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ORIGINAL PAPER

Behaviour of square footing on sand reinforced with coir geocell

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Abstract The use of geosynthetics as a ground improvement technique offers the advantages such as space saving, environmental sensitivity, material availability, technical superiority, higher cost savings and less construction time. Coir geotextiles can be considered as an efficient replacement to its synthetic counterparts due to its economy and excellent engineering properties. The present study aims at exploring the possibilities of utilising coir geocells as a potential reinforcement material for shallow foundations and thereby increasing the load carrying capacity of soil. Geocells were fabricated from coir geotextiles with the aim of providing an additional confinement to the soil. An enumerated parametric study was conducted by varying the relative density, depth of the first layer, width and height of coir geocell. The surface displacement profiles of the non-reinforced and coir geocell-reinforced soil indicate that the footing rotation and heave are considerably reduced with the provision of geocell. The results of the relative density study indicate that bearing capacity characteristics increase with denseness of the soil sample. It was also observed that geocell arrangement and configuration play a pivotal role in the performance characteristics of reinforced soil.

Keywords Coir geotextiles · Shallow foundations · Coir geocell · Confinement · Parametric study · Bearing capacity

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Abbreviations

B	Width of footing
b	Width of geocell reinforcement
q_r	Bearing pressure of reinforced soil
q_u	Bearing pressure of unreinforced soil
d	Pocket size of geocell
H	Height of coir geocell
IF	Improvement factor
s	Footing settlement
u	Depth to the first layer of reinforcement
R_d	Relative density of soil

Introduction

Geosynthetic is defined as a planar product manufactured from polymeric materials used in soil, rock, earth or other geotechnical engineering-related material as an integral part of a human-made project, structure or system. The usage of geosynthetic materials as a ground improvement technique has gained widespread approval due to its quality of construction, simplicity and time-saving parameter. Numerous researches have been conducted on the use of geosynthetic materials in reinforcing shallow foundations (Guido et al. 1986; Singh 1988; Khing et al. 1993; Yetimoglu et al. 1994; Sitharam and Sireesh 2005; Patra et al. 2005; Abu-Farsakh et al. 2013; Harikumar et al. 2016). Studies on various forms of geosynthetic reinforcement were conducted by Dash et al. (2004) and Lal et al. (2017a). A new technique of improving the quality of soils by providing three-dimensional cellular reinforcement is relatively new and is being effectively used in geotechnical applications. Geocells are 3D, honeycomb-like structures with interconnected cells. The soil is confined within these cells, thereby acting as a rigid base, reducing excessive settlements and preventing shear failure. Several researchers have investigated the potential of geocells as an efficient reinforcement material (e.g. Bathurst and Jarret 1989; Bush et al. 1990; Cowland and Wong 1993; Dash et al. 2001; Krishnaswamy et al. 2000; Hedge and Sitharam 2015).

The high cost of geosynthetics and rising environmental concerns over the excessive use of polymeric geosynthetics make it imperative to explore natural products for making construction, cost-efficient and eco-friendly. Natural geotextiles are manufactured mainly from jute and coir fibres, amongst which coir fibre is more strong and durable owing to its high lignin content. Coir is a natural fibre extracted from the husk surrounding the shell of the coconut fruit. Durability studies have shown that the longevity of coir is sufficient for long-term reinforcement applications (Lekha and Kavitha 2006; Rao and Balan 2000). Lekha (1997) and Ayyar and Dipu (1997) concluded that durability of coir mat can be increased by interlocking the mat between polyester and other durable materials. Ayyer and Girish (2000) conducted durability studies and reported that longevity of coir can be enhanced by coating it with bitumen and cement. In another major study, Datye (1988) established that bio-deterioration of coir can be minimised by treating the soil with antiseptics such as copper sulphate, zinc chloride and mercuric chloride. Hence, from these researches, it can be established that coir reinforcement is suitable for long-term reinforcement applications. Coir is a natural fibre obtained from coconut husk, and it can be easily spun and woven into geotextiles and mats. Due to its high lignin content, it is reputed to be the strongest of all natural fibres. Its usage as a reinforcement material, for slope protection, erosion-controlled blankets and subgrade stabilisation, has been studied (Vinod et al. 2009; Lal et al. 2017b; Sivakumar Babu et al. 2008; Lekha 1997; Subaida et al. 2009). Results of these studies have shown that the inclusion of coir products improves the bearing capacity of soil and reduces rutting in thin unpaved sections, which are an indicative of the potential of coir geotextiles as a reinforcement material. Rao and Balan (2000) observed that tensile characteristics of coir geotextiles are largely influenced by yarn properties and weaving pattern. The results of plate load tests indicate that increase in bearing capacity is more for woven coir geotextiles than non-woven ones. A key study comparing the effect of different coir reinforcement forms, i.e. geocell, planar and discrete fibres, was conducted by Lal et al. (2017a). They concluded that geocell is the most efficient form of reinforcement used in the study. Another important observation is that bearing capacity decreases with increase in placement depth of the geotextile. Due to lack of studies, wide acceptance of coir geotextiles for such reinforcement applications is not yet fully harnessed. Tension and pullout behaviour of coir geotextiles were investigated by Subaida et al. (2008). Literature survey shows that the use of coir geotextile in reinforcing sand foundations is rather limited. The previous studies, though limited in number, have brought out encouraging results on the application of coir geotextiles for reinforcement function.


Fig. 1 Photograph of coir geocell

The effect of coir geocell reinforcement on the bearing capacity of shallow foundations was studied by conducting plate load tests on laboratory model sections. The test variables included placement location of geocell, width of geocell, height of geocell and relative density of soil. The results indicate the immense potential of coir geocell as an efficient low-cost reinforcement material for shallow foundations. Optimum layout and configuration for the reinforcement were also found out.

Materials

Sand

Local river sand was used for the study. The sand had a specific gravity of 2.65, effective size of 0.32 mm, coefficient of uniformity of 2.56, coefficient of curvature of 0.88, maximum


Fig. 2 Photograph of test setup

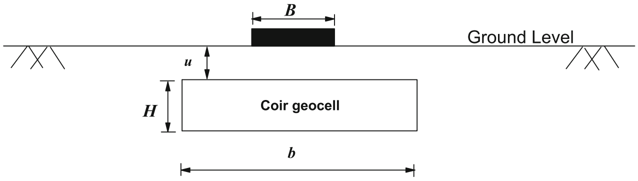

Fig. 3 Layout of reinforcement

dry unit weight of 16.4 kN/m^3 and minimum dry unit weight of 14.9 kN/m^3. All tests were done at 60% relative density to stimulate medium dense condition (Lal et al. 2017a). The soil was classified as poorly graded sand (SP) according to Unified Soil Classification System (USCS).

Coir geocell

The coir geotextiles used for manufacturing geocells were procured from Central Coir Research Institute, Alappuzha, Kerala, India. Properties and tensile load-strain characteristics of the studied geotextiles have been discussed in detail by the authors (Lal et al. 2017a). Contrary to various researchers (Dash et al. 2001; Krishnaswamy et al. 2000; Latha and Somwanshi 2009; Sitharam et al. 2007), geocells were made by cutting geotextiles to its requisite length and height from full rolls and stitching them using coir yarns to obtain a honeycomb-like structure (see Fig. 1) rather than inserting bodkin joints at the connections (Lal et al. 2017a). The pocket size (*d*) of the geocell used for the entire series of experiments was kept 50 mm.

Laboratory tests

Test setup

Photograph of the test setup is shown in Fig. 2. Details of the instrumentation used in the study are listed below:

a) Footing—150 × 150 × 25 mm
b) Test tank—750 × 750 × 750 mm
c) Hydraulic jack—100-kPa capacity
d) Dial gauge—0.01-mm accuracy (at either side of footing).

Reinforcement layout

The layout of geocell reinforcement is shown in Fig. 3. The parameters varied are depth to the first layer of geocell (*u*), width of geocell (*b*), height of geocell (*H*) and settlement (*s*). All the parameters are standardised with foundation width (*B*) as u/B, b/B, H/B and s/B.

Test procedure and program

Sand raining technique was used to fill sand in the test tank. Sand was poured from various heights through a perforated steel container, and corresponding densities obtained at different height of fall were calculated by placing steel containers of known weights and volume at different positions in the test tank. The height of fall required for attaining 60% relative density was found out. Sand raining was renewed, keeping this height of fall constant, up to the level of foundation (Lal et al. 2017a). The hydraulic jack was carefully positioned at the centre of the footing to avoid eccentricity in loading. The footing was loaded up to a settlement level (s/B) of 25%. Settlements were measured with the aid of dial gauges at either end of the footing. Four different series of tests have been conducted as listed in Table 1. Test series 1 on unreinforced sand was conducted to quantify the improvement due to the provision of geocell. Test series 2 to 5 on geocell-reinforced soil was conducted to study the effect of depth to the first layer of reinforcement, width, height of geocell and relative density, respectively. Tests were also repeated to check the accuracy of

Table 1 Summary of tests conducted

Test series	Reinforcement type	Placement depth of reinforcement	Width (b/B), height of geocell (H/B) and relative density (R_d) of soil	Purpose of study
1	Unreinforced	–	–	To evaluate the degree of improvement
2	Coir geocell	u/B varied (0, 0.1, 0.2, 0.3, 0.5)	$b/B = 3$, $H/B = 0.33$ and $R_d = 60\%$	To find the optimum depth to the first layer of reinforcement
3	Coir geocell	u/B optimum	b/B varied (1, 2, 3, 4, 5), $H/B = 0.33$ and $R_d = 60\%$	To study the influence of reinforcement width
4	Coir geocell	u/B optimum	b/B optimum, H/B varied (0.167, 0.33, 0.5, 0.67, 0.84) and $R_d = 60\%$	To study the effect of height of geocell
5	Coir geocell	u/B optimum	b/B optimum, H/B optimum and relative density (R_d) varied, i.e. 30, 50, 60 and 70%	To study the effect of relative density on bearing capacity characteristics

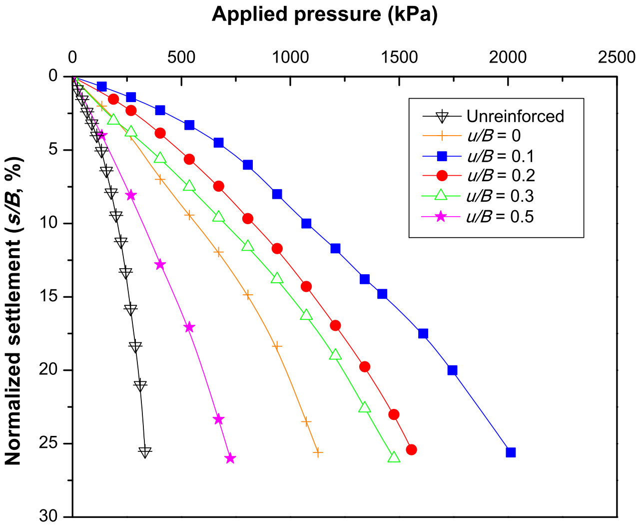

Fig. 4 Applied pressure vs. settlement at different placement depth of reinforcement

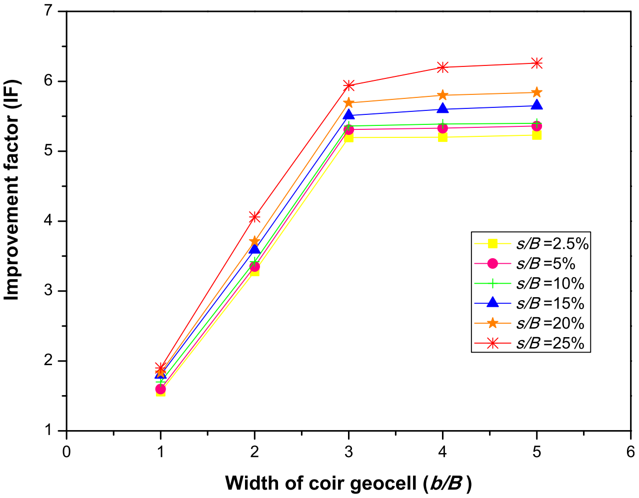

Fig. 6 Improvement factor at different normalised settlements for various widths of geocell

test results. A non-dimensional term called improvement factor (see Eq. 1) was introduced to assess the degree of improvement.

$$\textit{Improvement} \qquad \textit{factor} = \frac{q_r}{q_u} \tag{1}$$

where q_r is the bearing capacity of geotextile-reinforced soil and q_u is the bearing capacity of unreinforced soil, both measured at same settlement.

Results and discussion

Depth to the first layer of reinforcement

The load-settlement behaviour of sand beds reinforced with coir geocell placed at various depths is shown in Fig. 4. It can be seen that coir geocell-reinforced foundation provides better performance than unreinforced one in all cases. This is due to an interface friction developed between soil and coir geotextile, the interlocking of soil between the apertures of geocell and also due to the confinement effect provided by the three-dimensional geocell. The performance improvement due to the provision of geocell is represented quantitatively by means of a non-dimensional improvement factor (Eq. 1). Figure 5 shows the variation of improvement factor with placement depth at different settlement levels. From the figure, it is observed that improvement increased up to a depth of 0.1 times the foundation width, and thereafter, a decreasing trend was observed. For example, for a settlement level of 15%, the improvement factor increases from 3.1 to 5.51 when the placement depth is changed from the level of foundation to a depth of 0.1 *B*, after which it reduces to 4.25 for a depth of 0.2 *B* from the base of the foundation. A minimal overburden length is

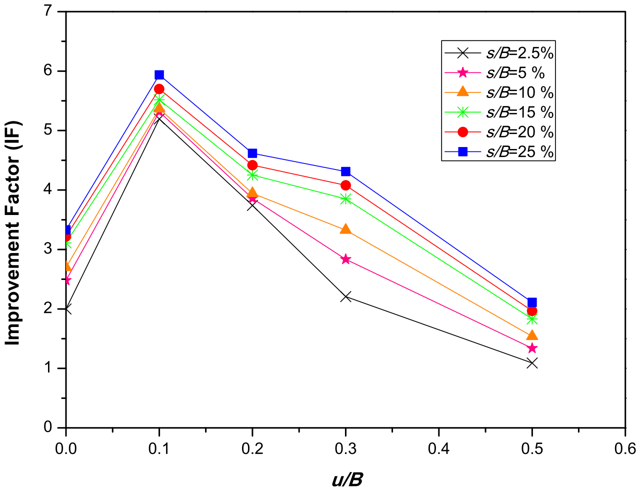

Fig. 5 Improvement factor at different normalised settlements for various placement depth of geocell

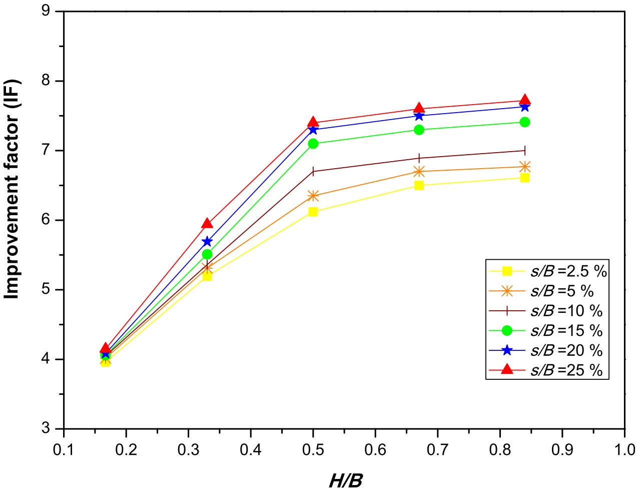

Fig. 7 Improvement factor at different normalised settlements for various height of geocell

Table 2 Comparison of improvement in bearing capacity from previous studies

Study	Geocell reinforcement parameters	Improvement factor (IF) in bearing capacity (s/B = 10%)
Dash et al. (2001)	$u/B = 0.1$, $H/B = 0.8$, $b/B = 12$	2.16
Latha and Somwanshi (2009)	$u/B = 0.05$, $H/B = 0.6$, $b/B = 5.93$	1.9
Tafreshi and Dawson (2010)	$u/B = 0.1$, $H/B = 0.66$, $b/B = 4.2$	2.47
Present study	$u/B = 0.1$, $H/B = 0.67$, $b/B = 3$	6.89

necessary for the effective mobilisation of frictional resistance between the coir geocell and soil and also to prevent the interaction between the geocell and the model footing. This length can be achieved when the reinforcement is kept at 0.1 *B*. Identical findings were observed by Dash et al. (2001). Sitharam and Sireesh (2005) established an optimum depth of 0.05 *B*. With further increase in depth of reinforcement ($u/B > 0.1$), the geocell falls out of the most effective zone where it could intercept the applied pressures and reduce the footing settlement. Improvement factor escalated with settlement, indicating that initial deformations are essential for the complete activation of frictional resistance between soil and geocell.

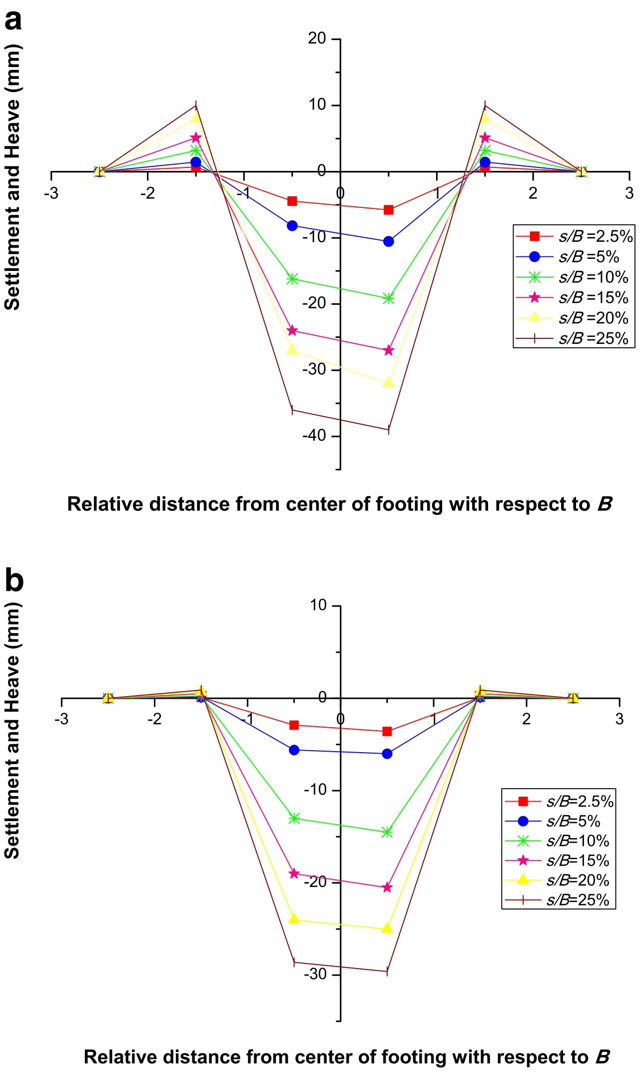

Fig. 8 Surface displacement profiles at different normalised settlements for **a** unreinforced soil and **b** geocell-reinforced soil

Width of reinforcement

The geocell was kept at optimum depth ($u/B = 0.1$) and width of reinforcement was varied as indicated in Table 1 (test series 3). Figure 6 depicts the variation of improvement factor with different widths of geocell reinforcement. Improvement factor increased from 1.56 to 6.26 when the reinforcement width was increased from *B* to 5 *B*. It can be observed from the figure that beyond a b/B ratio of 3, there was no significant improvement. For example, for a settlement level (s/B) of 15%, the percentage increase in improvement factor when the width ratio (b/B) increased from 1 to 2 and 2 to 3 was 99 and 53%, respectively, whilst that from 3 to 4 and 4 to 5 was only 1.6 and 0.9%, respectively. Only a certain fraction of reinforcement lying in the pressure zone beneath the footing will have its frictional strength efficiently mobilised, and beyond this length, the effect of reinforcement is negligible, which may be the reason for the above-mentioned phenomena. Therefore, in the present study, the optimum width is taken as 3 *B*. Sitharam and Sireesh (2005), based on their studies conducted on geocell-sand mattress over clay bed, observed that the optimum width for efficient performance was around 4.9 *B*. Dash et al. (2001) observed that beyond 4 *B*, there is no significant improvement in bearing capacity with the provision of geocells. The difference in b/B values obtained by various researchers is due to the difference in the type of reinforcement material and soil properties used for the study (Lal et al. 2017a).

Height of coir geocell and planar reinforcement layers

The geocell was kept at optimum depth and width, while the height of reinforcement was varied as indicated in Table 1 (test series 4). Variation of improvement factor with height of geocell is shown in Fig. 7. With the increase in height of geocell, the applied load is spread over deeper layers of soil, thereby resulting in higher improvement values. Improvement

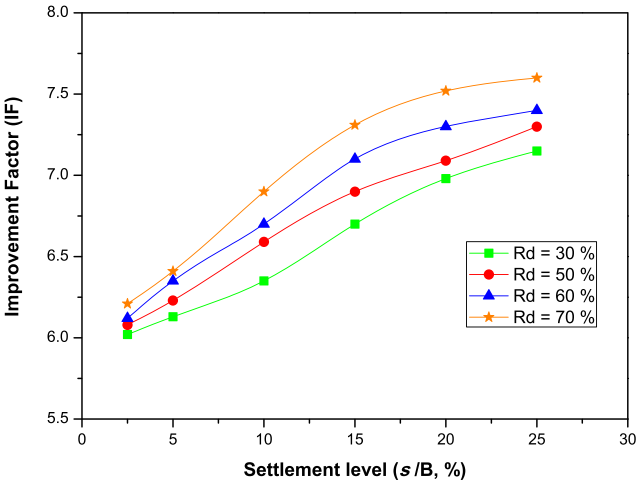

Fig. 9 Variation of improvement factor vs. normalised settlement at various relative densities

factor increased from 3.96 to 7.72, when the height of geocell is increased from 0.167 *B* to 0.84 *B*. But the bearing capacity improvement is not proportional to the height of the geocell due to buckling of the geocell walls. For example, for a settlement level (*s*/*B*) of 15%, the bearing capacity enhances by 36% when the height of geocell is increased from 0.167 *B* to 0.33 *B*, 29% from 0.33 *B* to 0.5 *B*, whilst it is only 2.8 and 1.5% from 0.5 *B* to 0.67 *B* and 0.67 *B* to 0.84 *B*, respectively. Similar findings were observed by Dash et al. (2001), Sitharam and Sireesh (2005) and Lal et al. (2017a). Therefore, in the present study, optimum height of the geocell is taken as 0.5 *B* since there is no significant improvement in bearing capacity characteristics after an *H*/*B* ratio of 0.5.

Table 2 shows the comparison of bearing capacity improvement factor (IF) obtained by using synthetic geocells and the geocells manufactured from coir geotextiles in the present study. It can be clearly seen that coir geocells provide better performance compared to synthetic ones. The probable reason may be due to the better frictional interaction between the coir geotextile and soil, thereby increasing the tensile strength and load bearing capacity of soil. Lal et al. (2017a) in their comprehensive study on different form of coir geotextiles reported that even at small-strain levels, the soil is able to develop a better and efficient frictional interaction with the geotextile.

Surface deformations

The surface displacement (heave/settlement) profiles of the non-reinforced and coir geocell-reinforced soil placed at optimum depth, width and height of geocell (0.1 *B*, 3 *B* and 0.5 *B*, respectively) are shown in Fig. 8. According to various researchers (Dash et al. 2004; Latha and Somwanshi 2009), maximum heave occurred at a distance of 1.5 *B* from the centre of the foundation. Hence, in the present study, dial gauges for measuring heave were placed at a distance of 1.5 *B* from the centre of the footing and corresponding surface deformations (heave/settlement) were obtained. From the figure, it can be seen that footing rotation (indicated by the difference in settlement on either side of footing) and heave are considerably reduced with the provision of geocell. This is because of the ability of geocell to confine the soil and distribute the load to deeper soil layers, thereby acting as a rigid mat, preventing the surface heave. Lal et al. (2017c) studied the settlement and surface heave behaviour of planar coir geotextile-reinforced sand beds and stated that the provision of coir geotextiles increased the overall stiffness and strength characteristics of the soil resulting in substantial reduction in heave.

Table 3 Values of improvement factor at different normalised settlements for various relative densities, width and height of geocells

Parameter		Improvement factor (IF) = $\frac{q_r}{q_u}$					
		s/*B* = 2.5%	*s*/*B* = 5%	*s*/*B* = 10%	*s*/*B* = 15%	*s*/*B* = 20%	*s*/*B* = 25%
b/*B*	1	1.56	1.6	1.7	1.8	1.83	1.9
	2	3.28	3.35	3.42	3.59	3.71	4.06
	3	5.19	5.31	5.36	5.51	5.69	5.94
	4	5.2	5.33	5.39	5.6	5.8	6.2
	5	5.23	5.36	5.4	5.65	5.84	6.26
H/*B*	0.167	3.96	4.02	4.05	4.06	4.09	4.15
	0.33	5.19	5.31	5.36	5.51	5.69	5.94
	0.5	6.12	6.35	6.7	7.1	7.3	7.4
	0.67	6.5	6.7	6.89	7.3	7.5	7.6
	0.84	6.61	6.77	7	7.41	7.63	7.72
R_d	30	6.02	6.13	6.35	6.7	6.98	7.15
	50	6.08	6.23	6.59	6.9	7.09	7.3
	60	6.12	6.35	6.7	7.1	7.3	7.4
	70	6.21	6.41	6.9	7.31	7.52	7.6

Relative density

A detailed study is also conducted to evaluate the effect of relative density on the bearing capacity characteristics of reinforced soil. Coir geocell-sand interactions were tested at optimum depth, height and width under four different relative densities, i.e. 30, 50, 60 and 70%. By sand raining technique, the height of fall required to achieve the required relative densities was obtained. Figure 9 shows the variation of improvement factor vs. normalised settlement at various relative densities. From the figure, it can be seen that with the increase in relative density of soil, bearing capacity increases. For example, the IF at a settlement level (s/B) of 10% for a relative density (R_d) of 30% is only 6.35 whilst that for a relative density of 70% is 6.9. The probable reason may be due to the elevated dilation of sands at higher relative densities which lead to a greater frictional mobilisation between the coir geocell and the soil. Similar trends were observed by Dash et al. (2004). The values of improvement factor at various relative densities, width and height of geocells are presented in Table 3.

Conclusions

A detailed parametric study of the performance assessment of coir geocell-reinforced shallow foundation was conducted. Based on the study, the following conclusions can be drawn:

1) Performance characteristics of foundation can be significantly enhanced by the inclusion of coir geocells. This is due to the confining effect offered by the three-dimensional structure of the geocell and the interlocking of soil between the apertures of geocell.
2) The reinforcement arrangement and configuration play a decisive role in the performance characteristics of reinforced soil.
3) A significant increase in bearing capacity was attained when geocell was placed at a depth of 0.1 *B* from the base of the foundation.
4) Bearing capacity improvement is not proportional to the height of the geocell due to buckling of the geocell walls.
5) Optimum width and height of geocell were obtained as 3 *B* and 0.5 *B*, respectively.
6) For a settlement level (s/B) of 15%, bearing capacity improved by a factor of 7.1 by providing the geocell at optimum depth, width and height.
7) The footing rotation and heave are considerably reduced with the provision of geocell.
8) Improvement factor increases with increase in relative density. This is due to dilation of sands at higher relative densities which lead to a greater frictional mobilisation between the coir geocell and the soil.

However, the results obtained are subjected to scale effects and cannot be directly applied to field cases. However, the general trend and basic mechanisms may be similar. The results obtained in the present study are reassuring, and hence, there is a wide scope for further studies in this area.

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