

Performance assessment of footings on geogrid-reinforced manufactured sand and river sand beds

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Abstract

Owing to the rapid growth of construction activities, particularly in urban areas, the availability of suitable land for construction is steadily decreasing. Consequently, reinforced soil foundation systems are increasingly being adopted. Additionally, the depletion of natural river sand has led to its limited availability, prompting the need for alternative materials such as manufactured sand (M-sand). This study investigates the performance of circular and square model footings resting on reinforced M-sand and river sand beds under static loading conditions. Experimental tests were conducted on both sand types by varying key parameters such as relative density (30% and 50%), number of reinforcement layers (1-5), spacing between the reinforcement layers (0.3B, 0.4B and 0.5B), and footing shape. The results indicated a significant increase in the bearing capacity compared to unreinforced sand beds. The bearing pressure increased with an increase in the number of reinforcement layers up to an optimum of four layers. However, beyond this, a noticeable reduction in the bearing pressure was observed. Among reinforcement spacings, 0.3B delivered the highest bearing pressure, while larger spacings resulted in lower improvement. Increasing the relative density from 30% to 50% potentially improved the load-carrying capacity. With respect to the footing geometry, as the number of reinforcement layers increased from one to four, circular footings sustained a higher bearing capacity ratio, increasing from 2.89 for 1 layer to 12.25 for four layers, compared to square footings resting on the M-sand bed. The experimental results were compared with analytical predictions based on bearing-capacity approaches. The analytical results showed good agreement with experimental observations. Overall, the results demonstrate that M-sand can be effectively used as a backfill material in place of river sand, as it exhibits a comparable bearing resistance for a given settlement.

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1. Introduction

Foundations form the lowest part of a structure and are supported by soil at various depths. They receive the total load from the superstructure and safely transfer it to the ground. Therefore, the supporting soil must have a suitable bearing capacity to carry these loads. Although some soils naturally have high bearing capacity, others are moderately weak, making it necessary to improve their strength using suitable ground-improvement techniques such as chemical stabilization, which

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increases soil strength through cementitious reactions, and mechanical reinforcement, which improves load distribution without altering soil composition.

Several researchers, including Karimiazar et al. [1], Sharifi Teshnizi et al. [2], Arjmandzadeh R et al. [3], Mirzababaei M et al. [4] have investigated environmentally friendly chemical stabilizers as alternatives to conventional cement and lime. Cement kiln dust, nano-silica, nano-alumina, and their combinations with lime or cement have been reported to significantly improve the engineering properties of cohesive soils like loess, marl, expansive clay, and collapsible soils. These studies showed significant improvements in strength, stiffness, and durability, and reduced swelling, through the formation of cementitious compounds such as calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH), along with pore refinement and enhanced interparticle bonding. Thus, chemical stabilization has proven effective for improving cohesive soils.

In contrast, granular foundation materials such as sand are more commonly improved through mechanical reinforcement techniques. The bearing capacity of soil depends on its shear strength, whereas the compressibility of the supporting soil influences the settlement of a footing. Incorporating reinforcement into the soil mass increases its shear resistance through friction and soil–reinforcement interaction, consequently reducing footing settlement. Sand plays a substantial role in the construction industry; however, excessive extraction of river sand from streambeds has raised environmental concerns and rapidly depleted natural resources. As a result, high-quality river sand has become scarce and is often transported from distant locations, increasing costs and environmental impacts. To address this issue, manufactured sand (M-sand) has emerged as a sustainable and reliable alternative to river sand for construction applications. Although M-sand has secured acceptance as a replacement for river sand in concrete applications, its performance as a reinforced foundation bed material supporting shallow foundations has not been sufficiently investigated.

Earlier studies on reinforced foundation beds [5-32] have focused on sand beds by varying parameters such as footing type, reinforcement concerning its material, type, size, placement depth, and spacing between reinforcement layers. Regarding the footing shape, a study by Badakhshan and Noorzad [5] reported that the bearing capacity ratio (BCR) of circular footings was higher than that of square footings. Similarly, Makarchian and Ehsan Badakhshan [6] observed that the BCR increased with an increase in the number of reinforcement layers for both footing types and concluded that providing reinforcement is more effective beneath circular footings than square footings. Regarding reinforcement characteristics, Durga Prasad et al. [7] reported that three-dimensional geogrids exhibited greater performance compared to conventional planar geogrids; Harikumar et al. [8] observed that soil reinforced with grid anchors achieved a higher maximum bearing capacity than soil reinforced with regular geogrids; Imran et al. [9] findings showed that, compared to polymeric fibres, rubber tyres have higher tensile strength, lower elongation at break, and lower water permeability. Thakur et al. [10] studied the combined effect of geocell-geogrid reinforced sand beds. A combination of geocell and geogrid-reinforced sand beds decreases settlement by approximately 28.65% compared to the geocell-reinforced sand bed alone.

Concerning the reinforcement length, Makkar et al. [11] concluded that to achieve optimal improvement in footing performance on reinforced sand, the length of each geogrid layer should be equal to or greater than five times the footing width; in a similar study, Khing et al. [12] reported that the maximum increase in bearing capacity was obtained when the depth of the first reinforcement layer was less than one time the width of the footing, and the minimum width of the geogrid was approximately six times the foundation width. With respect to the number of reinforcement layers, the works of [8,11,13-15] proved that the greatest increase in bearing capacity is achieved when four layers of reinforcement are provided—the study by Makkar et al. [11] demonstrated that using four layers of geogrids resulted in a bearing capacity ratio (BCR) of 3.71, highlighting the effectiveness of soil reinforcement. Similarly, Patel et al. [15] reported an increase of up to 3.6 times in the bearing capacity when four layers of cement-bag strip reinforcement were used compared with unreinforced sand.

In contrast, Basudhar et al. [16] reported a continuous increase in the BCR with each additional reinforcement layer and noted that a three-layer reinforced system resulted in a bearing capacity approximately 4.5 times greater than that of the unreinforced case.

Several researchers [13-23] have emphasized the importance of the depth and spacing between reinforcement layers, according to Basudhar et al. [16], Yetimoglu et al. [18] and Abu-Farsakh et al. [22], the optimal depth of the first reinforcement layer is approximately 0.3 times the footing width. Furthermore, studies by Durga Prasad et al. [7], Makkar et al. [11] and Mosallanezhad et al. [23] recognized the optimal spacing between successive reinforcement layers as 0.25 times the footing width. Similarly, Yetimoglu et al. [18] proposed that the ideal spacing typically lies between 0.2 and 0.4 times the footing width. Shanmugasundaram et al. [33] carried out an experimental study on the load-settlement behavior of circular footing resting on manufactured sand (M-sand). The investigation focused on evaluating the load-carrying capacity of circular footings placed on M-sand beds compacted at four relative densities: 25%, 50%, 75%, and 90%. The results confirmed that a relative density of 90% achieved higher bearing capacity and reduced settlement. Similarly, Vijaya et al. [34] reported that the higher the density of the M-sand bed, the greater the bearing capacity. Although several studies have investigated reinforced sand foundations, most have focused on natural river sand as the foundation bed material, while M-sand as a foundation bed material has received comparatively less attention. The present study addresses these research gaps by conducting experimental investigations for footings resting on unreinforced and reinforced M-sand beds by varying parameters such as the relative density of the sand bed, number of reinforcement layers, type of footings and spacing between reinforcements and the results were compared with those obtained for footings resting on reinforced river sand beds. The findings showed that reinforced M-sand can serve as a sustainable and reliable alternative to river sand for shallow foundation applications, contributing to both geotechnical engineering practice and sustainable infrastructure development.

2. Materials and Methodology

2.1 Sand

M-sand and river sand are classified as poorly graded sand (SP) based on the Unified Soil Classification System (ASTM D2487-17e1) [35] and Indian Standard Classification IS 1498:1970 [36][37]. In terms of physical properties, M-sand has rough-textured, angular particles with sharp edges, resulting in good particle interlocking and higher frictional resistance at a given relative density. In contrast, river sand is rounded with a smooth surface, has lower particle interlocking, and shows lower frictional resistance at the same relative density as M-sand. M-sand is obtained by crushing rocks, and hence its density will generally be higher when compared to river sand. Table I shows the Properties of M-Sand and river sand and Fig. 1 shows the gradation curve of M-Sand and river sand.

Table 1. Properties of M-sand and river sand

Properties	Unit	Value	
		M-sand	River Sand
Specific gravity		2.58	2.53
D ₁₀	mm	0.094	0.15
D ₃₀	mm	0.27	0.29
D ₆₀	mm	0.94	0.52
Coefficient of uniformity (C _u)		10	3.46
Coefficient of curvature (C _c)		0.825	1.07
Maximum unit weight	kN/m ³	20.06	17.95
Minimum unit weight	kN/m ³	15.59	14.42
Dry unit weight at 50% relative density	kN/m ³	17.55	15.99
Angle of Internal Friction at 50% relative density	°	48	39
Dry unit weight at 30% relative density	kN/m ³	16.70	15.32
Angle of Internal Friction at 30% relative density	°	42	33

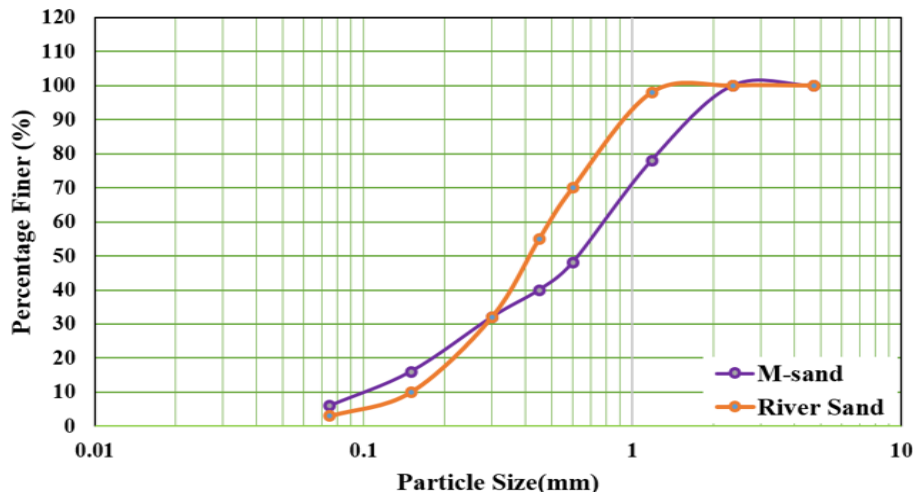


Fig. 1. Gradation curve for M-sand and river sand

2.2 Geogrid

The reinforcement employed was a biaxial geogrid procured from Geotech Industries Private Limited, the manufacturer. The specifications, aperture size, rib thickness, joint thickness and ultimate tensile strength were obtained from the manufacturer's datasheet and are summarized in Table II. Fig. 2 shows the type of reinforcement used.



Fig. 2. Biaxial geogrid

Table 2. Properties of geogrid

Properties	Unit	Value
Structure	-	Biaxial, mesh type, square aperture
Rib Thickness	mm	3
Joint Thickness	mm	5
Aperture Size	mm	35 *35
Tensile Strength	kN/m	40

2.3 Footing

Two model footing shapes, Square and Circular, with dimensions of 100 mm × 100 mm and 100 mm in diameter, with a thickness of 10 mm, made of mild steel were used for the experimental work, as shown in Fig. 3 as per reference [5] and [6].



Fig. 3. Model square and circular footing

2.4 Experimental Setup

The sand bed was prepared in a circular test tank (diameter 500 mm, height 390 mm) using a controlled compaction method to achieve a relative density (D_r) of 50%. Makkar et al. [11] reported that medium dense sand typically exhibited a relative density ranging from 35% to 65%. The performance of footings on M-sand and river sand beds compacted at a lower density of 30% was also investigated. According to the Indian Standard IS: 1888-1982 [38]. The test tank diameter should be at least five times the width of the model footing to minimize boundary effects. Accordingly, this study used a 500 mm diameter tank.

For the unreinforced condition, the sand bed was prepared to a height of 360 mm by placing sand in four equal layers, each 90 mm in thickness. In the reinforced condition, the reinforcements were placed at predetermined depths between the sand layers, starting from the bottom of the footing. Yetimoglu et al. [18] suggested that the optimum depth of the first reinforcement layer is 0.3 times the footing width (B), and that the spacing between reinforcement layers generally varies between 0.2 B and 0.4 B . Based on these recommendations, we positioned the first reinforcement layer at a depth of $U = 0.3B$ below the footing base. We varied the spacing between successive reinforcement layers (H) to 0.3, 0.4, and 0.5 B . The number of reinforcement layers was varied from one to five.

The reinforcement width was maintained at five times the footing width (5 B), as recommended in previous studies [12]. The reinforcements were provided in the form of circular disks. To eliminate sidewall friction effects, a clearance of 5mm was maintained between the reinforcement edges and the tank walls. Previous studies by A. K. Nazir and El-Mahallawy [23] indicated that bearing pressure increases significantly when the reinforcement length is equal to or greater than five times the footing width. Other researchers also reported similar observations [24]-[26]. The prepared sand bed was subjected to static loading using a 500 kN capacity loading frame. The load was applied at a constant displacement rate of 1.2 mm/min, as shown in Fig. 4. Fig. 5 illustrates the experimental methodology adopted for the model footing tests.



Fig. 4. Preparation of sand bed

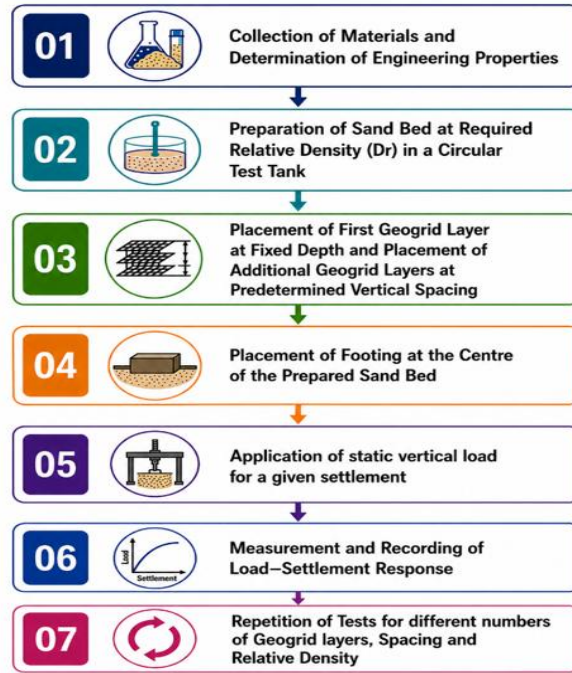


Fig. 5. Methodology adopted for model footing test

Fig. 6 Illustrates the schematic layout of a footing resting on a reinforced sand bed. In this figure, N denotes the number of reinforcement layers, U represents the depth of the first reinforcement layer measured from the bottom of the footing, and H indicates the vertical spacing between successive reinforcement layers. Symbol B refers to the diameter and width of the circular and square footing, and b denotes the length (or width) of the reinforcement. Table III Presents descriptions of the experiments carried out in different series.

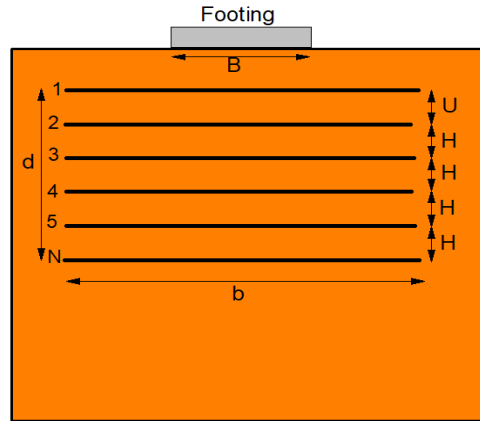


Fig. 6. Sand bed with layers of reinforcements

Table 3. Description of experimental test series

Type of soil	Type of footing	Relative Density (D_r) (%)	Depth of first layer (U/B)	Spacing (H/B)	Number of Layers (N)
M-Sand	Circular	50	0.3	0.3, 0.4, 0.5	1,2,3,4,5
	Square	50	0.3	0.3, 0.4, 0.5	1,2,3,4,5
River Sand	Circular	50	0.3	0.3, 0.4, 0.5	1,2,3,4,5
	Square	50	0.3	0.3, 0.4, 0.5	1,2,3,4,5
M-Sand	Circular	30	0.3	0.3, 0.4, 0.5	1,2,3,4,5
	Square	30	0.3	0.3, 0.4, 0.5	1,2,3,4,5
River Sand	Circular	30	0.3	0.3, 0.4, 0.5	1,2,3,4,5
	Square	30	0.3	0.3, 0.4, 0.5	1,2,3,4,5

3. Experimental Results and Discussion

3.1 Impact of Number of Reinforcement Layers (N)

A series of experiments was carried out by varying the number of reinforcement layers from one to five at different reinforcement spacings and relative densities. The performance of the footing for different reinforcement configurations was evaluated in terms of bearing pressure and settlement. The bearing pressure was evaluated at a settlement of 25 mm, in accordance with the approach adopted by previous researchers. [8], as this settlement allows effective mobilization of the soil–reinforcement interaction. At smaller settlements, such as 5 mm or 10 mm, the reinforcement may not be fully mobilized, resulting in a lower apparent improvement in bearing capacity. Therefore, the bearing pressure was evaluated at a settlement of 25 mm.

Fig. 7 and Fig. 8 present the bearing pressure–settlement relationships for square and circular footings placed on unreinforced and reinforced M-sand beds, respectively, with reinforcement parameters of $U = 0.3B$, $H = 0.3B$, and a relative density (D_r) of 50%. The performance of footings on reinforced M-sand beds is significantly better than on unreinforced M-sand beds, consistent with findings reported in the literature. [33]. For instance, the bearing pressure attained for a square footing under unreinforced conditions is 494 kPa, and for a single layer of reinforcement it was measured to be 1363 kPa.

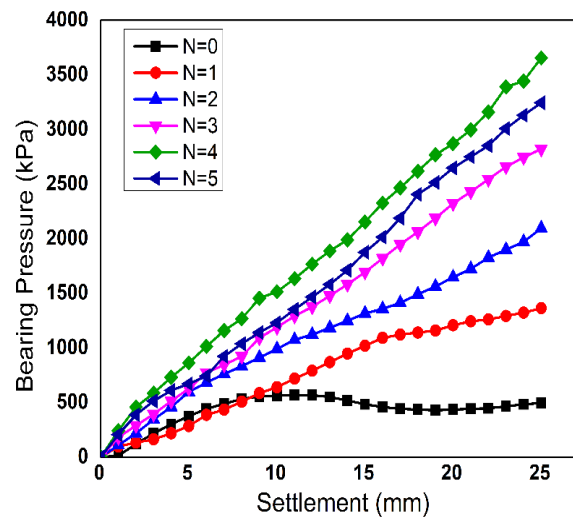


Fig. 7. Effect of reinforcement layers on the performance of square footing in unreinforced and reinforced M-Sand bed at $D_r=50\%$

With respect to the square footing, the bearing pressure increased by approximately 2.75 times with the inclusion of a single reinforcement layer. In contrast, an enhancement of approximately 2.89 times was observed for the circular footing. Furthermore, bearing pressure increased consistently with the addition of up to four reinforcement layers, reaching 3654 kPa for the square footing with four layers; however, adding a fifth layer reduced the bearing pressure to 3244 kPa, representing an 11.22% decrease. For the circular footing, bearing pressure increased to 3764 kPa with four layers, and decreased to 3510 kPa with five layers, a 6.75% reduction. Beyond the four reinforcement layers, the rate of improvement in the bearing pressure declined, as reported in earlier studies. [14]. The reduction in bearing pressure beyond four reinforcement layers was mainly because the fifth reinforcement layer was located beyond the stress-influenced zone below the footing, resulting in limited mobilization of tensile resistance. Furthermore, increased reinforcement depth may reduce stress interaction between the footing and the deepest layer, reducing reinforcement efficiency.

Fig. 9 and Fig. 10 illustrate the bearing pressure–settlement relationships for square and circular footings resting on unreinforced and reinforced river sand beds, respectively, with reinforcement parameters of $U = 0.3B$, $H = 0.3B$, and a relative density (D_r) of 50%. As in previous observations, four reinforcement layers provided the highest bearing resistance at a settlement of 25 mm.

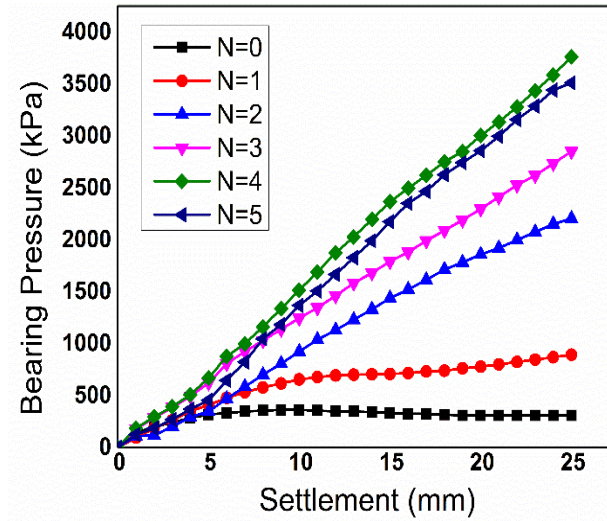


Fig. 8. Effect of reinforcement layers on the performance of circular footing in unreinforced and reinforced M-Sand bed at $D_r=50\%$

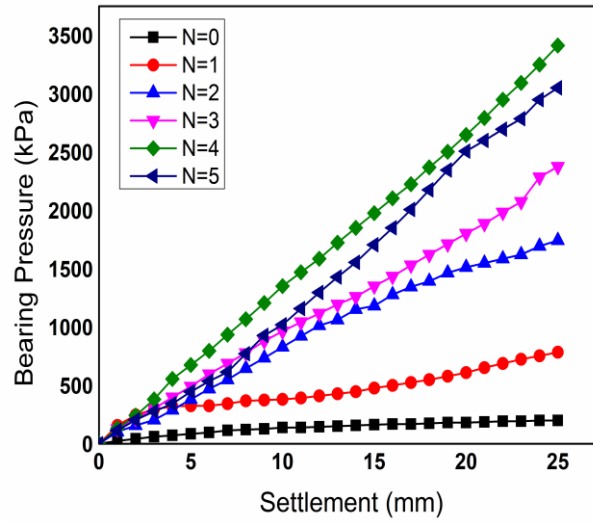


Fig. 9. Effect of reinforcement layers on the performance of a square footing in unreinforced and reinforced river sand bed at $D_r=50\%$

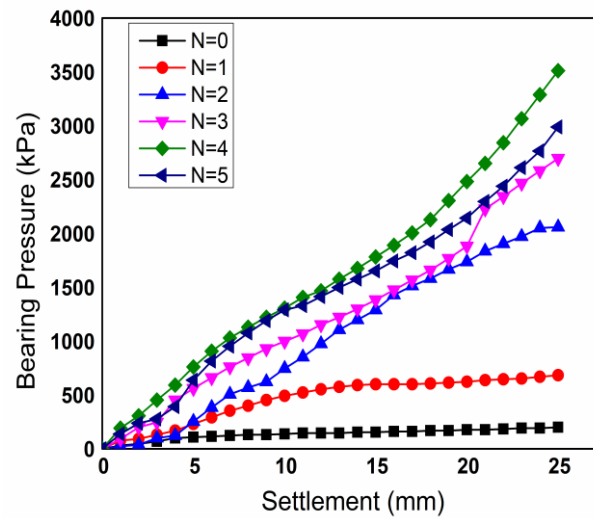


Fig. 10. Effect of reinforcement layers on the performance of circular footing in unreinforced and reinforced river sand bed at $D_r=50\%$

For the square footing resting on a reinforced river sand bed with four reinforcement layers, the bearing pressure increased by approximately 17.15 times compared with the unreinforced condition. In the case of the circular footing, the bearing pressure exhibited an enhancement of about 17.55 times relative to the unreinforced sand bed. Based on these results, the optimum number of reinforcement layers was determined to be four.

To check footing performance at a lower density, experiments were also conducted for footings resting on M-sand and river sand beds compacted to a relative density of $D_r = 30\%$. Fig. 11 and Fig. 12 present the bearing pressure–settlement relationships for square and circular footings placed on unreinforced and reinforced M-sand beds, respectively, with reinforcement parameters of $U = 0.3B$, $H = 0.3B$, and a relative density (D_r) of 30%.

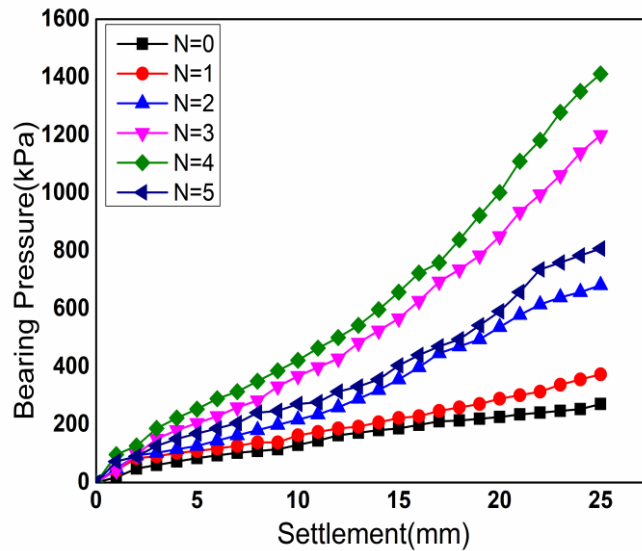


Fig. 11. Effect of reinforcement layers on the performance of a square footing in unreinforced and reinforced M-Sand bed at $D_r=30\%$

Footing performance was comparatively low at a relative density of 30% compared with 50% under both unreinforced and reinforced conditions. The optimum number of reinforcement layers was four, resisting a bearing pressure of 1411kPa for a square footing and 1836kPa for a circular footing. Shanmugasundaram et al. [33] reported that increasing the relative density of the M-sand bed increases the bearing capacity.

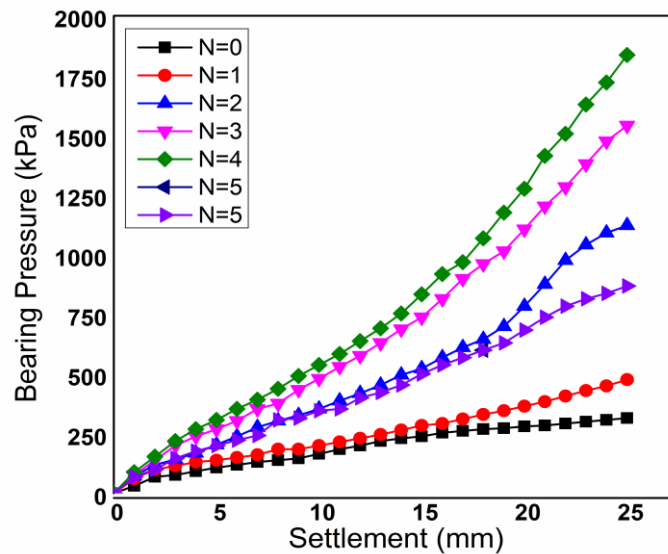


Fig. 12. Effect of reinforcement layers on the performance of circular footing in unreinforced and reinforced M-Sand bed at $D_r=30\%$

Fig. 13 and Fig. 14 presents the performance of the square and circular footing resting on a river sand bed compacted to a relative density of $D_r = 30\%$, with $U=0.3B$ and $H=0.3B$. It follows the same trend as the M-sand bed, with an optimum number of reinforcements of four, with a maximum pressure of 808kPa for the square footing and 1029 kPa for the circular footing. These findings are consistent with Makkar et al. [11] who reported that the bearing capacity of reinforced soil increases progressively as the number of reinforcement layers increases from one to four. Beyond the four layers, however, the additional improvement in bearing capacity becomes marginal.

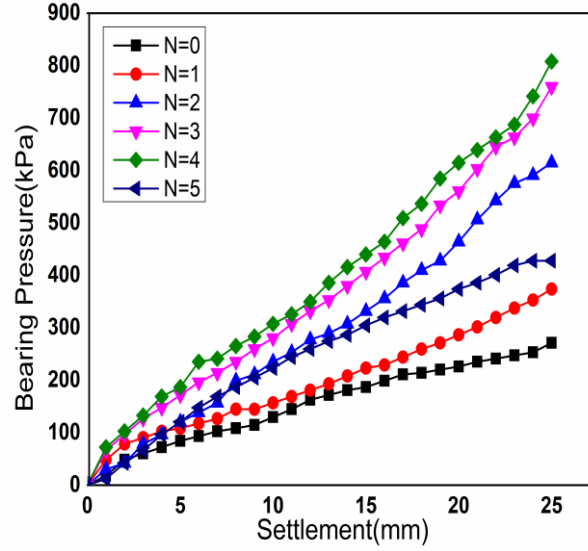


Fig. 13. Effect of reinforcement layers on the performance of square footing in unreinforced and reinforced river sand bed at $D_r=30\%$

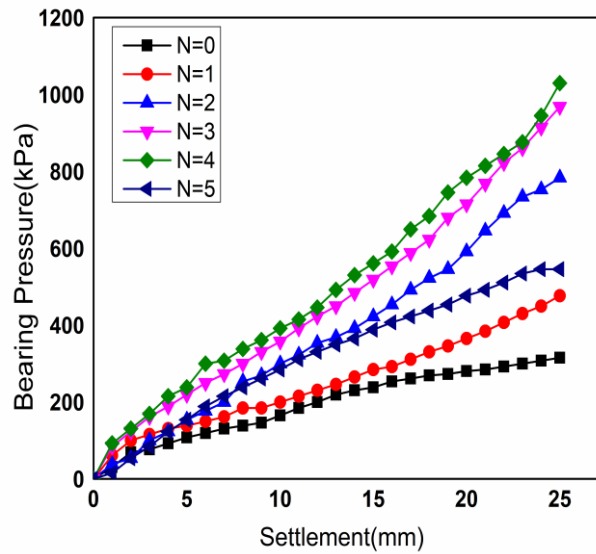


Fig. 14. Effect of reinforcement layers on the performance of circular footing in unreinforced and reinforced river sand bed at $D_r=30\%$

3.2 Impact of Reinforcement Layers on Bearing Capacity Ratio

The experimental results were examined based on the bearing capacity ratio (BCR). BCR is the ratio of the bearing capacity of soil in the reinforced condition to the bearing capacity of soil in unreinforced conditions, as given by the equation (1)

$$BCR = \frac{q_r}{q_{ur}} \quad (1)$$

Fig. 15 shows the variation in the BCR with respect to the number of reinforcement layers for square and circular footings resting on reinforced M-sand beds compacted at a relative density of 50%. As the layers of reinforcement is increased from one to four, the BCR for the square footing rose from 2.75 to 7.39, while for the circular footing it increased from 2.89 to 12.25.

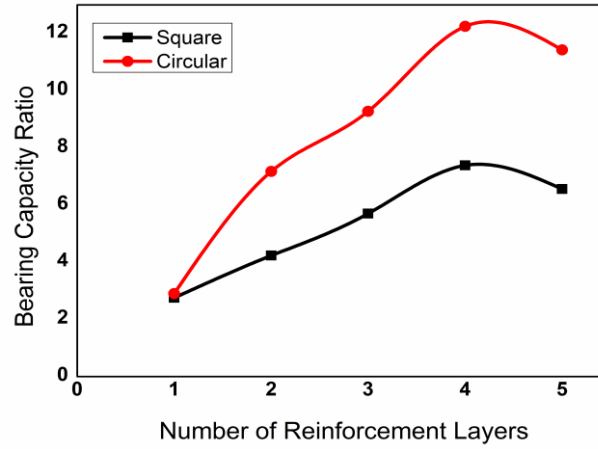


Fig. 15. Variation of BCR with number of reinforcement layers for circular and square footing resting on M-sand bed at $D_r=50\%$

Similarly, Fig. 16 illustrates the relationship between BCR and the number of reinforcement layers for square and circular footings supported on reinforced river sand beds compacted at a relative density of 50%. With an increase in the number of reinforcement layers from one to four, the BCR increased from 3.93 to 17.15 for the square footing and from 3.42 to 17.57 for the circular footing. River sand exhibited high BCR values of 17.15 and 17.57 for four reinforcement layers for the square and circular footings. This variation was mainly due to the lower bearing pressure under unreinforced conditions compared to reinforced conditions and to the optimum reinforcement configuration, which maximized load-carrying capacity. It was also observed that, for both M-sand and river sand beds, circular footings consistently exhibited higher BCR values than square footings, as reported by [6]. These observations agree with the outcomes of Ehsan Badakhshan and Ali Noorzad. [5] who examined the influence of footing shape on geosynthetic-reinforced sand beds and reported that circular footings demonstrate a greater improvement in BCR than square footings under reinforced conditions.

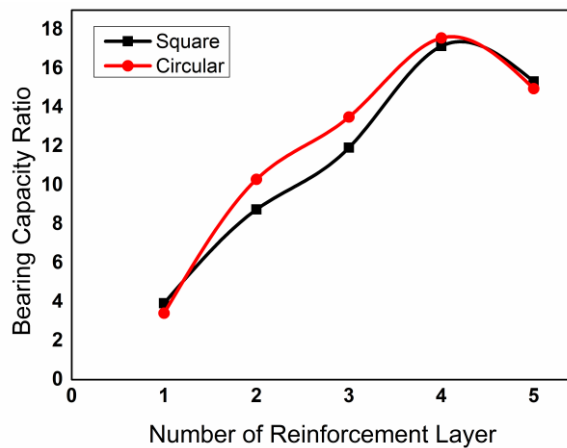


Fig. 16. Variation of BCR with number of reinforcement layers for circular and square footing resting on river sand bed at $D_r=50\%$

3.3 Impact of Spacing Between Reinforcement Layers

The spacing between reinforcement layers plays a crucial role in distributing bearing pressure within the soil mass. As layer spacing increases, the reinforcement tends to behave like a rigid boundary, restricting effective stress transfer to the lower layers.

Experimental studies were conducted on circular and square footings resting on reinforced M-sand beds and river sand beds compacted at a relative density of 50% by varying the spacing between reinforcement layers from $H = 0.3B$ to $H = 0.5B$, while maintaining the depth of the first reinforcement layer constant at $U = 0.3B$ for all test conditions. Fig. 17 illustrates the value of the bearing pressure for square footings on reinforced M-sand at a settlement of 25 mm. For reinforcement spacing of $H = 0.3B$, bearing pressures of 2095 kPa, 2822 kPa, 3654 kPa, and 3244 kPa were observed for two, three, four, and five reinforcement layers, respectively. However, increasing the spacing to $H = 0.4B$ and $H = 0.5B$ significantly reduced bearing pressure.

A similar pattern was noted for circular footings, as shown in Fig. 18 where maximum bearing pressures of 2204 kPa, 2854 kPa, 3764 kPa, and 3510 kPa were recorded for two, three, four, and five reinforcement layers, respectively, at $H = 0.3B$, compared with lower values at larger spacings of $H=0.4B$ and $H=0.5B$. These observations are consistent with the findings of Kumar et al. [27] who reported that the maximum improvement in bearing capacity and the greatest reduction in settlement occurred when the geotextile reinforcement was placed at a spacing of $0.3B$.

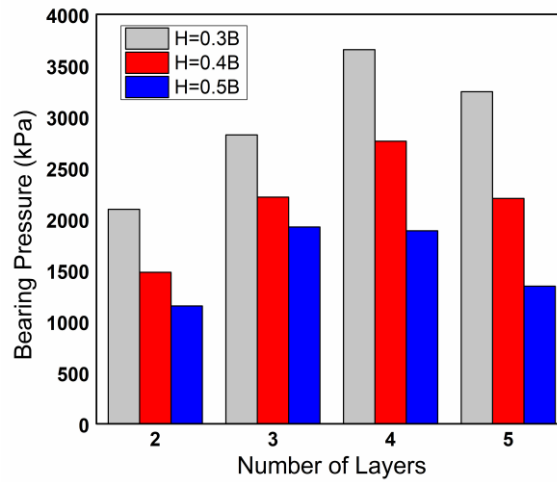


Fig. 17. Effect of spacing between reinforcement layers in M-sand bed supporting a square footing

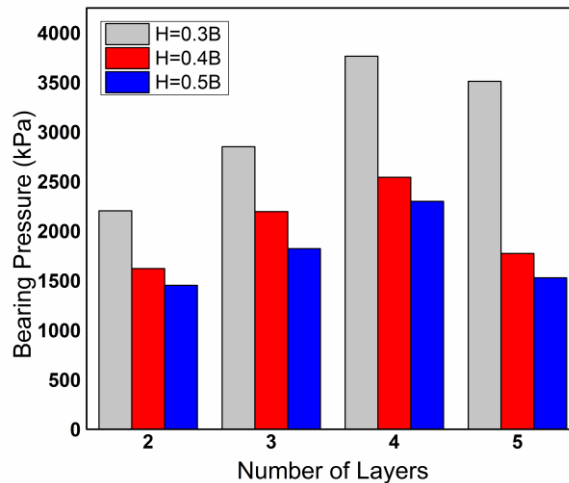


Fig. 18. Effect of spacing between reinforcement layers in M-sand bed supporting a circular footing

Similar experiments evaluated the influence of reinforcement layer spacing in river sand beds supporting circular and square footings. The river sand bed exhibited trends comparable to those observed in the M-sand bed, indicating that the optimum spacing between reinforcement layers is $H = 0.3B$ when compared with spacings of $H = 0.4B$ and $H = 0.5B$, as illustrated in Fig. 19 and Fig. 20.

For a configuration with four reinforcement layers, the square footing sustained bearing pressures of 3413 kPa, 2822 kPa, and 2021 kPa at reinforcement spacings of $H = 0.3B$, $H = 0.4B$, and $H = 0.5B$, respectively. Similarly, the circular footing resisted bearing pressures of 3510 kPa, 2512 kPa, and 1682 kPa for the same spacings.

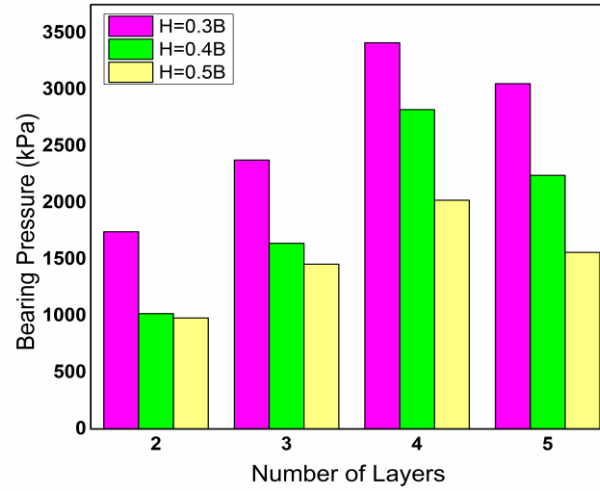


Fig. 19. Effect of spacing between reinforcement layers in river sand bed supporting a square footing

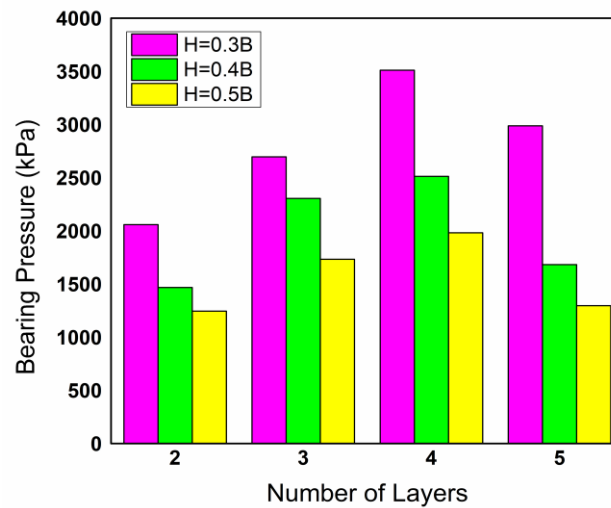


Fig. 20. Effect of spacing between reinforcement layers in river sand bed supporting a circular footing

3.4 Comparison of Performance of Footing Resting on Manufactured Sand Bed and River Sand Bed

Fig. 21 presents the bearing pressure–settlement response of a square footing resting on M-sand and river sand beds compacted at a relative density of 50% under both unreinforced and reinforced conditions at a reinforcement spacing of $H=0.3B$. The results show that the footing supported by the M-sand bed consistently exhibits superior performance compared to that supported by the river sand bed. In the unreinforced condition, the bearing pressure mobilized by the footing on M-sand is approximately 2.48 times greater than that on river sand at a settlement of 25 mm. A similar trend was observed under reinforced conditions. At a settlement of 25 mm, the bearing pressure sustained by the square footing on M-sand is about 1.73, 1.20, 1.18, 1.07, and 1.06 times higher than that on river sand when the number of reinforcement layers increases from one to five, respectively. Fig. 22 illustrates the bearing pressure–settlement behavior of a circular footing resting on M-sand and river sand beds at $D_r=50\%$ under both unreinforced and reinforced conditions at a reinforcement spacing of $H=0.3B$.

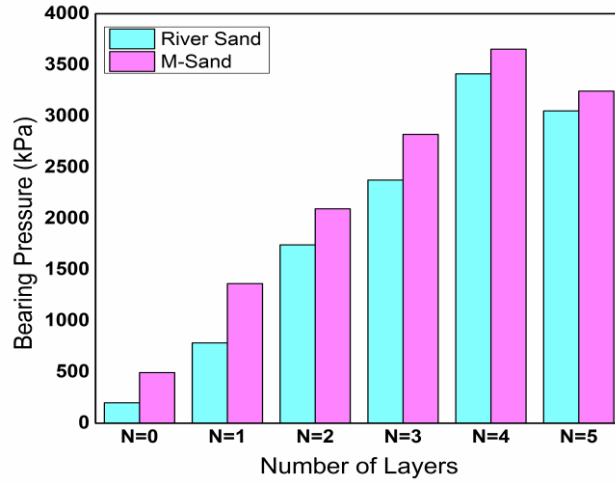


Fig. 21. Comparison of square footing resting on M-Sand and river sand bed under unreinforced and reinforced conditions at $D_r=50\%$ and $H=0.3B$

The results demonstrate that the circular footing supported on the M-sand bed consistently outperforms that supported on the river sand bed by sustaining higher bearing pressures. At a settlement of 25 mm, the bearing pressure mobilized by the footing on M-sand was approximately 1.54 times greater than that on river sand in the unreinforced case. Under reinforced conditions, the corresponding bearing pressures are approximately 1.30, 1.07, 1.05, 1.09, and 1.18 times higher for one to five reinforcement layers, respectively, compared with the footing resting on river sand.

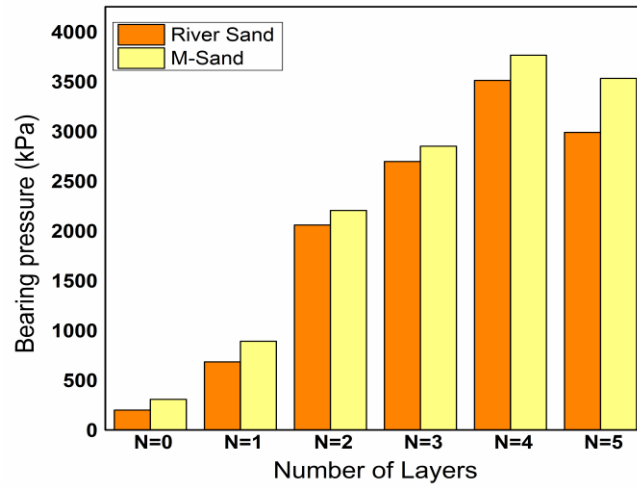


Fig. 22. Comparison of circular footing resting on M-Sand and river sand bed under unreinforced and reinforced conditions at $D_r=50\%$ and $H=0.3B$

3.5 Validation of Experimental Research with Analytical Approach

It was concluded that circular and square footings resting on a manufactured sand bed with a spacing of $H=0.3B$ and $D_r=50\%$ exhibited a higher bearing pressure. The Experimental results were compared with those obtained using the analytical method. The bearing capacity of the soil under unreinforced conditions is determined by Terzaghi's equation using (2) and (3).

$$q_{ur} = \gamma D_f N_q + 0.3 \gamma B N_\gamma \quad (2)$$

$$q_{ur} = \gamma D_f N_q + 0.4 \gamma B N_\gamma \quad (3)$$

For the reinforced condition, the bearing capacity of the soil was determined using the Binquet and Lee [28] approach as given by Equations (4) and (5).

$$q_r = q_{ur} + \Delta q \quad (4)$$

$$\Delta q = \frac{T}{A} \quad (5)$$

where q_r is the reinforced bearing pressure (kN/m^2), q_{ur} is the unreinforced bearing pressure (kN/m^2), Δq is the bearing pressure due to reinforcement (kN/m^2), γ is the unit weight of soil in (kN/m^3), D represents the depth of footing (m), B represents the width of the footing (m); N_q and N_γ are the bearing capacity factors; T is the effective tensile force of the reinforcement per layer (kN); and A is the area of the footing (m^2).

Fig. 23 and Fig. 24 presents a comparison between the BCR values obtained from the experimental and analytical solutions for the circular and square footings. For the analytical condition, the BCR value increased from 2.5 to 10.5 for the circular footing and from 3.5 to 12.7 for the square footing, provided with one to five layers of reinforcement. To quantitatively validate the analytical model, a linear regression analysis was performed between the experimental and analytical BCR values for both footing shapes. The coefficient of determination (R^2) obtained from the regression analysis was 0.944 for the circular footing and 0.905 for the square footing. These results indicate a strong correlation between the analytical predictions and the experimental measurements, demonstrating that the analytical model successfully captures the trend of bearing capacity improvement due to geogrid reinforcement. The slightly higher R^2 value obtained for the circular footing suggests that the analytical model provides better agreement with the experimental results for circular footings than for square footings.

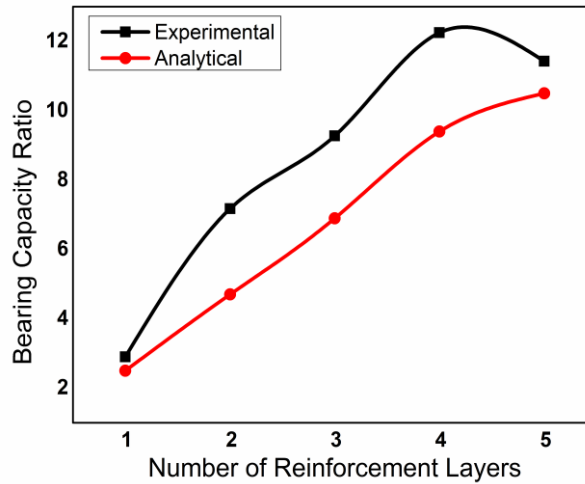


Fig. 23. Comparison of analytical and experimental BCR values of a circular footing on M-sand

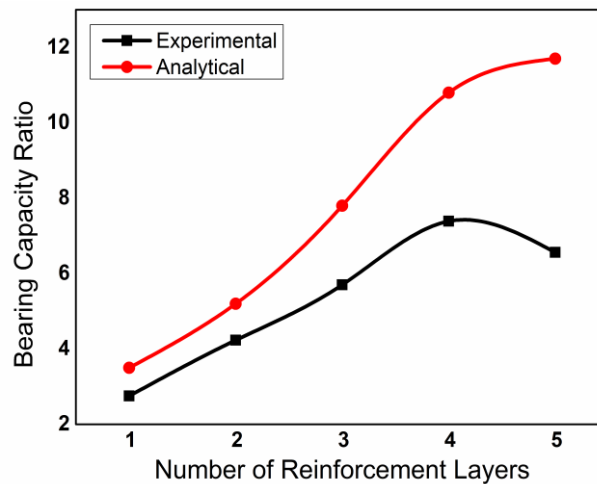


Fig. 24. Comparison of analytical and experimental BCR values of a square footing on M-sand

The experimental findings show values about 1.3 times higher for the circular footing and about 1.46 times lower for the square footing than the analytical results under the optimum case of four reinforcements. This variation is mainly because, under experimental conditions, circular footings often exhibit an axisymmetric stress distribution, resulting in uniform load transfer and consequently a higher BCR than the analytical findings. Whereas, in the case of a square footing, stress concentration near the edges and corners will generally be less when compared to the center. Thus, the BCR is lower than the analytical value. This variation may also be attributed to the Banquet and Lee analytical approach, which assumes idealized reinforcement behavior and does not explicitly account for footing shape effects.

4. Conclusions

From the experimental findings, the following conclusions are drawn.

- M-sand presented a higher angle of internal friction than river sand at the same relative density due to its angular particle shape, rough surface texture, and improved particle interlocking. Consequently, it tested bearing pressure comparable to or higher than that of river sand, indicating that M-sand is a suitable alternative foundation bed material.
- An increase in the relative density of the sand bed improves the bearing capacity of the soil. Footings resting on both M-sand and river sand beds compacted to a relative density of 50% showed higher bearing pressure compared to 30% relative density.
- The bearing pressure increases with an increase in the number of reinforcement layers. The optimal number of reinforcement layers for circular and square footings placed over reinforced M-Sand and river sand beds was four. Beyond four layers, the bearing pressure value decreases.
- When the soil layer was reinforced with four layers of reinforcement, the BCR increases from 2.75 to 7.39 in the case of a square footing and from 2.89 to 12.25 for a circular footing on the M-sand bed at $D_r=50\%$.
- Similarly, for the river sand bed at $D_r=50\%$, the BCR value increases from 3.93 to 17.15 for a square footing and from 3.42 to 17.57 for a circular footing.
- Both circular and square footings supported on M-sand and river sand exhibited improved performance when the reinforcement layers were placed at the optimal spacing of $H=0.3B$.
- Under the optimum reinforcement configuration, the circular footing exhibited higher BCR values than the square footing. For the M-sand bed, the BCR increased from 7.39 (square footing) to 12.25 (circular footing), representing an improvement by a factor of 1.65. Similarly, for the river sand bed, the BCR increased from 17.15 to 17.57, an improvement factor of 1.02. These results demonstrate the superior performance of the circular footing compared to the square footing.
- The square and circular footings resting on an M-sand bed showed a slight increase in bearing pressure by a factor of 1.1 and 1.09, respectively, compared to those on a river sand bed, for the optimum number of reinforcement layers. This suggests that the M-sand can be effectively used as a foundation bed material.
- The BCR value expected by using equations for circular and square footings resting on the M-sand bed was in good agreement with the test results. However, the experimental findings show slightly higher values (1.3 times) for circular footings and lower values (1.46 times) for square footings than the analytical results for the optimum case of four reinforcements.
- The study establishes that reinforced manufactured sand can serve as a technically viable alternative to river sand for foundation applications. This finding is particularly important in regions where natural river sand is limited, and sustainable construction materials are encouraged.
- The present study is limited to selected relative densities and static loading conditions. Future studies should consider large-scale and field validation, cyclic and dynamic loading, different reinforcement materials and configurations, varying footing geometries, and numerical modelling to assess the performance of reinforced M-sand foundations under practical engineering conditions.

References

- [1] Karimiazar J, Sharifi Teshnizi E, O'Kelly BC, Sadeghi S, Karimizad N, Yazdi A, et al. Effect of nano-silica on engineering properties of lime-treated marl soil. *Transportation Geotechnics*. 2023;43:101-123. <https://doi.org/10.1016/j.trgeo.2023.101123>
- [2] Sharifi Teshnizi E, O'Kelly BC, Karimiazar J, et al. Effects of cement kiln dust on physicochemical and geomechanical properties of loess soil, Semnan Province. *Iran. Arab J Geosci*. 2022;15:1482. <https://doi.org/10.1007/s12517-022-10751-w>
- [3] Karimiazar J, Sharifi Teshnizi E, Mirzababaei M, Mahdad M, Arjmandzadeh R. California Bearing Ratio of a Reactive Clay Treated with Nano-Additives and Cement. *Journal of Materials in Civil Engineering*. 2022;34(2). [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0004028](https://doi.org/10.1061/(ASCE)MT.1943-5533.0004028)
- [4] Mirzababaei M, Karimiazar J, Sharifi Teshnizi E, Arjmandzadeh R, Bahmani SH. Effect of Nano-Additives on the Strength and Durability Characteristics of Marl. *Minerals*. 2021;11(10):1119. <https://doi.org/10.3390/min11101119>
- [5] Badakhshan E, Noorzad A. Effect of footing shape and load eccentricity on behavior of geosynthetic reinforced sand bed. *Geotextiles and Geomembranes*. 2017;45(2):58-67. <https://doi.org/10.1016/j.geotexmem.2016.11.007>
- [6] Makarchian M, Badakhshan E. Comparison of bearing capacity of footings with same area resting on reinforced sand. *GEOMATE Journal*. 2017;12(29):9-16. <https://doi.org/10.21660/2017.29.79025>
- [7] Durga Prasad B, Hariprasad C, Umashankar B. Load-settlement response of square footing on geogrid reinforced layered granular beds. *International Journal of Geosynthetics and Ground Engineering*. 2016;2:1-10. <https://doi.org/10.1007/s40891-016-0070-6>
- [8] Harikumar M, Sankar N, Chandrakaran S. Behaviour of model footing resting on sand bed reinforced with multi-directional reinforcing elements. *Geotextiles and Geomembranes*. 2016;44(4):568-578. <https://doi.org/10.1016/j.geotexmem.2016.03.008>
- [9] Khan I, Sharma RK. Bearing Capacity Evaluation of Square Footing Resting on Reinforced Sand. *Journal of Mining and Environment*. 2023;14(3):813-824.
- [10] Thakur V, Sharma RK. Experimental evaluation on behavior of geocell-geogrid reinforced sand subjected to combined static and cyclic loading. *Indian Geotechnical Journal*. 2024;54(4):1406-1419. <https://doi.org/10.1007/s40098-023-00815-3>
- [11] Makkar FM, Chandrakaran S, Sankar N. Behaviour of model square footing resting on sand reinforced with three-dimensional geogrid. *International Journal of Geosynthetics and Ground Engineering*. 2017;3:1-10. <https://doi.org/10.1007/s40891-016-0083-1>
- [12] Khing KH, Das BM, Puri VK, Cook EE, Yen SC. The bearing-capacity of a strip foundation on geogrid-reinforced sand. *Geotextiles and Geomembranes*. 1993;12(4):351-361. [https://doi.org/10.1016/0266-1144\(93\)90009-D](https://doi.org/10.1016/0266-1144(93)90009-D)
- [13] Mosallanezhad M, Hataf N, Ghahramani A. Experimental study of bearing capacity of granular soils, reinforced with innovative grid-anchor system. *Geotechnical and Geological Engineering*. 2008;26:299-312. <https://doi.org/10.1007/s10706-007-9166-z>
- [14] Shrigondekar A, Ullagaddi P. Bearing capacity analysis of a square footing supported on geogrid reinforced sand. *International Journal on Emerging Technologies*. 2020;11(3):169-176.
- [15] Patel SK, Sahay M. Load-Settlement Response of Square Footing Resting on Sand Bed Reinforced with Cement Bag Strip. *Transportation Infrastructure Geotechnology*. 2025;12(1):61. <https://doi.org/10.1007/s40515-024-00527-y>
- [16] Basudhar PK, Saha S, Deb K. Circular footings resting on geotextile-reinforced sand bed. *Geotextiles and Geomembranes*. 2007;25(6):377-384. <https://doi.org/10.1016/j.geotexmem.2006.09.003>
- [17] Omar MT, Das BM, Puri VK, Yen SC. Ultimate bearing capacity of shallow foundations on sand with geogrid reinforcement. *Canadian Geotechnical Journal*. 1993;30(3):545-549. <https://doi.org/10.1139/t93-046>
- [18] Yetimoglu T, Wu JT, Saglam A. Bearing capacity of rectangular footings on geogrid-reinforced sand. *Journal of Geotechnical Engineering*. 1994;120(12):2083-2099. [https://doi.org/10.1061/\(ASCE\)0733-9410\(1994\)120:12\(2083](https://doi.org/10.1061/(ASCE)0733-9410(1994)120:12(2083)
- [19] Munawir A. The effect of spacing between geogrid and footing length on rectangular footing under eccentric load. *GEOMATE Journal*. 2020;18(69):208-215. <https://doi.org/10.21660/2020.69.25967>
- [20] Benmebarek S, Djeridi S, Benmebarek N, Belounar L. Improvement of bearing capacity of strip footing on reinforced sand. *International Journal of Geotechnical Engineering*. 2018;12(6):537-545. <https://doi.org/10.1080/19386362.2017.1309136>
- [21] Ali JYM, A'amal AH. Optimum reinforcement depth ratio for sandy soil enhancement to support ring footing subjected to a combination of inclined-eccentric load. *Journal of Engineering*. 2023;29(11):95-108. <https://doi.org/10.31026/j.eng.2023.11.06>

- [22] Abu-Farsakh M, Chen Q, Sharma R. An experimental evaluation of the behavior of footings on geosynthetic-reinforced sand. *Soils and Foundations*. 2013;53(2):335-348. <https://doi.org/10.1016/j.sandf.2013.01.001>
- [23] El Sawwaf, Nazir AK. Behavior of repeatedly loaded rectangular footings resting on reinforced sand. *Alexandria Engineering Journal*. 2010;49(4):349-356. <https://doi.org/10.1016/j.aej.2010.07.002>
- [24] Cicek E, Guler E, Yetimoglu T. Effect of reinforcement length for different geosynthetic reinforcements on strip footing on sand soil. *Soils and Foundations*. 2015;55(4):661-677. <https://doi.org/10.1016/j.sandf.2015.06.001>
- [25] Bilgin Ö, Mansour E. Effect of reinforcement type on the design reinforcement length of mechanically stabilized earth walls. *Engineering Structures*. 2014;59:663-673. <https://doi.org/10.1016/j.engstruct.2013.11.013>
- [26] Latha GM, Somwanshi A. Bearing capacity of square footings on geosynthetic reinforced sand. *Geotextiles and Geomembranes*. 2009;2(4):281-294. <https://doi.org/10.1016/j.geotexmem.2009.02.001>
- [27] Kumar S, Solanki CH, Patel JB, Sudevan PB, Chaudhary PM. Study on square footing resting on prestressed geotextile reinforced sand. In: *International Congress and Exhibition. Sustainable Civil Infrastructures: Innovative Infrastructure Geotechnology*. Cham: Springer International Publishing; 2017. p. 70-81. https://doi.org/10.1007/978-3-319-63570-5_7
- [28] Binquet J, Lee KL. Bearing capacity tests on reinforced earth slabs. *Journal of the Geotechnical Engineering Division*. 1975;101(12):1241-1255. <https://doi.org/10.1061/AJGEB6.0000219>
- [29] Gupta R, Kumar R, Jain PK. Behavior of circular footing resting on three-dimensional confined sand. *International Journal of Advanced Engineering Technology*. 2014;5(2):11-13.
- [30] Lovisa J, Shukla SK, Sivakugan N. Behaviour of prestressed geotextile-reinforced sand bed supporting a loaded circular footing. *Geotextiles and Geomembranes*. 2010;28(1):23-32. <https://doi.org/10.1016/j.geotexmem.2009.09.002>
- [31] Kazi M, Shukla SK, Habibi D. An improved method to increase the load-bearing capacity of strip footing resting on geotextile-reinforced sand bed. *Indian Geotechnical Journal*. 2015;45(1):98-109. <https://doi.org/10.1007/s40098-014-0111-9>
- [32] Nasr AMA, Azzam WR. Behaviour of eccentrically loaded strip footings resting on sand. *International Journal of Physical Modelling in Geotechnics*. 2017;17(3):177-194. <https://doi.org/10.1680/jphmg.16.00008>
- [33] Shanmugasundaram V, et al. Experimental study of load settlement behaviour of circular footing rested over M-sand. *AIP Conference Proceedings*. 2020;2240(1). <https://doi.org/10.1063/5.0010996>
- [34] Tejaswini BR, Vijaya S, Gangadhara S. Study on Performance of Footing and Effect of Reinforcement on Manufactured Sand Bed. In: *International Conference on Advances in Concrete, Structural, & Geotechnical Engineering*. Singapore: Springer Nature Singapore; 2024. 3:227-245. https://doi.org/10.1007/978-981-96-0755-6_19
- [35] ASTM D2487-17e1. Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System). ASTM International, West Conshohocken, PA, USA; 2017.
- [36] Bureau of Indian Standards (BIS). IS 1498:1970, Classification and Identification of Soils for General Engineering Purposes. Bureau of Indian Standards, New Delhi, India; 1970 (Reaffirmed 2020).
- [37] Bureau of Indian Standards (BIS). IS 2720 (Part 4):1985 (Reaffirmed 2020), Methods of Test for Soils-Part 4: Grain Size Analysis. New Delhi, India; 1985.
- [38] Bureau of Indian Standards (BIS). IS:1888 (1982) Method of load test on Soils. Bureau of Indian Standards, New Delhi, India; 1982.