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SHORT COMMUNICATION

Behaviour of model footing resting on sand reinforced with number of layers of coir geotextile

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Abstract Several methods of ground improvement techniques were developed and tried for stabilizing weak soils. The technique of reinforcing the soil becomes one of the important methods. The performance of granular soils which are strong in compression and shear, but weak in tension can be substantially improved by introducing reinforcing element in the direction of tensile strain. Compared to the numerous works done in the area of bearing capacity of unreinforced soil, less work has been done in the determination of bearing capacity of reinforced soil. In this present investigation, bearing capacity of coir geotextile reinforced sand was determined for number of layers of geotextile. The comparison was made with the parameters like peak stress, bearing capacity ratio, and settlement reduction factor for different *d*/*B* ratios. The experimental values of bearing capacity were validated with theoretical values.

Keywords Foundation · Geotextile · Shallow foundation

List of symbols

B	Width of footing
U	Top layer spacing, i.e., spacing between top layer of reinforcement and bottom of footing
h	Vertical spacing between reinforcement layers
l	Length of reinforcement
d	Total depth of reinforcement
N	Number of reinforcement layers
T	Tensile force in reinforcement
$q_{u(R)}$	Ultimate bearing capacity of reinforced soil foundation
δ	Mobilized friction angle along vertical punching failure surfaces
T_i	Tensile force acting on vertical punching failure Surfaces
α	Angle of tensile force T_i to horizontal
γ	Unit weight of soil
D_f	Embedment depth of footing
Φ	Friction angle of soil
c	Cohesion of soil
q	Surcharge load
$q_{u(UR)}$	Ultimate bearing capacity of unreinforced soil in general shear failure zone

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Introduction

Rapid increase in infrastructural activities and decrease in availability of good construction sites have led to increase in several methods of ground improvement techniques, in which the technique of reinforcing the soil is one of the important methods. The performance of granular soils which are strong in compression and shear, but weak in tension can be substantially improved by introducing reinforcing material in the direction of tensile strain. Several researchers have studied beneficial effects of metal and geosynthetic reinforcements in improving the performance of soil. Some of the important studies conducted on behaviour of footing on reinforced soil bed are by Binquet and Lee [6], Huang and Tatsuoka [12], Guido et al. [11], Omar et al. [19], Khing et al. [13], Yetimoglu et al. [26], Adams and Collin [3], Abu-Farsakh et al. [1], Latha and Somwanshi [15], Abu-Farsakh et al. [2], etc. From the available literature, it was observed that majority of research was carried out on strip footing resting on reinforced sand bed. Over the last two decades, the beneficial effects of using planar reinforcement to increase the bearing capacity of sand have been clearly demonstrated by several investigators [4, 5, 9, 13, 23], etc.). The increase in bearing capacity in reinforced soil can be understood by two fundamental reinforcement mechanisms viz, confinement effect, membrane effect. First, frictional interaction is induced in interface of soil and reinforcement, due to the relative displacement between them. The vertical deformation of the soil decreases when the interlocking developed between the soil and geotextile. The bearing capacity increases by inducing reinforcement in soil because of improvement in lateral confinement, there by increases the compressive strength of the soil. This mechanism is named lateral restraint method or confinement effect [12, 17]. Furthermore, the reinforcement in soil will deformed and tensioned when the footing moves downward against the application of load. Therefore, the reinforcement should have sufficient length and tensile strength to avoid failure due to pull out and rupture. This mechanism is called membrane effect [7, 10, 14].

The investigators Chenn and Abu-Farsakh [25] worked out the analytical solutions for confinement effect and membrane effect by limit equilibrium analysis of reinforced soil foundation. In this analysis, they considered tensile force of reinforcement, i.e., tensile membrane effect. They concluded that, to increase the efficiency of reinforced soil, all the reinforcement layers must be placed above the failure zone. In addition, to find ultimate bearing capacity of reinforced soil foundation, there is a need to determine the shape of the reinforcement at ultimate load. Geotextile reinforcement used as a tensioned membrane, lateral confinement, improved bearing capacity, and the tensioned membrane effect have been identified as the major geosynthetic reinforcement mechanisms [10]. Geotextile materials not only provide the required in-plane transmissivity, but they also render an inexpensive reinforced soil system. As the availability of suitable construction sites decreases, there is an increasing need to utilize poor soils for foundation support and earthwork construction [18].

Significance of coir geotextile

In the present investigation, naturally available coir mat was used as reinforcement in sand. Natural Geotextiles are manufactured in India from jute and coir fibres, among which coir fibre is the strongest and most durable owing to its high lignin content. Coir is a locally available, sustainable organic material having high tearing strength, initial stiffness, and good hydraulic properties. Woven coir geotextiles are manufactured today with wide ranges of physical properties. The use of coir as a reinforcement material has been studied by various researchers [20, 22, 24]. As the synthetic materials may cause environmental problem, also on the other hand, coir is abundantly available in India and it will work out economically. Coir geotextile develops good interface friction with granular soil which can induce tensile stress in the reinforcement when reinforced with in the soil [22].

The model test was conducted for one layer, two layers, three layers, and four layers of coir geotextile reinforced sand with ratio of depth of level of sand to the first layer of reinforcement to the width of foundation, $u/B = 0.3$ and $d/B = 0.3$, 0.8, 1.3, and 1.8, where d is the total depth of the reinforcement from the top level of the sand. The bearing capacity ratio and settlement reduction factor of each ratio were calculated and analysed. Most importantly, the experimental ultimate bearing capacity of unreinforced sand and number of layers of coir geotextile reinforced sand were valuated with the obtained theoretical ultimate bearing capacity of respective set. The theoretical bearing capacity ratio and experimental bearing capacity ratio were compared and concluded.

Materials and methods

Materials used

Poorly graded sand (prepared by locally available river sand sieved through 1 mm IS sieve) was used in the present study which was sorted by particle sizes. The sand was to make it a poorly graded sand and to avoid segregation during preparation of the sand bed. Table 1 shows the properties of sand used.

Coir geotextile was procured from Karnataka coir board, Bangalore. The properties of the coir geotextile are shown in Table 2.

Table 1 Properties of sand used

Property	Values
Specific gravity (G)	2.67
Coefficient of uniformity, (Cu)	1.4
Coefficient of Curvature (Cc)	1.03
Effective diameter of particle D_{10} (mm)	0.2
Maximum dry density (kN/m^3)	18.7
Minimum dry density (kN/m^3)	14.7
Compacted density (kN/m^3)	16.9
Relative density (%)	60

Table 2 Typical properties of coir geotextile

Mass/unit area (g/m^2)	835
Thickness (mm)	6.81
Yarn count	
Direction A (Ne)	2/0.24^5
Direction B (Ne)	2/0.22^5
No. of yarns/dm	
Direction A/dm	7
Direction A/dm	9
Yarns twist (Turns/m)	
Direction A	73
Direction B	63
Cover factor	10.8
Breaking load (*N*)	252
Elongation (%)	31

Optimum size of coir mat opening used

As the strength of reinforced soil depends on angle of internal friction and shear stress, and some other factors influence these parameters of reinforcement, direct shear test was conducted for the case of coir mat-reinforced sand to determine the optimum mesh opening size. Sand in all the tests was compacted to ensure a relative density of 60% and properties of sand used are shown in Table 1. It was observed that the coir mat opening of size 20 × 20 mm gave maximum value of internal friction with a marginal variation of 1^0 for coir mat of opening 10 × 10 mm [21].

Model footing and configuration of coir mat used

The load tests were carried out using a loading frame. The test tank used in the present study had internal diameter of 500 mm and internal height of 600 mm. The model footing of diameter of 100 mm with a thickness of 10 mm which is sufficient to bear bending stresses. The size of test tank was equal to 4–5 times the dimensions of the model footing to reduce the boundary effect of the tank. The bottom of the model footing was made rough by coating with thin layer of epoxy resin with sand particles sprinkled over it. Figure 1a shows schematic diagram of the arrangement of number of layers used in the present investigation and Fig. 1b shows the schematic test set up. Table 3 shows reinforcement configuration along with variable parameters used for the model footing tests in which *d* is the total depth of the reinforcement from the top level of the sand. The number of layers was varied from single layer to a maximum of four layers. These were placed at specific depths while preparing the sand bed for each model footing test.

The depth of layer of reinforcement in case of the coir mat from the bottom of the footing is measured as *u*, and model footing tests for number of layers of mat reinforcement were conducted. The aim of the present study is to comparatively analyze the performance of number of layers of mat reinforcement, in terms of BCR, SRF, and peak strain, and compare with the values obtained using analytical equation proposed by Chenn and Abu-Farsakh [25].

Preparation of sand bed and loading of model footing

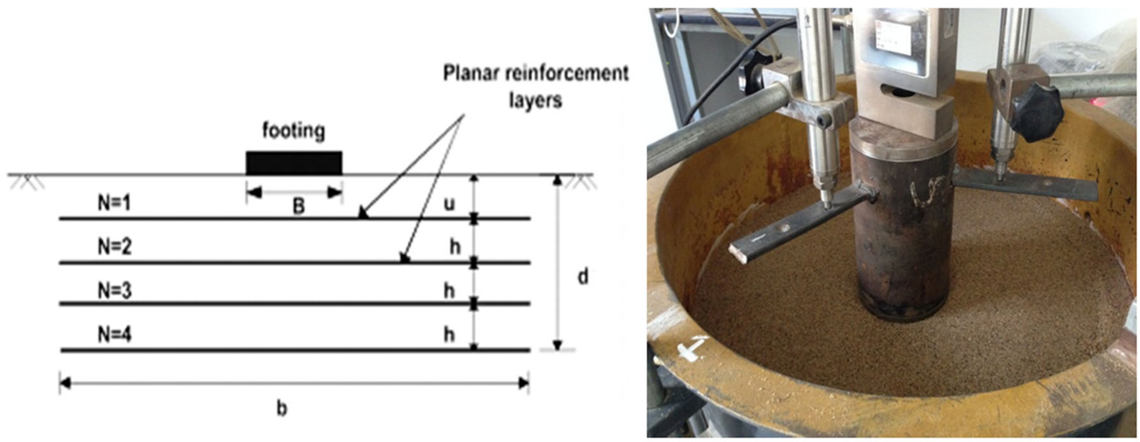
The sand was compacted by means of 2.5 kg rammer falling at a height of 30.5 mm, in layers of 50 mm to have a relative density of 60%. Sand beds were prepared by pouring the sand using raining technique to attain a compacted density of 16.9 kN/m^3 for all the tests.

Tests with reinforced sand beds were carried out by placing the coir mat at the predetermined depths while preparing the sand beds. After preparing the bed, surface was levelled and the footing was placed exactly at the centre to avoid eccentric loading. The footing was loaded by load frame and the load was applied at the rate of 1.25 mm/min. The three dial gauges fixed diametrically opposite on the model footing to measure the footing settlement. Tests on model footing resting on unreinforced sand bed were also carried out. The model test was conducted for one layer, two layers, three layers, and four layers of coir mat-reinforced sand with ratio of depth of level of sand to the first layer of reinforcement to the width of foundation, $u/B = 0.3$ and $d/B = 0.3$, 0.8, 1.3, and 1.8. Load–settlement readings were taken until the footing failed or deformation exceeded with no substantial increase in load. Coir mat having diameter slightly less than diameter of tank was used. The ultimate load and corresponding peak strain were obtained from load settlement curve, corresponding to the point at which the yielding of the model footing occurred. The model footing test was carried out for unreinforced sand to compare the result with reinforced sand.

Results and discussion

Bearing capacity behaviour

The load test conducted for unreinforced sand and sand reinforced with coir mat of mesh size of 20 × 20 mm with $u/B = 0.3$ and for various d/B ratios. Using the results of load test, variation of load intensity versus percentage strain of unreinforced sand and mat-reinforced sand at different depth ratios and different number of layers was plotted, as shown in Fig. 2. The peak stress for each layer of reinforced sand was obtained. Sand reinforced with



(a) Location of coir mat **(b)** Configuration of loading frame

Fig. 1 Configuration of multiple layers of mat. **a** Location of coir mat. **b** Configuration of loading frame

Table 3 Details of spacing of coir mat layers

No. of mat layers '*N*'	Depth of top mat layer below footing '*u*'	*h*/*B*	Total depth of mat layer '*d*'
1	0.3 B	–	0.3 B
2		0.5	0.8 B
3		0.5	1.3 B
4		0.5	1.8 B

single-layer coir mat-enhanced more than five times the ultimate bearing capacity over the unreinforced sand. Introduction of coir mat increases confining stress by locking the soil particles in between the openings causing an increase in load carrying capacity. Furthermore, increase in peak strength becomes more prominent with increase in number of mat layers, as shown in Fig. 2.

Using the results obtained by experimental investigation, the peak stress, corresponding peak strain for number of layers of coir mat, has been tabulated, as shown in Table 4, and the variation of the same is shown in Fig. 3.

The footing over the coir mat reinforcement carried load as high as five times the ultimate capacity of footings on unreinforced soil. This behaviour is possibly the result of two aspects. First, due to its mesh structure, the coir mat contains and confines the sand more effectively. As a result, a better composite material is formed, which helps to redistribute the footing load over a wider area. Second, the coir mat reinforcement system acts as an interconnected cage and is anchored from both sides of the loading area, due to friction and passive resistance developed at the soil/mat interfaces. Furthermore, because of shear and bending rigidity of the geotextile layer, the footing load is carried even after shear failure of the sand inside the coir mat mesh beneath the footing. Model footing adopted in laboratory study may not play a same role as in the prototype and it may cause little influence on the experimental results.

Fig. 2 Load intensity versus % strain for sand reinforced with number of layers of coir geotextile

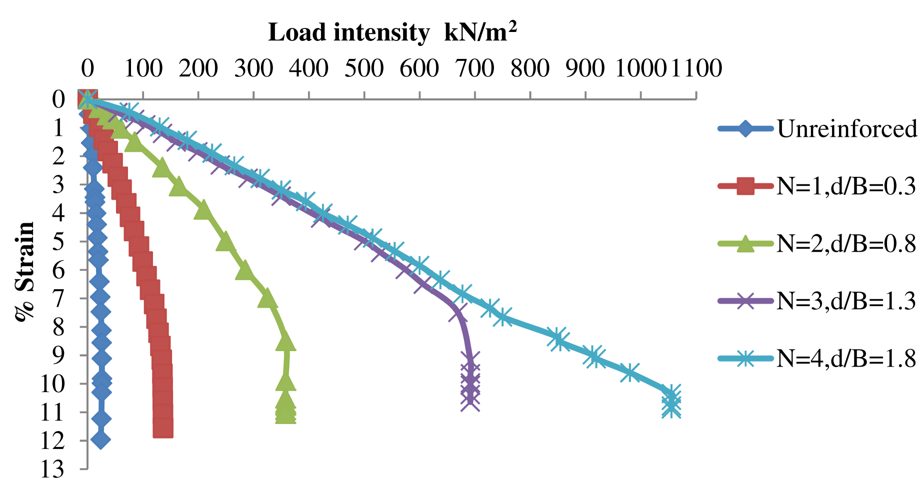


Table 4 Corresponding peak strain for various peak stains at different d/B Ratios

Test series	Variable parameters	peak stress corresponding to				
		$s/B = 2\%$	$s/B = 4\%$	$s/B = 6\%$	$s/B = 8\%$	$s/B = 11\%$
Unreinforced		10	15	20	25	24.9
$N = 1$	$d/B = 0.3$	40	72	102	126	120
$N = 2$	$d/B = 0.8$	115	215	286	350	356
$N = 3$	$d/B = 1.3$	208	401	575	680	690
$N = 4$	$d/B = 1.8$	235	425	610	798	1054

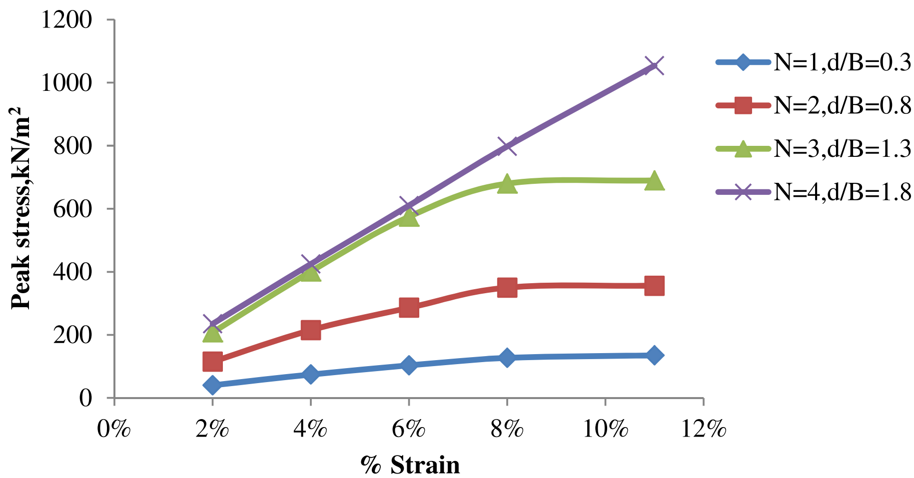


Fig. 3 Variation of peak stress versus % strain for different d/B ratios

Effect of number of layers on peak stress and BCR

To compare the variation of peak stress and BCR for sand reinforced with number of layers of the coir mat, the graph has been plotted for the peak strains of 2, 4, 6, 8, and 11%, corresponding peak stress, as shown in Fig. 3. The insertion of coir mat layers in sand has an enhanced effect of peak stress for all the values of % strain. Figure 4 evidently shows that the BCR considerably improves with the number of coir mat layers, though the rate of increase in BCR decreases with the increasing number of mat layers until $N = 3$ after which the rate of BCR becomes much less.

A similar conclusion that $N = 3$ is the optimum number of layers was indicated by previous studies of strip or square footings over reinforced sands [8, 16]. However, it should be mentioned that the optimum number of coir mat layers is much dependent on the vertical spacing between geotextile layers and the embedded depth of the first layer. This is due to the fact that soil reinforcement would be significant when positioned in the effective zone under the footing.

Effect of number of layers on settlement

To understand the effect of number of layers of reinforcement on settlement, Settlement Reduction Factor (SRF) was calculated, which is defined as a ratio of $SRF = (S_o–S_r)/S_o \times 100$, where S_r is the settlement obtained corresponding to stresses = 5, 10, 15, 20, and 25 kN/m^2 for different d/B ratios and S_o is the settlement obtained for unreinforced sand at corresponding stresses. The present results comprises with the earlier investigations conducted by Omar et al. [19] and, Das et al. [8]. The results indicated that the magnitude of settlement ratio (s/B) at ultimate bearing capacity increased along with an increase of the ultimate bearing capacity for tests on reinforced sand over unreinforced sand.

Figure 5 shows typical variation of settlement reduction factor (SRF) versus different stresses for $N = 1, 2, 3, 4$ layers of reinforcement. It can be seen that with increase in stress (which indicates greater mobilization of shear strength), SRF increases for coir mat-reinforced sand. However, it was found that the increase in SRF becomes marginal with increase in stress when the number of layers of reinforcement is $N = 2$, $N = 3$ and $N = 4$.

Variation of Settlement Reduction Factor versus d/B for different normalized stress is shown in Fig. 6. It was observed that the SRF is increases along with the addition of each layer of the mat reinforcement at all load intensities. The increase in SRF with increase in u/B ratio is attributed to the fact that the sand particles gets interlocked in the grid space of mat which provides lateral restraint causing increase in SRF.

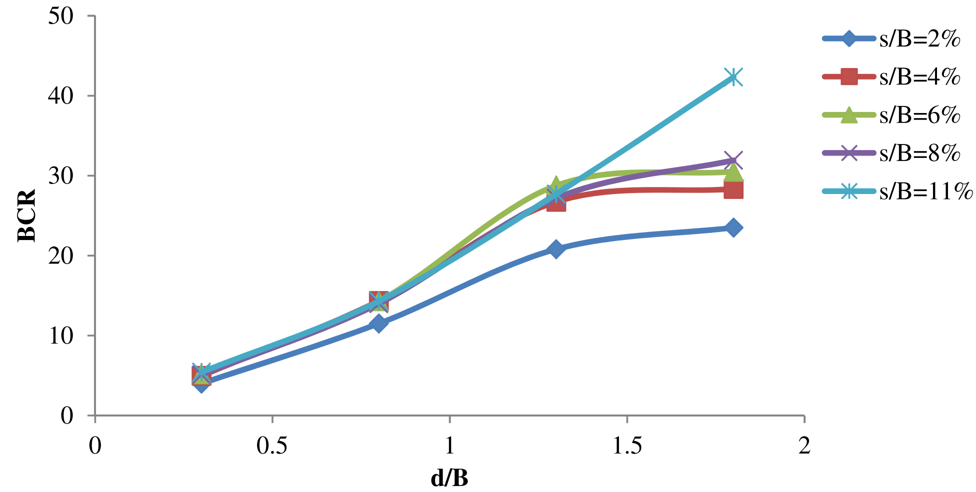


Fig. 4 Variation of BCR with different *d/B* ratios

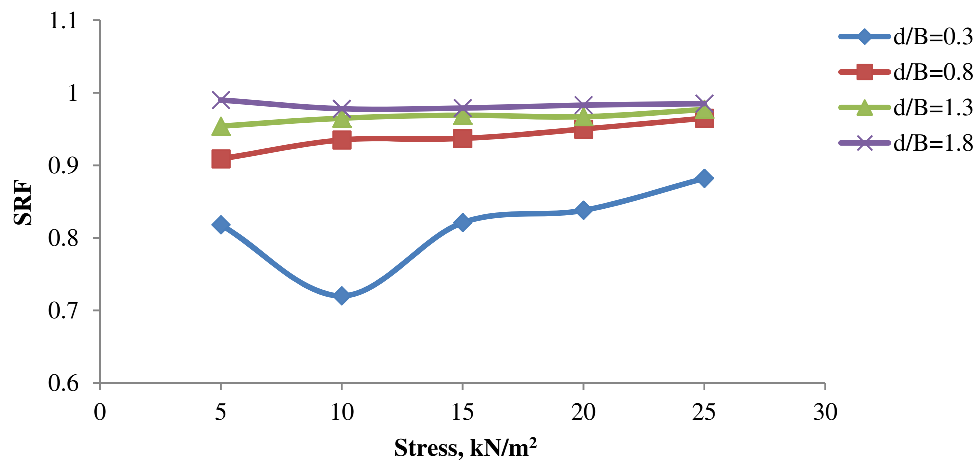


Fig. 5 Variation of settlement reduction factor versus various stress levels for different *d/B* ratios

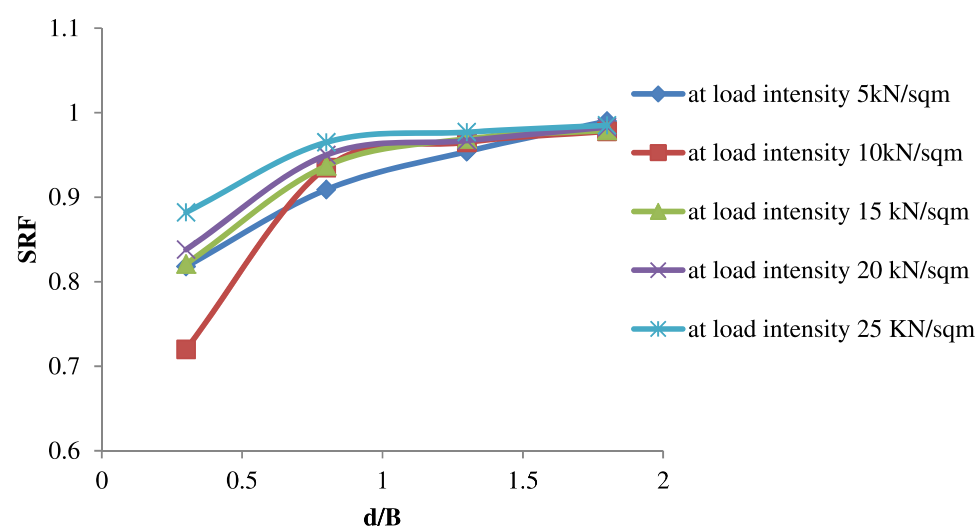


Fig. 6 Variation of settlement reduction factor versus *d/B* for different normalized stress

Theoretical validation of ultimate stress of coir mat-reinforced sand

To determine the applicability of model footings tests to assess the performance of coir mat-reinforced sand, initially, tests were done using coir mat-reinforced sand by varying number of layers staring from $N = 1$, 2, 3, and 4 layers. The theoretical ultimate bearing capacity of the unreinforced sand for circular footing was calculated by Eq. (1):

$$q_{u(\mathrm{UR})} = 0.3 \cdot \gamma \cdot B \cdot N_{\gamma}, \tag{1}$$

where $q_{u(\mathrm{UR})}$ is ultimate bearing capacity of unreinforced soil in general shear failure zone; γ is unit weight of soil; B is width of footing; and N_{γ} is bearing capacity factor.

The ultimate bearing stress of sand reinforced with number of layers of coir mat was calculated according to analytical equations proposed by the Chenn and Abu-Farsakh [25], as shown in Eq. (2):

$$q_{u(\mathrm{UR})} = q_{u(\mathrm{UR})} + \sum_{i=0}^{N} \frac{4T_i\{U + (i-1)\}h}{B^2}, \tag{2}$$

where $q_{u(\mathrm{UR})}$ is ultimate bearing capacity of reinforced soil, u is top layer spacing; T_i is tensile force in reinforcement; and h is vertical spacing between reinforcement layers.

The experimental ultimate bearing capacity of unreinforced sand and number of layers of coir mat-reinforced sand were determined using model footing tests and compared with the theoretical ultimate bearing capacity obtained using Eqs. (1) and (2) of respective set. The experimental ultimate (peak) stress was obtained from load intensity versus settlement for each configuration used in the investigation. The theoretical peak stress and experimental peak stress were compared. Table 5 shows comparative values of theoretical peak stress and experimental peak stress thus obtained.

The theoretical ultimate stress of coir mat reinforcement sand is in good agreement with the experimental results for both single layer of reinforcement as well as multiple layer of reinforcement. Thus, the experimental results of ultimate stress and peak strain obtained for single-layer coir mat-reinforced sand at $u/B = 0.3$ and coir mat-reinforced sand with multiple layers was comparatively assessed to assess the performance of multiple layers of mat reinforcement, which is the aim of the present investigation.

Table 5 Comparison of peak stress of unreinforced and coir mat-reinforced sand for different layers

Form of sand	Experimental peak stress (kN/m^2)	Theoretical peak stress (kN/m^2)
Unreinforced	25.87	20.55
$N = 1$	134.88	84.15
$N = 2$	357.70	253.75
$N = 3$	691.99	529.35
$N = 4$	1055.23	910.95

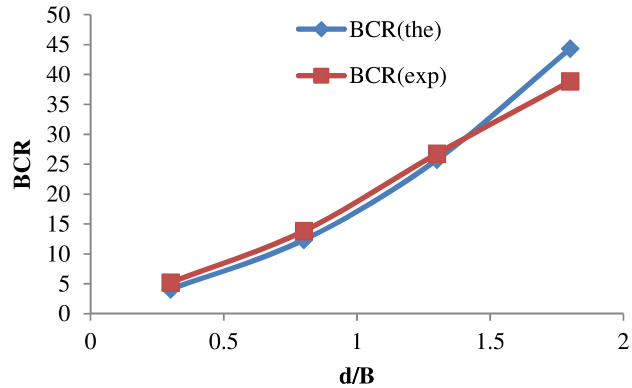


Fig. 7 Experimental BCR and theoretical BCR of coir mat-reinforced sand for different layers

It was observed that the difference between experimental and theoretical values were almost nearer. The bearing capacity ratio, which is defined as the ratio of peak stress obtained for reinforced sand to unreinforced sand, was calculated from theoretical and experimental ultimate bearing stress. The values of BCR theoretical and BCR experimental were plotted against various d/B ratios, as shown in Fig. 7. As per this plot, the theoretical BCR is stimulated with the BCR values obtained by the experimental results.

Conclusion

Model footing tests resting on reinforced sand under static loading, in which a number of layer of coir mat reinforcement were comparatively analysed to assess the performance of footings for both bearing capacity and settlement. Theoretical validation for the experimentally measured values of ultimate stress for coir mat-reinforced sand was also made. On the basis of results thus arrived at, the following major conclusions can be drawn:

1. Increase in number of layers of reinforcement increases the bearing capacity ratio (BCR) for a given mat size opening for coir mat.
2. Experimental results such as peak stress and BCR for various d/B ratios synchronize with the analytical results.
3. Variation of settlement reduction factor (SRF) shows a significant reduction in settlement, has settlement reduction factor (SRF) increases with increase in stress for coir geotextile.

4. Increase in settlement reduction factor (SRF) with increase in stress becomes marginal with increase in number of layer of reinforcement.
5. For multilayer system, BCR for a constant *u*/*B* ratio 0.3 and *S*/*B* ratio increases with increasing the number of coir mat layer. The BCR is maximum for $N = 4$. it can be said that the optimum number of layers in terms of bearing capacity and settlement reduction factor (SRF) corresponding to $N = 3$ to $N = 4$ layers.

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