The ratio of the geocell pocket size (d) to width of model foundation (B) is, thus, 0.67 ($d/B = 0.67$). This ratio is reported by Dash et al. (2003) around 0.8 times of footing width which is found to be the one that gives maximum performance improvement.

The geocell layer was prepared by cutting to the required length and height from a full pack. Fig. 3 shows the isometric view of the geocell used in the investigations.

The geocell and planar reinforcement used were both made and supplied by the same company. The type of geotextile is non-woven. The engineering properties of this geotextile, as listed

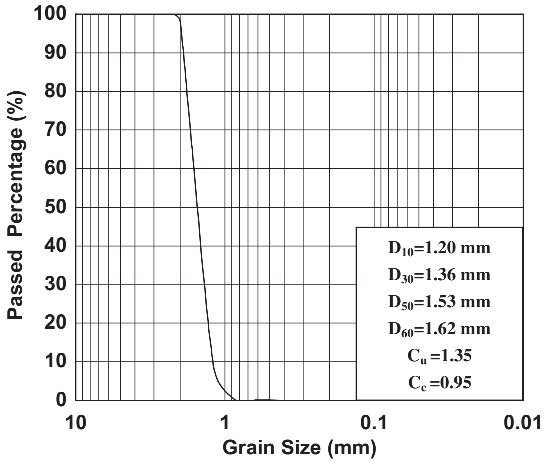

Fig. 2. Particle size distribution curve.

Table 1
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 72% relative density	37.5

by the manufacture, are presented in Table 2. The geocell is fabricated from the same geotextile material that forms the planar geotextile.

4. Preparation of model test and test procedure

In order to provide experimental control and repeatability of the tests, the raining technique (Kolbsuzewski, 1948) was used to deposit the soil in the testing tank at a known and uniform density. A moveable perforated steel plate was provided for raining the sand inside the testing tank (750 mm in length, 150 mm in width). It may be mounted above the testing tank to pour the sand from a specified height. The height of raining to achieve the desired density was determined *a priori* by performing a series of trials with different heights of raining. Sand was then rained from a pre-calibrated height to consistently maintain a relative density of 72% in all the tests.

In the case of the planar reinforcement, by considering the position of a reinforcement layer, the inner face of the tank was marked beneath the position of footing to facilitate accurate preparation of the reinforced sand bed. The soil was rained from prescribed height through the perforated plate in the tank and then on reaching the first reinforcement level, raining of sand was temporarily ceased. Thereafter the first layer of reinforcement was placed on the surface of the sand, after which the sand raining was continued until the desired level of the second layer of reinforcement was achieved. The preparation of the reinforced sand bed using one to four layers of reinforcement with a width equal to the full width of the tank and a specified length was continued up to the footing level.

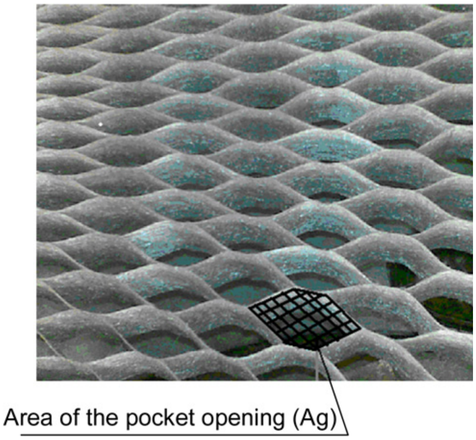

Fig. 3. Isometric view of the geocell.

Table 2
The engineering properties of the geotextile used in the tests.

Description	Value
Type of geotextile	Non-woven
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

In the case of the geocell reinforced bed, sand was rained up to the predetermined depth using depth-marking on the sides of the tank as guides. Then the geocell was placed on the top of the levelled sand bed. After that the cell pockets were filled with sand using the raining technique which continued up to the footing level.

For both cases of the planar and geocell reinforcement great care was taken to level the soil surface using a special ruler so that the relative density of the top surface was not affected. The model footing used was made of a steel rigid plate and measured, 148 mm in length, 75 mm in width and 20 mm in thickness.

In order to create plane strain conditions within the test arrangement, the length of the footing ($B = 148$ mm) was made almost equal to the width of the tank (=150 mm). On each side of the tank, a 1 mm wide gape was given to prevent contact between the footing and the side walls. The base of the model footing was made rough by covering it with epoxy glue and rolling it in sand. The two ends of the footing plate were polished to have a smooth surface and also coated with petroleum jelly to minimize the end friction effects. The model footing was placed at the desired position on the soil, with a length of the footing parallel to the width of the tank. In order to provide vertical loading alignment, a small hemi-spherical indentation was made at the centre of the footing model. A load cell was placed on the loading shaft to record the applied loads and its lower end equipped with a hemi-spherical protrusion that engaged with the seating on the footing. A LVDT was placed on the footing model accurately to measure the settlement of the footing during the loading. The static load was applied at a rate of 1.0 kPa per second until reaching failure. In the absence of a clear-cut failure, the footing was loaded to reach a constant value of applied stress.

5. Test parameters and testing program

The geometry of the test configurations for both the geocell and the planar reinforcement considered in these investigations is shown in Figs. 4 and 5, respectively. Also, the details of both geocell and planar reinforced tests are given in Table 3. In the case of geocell reinforced bed, two series of tests (test series 2 and 3) were

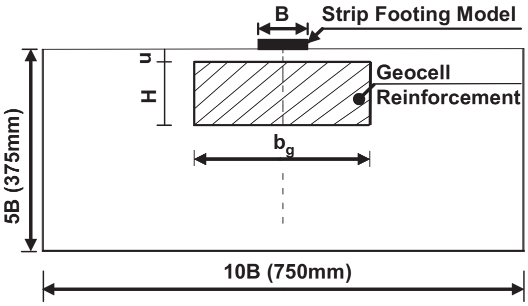

Fig. 4. Geometry of the geocell reinforced foundation bed.

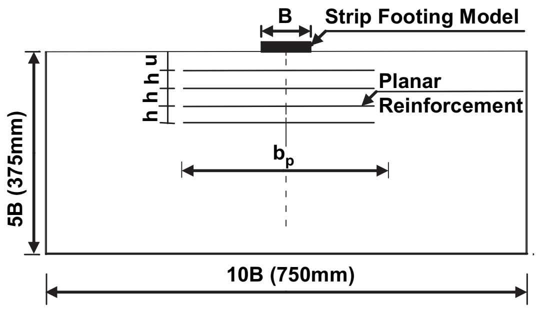

Fig. 5. Geometry of the planar reinforced foundation bed.

conducted by varying the height of geocell (H), the width of the geocell (b_g) and the depth to the top of geocell layer below the footing (u).

In the case of the planar reinforced bed, two series of tests (test series 4 and 5) were conducted by varying the number of layers (N), the width of the planar reinforcement (b_p) and the depth to the top of first reinforcement layer from the base of the footing (u). All these variable parameters used to describe the tests are expressed in non-dimensional form with respect to footing width (B) as u/B, H/B, b_g/B and b_p/B. Test series 1 were carried out on unreinforced sand to quantify the improvements due to reinforcements.

It should be noted that many of the tests described in Table 3 were repeated carefully at least twice 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 results obtained depicted a close match between results of the two or three trial tests with maximum differences in results of around 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.

In order to provide a meaningful comparative assessment between the planar and geocell reinforcement, the quantity of material used must be matched. Hence, Table 4 shows the quantity of material used in each test relative to that used in the least reinforced test. This value, termed 'a', is equivalent to the mass of a single sheet of planar reinforcement of the smallest width used in the tests. The table indicates the amount of geotextile relation to this minimum case, whether provided in the form of wider or multiple planar reinforcements and or in the form of wider or higher geocell inclusions (which are manufactured of the same geotextile). As can be seen, assessment of performance was undertaken for arrangements with planar sheet and geocell reinforcement of the same mass of geotextile being paired together. For example, the experiment reinforced by two layers of short planar reinforcement has exactly the same mass of geotextile as that reinforced by the short geocell reinforcement at $H/B = 0.66$. This pair both have two units 'a' of reinforcement the same as the long pair of one layer for planar or $H/B = 0.33$ for geocell reinforcement. It should be noted that the amount of material used in each test is a function of reinforcement width and of the number of layers of planar or height of geocell reinforcement.

6. Results and discussions

The performance improvement due to the provision of reinforcement is represented using two non-dimensional improvement factors:

(1) Improvement in bearing pressure of footing (IF: improvement factor) which compares the bearing pressure of the planar or geocell reinforcement bed to that of the unreinforced bed at a given settlement, s_i.

(2) Improvement in footing settlement (PRS: percentage reduction in footing settlement) which compares the settlement of the planar or geocell reinforcement bed to that of the unreinforced bed at the same bearing pressure. The values of bearing pressures selected are those that cause the indicated amount of

Table 3
Scheme of the bearing capacity tests for unreinforced and reinforced (planar and geocell) sand.

Test series	Type of reinforcement	H/B or N	u/B	b_g/B or b_p/B	No. of tests	Purpose of the tests
1	Unreinforced	–	–	–	$1 + 2^*$	To quantify the improvements due to reinforcements
2	Geocell reinforced	$H/B = 0.33$	0, 0.1, 0.25, 0.5, 1	$b_g/B = 4.2$	$5 + 2^*$	To arrive at the optimum values of u/B
3	Geocell reinforced	$H/B = 0.33$, 0.66, 1, 1.33	0.1	Short width: $b_g/B = 2.1$ Medium width: $b_g/B = 3.2$ Long width: $b_g/B = 4.2$	$12 + 4^*$	To study the effect of the H/B and reinforcement width at optimum values of u/B
4	Planar reinforced	$N = 1$	0.2, 0.4, 0.6, 1, 1.2	$b_p/B = 5.5$	$5 + 2^*$	To arrive at the optimum values of u/B
5	Planar reinforced	$N = 1, 2, 3, 4$	0.35	Short width: $b_p/B = 2.8$ Medium width: $b_p/B = 4.1$ Long width: $b_p/B = 5.5$	$12 + 4^*$	To study the effect of the number of reinforced layers and reinforcement width at optimum values of u/B

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

Table 4
The quantity of geotextile material for the planar and geocell reinforcement used in testing program.

Planar reinforcement				Geocell reinforcement			
Number of reinforced layers, *N* (see Fig. 5)	Reinforcement width to footing width, b_p/B			Height of reinforcement, *H*/*B* (see Fig. 4)	Reinforcement width to footing width, b_g/B		
	Short width	Medium width	Long width		Short width	Medium width	Long width
	2.8	4.1	5.5		2.1	3.2	4.2
1	*a*[*]	1.5*a*	2*a*	0.33	*a*	1.5*a*	2*a*
2	2*a*	3*a*	4*a*	0.66	2*a*	3*a*	4*a*
3	3*a*	4.5*a*	6*a*	1	3*a*	4.5*a*	6*a*
4	4*a*	6*a*	8*a*	1.33	4*a*	6*a*	8*a*

[*] See text above for definition of parameter '*a*'.

settlement in the unreinforced case, s_{unrein}. They are defined as follows:

$$\mathrm{IF_p} = \frac{q_{\text{planar}}}{q_{\text{unrein}}} \quad \text{OR} \quad \mathrm{IF_g} = \frac{q_{\text{geocell}}}{q_{\text{unrein}}}$$
$$\text{For} \quad s_i\Big/B = 2\%, \ 4\%, \ 6\%, \ 8\%, \ 10\% \ \text{and} \ 12\% \qquad (1)$$

$$\mathrm{PRS_p} = \left(1 - \frac{s_{\text{planar}}}{s_{\text{unrein}}}\right)*100 \ \text{OR} \ \mathrm{PRS_g} = \left(1 - \frac{s_{\text{geocell}}}{s_{\text{unrein}}}\right)*100$$
$$\text{For} \ s_{\text{unrein}}\Big/B = 2\%, \ 4\%, \ 6\%, \ 8\%, \ 10\% \ \text{and} \ 12\% \qquad (2)$$

where q_{unrein}, q_{planar} and q_{geocell} are the values of bearing pressure of the unreinforced bed, the planar reinforced bed and the geocell reinforced bed at a given settlement, respectively. It should be noted that, if the footing on unreinforced sand reaches its ultimate capacity at a certain settlement, the bearing pressure is taken as the ultimate value while calculating IF at a higher settlement. Also s_{planar} and s_{geocell} are the value of the settlement of the planar and geocell reinforced bed at a given bearing pressure corresponding to s_{unrein}, respectively. These terms are explained in Figs. 6a,b.

It should be noted that, in most of the researches dealing with bearing capacity of footings, the performance of footing due to the provision of reinforcement is only investigated by considering the bearing capacity without considering the settlement limit criterion (DeMerchant et al., 2002; Dash et al., 2003; Sitharam and Sireesh, 2005), whereas in many cases, the practical design of shallow foundations is governed by settlement rather than bearing capacity. Furthermore, the improvement in bearing capacity due to the provision of reinforcement is frequently estimated at an unrealistically high range of footing settlement level, up to 40–50% of footing width (Krishnaswamy et al., 2000; Dash et al., 2003; Sitharam et al., 2007), whereas this range of settlement level is not acceptable (in practice cases, the amount of settlement must not be large) for the design of the footings in most practical circumstances.

Hence, in the current research, contrary to most studies, the performance improvement due to the provision of reinforcement in the sand bed has been investigated with special emphasis on the reduction of footing settlement and on the improvement in bearing capacity of footings for the range of footing settlement less than 12% of footing width. Despite the value of footing settlement equals 12% of footing width is considered an absolute upper limit, however, the examples given in this paper emphasized the behaviour at more tolerable settlement ratios (e.g., 5%).

6.1. Determination of the optimum value of *u*/*B* ratio

For the geocell reinforcement case, the optimum value of the ratio *u*/*B* is obtained from test series 2 in Table 3. The tests are done for different depths of placement of geocell below the footing base (*u*/*B*), while b_g/B and *H*/*B* values are kept constant at 4.2 and 0.33, respectively. The corresponding improvement in bearing pressure factor ($\mathrm{IF_g}$) with *u*/*B* at different values of settlement is depicted in Fig. 7.

It shows the improvement factor ($\mathrm{IF_g}$) initially slightly increasing when *u*/*B* increases from 0 to 0.1, but thereafter, the value of $\mathrm{IF_g}$ decreases with depth of placement. The slight increase in performance improvement with *u*/*B* of 0.1 could be due to the available

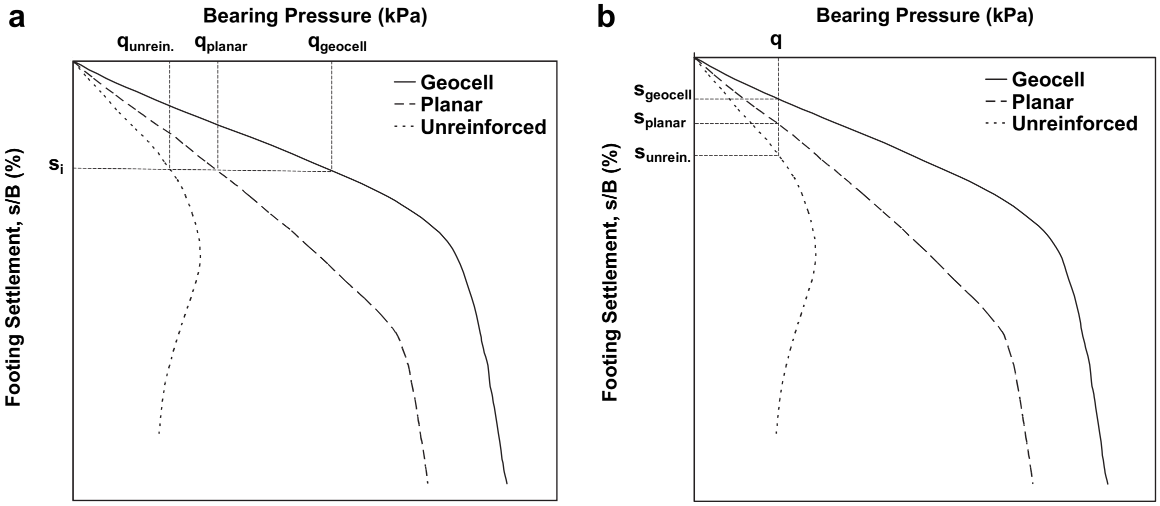

Fig. 6. Definition of parameters to calculate the values of improvement in bearing pressure (IF) and percentage reduction in settlement (PRS), (a) IF and (b) PRS.

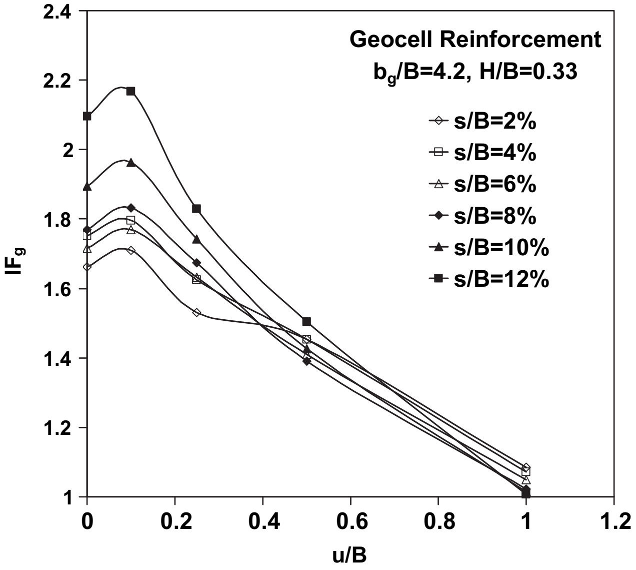

Fig. 7. Variation of improvement bearing pressure factor (IF_g) with u/B of the geocell reinforcement at different value of settlement.

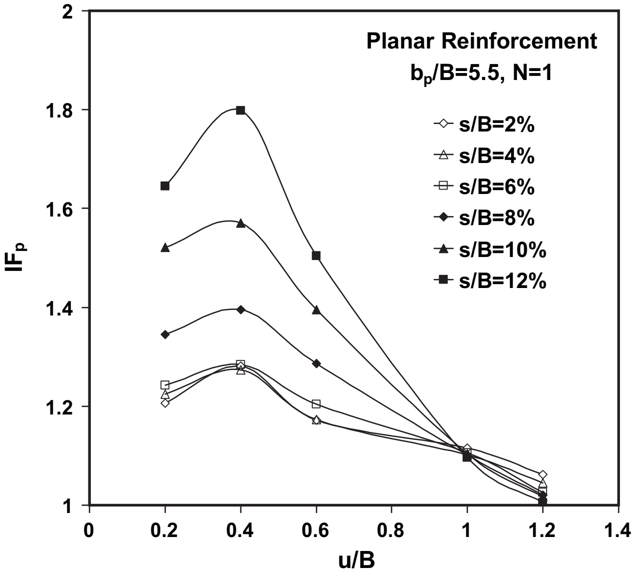

Fig. 8. Variation of improvement bearing pressure factor (IF_p) with u/B of planar reinforcement at different values of settlement.

competent sand layer (relatively dense sand, $D_r = 72\%$) above the geocell reinforcement, which serves as a cushion, preventing the direct contact of the footing base with the cell walls and distributing the footing pressure more uniformly over the cellular reinforcement. Sitharam and Sireesh (2005) reported somewhat similar findings that the bearing capacity of a circular footing on a geogrid cell reinforced bed improved significantly to a depth of placement of $u/B = 0.05$. Therefore, in the present study in all the tests, the geocell reinforcement was placed at $u/B = 0.1$.

It is interesting to note that when the depth of placement, u/B reaches around the width of footing ($u/B = 1$), the influence of geocell reinforcement becomes practically negligible and the reinforced bed behaves like an unreinforced case. At this value of u/B, stress applied by the footing is concentrated on the unreinforced soil mass above the reinforcement so that the failure mechanism tends to the unreinforced one. Sitharam and Sireesh (2005) reported a similar result in the case of $u/B = 1$ for a cellular mattress.

For the planar reinforcement case, the improvement bearing pressure factor (IF_p) with u/B at a different value of settlement is depicted in Fig. 8. The results are obtained for a reinforced foundation bed with one planar reinforcement layer and for different depths of placement of the planar reinforcement below the footing base (u/B), while b_p/B is kept constant at 5.5 (test series 4 in Table 3). From this figure, it has been found that with an increase in u/B ratio, the value of IF_p increases up to the value of $u/B = 0.35$–0.4, approximately, after which, with a further increase in u/B ratio, the value of IF_p decreases. Ghosh et al. (2005) reported a similar finding in that bearing capacity of a square footing on pond ash reinforced with jute-geotextile improved significantly in the range of $u/B = 0.3$–0.35.

The probable reason for these optimum u/B values is that for $u/B < 0.35$ the overburden was not sufficient to develop enough frictional resistance at the interface of the reinforcement and sand. The lack of sufficient confining pressure for the top reinforcement layer beyond the footing edges at low depth ratio values is also attributed. Abedin et al. (1997) found an increase in bearing capacity up to approximately 2.7 times by placing the reinforcement within homogeneous sand at a depth within the range of $u/B = 0.25$–0.75 times of the smallest dimension of the footing. They explained that at smaller upper thicknesses, the soil mass above the reinforcing layer could have insufficient overburden to generate enough friction at the soil reinforcement interface.

Increasing u/B beyond 0.30–0.4 means that the top layer of reinforcement is located out of the most effective zone, so a decrease in value of IF was observed at all settlements until the value of u/B reaches a depth of 1.2 times of the footing width ($u/B = 1.2$). Then, the reinforcement layer lies outside the failure zone beneath the foundation and so the influence of planar reinforcement becomes completely negligible. Akinmusuru and Akinbolade (1981) and Ghosh et al. (2005) indicated similar results with a decrease in bearing capacity with increase in the value of u/B. Therefore, in the present study, the top planar reinforcement was placed at $u/B = 0.35$ in every case.

The vertical spacing of the reinforcement between the bottom of the previous layer and the top of the next layer were selected to be equal to u/B and held constant in all the tests at $h/B = 0.35$. A similar approach, with matching values of u/B and h/B, were used by Yoon et al. (2004) and Ghosh et al. (2005) to obtain a maximum value of bearing capacity and a minimum value of footing settlement.

6.2. The general behaviour of the geocell and planar reinforcement

Fig. 9 presents the bearing pressure–settlement behaviour of the geocell and planar reinforced foundation beds for long reinforcement width ($b_g/B = 4.2$ & $b_p/B = 5.5$) which is named in Table 5 as ‘long width’. The mass of geotextile used in any matching pair of geocell and planar reinforcement is exactly the same. The matching pairs are $H/B = 0.33$ & $N = 1$; $H/B = 0.66$ & $N = 2$; $H/B = 1$ & $N = 3$; and $H/B = 1.33$ & $N = 4$.

From Fig. 9, it may be clearly observed that, with increasing the mass of reinforcement (increase in the height of the geocell reinforcement; H/B or in the number of layers of planar reinforcement; N); both stiffness and bearing pressure (bearing pressure at a specified settlement) considerably increase. In the case of the unreinforced sand beds, it is apparent that the bearing capacity failure has taken place at a settlement equal to 12% of footing width while in the case of both the geocell and planar reinforced sand beds; no clear failure point is evident for the larger masses of reinforcement ($N \geq 2$ or $H/B \geq 0.66$). Beyond a settlement of

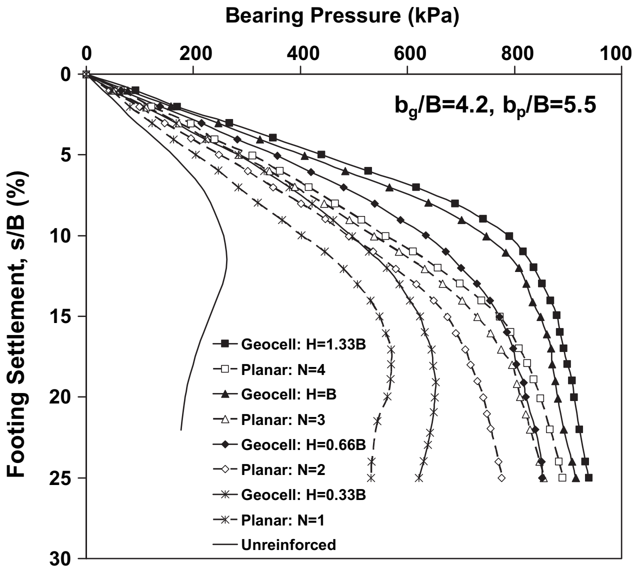

Fig. 9. Variation of bearing pressure with settlement for the geocell and planar reinforcement with long width ($b_g/B = 4.2$ & $b_p/B = 5.5$).

10–16% there is a reduction in the slope of the pressure–settlement curve. However, when lightly reinforced ($N = 1$ and $H/B = 0.33$, respectively, for planar reinforcement and geocell reinforcement) failure is observed at settlements of 16–18% with clear post-failure reductions in bearing capacity.

At this range of settlement, heave of the fill surface starts. It is attributable to the soil reinforcement composite material breaking locally in the region under and around the footing, because of high deformation induced by the large settlement under the footing. This leads to a reduction in the load carrying capacity of the footing indicated by the softening in the slope of the pressure–settlement responses (Fig. 9). Beyond this stage, the slope of the moderately and heavily reinforced cases remains almost constant with the footing bearing pressure continuously increasing. The foundation bed continues to take additional load through mobilization of its rigidity and anchorage derived from the adjacent stable soil mass, thereby giving rise to the improved performance. Because no clear bearing capacity failure has been observed, even at a settlement of 25%, it is probable that no yield condition is to be found at conventional stress levels.

6.3. *The influence of height of the geocell and the number of layers of the planar reinforcement*

In order to investigate clearly the performance of the geocell reinforcement and planar reinforcement in increasing the bearing pressure and decreasing the settlement of a reinforced sand bed due to an increase in the thickness of the geocell (H/B) or in the number of layers of the planar reinforcement (N) compared to the unreinforced one, the values of bearing pressure improvement factor (IF) and percentage reduction settlement (PRS) are calculated at different levels of settlement. The variation of these two parameters, IF and PRS with footing settlement for long, medium and short reinforcement width are shown in Figs. 10 and 11, respectively.

Generally, from these figures, it is of interest to note that improvement in bearing pressure (IF) and the percentage reduction in settlement (PRS) are higher at a higher settlement of footing for both planar and geocell cases, irrespective of the number of planar reinforcement layers (N), the height of geocell reinforcement (H/B) and the reinforcement width. This indicates that the reinforcing efficacy increases with increase in footing penetration. Furthermore, the results show that the trend and magnitude of IF and PRS differ with strain level. The nature of the curves may be classified into two groups; one for settlement level, $s/B < 6\%$, and the other for $s/B > 6\%$. For the second group (higher settlement levels) geotextile inclusion increases the values of IF and PRS, significantly. Moreover, for the second group, the rate of increase of IF and PRS with an increase of N or H/B is more compared to that for the first group (lower settlement levels) where the rate of increase of IF and PRS is not very significant. This means that the internal confinement provided by the soil reinforcement increases with increase in the imposed settlement level on the reinforced system.

It can be seen that the values of IF and PRS increase steadily with an increase in the height of the geocell (H/B) or the layers of planar reinforcement (N). The reason is that more reinforcement considerably increases the stiffness of the reinforced sand bed compared to the unreinforced sand. The rate of reduction in footing settlement and the rate of enhancement in the load carrying capacity of the footing can also be seen to reduce with increase in the value of H/B and N (the distance between the curves decreases with increase in the value of H/B or N). Furthermore, one can anticipate that the improvement rates will become almost insignificant with increase in the number of planar layers (N) or the height of the geocell (H/B). The reason is that the zone of soil influenced by the footing loading extends to a depth of about one to two times the footing width. Therefore, marginal performance improvement would be expected when the value of H/B reaches around 1.5 to two or the value of N increases to five to six layers. Similar results have been reported by Yoon et al. (2004) and Ghosh et al. (2005) regarding small improvements in settlement of footings and in bearing pressure of footings due to additional layers of planar reinforcement. Also, Sitharam and Siresh (2005) and Sitharam et al. (2007) have observed the marginal performance improvement when the height of a geocell increased to around 1.8 times of the diameter of a circular footing supported on a reinforced clay bed.

A further observation is that, with an increase in the height of the geocell or the number of planar reinforced layers, the rigidity of the reinforced system increases, which restrains the soil against heave thereby reducing heaving on fill surface. Hence, with an increase the mass of reinforcement in depth of the sand, especially in the case of the geocell, the heaving of soil surface beside the footing is completely restrained and the geocell behaves like a slab giving rise to settlement on the adjacent fill surface.

6.4. *The influence of reinforcement width*

When comparing the values of IF and PRS from Figs. 10 and 11, for the same height of geocell (H/B) or the same number of layers of planar geotextile (N) at a different reinforcement width, it is clear that the performance of the footing in terms of bearing pressure (IF) and reduction in settlement (PRS) for both the geocell and planar reinforcement are significantly improved with an increase in the width of reinforcement. This improvement continues to around four and five times of footing width for the geocell and planar reinforcement, respectively. On the other hand, further increase in performance is likely to become negligible for more than the above values. Consider, for example for the geocell case with $H/B = 1$ at settlement ratio of $s/B = 4\%$. The bearing pressure increases 64, 133 and 153% ($IF_g = 1.64$, 2.33, and 2.53) for short, medium and long reinforcement width, respectively. These values imply that the percent increase in bearing pressure for variation of b_g/B between 2.1 and 3.2 is substantially greater than those for variation of b_g/B between 3.2 and 4.2, confirming that with an increase in the value

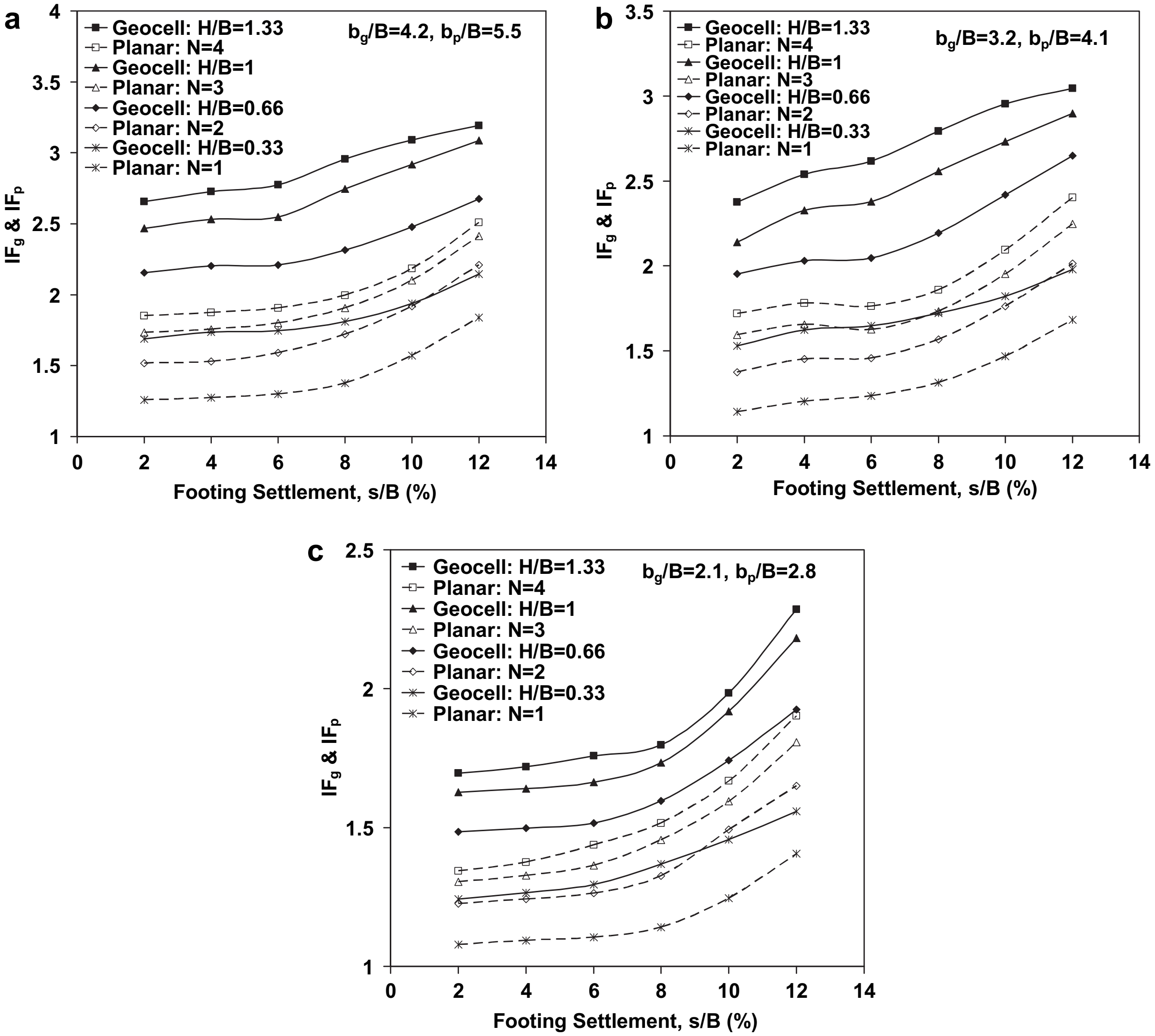

Fig. 10. Variation of the bearing capacity improvement factor (IF) with footing settlement for the geocell and planar reinforcement, (a) long width ($b_g/B = 4.2$ & $b_p/B = 5.5$), (b) medium width ($b_g/B = 3.2$ & $b_p/B = 4.1$) and (c) short width ($b_g/B = 2.1$ & $b_p/B = 2.8$).

of b_g/B more than 4.2 (long width) further substantial increased bearing capacity can not be expected. A similar pattern can be observed for the variation of IF_p for the planar reinforcement, and also the variation of PRS, with increases in the reinforcement width for both the geocell and planar reinforcement.

6.5. Comparison of the performance of geocell and planar reinforcement

From the results presented in Fig. 9, it is seen clearly that, for all the cases with the same mass of geotextile material (see Table 4 that compares the mass of the geocell and planar reinforcement), the geocell reinforced bed system has a higher stiffness (i.e., a greater slope of the pressure settlement response curve) and a greater carrying load capacity as compared with the planar reinforced one at any given footing settlement. Also, Figs. 10 and 11 depict that at the same mass of geotextile material, the geocell reinforcement is more effective in increasing the bearing pressure of the footing (IF) and in reducing footing settlement (PRS) than is the planar reinforcement. For example, in the case of the long reinforcement width at a settlement ratio of 6%, the bearing pressure increases 177% ($IF_g = 2.77$) due to the geocell reinforcement (with $H/B = 1.33$), whereas there is only a 91% enhancement ($IF_p = 1.91$) for the planar reinforcement (with $N = 4$), yet both the geocell and planar system have the same mass. It means that there is a 45% enhancement due to the geocell reinforcement compared to the planar reinforcement when the same geotextile material is used for both the geocell and planar reinforcement. Also in this case, the footing settlement decreases 63% ($PRS_g = 63\%$) for the geocell reinforcement, whereas there is a 47% reduction ($PRS_p = 47\%$) for the planar reinforcement. This indicates that the performance of the geocell reinforcement is about 35% better as regards footing settlement than that of the planar reinforcement. From this comparison, it can be concluded that the geocell reinforced footing bed behaves as a much stiffer system and it is consistently more efficient compared to the planar reinforced footing bed case for the same mass of geotextile.

From Figs. 10 and 11, it can also be seen that, the reinforcement with the geocell inclusion results in a better performance compared to that of the planar reinforcement even when comprising a lesser quantity of geotextile material. For example, in the case of the

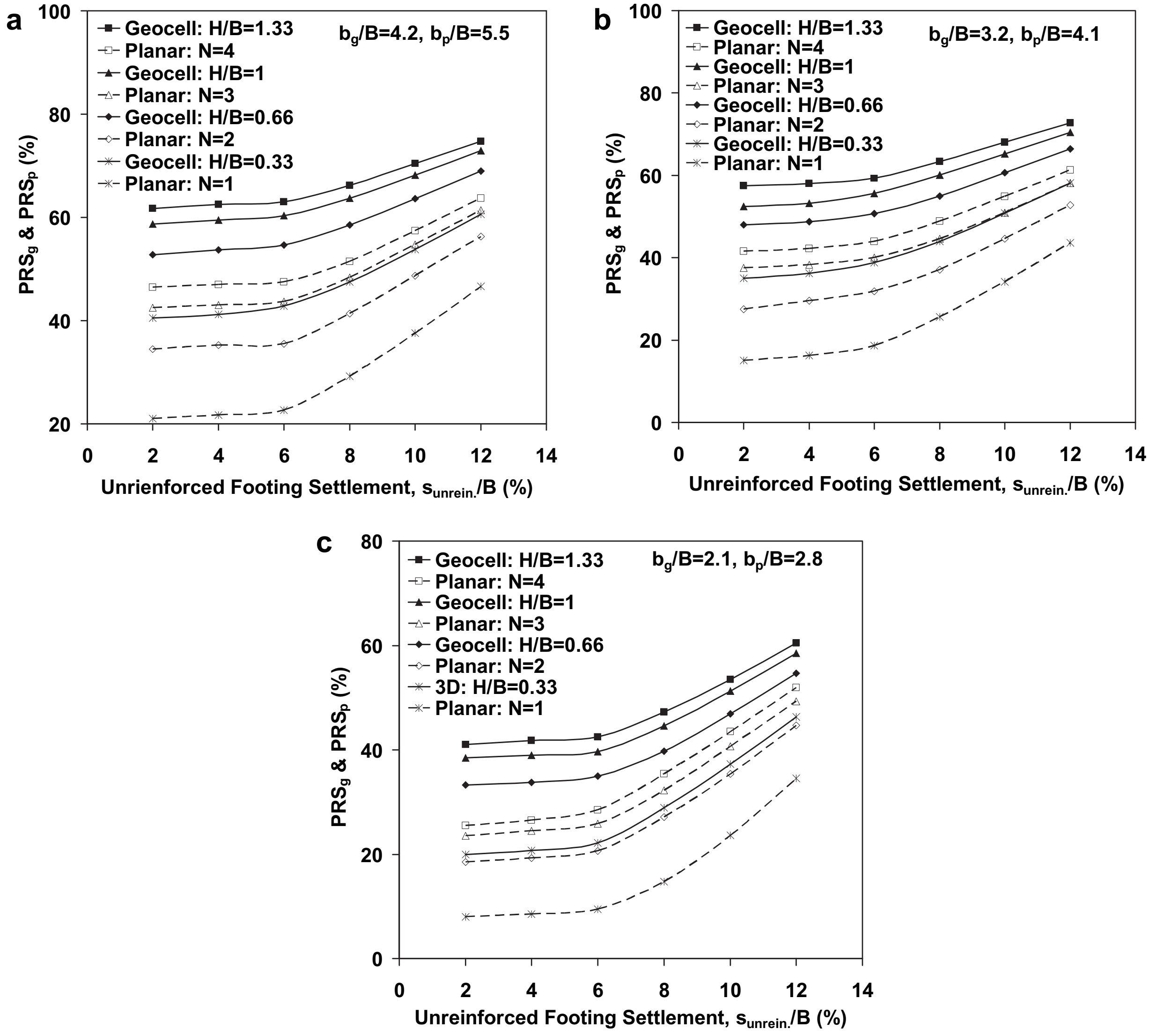

Fig. 11. Variation of the percentage reduction in settlement (PRS) with footing settlement for the geocell and planar reinforcement, (a) long width ($b_g/B = 4.2$ & $b_p/B = 5.5$), (b) medium width ($b_g/B = 3.2$ & $b_p/B = 4.1$) and (c) short width ($b_g/B = 2.1$ & $b_p/B = 2.8$).

medium reinforcement width, consider the geocell reinforcement (with $H/B = 0.66$) which has half the quantity of geotextile material compared to the planar reinforcement (with $N = 4$). At a settlement ratio of 6%, the bearing pressure increases 105% ($IF_g = 2.05$) for the geocell reinforcement (with $H/B = 0.66$), whereas there is only a 76% enhancement ($IF_p = 1.76$) for the planar reinforcement (with $N = 4$). For this example, the value of PRS is comparable for the geocell and planar geotextile arrangements just described ($PRS_g = 51\%$ and $PRS_p = 44\%$). It is, therefore, inferred that use of the geocell reinforcement could be compared to that of the planar reinforcement even where less material was used in the geocell arrangement.

In order to show more clearly the performance of the geocell reinforcement compared to that of the planar reinforcement at the same (or lesser) quantity of material, the improvement in bearing pressure factor (IF) and percentage reduction settlement (PRS) with the amount of geotextile material used (in terms of parameter '*a*', explained earlier in Table 4) are shown in Figs. 12a,b and 13a,b for two settlement ratios of the unreinforced sand ($s/B = 4$ and 8%, respectively).

This data, as presented in Fig. 12, may be used to select options. For example, at a settlement ratio of 4% ($s_i/B = 4\%$), Fig. 12a shows that, to achieve about the 85% enhancement in bearing pressure ($IF = 1.85$) over the unreinforced case, there are three choices:

(1) Four layers ($N = 4$) of long width planar reinforcement with the amount of geotextile material used is equal to '8*a*'. In this case, the value of PRS is about 47%. (PRS obtained as 47% from Fig. 13a).
(2) The long width of geocell with $H/B = 0.41$ (H/B interpolated as 0.41 from Fig. 12a) and the amount of geotextile material used is equal to '2.47*a*'. In this case, the value of PRS is about 44% (PRS interpolated as 44% from Fig. 13a).
(3) The medium width of geocell with $H/B = 0.51$ (H/B interpolated as 0.51) and the amount of geotextile material used is equal to '2.37*a*'. In this case, the value of PRS is about 43% (PRS interpolated as 43% from Fig. 13a).

It is clear that insufficient reinforcement is provided by the short geocell installation and also by the short and medium planar

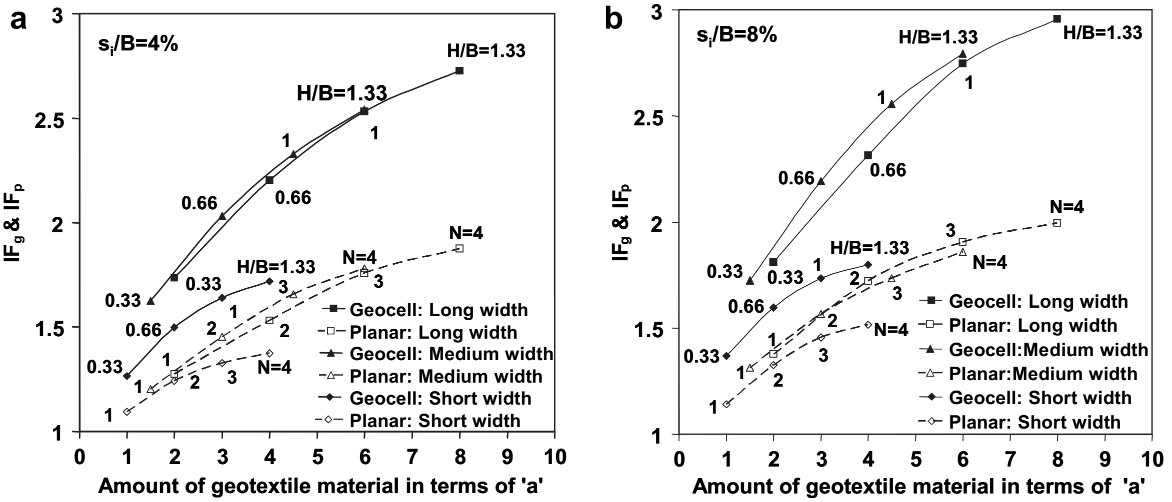

Fig. 12. Variation of improvement in bearing pressure (IF) with the amount of geotextile material used for the geocell and planar reinforcement with short, medium and long reinforcement width for two settlement levels, (a) $s_i/B = 4\%$ and (b) $s_i/B = 8\%$.

installation, regardless of the height (H/B) of the geocell reinforcement and the number of layers (N) of planar reinforcement, to gain a bearing pressure factor (IF) of 1.85.

This comparison indicates that:

- The performance of the geocell is much improved over that of the planar one. Putting this another way, the same improvement in bearing pressure can always be achieved by significantly less geotextile employed in a geocell arrangement than in planar sheets. Therefore, use of geocell reinforcement is expected to be a much more efficient means of providing improved bearing capacity than a planar reinforcement scheme (the economical investigation depends on the fabrication costs for the geocell material).
- By comparison of the long and medium width of geocell reinforcement (choices 2 and 3), it can be seen that the medium width geocell with a higher H/B (=0.51) is a little more efficient than the long width with shorter H/B (=0.41). Hence, it can be concluded that there are optimum values of reinforcement width and height of geocell that will provide best performance regarding the bearing pressure and settlement of footings supported on geocell reinforcement.
- When the reinforcement width increases beyond a certain amount, the improvement rates slow down or become almost insignificant. At this stage further reinforcement can only be gained by increasing the height (geocell reinforcement) or the number of layers (planar reinforcement).
- For the above three choices, the maximum percentage reduction in footing settlement is obtained as roughly 45% while the amount of geotextile material used in the planar reinforced bed is more than three times of that used in the geocell reinforced bed.

The results imply that the increase in bearing capacity and the decrease in footing settlement is significantly greater for geocell reinforcement usage compared to that of the planar reinforcement.

It is suggested that this behaviour is due to the following reasons:

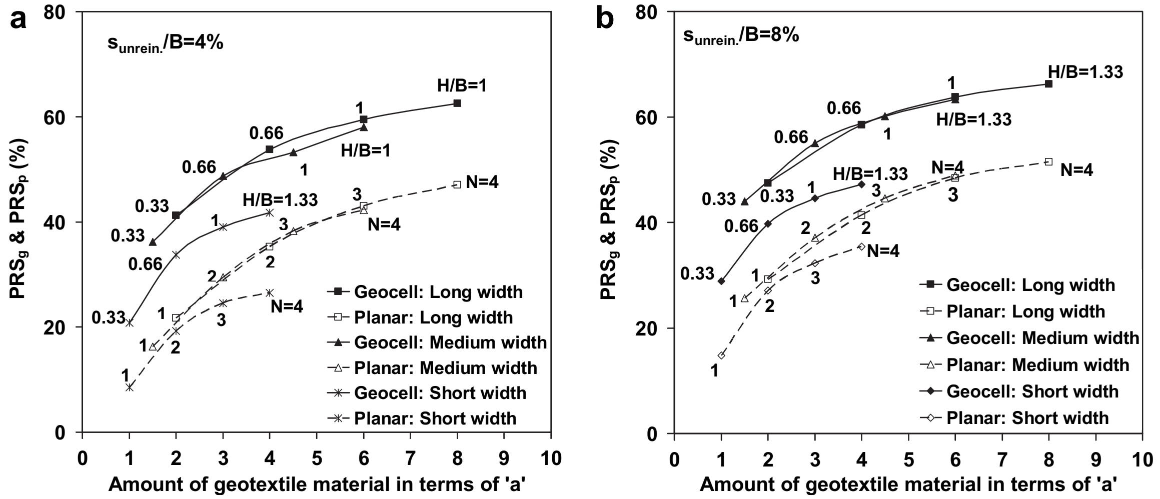

Fig. 13. Variation of percentage reduction in settlement of footing (PRS) with the amount of geotextile material used for the geocell and planar reinforcement with short, medium and long reinforcement width for two settlement levels of unreinforced bed, (a) $s_{\text{unrein}}/B = 4\%$ and (b) $s_{\text{unrein}}/B = 8\%$.

- In the case of a planar reinforcement system, the reinforcing action is solely dependent on the frictional bond between the two successive horizontal planer reinforcements and on the shear strength of the soil between two planar sheets. Hence, when the applied load on the footing transfers downwards, the soil mass between two adjacent layers tends to get squeezed out once frictional resistance with the reinforcement surface is overcome. Such movement limits the ability of the total system to act compositely, thereby limiting the load carrying capacity and permitting footing settlement.
- Due to its three-dimensional mechanism, the cell walls of geocell reinforcement keep the encapsulated soil from being displaced from the applied load by confining the material by hoop action of a cell thereby increasing the shear strength of the composite system. The load redistribution that occurs within the confined zone involves a three-dimensional interaction between the infill materials and the cellular structure. Vertical stress applied to the infill induces a horizontal active pressure at the perimeter of the cell. The infill wall interface friction transfers load into the cell structure which, in turn, mobilises resistance in surrounding cells. It is also evident that cells that surround a loaded cell offer greater passive resistance due to the lateral strain in the vicinity of the load. The combined effect of these mechanisms acts like a large mat that spreads the applied load over an extended area, instead of directly at the point of contact, and provide a composite slab with high flexural stiffness and load support capabilities within the geocell reinforcement – consequently leading to an improvement in the overall performance in bearing pressure and settlement.
- The moment of inertia, and hence shear and bending rigidity, of the geocell is significantly greater than that containing planar reinforcement with the same mass. Furthermore, the sand in the pockets forms a better composite material and the geocell behaves as a stiffer bed that redistributes stress over a wider area giving an increase in the bearing capacity and a reduction in the settlement of the footing.

7. Limitation and applicability

The results presented herein provide encouragement for the application of geocell reinforcement instead of conventional layered geosynthetic reinforcement (for an equal or lesser amount of material). But it should be noted that the experimental results are obtained for only one type of geotextile, one pocket size of the geocell, one size of footing width, and one type of sand. Thus, full application should only be made after considering the above limitations.

Likewise, the present test results are based on the tests conducted on a small model strip foundation in plane strain conditions. For other conditions, such as in the study of the behaviour of square or circular footings with a larger size, a three-dimensional physical model would be very useful.

Furthermore, although Milligan et al. (1986) and Adams and Collin (1997) in their studies on large- and small-scale tests on the behaviour of granular layers with geogrid reinforcement showed that the general mechanisms and behaviour observed in the small model tests could be reproduced at large-scale. Thus future tests need to be conducted with larger scale foundations at various conditions. For example, different footings (in size, shape and depth) and different characteristics and pocket size of the geocell could be studied to validate the present findings. In particular it seems unlikely that a geocell system with $d = 5$ cm pocket size would be optimal for the reinforcement of conventional strip footings (which, typically, are of the order of 0.5–2.0 m width). It appears probable that they would need to be significantly larger. Whether the scaling is linear with footing size, however, is not known and further study is warranted to determine the existence of scale effect, if any.

Although, the results of this study may be somewhat different to full-scale foundation behaviour in the field, the general trend may be similar. Overall, qualitatively, this study provides insight into the basic mechanism that establishes the bearing pressure versus settlement response of the geocell and planar (forms of geotextile) geosynthetic reinforced sand bed. These results could be helpful in designing large-scale model tests and their simulating through numerical models.

8. Summary and conclusions

In this research, laboratory model tests results were used to compare the potential benefits of reinforcing foundation sand with geocell and with planar forms of geotextile reinforcement that had the same basic characteristics. Benefits were assessed in terms of increased bearing capacity and decreased settlement of a strip footing subjected to a monotonically increasing load. The quantified comparisons were carried out over a range of settlement less than 12% of the footing width. The various parameters studied in this testing program include the reinforcement width, the number of planar layers and the height of the geocell below the footing base. Based on the results obtained, the following conclusions can be extracted:

(1) Provision of the geocell reinforcement in reinforcing the sand layer significantly increases the load carrying capacity, reduces the footing settlement and decreases the surface heave of the footing bed more than the planar reinforcement with the same characteristics and the same mass used.
(2) Overall, with increase in the number of planar reinforcement layers, the height of geocell reinforcement and the reinforcement width, the bearing pressure of the foundation bed increases and the footing settlement decreases. The efficiency of reinforcement was decreased by increasing the above parameters.
(3) The optimum depth of the topmost layer of planar reinforcement is approximately 0.35 times of the footing width while the depth to the top of the geocell should be approximately 0.1 times of the footing width.
(4) The tests performed with different reinforcement widths (short, medium and long reinforcement width) indicate that increasing the reinforcement width more than 4.2 and 5.5 (approximately) times of footing width for the geocell and planar reinforcement, respectively, would not provide much additional improvement in bearing pressure nor additional reduction in footing settlement.
(5) For amounts of settlement that are tolerated in practical applications, improvements in bearing capacity greater than 200% and reductions in settlement by 75% can be achieved with the application of geocell reinforcement, whereas planar reinforcement arrangements can only deliver 150 and 64% for these two quantities, respectively.
(6) The comparative investigations imply that in order to achieve a specified improvement in bearing pressure and footing settlement, less mass of material would be used in a geocell implementation compared to a planar one. In the example given in this paper, a geocell reinforcement achieved a similar performance to a planar reinforcement arrangement that contained three times as much mass of geotextile material.

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References

Abedin, Z., Hassan, M., Dewan, A.S., 1997. Bearing Capacity of a Jute Cloth Reinforced Composite Sand Bed. Proceedings of the 14th International Conference on Soil Mechanics and Foundation Engineering. Homburg vol. 3, 1553–1556.

Adams, M.T., Collin, J.G., 1997. Large model spread footing load tests on geosynthetic reinforced soil foundations. ASCE. Journal of Geotechnical and Geoenvironmental Engineering 123 (1), 66–72.

Akinmusuru, J.O., Akinbolade, J.A., 1981. Stability of loaded footings on reinforced soil. Journal of Geotechnical Engineering. ASCE 107 (6), 819–827.

Bush, D.I., Jenner, C.G., Bassett, R.H., 1990. The design and construction of geocell foundation mattress supporting embankments over soft ground. Geotextiles and Geomembranes 9 (1), 83–98.

Cowland, J.W., Wong, S.C.K., 1993. Performance of a road embankment on soft clay supported on a geocell mattress foundation. Geotextiles and Geomembranes 12 (8), 687–705.

Dash, S.K., Krishnaswamy, N.R., Rajagopal, K., 2001a. Bearing capacity of strip footings supported on geocell-reinforced sand. Geotextiles and Geomembranes 19 (4), 235–256.

Dash, S.K., Rajagopal, K., Krishnaswamy, N.R., 2001b. Strip footing on geocell reinforced sand beds with additional planar reinforcement. Geotextiles and Geomembranes 19 (8), 529–538.

Dash, S.K., Sireesh, S., Sitharam, T.G., 2003. Model studies on circular footing supported on geocell reinforced sand underlain by soft clay. Geotextiles and Geomembranes 21 (4), 197–219.

Dash, S.K., Rajagopal, K., Krishnaswamy, N.R., 2004. Performance of different geosynthetic reinforcement materials in sand foundations. Geosynthetics International 11 (1), 35–42.

DeMerchant, M.R., Valsangkar, A.J., Schriver, A.B., 2002. Plate load tests on geogrid-reinforced expanded shale lightweight aggregate. Geotextile and Geomembranes 20 (3), 173–190.

El Sawwaf, M.A., 2007. Behaviour of strip footing on geogrid-reinforced sand over a soft clay slope. Geotextile and Geomembranes 25 (1), 50–60.

Ghosh, A., Ghosh, A., Bera, A.K., 2005. Bearing capacity of square footing on pond ash reinforced with jute-geotextile. Geotextile and Geomembranes 23 (2), 144–173.

Hufenus, R., Rueegger, R., Banjac, R., Mayor, P., Springman, S.M., Bronnimann, R., 2006. Full-scale field tests on geosynthetic reinforced unpaved on soft subgrade. Geotextiles and Geomembranes 24 (1), 21–37.

Jenner, C.G., Basset, R.H., Bush, D.I., 1988. The use of slip line fields to asses the improvement in bearing capacity of soft ground given by cellular foundation mattress installed at the base of an embankment. In: Proceedings of International Geotechnical Symposium on Theory and Practice of Earth Reinforcement. Balkema, Rotterdam, pp. 209–214.

Kolbsuzewski, J. 1948. General Investigation of the Fundamental Factors Controlling Loose Packing of Sands, Proc.. of the 2nd Int. Conf. on Soil Mech. and Found. Eng., Rotterdam, Vol. VII, pp. 47-49.

Krishnaswamy, N.R., Rajagopal, K., Madhavi Latha, G., 2000. Model studies on geocell supported embankments constructed over soft clay foundation. Geotechnical Testing Journal, ASTM 23 (1), 45–54.

Madhavi Latha, G., Murthy, V.S., 2007. Effects of reinforcement from on the behaviour of geosynthetic reinforced sand. Geotextiles and Geomembranes 25 (1), 23–32.

Milligan, G.W.E., Fannin, R.J., Farrar, D.M., 1986. Model and full-scale tests of granular layers reinforced with a geogrid. In: Proceedings of Third International Conference on Geotextiles, Vol. 1 Vienna61–66.

Mitchell, J.K., Kao, T.C., Kavazanjiam Jr., E., 1979. Analysis of Grid Cell Reinforced Pavement Bases. Technical Report No. GL-79–8, US Army Waterways Experiment Station.

Moghaddas Tafreshi, S.N., Khalaj, O., 2008. Laboratory tests of small-diameter HDPE pipes buried in reinforced sand under repeated load. Geotextiles and Geomembranes 26 (2), 145–163.

Patra, C.R., Das, B.M., Atalar, C., 2005. Bearing capacity of embedded strip foundation on geogrid reinforced sand. Geotextile and Geomembranes 23 (5), 454–462.

Patra, C.R., Das, B.M., Bohi, M., Shin, E.C., 2006. Eccentrically loaded strip foundation on geogrid-reinforced sand. Geotextile and Geomembranes 24 (4), 254–259.

Rea, C., Mitchell, J.K., 1978. Sand Reinforcement Using Paper Grid Cells. ASCE Spring Convention and Exhibit, Pittsburgh, PA, April, pp. 24-28, Preprint 3130.

Sitharam, G., Sireesh, S., 2005. Behavior of embedded footings supported on geogrid cell reinforced foundation beds. Geotechnical Testing Journal 28 (5), 452–463.

Sitharam, G., Sireesh, S., Dash, S.K., 2007. Performance of surface footing on geocell-reinforced soft clay beds. Geotechnical and Geological Engineering 25 (5), 509–524.

Sireesh, S., Sitharam, T.G., Dash, S.K., 2009. Bearing capacity of circular footing on geocell-sand mattress overlying clay bed with void. Geotextiles and Geomembranes 27 (2), 89–98.

Shimizu, M., Inui, T., 1990. Increase in the bearing capacity of ground with geotextile wall frame. In: Proceedings of Fourth International Conference on Geotextiles Geomembranes and Related Products, Vol. L. Hague, Netherlands, p. 254.

Wesseloo, J., Visser, A.T., Rust, E., 2009. The stress-strain behaviour of multiple geocell packs. Geotextiles and Geomembranes 27 (1), 31–38.

Yoon, Y.W., Cheon, S.H., Kang, D.S., 2004. Bearing capacity and settlement of tire-reinforced sands. Geotextile and Geomembranes 22 (5), 439–453.