



Evaluation of Load-Settlement Behaviour of Square Model Footings Resting on Geogrid Reinforced Granular Soils

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Abstract. Reinforced soil foundation is a soil foundation containing reinforcing elements or inclusions in the form of strips, grids or ties which are placed horizontally. The purpose of this research was to study the load settlement behavior of square footings placed on geogrid reinforced sandy soil foundation using model tests. While the geometric parameters are specific to certain specifications and conditions such as gradation, relative density of soil beneath the foundation etc., the type, aperture size, stiffness and thickness etc. of geogrid may have some effect on the critical parameters of the reinforced soil foundation. Therefore, two types of geogrid have been used in this study to investigate the load settlement behavior for model footings reinforced with uniaxial (UNX100) and biaxial (BIX100) polyester geogrids resting on poorly graded medium sand. Parameters of this study include the depth to the first reinforcement layer, spacing between reinforcement layers, plan area of the reinforcement and the grade of reinforcement. Load tests were conducted on model footings made of mild steel plates (100 mm * 100 mm size) in four phases to evaluate the effects of single and multiple layers of geosynthetic reinforcement placed below shallow spread footings and to quantify the difference in performance between the uniaxial and biaxial Geogrid reinforcement. Based on the current study, values for optimum embedment depth, optimum spacing between geogrid layers, and optimum plan area of reinforcement for both types of geogrid have been proposed. It was observed that inclusion of reinforcement increased the bearing capacity as well as decreased the settlement of the foundation. The presence of geogrid in the soil makes the relationship between the settlement and applied pressure of the reinforced soil almost linear. Biaxial geogrid performs better than uniaxial geogrid, though the uniaxial reinforcement also leads to significant improvement in performance of footings compared to unreinforced footings.

Keywords: Square footing · Geogrid · Sand bed · Laboratory model tests
Uniaxial geogrid · Biaxial geogrid · Load tests · Bearing capacity ratio

1 Introduction

Reinforced earth is a material composed of soil fill strengthened by the reinforcement such as rods, bars, fibers and nets. Reinforcements interact with soil by means of frictional resistance. The concept of strengthening the soil by reinforcement is of very old origin. From the olden times attempts have been made to improve mechanical properties of soil by; adding straw or bamboo strips etc. Reinforced earth systems are used today in a variety of civil engineering applications owing to its particular advantages such as cost reduction, simplicity and ease of construction. The reinforced soil foundation system has been a technical and commercial success due to its numerous advantages and thus garnered the attention of the academic circles for research and development in this field. One of the applications of reinforced soil is that it can prove to be an effective alternative to the conventional ground improvement techniques in the improvement of bearing capacity of weak soils. Reinforced earth systems have nowadays found a wide range of civil engineering applications. The reinforced soil foundation derives its reinforcing function from the frictional bond between the reinforcement and the soil. This is the reason that granular cohesionless soils have usually been specified in literature. Vidal (1968) did some pioneering work to illustrate the use of reinforced soil foundation systems for the improvement of the bearing capacity of soft subsoil foundation. Reinforced foundation beds show a good improvement in the bearing capacity and in reducing foundation settlement. In the past, beneficial effect of incorporating tensile reinforcing strips in granular soil fills has been described. In this pursuit, soil reinforced with strips, fabrics, grids and cells are becoming very common. Research is being carried out to study the effect of inclusions below the foundations in increasing the bearing capacity of foundations, all around the globe. During the last three decades, several laboratory model tests and a few field tests have been performed to investigate the ultimate and allowable bearing capacity of shallow foundations supported by single or multiple layered geogrid reinforced sand or clay. Some of the investigators have evaluated the useful effect of using geogrid as a soil reinforcement under the footings by conducting laboratory model tests (Guido et al. 1986; Omar et al. 1993; Das et al. 1994; Das and Khing 1994; Das and Omar 1994; Yetimoglu et al. 1994; Huang and Menq 1997; Das et al. 1998; Shin et al. 2002; Kumar and Saran 2003; Kumar et al. 2007). Adams and Collin (1997) conducted large scale model footing tests to study the ultimate bearing capacity on Geogrid reinforced soil.

Binquet and Lee (1975a, b) have presented the results of model tests with strip footing on reinforced sand foundations for three conditions and showed that the load-settlement and ultimate bearing capacity of footing can be improved by a factor of about 2 to 4 times the bearing capacity of unreinforced soil at comparable settlements for otherwise identical conditions. Akinmasuru and Akinbolade (1981) presented results of laboratory model tests with square footing on a deep homogeneous sand bed reinforced with flat strips of rope fiber material and reported that different types of failure mode observed are in agreement with the modes of failure identified by Binquet and Lee (1975a, b). Similar studies have been reported by many other researchers (e.g. Fragaszy and Lawton 1984; Mahmoud and Abdrabbo 1989; Chadbourne 1994; Dash et al. 2003; Abu-Farsakh et al. 2013; Panda and Ray 2014; Prasad et al. 2016; Budania et al. 2017). Singh (1988) has conducted model plate load tests on reinforced sand beds using aluminum strips, and grid

reinforcements and concluded that for a given reinforcement material, the thickness of the reinforcement will not influence mobilization of interfacial friction. Further, many researchers (e.g. Guido et al. 1987; Mandal and Sah 1992; Shin et al. 1993; Fahel et al. 2000; Chen 2007; Chen et al. 2007; Abu-Farsakh et al. 2007; Abu-Farsakh et al. 2008; Sharma et al. 2009; Ornek 2009; Laman et al. 2009; Abdelhadi 2013; Pathan et al. 2017) have reported extensive experimental and numerical study on clayey soil reinforced soil foundation. Therefore, in this paper, authors have made an attempt to investigate load-settlement behavior of square model footings resting on Geogrid reinforced granular soils.

In the present study, the load settlement behavior was studied for model footings reinforced with uniaxial geogrid (UNX100) and biaxial geogrid (BIX100), both polyester geogrids, resting on sand classified as poorly graded at a relative density equal to 50% and quantum of improvement was observed for each grade. Parameters of the testing program include the spacing between reinforcement layers, the depth to the first reinforcement layer, plan area of the reinforcement, the grade of reinforcement. Load tests were conducted on model footings made of mild steel plates (100 mm * 100 mm size) in four phases to evaluate the effects of single and multiple layers of geosynthetic reinforcement placed below shallow spread footings and to quantify the difference in performance between the uniaxial and biaxial geogrid reinforcement. Based on the current study, values for optimum embedment depth, optimum spacing between geogrid layers, and optimum plan area of reinforcement for both types of geogrid have been proposed in the results. It was observed that inclusion of reinforcement increased the bearing capacity as well as decreased the settlement of the foundation. The increase in bearing capacity was expressed in a non-dimensional form, called Bearing Capacity Ratio.

2 Objective of Current Investigation

Although the basic principles of reinforced soil foundation are simple and easy to translate in the field, the theoretical aspects involved in the reinforced soil concept are numerous. Thus warranting extensive research regarding various parameters involved. The purpose of this research was to study the load settlement behaviour of square footings placed on geogrid reinforced sandy soil foundation and to observe the various parameters instrumental to their performance using model tests. The main objective of this work is to study the behaviour of axially loaded square footing on sand bed with and without reinforcement, study the various parameters contributing to their performance and to find out improvement in bearing capacities using two types of geogrid reinforcement. Parameters of the testing program include the depth to the first reinforcement layer, the spacing between reinforcement layers, plan area of the reinforcement, the grade of reinforcement.

A review of the existing literature revealed that most of the experimental studies on geogrid reinforced sand foundation were carried out using a single type of geogrid. Although the geometric parameters of the reinforced soil foundation are governed by certain specifications and conditions such as gradation, Relative density of soil beneath the foundation among others; the type, aperture size, stiffness and thickness etc. of geogrid may also have some effect on the critical parameters of the reinforced soil foundation, therefore two types of geogrid have been used in this study which will help to shed some light on the matter.

3 Experimental Study and Sample Preparations

The experimental program has been designed to study the bearing capacity of axially loaded square footing on single and multi-layered geogrid reinforced sand bed. For this purpose, the laboratory model tests were conducted on square footings in one density (50%). Load tests were performed to evaluate the effects of single and multiple layers of geosynthetic reinforcement placed below shallow spread footings. Two types of geogrid are evaluated, a biaxial geogrid and a uniaxial geogrid. Parameters of the laboratory model tests consist of the embedment depth of reinforcement, spacing between individual reinforcement layers, plan area of the reinforcement, the grade of reinforcement. All tests were performed in a test pit constituted by a steel tank of dimensions $0.5 \text{ m} \times 0.5 \text{ m} \times 0.6 \text{ m}$. Figure 1 shows the typical diagram depicting various geometric parameters of reinforced soil foundation.

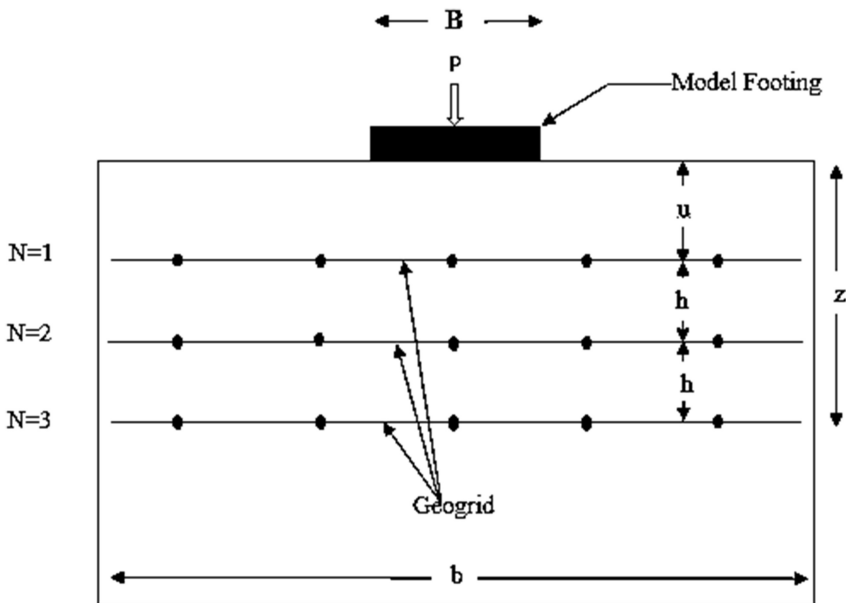


Fig. 1. Typical diagram depicting various geometric parameters of reinforced soil foundation

3.1 Materials

1. Sand

Locally available river sand was used as granular bed during the testing program. The relevant properties of the materials were determined following Indian standard test procedures. The sand used in the experimental program has been mined from the river bed of River Sindh. It was cleaned and washed properly to get rid of any tree roots, pebbles and other unwanted matter. The sand is classified as poorly

graded sand (SP) by the Indian Standard Soil Classification System. The grain-size distribution for the sand is shown in Fig. 2. Table 1 lists the physical properties of the sand used in the study. All the tests have been conducted as per relevant Codal procedures (IS: 1498; IS: 2720).

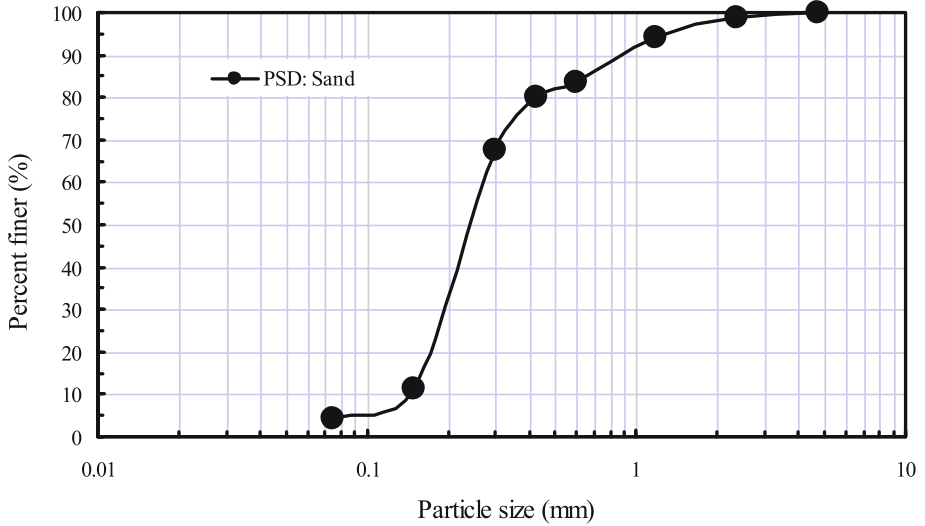


Fig. 2. Particle size distribution curve of sand

Table 1. Physical properties of sand used in the study

Property	Value
D_{10} (mm)	0.145
D_{30} (mm)	0.19
D_{60} (mm)	0.26
D_{50} (mm)	0.24
Coefficient of curvature, C_C	0.96
Coefficient of uniformity, C_U	1.79
Specific gravity, G	2.67
Maximum dry unit weight (kN/m^3)	17.2
Minimum dry unit weight (kN/m^3)	15.1
Friction angle, ϕ (at $D_R = 50\%$)	35.92°
e_{\max}	0.77
e_{\min}	0.55

2. Geogrid

Based on the stress transfer, two types of geogrid- uniaxial (UNX100) and biaxial (BIX100) were used as reinforcement. These are polyester (PET) geogrid reinforcement for soil. These geogrids are constructed of high molecular weight and high tenacity knitted polyester yarns with a proprietary coating. UNX100 has a Tensile strength (ASTM D 6637 – Method A; ASTM D4354) of 100 kN/m in machine Direction (MD) and 30 kN/m in Cross Machine Direction (CMD) with aperture size 29 mm × 62 mm and BIX100 has a Tensile strength (ASTM D 6637 - Method A; IS: 13325) of 100 kN/m (both in Machine Direction-CD as well as Cross Machine Direction-CMD) with aperture size 29 mm × 29 mm (Fig. 3).

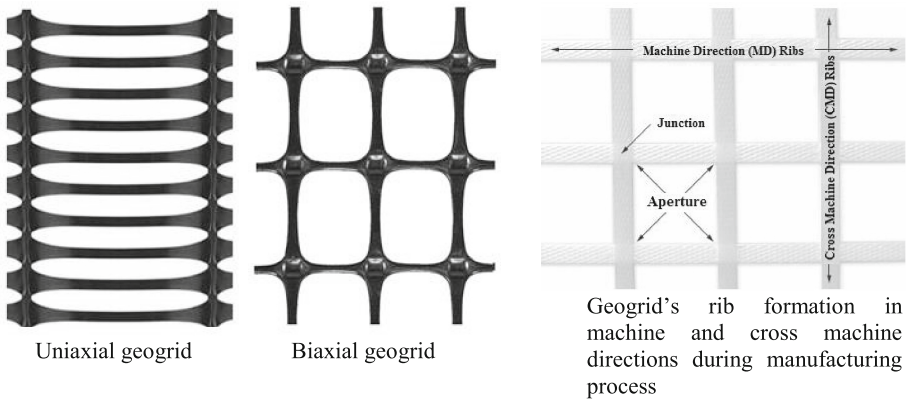


Fig. 3. Types of geogrid used in the study

3.2 Equipment Used

Test Tank

The load tests were conducted in a tank measuring 0.5 m × 0.5 m × 0.6 m and made up of mild steel of 12 mm thickness. Scales were fitted on the internal walls of the tank so that it will be helpful in maintaining the required density accurately. The sides of the tank are heavily braced to avoid lateral yielding. As per the provisions of IS 1888-1962, the width of the test pit should not be less than 5 times the width of the test plate, so that the failure zones are freely developed without any interference from sides. Also, Chummar (1972) suggested that in case of cohesionless soil, the failure zone extends upto 5B to the sides and 3B below the footing. In order to ensure the development of failure zones fully and freely without any interference from the sides and bottom of the tank, a model footing of size 100 mm*100 mm was adopted for this tank size. Additionally the sides and bottom of the tank were lined with polythene sheets for the same purpose. Figures 4 and 5 show the schematic section and plan respectively of the test tank used.

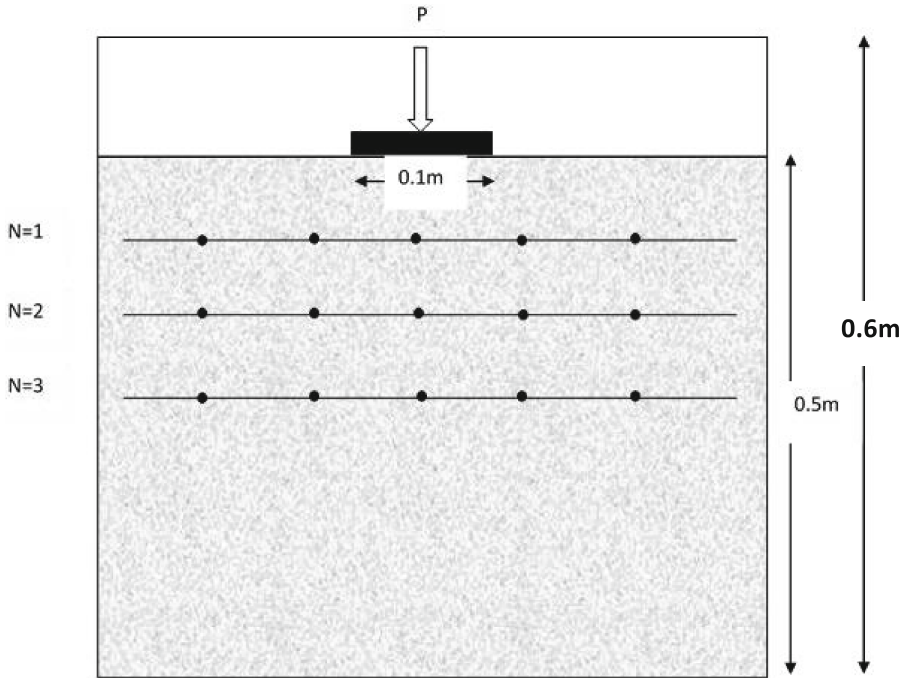


Fig. 4. Schematic section of the test tank used

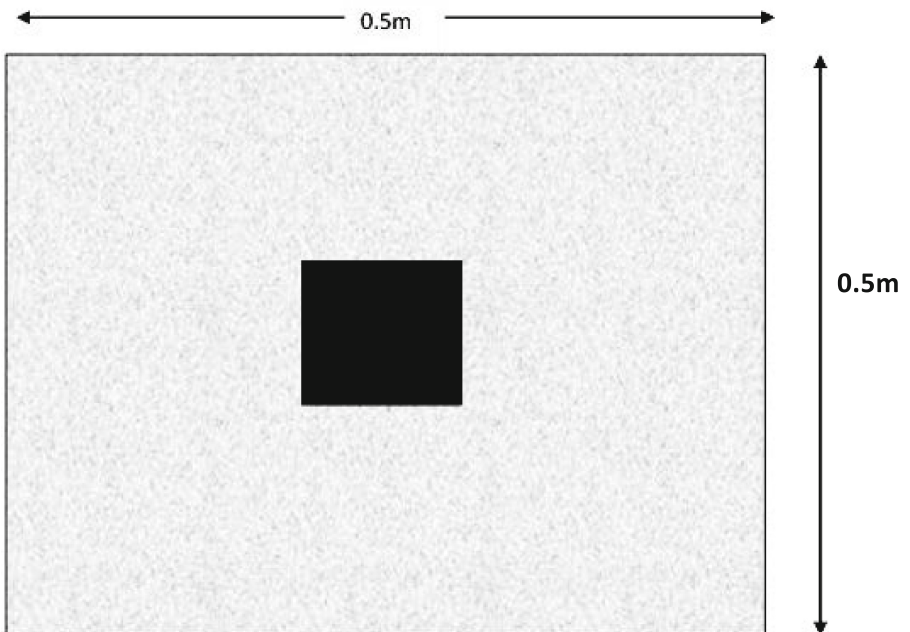


Fig. 5. Schematic plan of the test tank used

The applied loads were resisted against a reaction frame and the frame consisted of four columns supporting two horizontal beams on which the Load transferring shaft rests. The footings were loaded with a manually operated screw jack. The model foundation used for this study was 100 mm * 100 mm in size. It was made out of a mild steel plate with a thickness of 25 mm. Square footing was selected to minimize the dimensional effects (strip and rectangular footings). The bottom of the model foundation was made rough by coating it with glue and then rolling it over sand. Proving ring of 5 kN capacity was used which had a least count of 6.017 N. Two Dial gauges with least count 0.01 mm and range 25 mm were used in the test program. The dial gauges were kept on the rims of the tank as the entire tank had steel strips welded wide enough to accommodate the magnetic base of the dial gauge. The dial gauge needles were placed over the footing loaded with the load transferring column. Settlement occurring as a result of load application was recorded by two dial gauges. Required settlement was taken as the average of the two dial gauge readings in mm. Figures 6a and 6b depicts the photographic image of the equipment used in this study.



Fig. 6a. Photographic image of equipment used in the study



Fig. 6b. Photographic image of sand sample at the start of experiment

3.3 Sample Preparation

The test foundation was prepared to a depth of $4B$ beneath the model footing to be tested in accordance with the Boussinesq stress-distribution theory. According to this theory, the stress below a footing reduces to a negligible value at a depth of about $3B$ from the base of footing. Also, Chummar (1972) suggested that in case of cohesionless soil, the failure zone extends upto $5B$ to the sides and $3B$ below the footing. Therefore, to be on the safer side, using an excavation depth of $4B$ should assure that the results were not influenced by previous tests.

The internal dimensions of the test tank were measured precisely with a steel scale and volume of sand to be filled in each layer was calculated. After fixing a density, at which all the tests are to be done by we can calculate the weight of sand needed for that particular thickness of sand layer. Here the density to be maintained was 1.61 g/cc and the sand was placed in 100 mm lifts. All tests were performed at 50% relative density. The box was filled by sand using sand raining technique. Sand was poured into the test tank in 100 mm layers from a fixed height by raining technique to achieve the desired average unit weight of compaction. The height of fall was fixed by making several trials in the test tank prior to the model test to achieve the desired unit weight. Once the backfilling process was completed, the sand was carefully leveled in the areas directly below the footing. This was to ensure that the surface footings had full contact with the

sand and that the load applied to the footing was normal. For the unreinforced test or the reference test, the model footing was placed on the surface. For the reinforced case, the first layer of geogrid was placed at the proposed depth below the base of the footing while the other consequent layers of geogrid were placed at particular depths to be tested. After placing the geogrid, small weights were placed all around the geogrid layer to keep the geogrid in position while the calculated weight of sand was being poured over it using sand raining technique.

3.4 Testing Procedure

A series of laboratory model footing tests were conducted on geosynthetic reinforced sand foundation (ASTM 1196, IS 1888). Two types of geogrid types UNX100 (uniaxial) and BIX100 (biaxial), both polyester geogrids were used as reinforcement inclusions in these tests. The footing was placed in position in the test tank. Load was applied through the load gauge and was maintained manually. Load was measured with the proving ring. A rocker plate and ball joint were fitted to the proving ring. Two dial gauges were placed on diagonally opposite sides to record settlements on the corners of the footings. The load was applied in increments. Load was increased by the next increment only when there was no substantial change (>2 mm/min) in settlement between any two time intervals. Each load increment was maintained manually. The settlement was recorded at 1, 2.25, 4, 6.25, 9, 16, 25, and 30 min intervals from the start of each load increment. After each series was finalized, the sand layer was carefully removed and the reinforcement layer was visually examined for distortions and/or damages.

3.5 Testing Program

Experimental studies were carried out to obtain the load-settlement response of a model square footing resting on unreinforced and reinforced granular beds. The parameters studied in this research were the effect of top layer spacing, vertical spacing between layers, grade of reinforcement, and embedment depth and plan area of reinforcement. From the laboratory model tests, settlement ratio versus bearing pressure response of footings is brought out for all the cases. The research was conducted in four phases (A, B, C & D) as outlined below:

1. *Phase-A*

Phase-A consisted of the test for evaluating the response of model footing placed on unreinforced soil.

2. *Phase-B*

This phase consisted of series B-1 and B-2. The primary purpose of Phase B was to evaluate the effects of different reinforcement depth with respect to footing size (u/B) and to quantify the difference in performance between the uniaxial and biaxial Geogrid reinforcement.

3. *Phase-C*

This phase consisted of series C-1 and C-2. The primary purpose of Phase C was to evaluate the effects of different reinforcement widths with respect to footing size

(b/B) and to quantify the difference in performance between the uniaxial and biaxial Geogrid reinforcement.

4. Phase-D

This phase consisted of series D-1 and D-2. The primary purpose of Phase D was to evaluate the effects of different reinforcement spacing with respect to footing size (h/B) and to quantify the difference in performance between the uniaxial and biaxial Geogrid reinforcement.

The testing parameters of the laboratory model tests are given in Table 2.

Table 2. Laboratory testing parameters

Test series	Model foundation	Type of geogrid	Constant parameters	Variable parameter	Objective
A-1	Square	–	$D_R = 50\%$	–	To determine q_u
B-1	Square	UNX 100	$N = 1$, $D_R = 50\%$, $b/B = 5$	$u/B = 0.2, 0.4, 0.6$	To determine $(u/B)_{opt}$
B-2	Square	BIX100	$N = 1$, $D_R = 50\%$, $b/B = 5$	$u/B = 0.2, 0.4, 0.6$	To determine $(u/B)_{opt}$
C-1	Square	UNX 100	$N = 1$, $D_R = 50\%$, $u/B = 0.4$	$b/B = 4, 4.5, 5$	To determine $(b/B)_{opt}$
C-2	Square	BIX100	$N = 1$, $D_R = 50\%$, $u/B = 0.5$	$b/B = 4, 4.5, 5$	To determine $(b/B)_{opt}$
D-1	Square	UNX 100	$N = 3$, $D_R = 50\%$, $u/B = 0.4$	$h/B = 0.2, 0.3, 0.4$	To determine $(h/B)_{opt}$
D-2	Square	BIX100	$N = 3$, $D_R = 50\%$, $u/B = 0.5$	$h/B = 0.2, 0.3, 0.4$	To determine $(h/B)_{opt}$

Where: UNX - Uniaxial geogrid type based on strength or stress transfer

BIX- Biaxial geogrid type based on strength or stress transfer

B = Width of foundation (m)

u = Location of the top layer of reinforcement from the bottom the foundation (m)

N = Number of reinforcement layers

h = Vertical distance between two consecutive Geogrid layers (m)

b = width of reinforcement layer (m)

D_R = Relative Density of Sand (%)

4 Results and Discussions

Laboratory bearing capacity tests were conducted on model footings made of mild steel plates (100 mm * 100 mm size). It was observed that inclusion of reinforcement increased the ultimate bearing capacity as well as decreased the settlement of the foundation. The increase in ultimate bearing capacity is generally expressed in a non-dimensional form, called Bearing Capacity Ratio, BCR_u (Binquet and Lee 1975a, b), which is expressed as:

$$BCR_u = q_{u(R)}/q_u \quad (1)$$

Where, $Q_{u(R)}$ = ultimate bearing capacity of reinforced soil.

q_u = ultimate bearing capacity of reinforced soil.

q_u = ultimate bearing capacity of unreinforced soil.

In most cases, shallow foundations in cohesion less soils are designed for limited settlement levels as design is often governed by settlement and not by ultimate bearing capacity and, hence the calculation of magnitude of BCR becomes meaningless. Hence it is necessary to determine the BCR at various levels of settlement to aid in the design process of foundation.

$$BCR_s = q_R/q_u \quad (2)$$

Where, q_R = load/unit area of reinforced soil at settlement level “s”.

q_u = load/unit area of unreinforced soil at settlement level “s”.

4.1 Test Series B-1 and B-2: To Find the Optimum Depth of Embedment “u”

Previous studies have shown that in order to obtain maximum advantage from the geogrid reinforcement layer, it is desirable that “u” be less than $0.67B$. For larger u/B , the failure surface will be fully located above the top layer of reinforcement. For Square model footing on sand, Guido et al. (1985) reported u/B_{opt} as 0.5, Yetimoglu et al. (1994) reported u/B_{opt} as 0.25. Chung and Cascante (2007) reported u/B_{opt} as 0.3–0.5. To verify these results u/B was varied in this test series.

To find out the optimum depth of reinforcement, ‘u’ was varied by adopting values of 0.2, 0.4, 0.6 times the width of the footing, ‘B’ for uniaxial geogrid UNX100 and 0.2,0.4,0.6 times the width of footing B for biaxial geogrid BIX100, (Test series-B1& B2). For both the series B-1 & B-2, other constant parameters were: relative density (D_R) = 50%, number of reinforcement layers (N) = 1, and plan area of reinforcement (b/B) = 5. Figures 7 and 8 show the plot of q vs. s/B ratios for various u/B ratios, presenting the variation of bearing pressure with settlement ratio for various reinforcement depth ratios. It can be seen from Figs. 6a and 6b that for geogrid grade

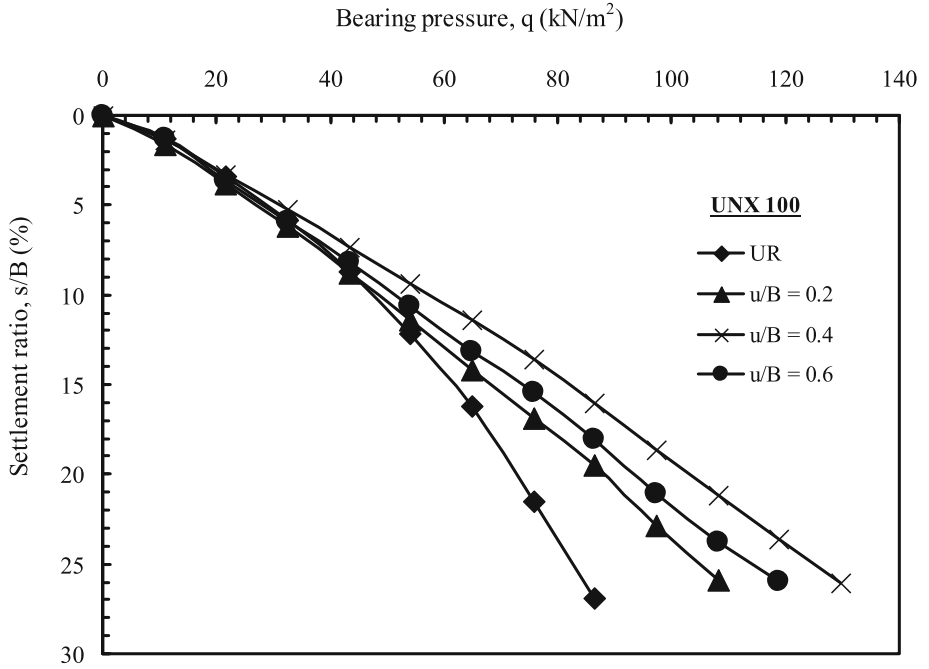


Fig. 7. Plot of q VS. s/B ratio for $N = 1$, $b/B = 5$ (series B-1)

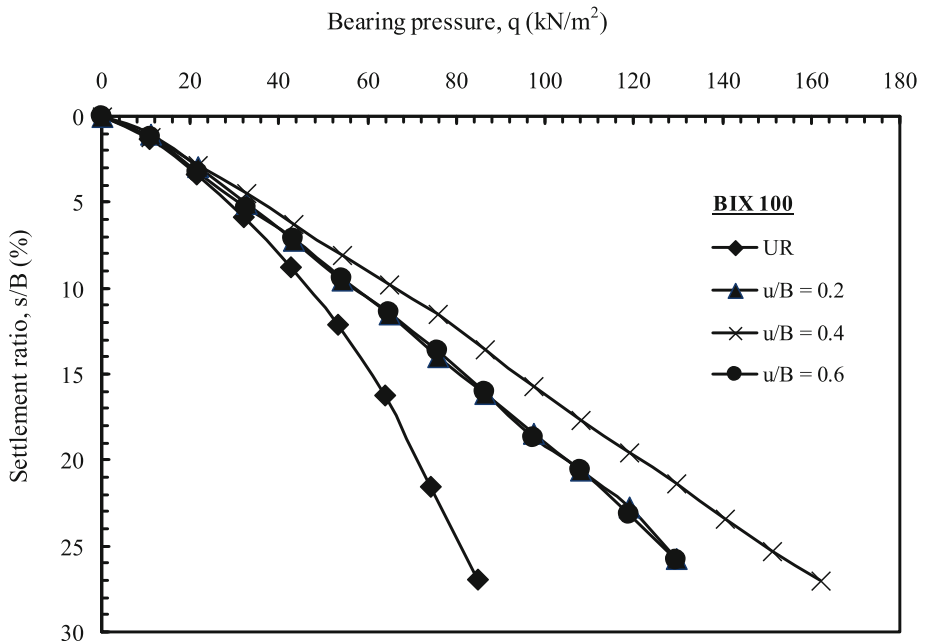


Fig. 8. Plot of q VS. s/B ratio for $N = 1$, $b/B = 5$ (series B-2)

UNX100, q_R is maximum for $u/B = 0.4$. Similarly as seen in Fig. 8, for geogrid grade BX100, q_R is also maximum for $u/B = 0.4$.

As the depth of the geogrid was varied for a value of settlement ratio equal to 10%, the percentage increase in the bearing pressures with respect to unreinforced sand were found out for different u/B values as shown in Table 3. Figure 9 represents the variation of bearing capacity ratio (BCR) with respect to changing u/B ratio achieved at a settlement of 10% of the footing width for each grade of geogrid. Figure 10 presents the variation of bearing capacity ratio with settlement ratio for Test series B. In case of UNX100, for a s/B ratio equal to 10%, the bearing capacity ratio increased by when the

Table 3. Calculation of bearing capacity ratio at $s/B = 10\%$ for varying u/B ratio

No. of Geogrid layers, N	u/B	Bearing capacity ratio (BCRs) = q_R/q_u obtained at $s/B(\%) = 10\%$ ($q_u = 47 \text{ kN/m}^2$)					
		b = 5B					
		UNX100			BIX100		
		q_R	BCRs q_R/q_u	Increase in bearing capacity (%)	q_R	BCRs q_R/q_u	Increase in bearing capacity (%)
1	0.2	48.2	1.03	2.55	56.4	1.20	20.00
1	0.4	57.8	1.23	22.98	66	1.40	40.43
1	0.6	51.4	1.09	9.36	56.8	1.21	20.85

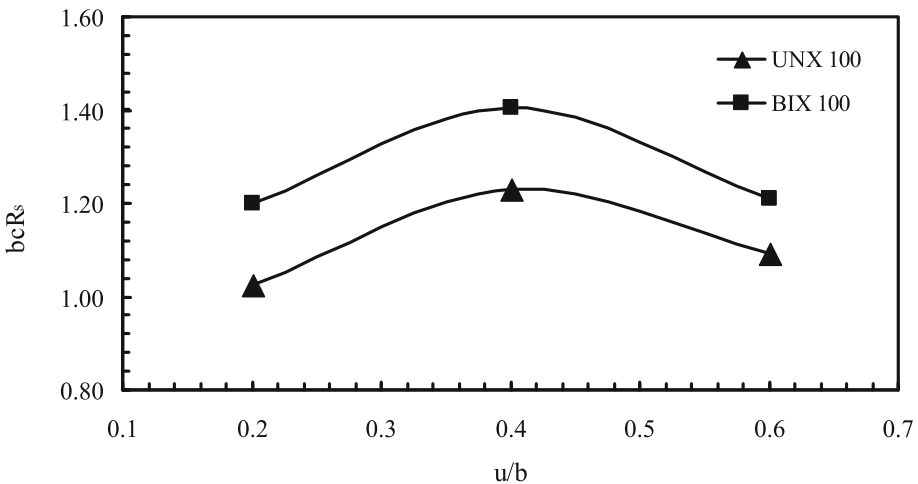


Fig. 9. Variation of bearing capacity ratio (BCR_s) with u/B for $N = 1$, $D_R = 50\%$, $b/B = 5$

geogrid reinforcement was placed at $u = 0.40B$ in comparison to that placed at $u = 0.2B$ or $0.6B$.

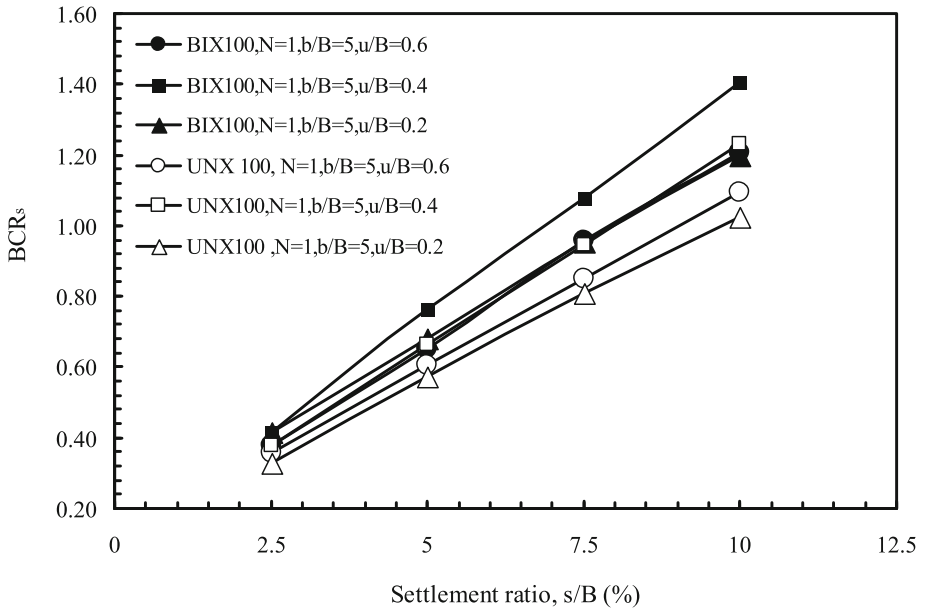


Fig. 10. Variation of bearing capacity ratio (BCR_s) with s/B for $N = 1$, $D_R = 50\%$, $b/B = 5$

4.2 Test Series C-1 & C-2: To Find the Optimum Width of Reinforcement in Terms of b/B

For the purpose of studying the effect of width of the reinforcement on load settlement behavior of the model foundation, ' b ' was varied by adopting the values equal to $4B$, $4.5B$, and $5B$ in the tests, while the depth of reinforcement was maintained at the optimum depth ($0.4B$) and the other parameters were kept at a constant value viz. $N = 1$ & $R_D = 50\%$. Figures 11 and 12 present the variation of bearing pressure with settlement ratio for different widths of geogrid placed in sand for UNX100 and BIX100 respectively. Omar et al. (1993) reported a value of $4.5B$ for square footing placed Geogrid reinforced sand. Yetimoglu et al. (1994) concluded an optimum width of $4.5B$ for a square footing. Ghazavi and Mirzaeifar (2010) reported an optimum value of $3B$. Latha and Somwanshi (2009) determined the optimum width of the reinforcement to be about $4B$ for a square footing placed on geogrid reinforced foundation.

The load-settlement response of footing for each variation of width of reinforcement was drawn, and it was observed that ultimate bearing capacity increases with increase in width of reinforcement for both types. Although first portions of the curves show minimal improvement, the latter portions show significant improvement in bearing capacity. This improvement in ultimate bearing capacity with width of reinforcement is often attributed to the extension of reinforcement into the adjacent soil mass beyond the active zone resulting in wide slab effect. Thus concluding the fact that the bearing capacity of reinforced sand increases considerably with increase in reinforcement size when placed within a certain effective zone. Table 4 shows the percentage increase in bearing capacity at a settlement ratio of 10%, as the plan area of the

geogrid was varied. As it is evident from the table, the percent improvement in bearing capacity with biaxial grade as reinforcement is greater than that due to uniaxial grade. Figure 13 represents the variation of bearing capacity ratio with respect to changing b/B ratio obtained at a settlement of 10% of the footing width for each grade of geogrid. Figure 14 presents the variation of bearing capacity ratio with settlement ratio for Test series C. For a settlement ratio equal to 10%, for UNX100, the bearing capacity ratio increased by 22.98% when the geogrid reinforcement was placed with $b = 5B$ compared to 40.43% for BIX100 when the geogrid reinforcement was placed with the same width.

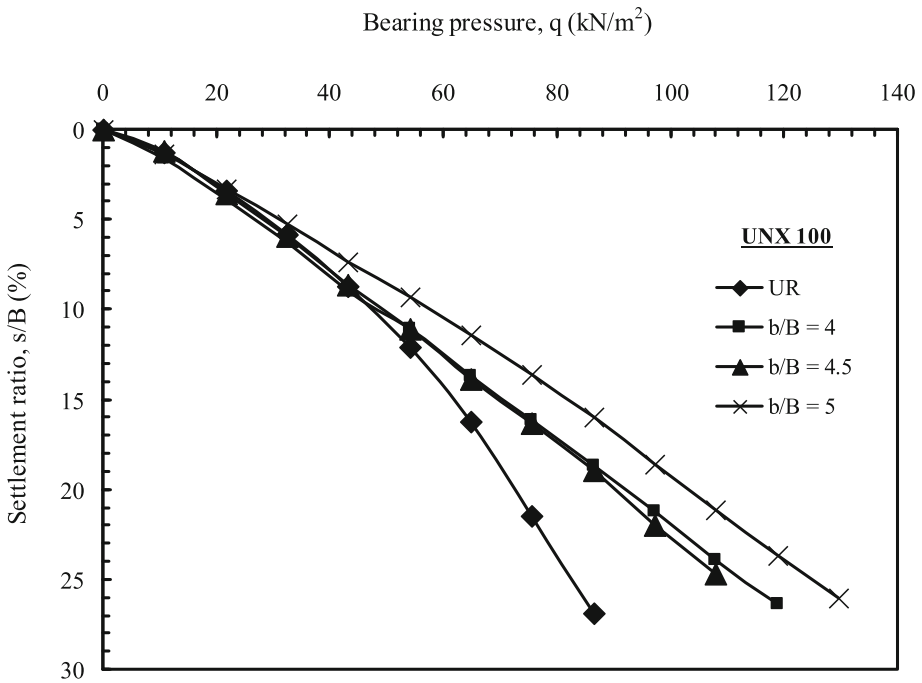


Fig. 11. Plot of q VS. s/B ratio for $N = 1$, $u/B = 0.4$, $D_R = 50\%$ (series C-1)

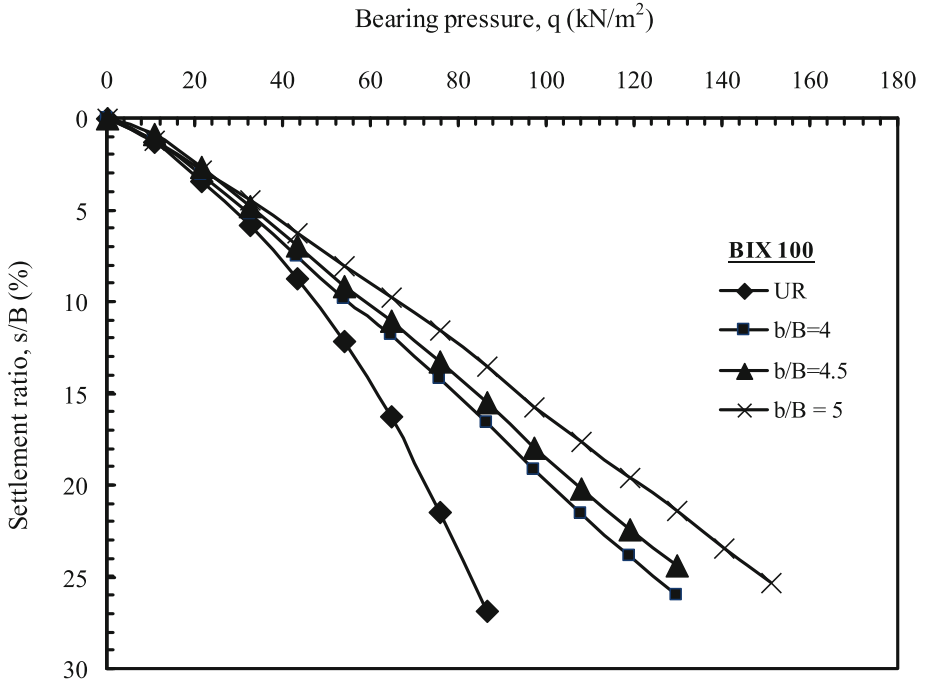


Fig. 12. Plot of q VS. s/B ratio for $N = 1$, $u/B = 0.4$, $D_R = 50\%$ (series C-2)

Table 4. Calculation of bearing capacity ratio at $s/B = 10\%$ for varying b/B ratio

No. of Geogrid layers N	b/B	Bearing capacity ratio (BCR_s) = q_R/q_u obtained at $s/B(\%) = 10\%$ ($q_u = 47 \text{ kN/m}^2$)					
		$u/B = 0.4$					
		UNX100			BIX100		
		q_R	BCR_s q_R/q_u	Increase in bearing capacity (%)	q_R	BCR_s q_R/q_u	Increase in bearing capacity (%)
1	4	48.5	1.03	3.19	54.8	1.17	16.60
1	4.5	49.4	1.05	5.11	58.8	1.25	25.11
1	5	57.8	1.23	22.98	66	1.40	40.43

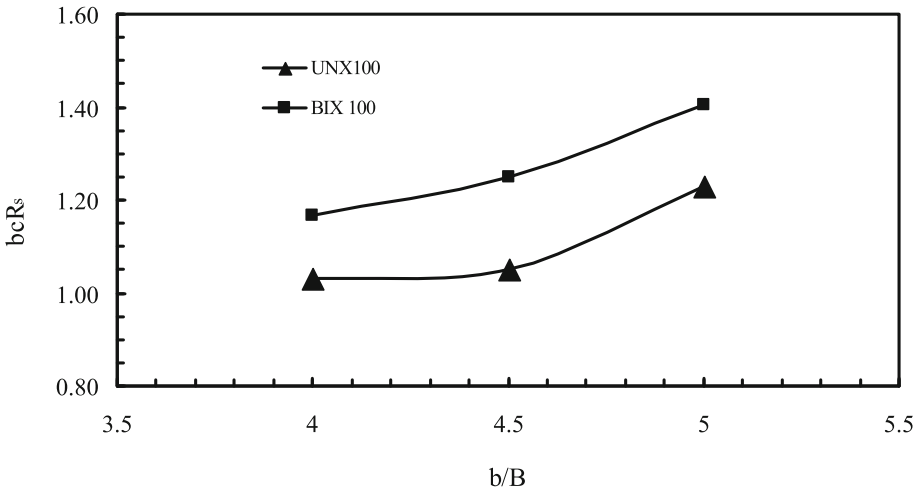


Fig. 13. Variation of bearing capacity ratio (*BCRs*) with *b/B* for $N = 1$, $D_R = 50\%$, $u/B = 0.4$

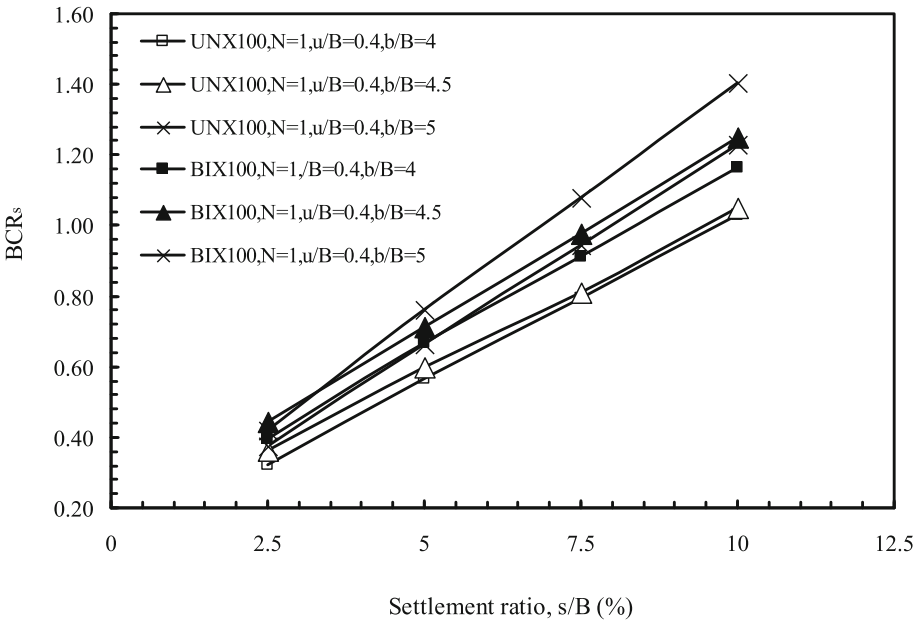


Fig. 14. Variation of bearing capacity ratio (*BCRs*) with *s/B* for $N = 1$, $D_R = 50\%$, $u/b = 0.4$

4.3 Test Series D-1 & D-2: To Find the Optimum Spacing Between Reinforcement Layers “h”

The effect of vertical spacing of reinforcement layers (h) on settlement ratio, BCR_S was investigated for surface footings by using three layers of geogrid in each test of series D-1 and D-2. The vertical spacing was varied from $0.2B$, $0.3B$ to $0.4B$. Figures 15 and 16 present the variation of bearing pressure with settlement ratio for different spacing of geogrid layers placed in sand for UNX100 and BIX100 respectively. As it is evident from the graphs, the q_R calculated at s/b ratio of 10% shows maximum value in case of $h/b = 0.3$ in case of UNX100 whereas in case of biaxial geogrid BIX100, optimum h/b is obtained at a value of $h/b = 0.4$. Omar et al (1993) reported a value of $0.33B$ for square footing placed geogrid reinforced sand. Yetimoglu et al. (1994) reported an optimum value between 0.2 and 0.4 times width of foundation. Similarly Adams and Collin (1997) reported a value of $0.25-1.25B$ for various sizes of square footings. Ghazavi and Mirzaeifar (2010) reported an optimum value of $0.3B$.

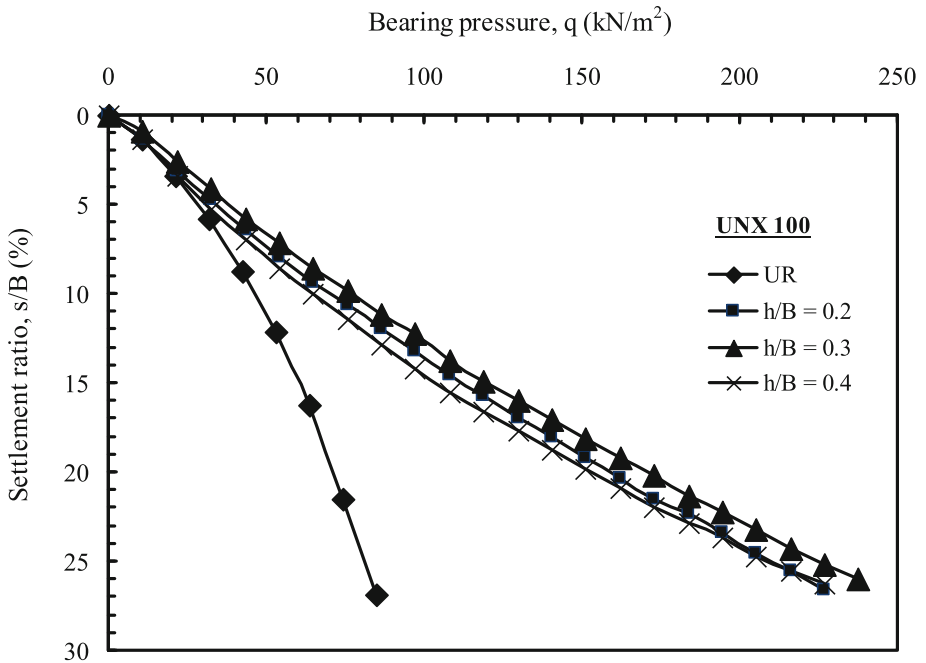


Fig. 15. Plot of q VS. s/B ratio for $N = 3$, $u/B = 0.4$, $D_R = 50\%$, (series D-1)

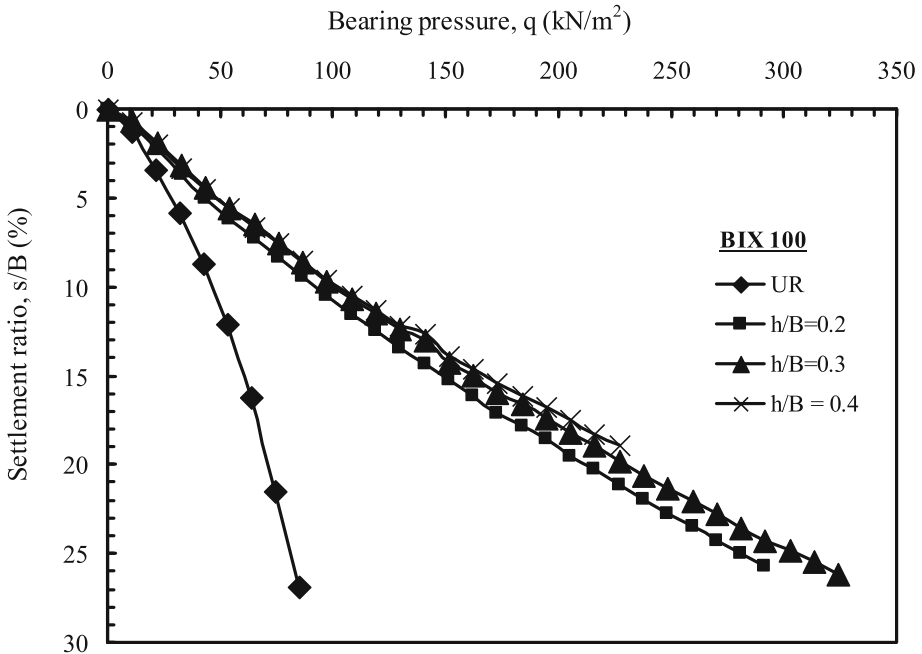


Fig. 16. Plot of q VS. s/B ratio for $N = 3$, $D_R = 50\%$, $b/B = 5$ (series D-2)

Table 5 shows the improvement in bearing pressure with respect to unreinforced sand for a settlement ratio equal to 10%, as the vertical spacing of the geogrid layers was varied keeping $N = 3$ & $D_R = 50\%$. As it is evident from the table, the percent improvement in bearing capacity with biaxial grade as reinforcement is greater than that due to uniaxial grade. Further the improvement is maximum for $h/B = 0.3$ for UNX100 and $h/B = 0.4$ for BIX100. Figure 17 represents the variation of bearing capacity ratio with respect to changing h/B ratio obtained at a settlement of 10% of the footing width for each grade of geogrid. Figure 18 presents the variation of bearing

Table 5. Calculation of Bearing Capacity Ratio at $s/B = 10\%$ for varying h/B ratio

No. of Geogrid layers N	h/B	Bearing capacity ratio(BCR_s) = q_R/q_u obtained at $s/B(\%) = 10\%$ ($q_u = 47 \text{ kN/m}^2$)					
		$u/B = 0.4$					
		UNX100			BIX100		
		q_R	BCR_s q_R/q_u	Increase in bearing capacity (%)	q_R	BCR_s q_R/q_u	Increase in bearing capacity (%)
3	0.2	70.2	1.49	49.36	92.8	1.97	97.45
3	0.3	77.5	1.65	64.89	101	2.15	114.89
3	0.4	65	1.38	38.30	102	2.17	117.02

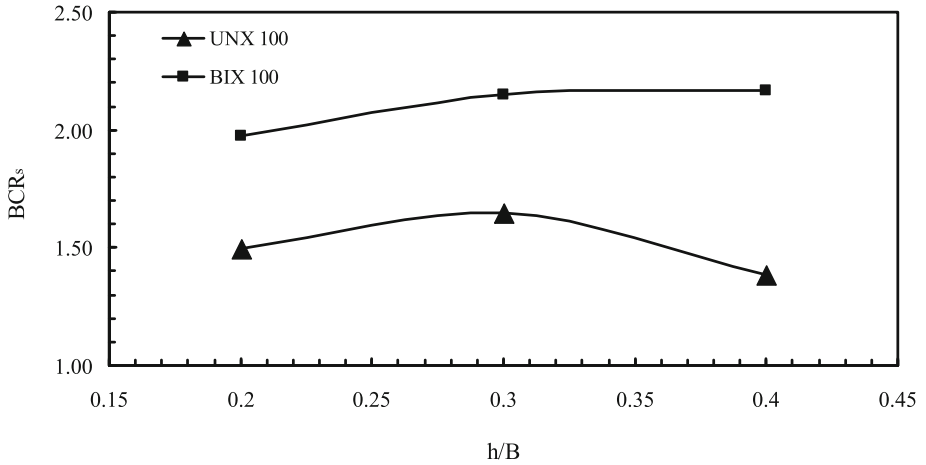


Fig. 17. Variation of bearing capacity ratio (BCR_s) with h/B for $N = 3$, $D_R = 50\%$, $u/B = 0.4$

capacity ratio with settlement ratio for Test series D. For a settlement ratio equal to 10%, for UNX100, the bearing capacity ratio increased by 64.89% when the geogrid reinforcement was placed with $h = 0.3B$ compared to 117.02% for BIX100 when the geogrid reinforcement was placed with $h = 0.4B$.

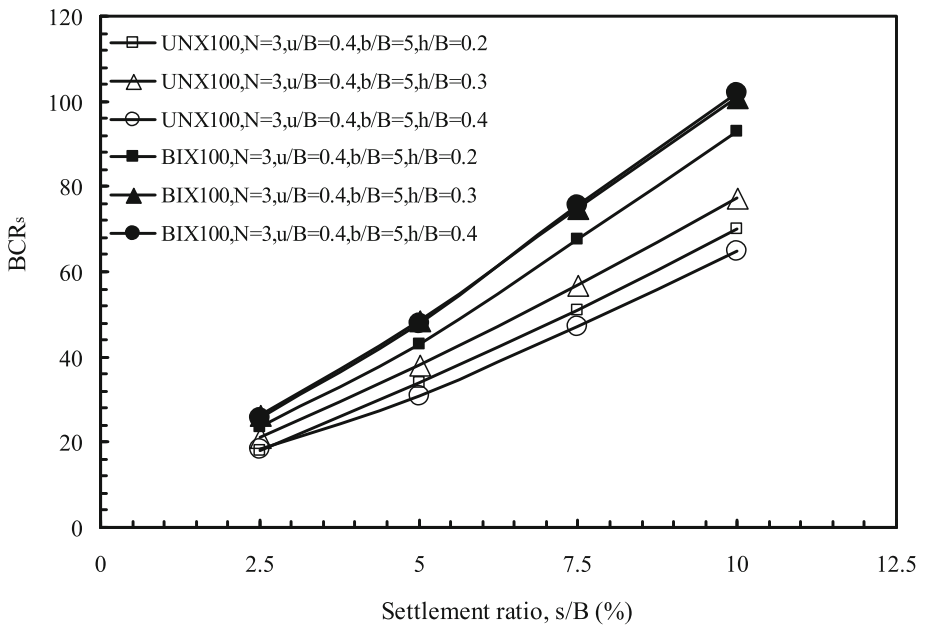


Fig. 18. Variation of bearing capacity ratio (BCR_s) with s/B for $N = 3$, $D_R = 50\%$, $u/b = 0.4$

5 Conclusion

Based on the test results obtained, the following conclusions can be made:

1. The presence of geogrid in the soil makes the relationship between the settlement and applied pressure of the reinforced soil almost linear. At a particular settlement, the bearing capacity will be more in case of reinforced condition than unreinforced case.
2. Biaxial geogrid performs better than uniaxial geogrid, though the uniaxial reinforcement also leads to significant improvement in performance of footings compared to unreinforced footings, thus, Inclusion of reinforcement in sand beneath the footing enhanced its bearing capacity, irrespective of grade of geogrid.
3. The depth of topmost layer is very effective in the performance of the reinforced system. An optimum value of $u = 0.4B$ was found in the present study both for uniaxial and biaxial reinforcement. Thus it can be inferred that the depth of embedment 'u' is independent of the grade of geogrid in the current study.
4. For the same soil and geogrid configuration, the ultimate bearing capacity increases with the increase in the width of geogrid, b and no. of layer of geogrid N . Maximum improvement was found at $5b$ in both cases. Hence concluding that improvement in bearing capacity by virtue of increase in width is not affected by grade of geogrid. No optimum no. of geogrid layers is tested in this study.
5. The spacing between the individual reinforcement layers (h) affects the improvement in bearing capacity. The improvement is maximum for $h/B = 0.3$ for UNX100 and $h/B = 0.4$ for BIX100. Thus the spacing between individual layers h is governed by the grade of geogrid reinforcement used.

The conclusions made in this study are based on a limited number of tests. Further laboratory research as well as full scale tests in this direction encompassing the several other variations in grade of geogrid used, type of founding soil as well as other factors will help in understanding of facts more clearly.

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