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Bearing Capacity of Strip Footing on Sand Slopes Reinforced with Geotextile and Soil Nails

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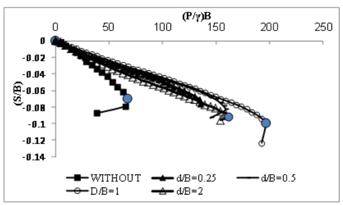
Graphical abstract



Abstract

This paper presents the results of laboratory model tests on the behavior of a strip footing supported by a single geotextile layer and by a row of soil nails in a sandy slope. A comparison between bearing capacity improvements in the two cases were made and analyzed. Parameters varied include depth of the reinforcing layer, edge distance of the footing, location of soil nail row, and location of the footing relative to the slope crest. Bearing capacity of non-stabilized cases were initially determined and then compared with those of stabilized slopes. Results indicate that stabilized earth slope using a single geotextile layer or a row of soil nails significantly improves bearing capacity of strip footing. This improvement in bearing capacity increases as soil nail spacing decreases. Overall improvement is significantly better when using a single geotextile layer to stabilize earth slope than using a row of soil nails.

Keywords: Geotextile; bearing capacity; soil nail; slope soil; strip footing

■1.0 INTRODUCTION

A number of situations where footings are constructed on sloping surfaces or adjacent to a slope crest are observed, such as footings for bridge abutments on sloping embankments. When a footing is located on sloping ground, bearing capacity of the footing may be significantly reduced, depending on the location of the footing with respect to the slope. Therefore, using a shallow foundation may not be possible, and an uneconomical foundation (such as piles or caissons) becomes the only suitable solution to the problem. Therefore, the subject of stabilizing earth slope has become one of the most interesting areas for scientific research over the years and has attracted much attention. Slope stability can be increased in different ways, including modifying slope surface geometry, using soil reinforcements, or installing continuous or discrete retaining structures such as walls or piles.

Numerous studies on the use of slope reinforcements to improve load-bearing capacity of footing on the slope have been conducted such all done by Selvadurai *et al*., 1989; Sawicki *et al*., 1991; Lee and Manjunath, 2000; Yoo, 2001; Dash *et al*., 2003; Boushehrian and Hataf, 2003; El Sawwaf., 2005; El Sawwaf., 2007; Abdrabbo *et al*., 2008; and Alamshahi *et al*., 2009. These investigations have demonstrated that slope stability cannot only be increased, but both ultimate bearing capacity and settlement characteristics of the foundation can also be significantly improved by adding reinforcements (layers of geogrids, strips, or geotextiles) in the earth slope.

Although planar geotextiles and geogrids have often been studied, several investigations have also highlighted the beneficial use of geosynthetic reinforcements in the construction of foundations and embankments. Rea and Mitchell (1978) and Mitchell *et al*. (1979) carried out a series of small-scale laboratory tests on footings supported over sand beds reinforced with square paper grid cells, and had observed different modes of failure. Shimizu and Inui (1990) carried out load tests on geotextile wall frames filled with sand overlying soft soil. Cowland and Wong (1993) reported a case study on the performance of an embankment supported on a geosynthetic mattress over soft clay. Jenner *et al*. (1988), using slip line theory, proposed a methodology to calculate increase in bearing capacity resulting from the addition of geosynthetic mattresses at the base of the embankment resting on soft soil. Krishnaswamy *et al*. (2000) carried out a series of laboratory model tests of earth embankments constructed on geosynthetic mattresses supported over a soft clay bed. Dash *et al*. (2001a) and Dash *et al*. (2001b) investigated the reinforcing efficacy of geosynthetic mattresses within a homogeneous sand bed supporting a strip footing. Dash *et al*. (2003, 2004) also reported load test results from a model circular footing supported on geosynthetic-reinforced sand overlying soft clay. In all the aforementioned studies, the beneficial aspects of geosynthetic constructions to improve bearing capacity of footings were reported.

Sireesh *et al*. (2009) reported that a substantial improvement in performance can be achieved with the addition of a geosynthetic mattress, of adequate size, over a clay subgrade with void. Beneficial effect could be obtained when the geosynthetic mattress spreads beyond the void in a distance which is at least equal to the diameter of the void.

Moghaddas and Dawson (2010), and El Sawwaf and Nazir (2012) studied repeated loads and cyclic loads, respectively, on model strip footings. They carried out a series of experimental studies to investigate the behavior of strip footings supported on three-dimensional and planar geotextile-reinforced sand beds subjected to repeated loads. The aforementioned researchers investigated the effects of partial replacement of compacted sand layer and the inclusion of a geosynthetic reinforcement, and found that the efficiency of sand-geogrid systems depends on the properties of cyclic load and the location of the footing relative to the slope crest.

The main purpose of this investigation was to acquire an extensive understanding of the mechanical behavior and failure mechanism of a strip footing supported on a sand bed adjacent to geotextile and soil nail-stabilized earth slope. The main objective of the study was to determine and establish the relationship among variable parameters of a geotextile layer and soil-nail row and bearing capacity of the footing. Moreover, it also aimed to determine the best location of geotextile layer or soil-nail row that can provide the most improvement in footing bearing capacity. Therefore, a series of experimental model tests were carried out and the obtained results were presented and discussed.

■2.0 LABORATORY MODEL TESTS

2.1 The Model Box

The main elements of the laboratory apparatus were a tank, a horizontal steel beam over the tank, and a sand raining box. The test box, with dimensions of 2.00 m × 0.60 m in plan and 0.6 m in depth, was made from steel. The front wall was made of glass 20 mm thick and supported directly on two steel columns. These columns were firmly fixed into two horizontal steel beams, which were firmly clamped to the laboratory ground using four pins. The glass side allowed viewing of the sample during preparation and observation of sand particle deformations during testing. The tank box was built to be sufficiently rigid to maintain plane strain conditions by minimizing out-of-plane displacement (Omar, 2006).

2.2 Model Footing

A model strip footing, which was made of steel, was fitted with a hole at its top center to accommodate a ball bearing. The footing was 580 mm in length, 50 mm in width, and 20 mm thick. The footing was placed on the sand bed with the length of the footing running the full width of the tank. The length of the footing was almost equal to the width of the tank to maintain plane strain conditions. The two ends of the footing plate were polished smooth to minimize end-friction effects. A rough base condition was achieved by fixing a thin layer of sand onto the base of the model footing using epoxy glue. The load was transferred to the footing through a ball bearing. Such arrangement produced a hinge, which allowed the footing to rotate freely as it approached failure and eliminated potential moment transfer from the loading fixture.

2.3 Materials Tested

The sand used was medium coarse with a minimum dry unit weight of 16.7 kN/m³, maximum dry unit weight of 18.74 kN/m³, uniformity coefficient of 4.55, and effective diameter of 0.14 mm. The specific gravity of sand particles was 2.64. The optimum moisture content was determined using standard Proctor test and was found to be 10%. The sieve analysis of the sand is shown in Figure 1. Different relative densities of the sand were used by forming designed weight of sand into a certain volume of soil bin by compaction. The properties of the soil sample are given in Table 1.

Table 1 Characteristics of sand sample

Parameter	Value	Parameter
Uniformity coefficient (Cu)	4.55	Uniformity coefficient (Cu)
Effective diameter (mm)	0.14	Effective diameter (mm)
Maximum dry unit weight (kN/m3)	18.74	Maximum dry unit weight (kN/m3)
Minimum dry unit weight (kN/m3)	16.7	Minimum dry unit weight (kN/m3)
Specific gravity (Gs)	2.64	Specific gravity (Gs)
Residual effective angle of internal friction (ϕ°)	38˚,40˚, and 41.1˚	Residual effective angle of internal friction (ϕ°)
Parameter	Value	Parameter
Uniformity coefficient (Cu)	4.55	Uniformity coefficient (Cu)

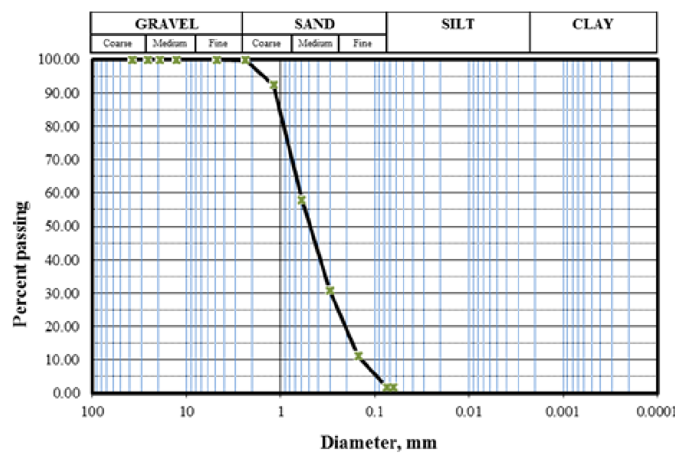


Figure 1 Grain size distribution of sand

A commercially available non-woven geotextile was used as the reinforcing material. The geotextile is 3.5 mm thick under 2kN/m², and its grab elongation is greater than 100%. Typical physical and technical properties of geotextiles were obtained from the data sheet of the manufacturer (Makarm Tex, Egypt, Cairo) and are presented in Table 2.

Table 2 Engineering properties of geotextile

Parameter	Value / type
Structure	Non-woven
Thickness(mm)	3.5
Weight (g/m²)	350
Grab tensile strength (M.D) (N)	930
Grab tensile strength (C.D) (N)	1500
Permeability (cm/s)	0.25
Transmissivity (L/M/H)	200

2.4 Test Setup and Programs

Model sand slopes 600 mm in height and 2000 mm in length with gradient of the slope face (2H: 1V) constant were constructed by pouring and compacting 50 mm of air-dried sand layers to cover the entire area of the test tank. A series of similar model tests under different test dimensions were carried out. The different setups included edge distance of footing (X), relative density of soil (D_r %), and depth to topmost layer of geotextile (d). The symbols used in this study are illustrated in Figure 2.

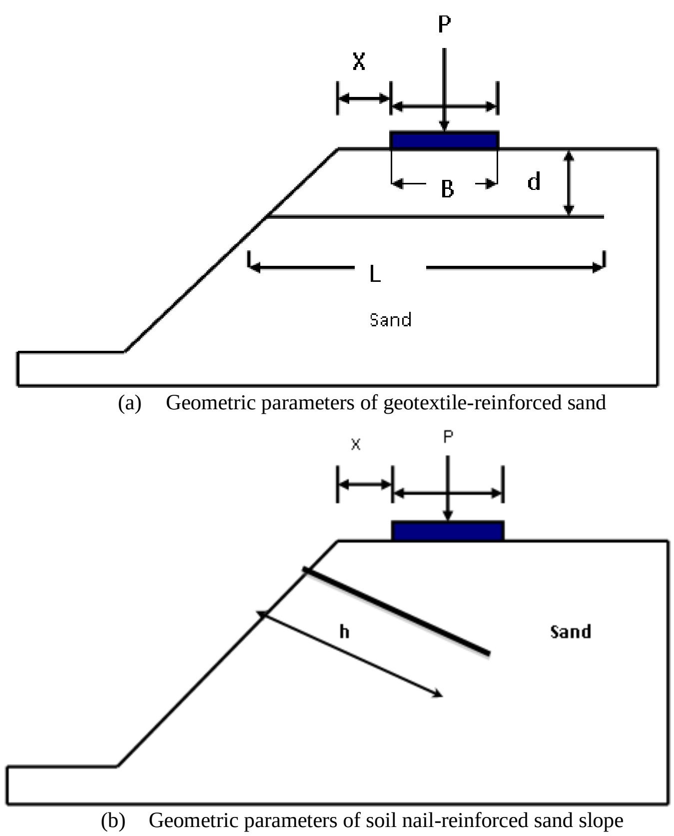
The term bearing capacity ratio (BCR) was used and described as BCR = q_r/q_o, where q_r and q_o were ultimate bearing capacities of the footing on reinforced and unreinforced sand slopes, respectively, with the same relative density.

A total of 57 tests in two different test programs were carried out. Initially, the response of the model footing supported on non-stabilized slopes was determined (9 tests, each one was repeated twice). Then, 9 series of tests (36 tests) were performed to study the effect of different parameters on the footing behavior, as shown in Figure 2a. Each series of test was carried out to study the effect of one parameter while the other variables were kept constant. Various conditions included edge distance of the footing (X/B) and reinforcement embedment depth to footing width ratios (d/B), as illustrated in Table 3. Finally, in the test program for soil nails, 3 series of tests (12 tests) were performed to investigate the footing response for the three cases when the footing was placed exactly on the slope crest and when it was placed away from the slope crest by distance X. For each case, four series of tests were conducted to determine the best location of soil nails that would provide maximum bearing capacity improvement, as shown in Figure 2b. Table 3 summarizes all tests programs with both constant and varied parameters illustrated. Several tests were repeated at least twice to verify repeatability and consistency

■3.0 RESULTS AND DISCUSSION

3.1 Geotextile-Stabilized Slopes

Typical variations of load, that is, (P/γ) B with settlement ratio (S/B) for four different d/B ratios (0.3, 0.5, 1, and 2) are presented in Figure 3. The installation of a geotextile significantly improves both initial stiffness (initial slope of load-settlement curves) and bearing load at the same settlement level for stabilized cases compared with non-stabilized earth slope. Also, bearing capacity improvements at failure are significantly dependent on d/B. However, the curves show that improvements in bearing capacity are accompanied by an increase in S/B. Comparing curves across the dotted line for the same level of S/B, Figure 3 illustrates that using a geotextile with d/B = 0.5 at the slope crest results in an increase in bearing capacity twice the value more than that of non-stabilized cases. The results for each parameter are discussed in the next sections.



(a) Geometric parameters of geotextile-reinforced sand

(b) Geometric parameters of soil nail-reinforced sand slope

Figure 2 Geometric parameters of reinforced sand slope

Table 3 Setup and programs of model tests

Series	Constant parameters	Variable parameters	Notes
I	Tests on non-reinforced sand slope D_r=60%	X/B = 0.0, 1.0, 2.0	Geotextile
II	Tests on non-reinforced sand slope D_r=70%	X/B = 0.0, 1.0, 2.0	Geotextile
III	Tests on non-reinforced sand slope D_r=85%	X/B = 0.0, 1.0, 2.0	Geotextile
1	D_r=60% & X/B=0.0	d/B=0.3, 0.5, 1.0, 2.0	Geotextile
2	D_r=60% & X/B=1.0	d/B=0.3, 0.5, 1.0, 2.0	Geotextile
3	D_r=60% & X/B=2.0	d/B=0.3, 0.5, 1.0, 2.0	Geotextile
4	D_r=70% & X/B=0.0	d/B=0.3, 0.5, 1.0, 2.0	Geotextile
5	D_r=70% & X/B=1.0	d/B=0.3, 0.5, 1.0, 2.0	Geotextile
6	D_r=70% & X/B=2.0	d/B=0.3, 0.5, 1.0, 2.0	Geotextile
7	D_r=85% & X/B=0.0	d/B=0.3, 0.5, 1.0, 2.0	Geotextile
8	D_r=85% & X/B=1.0	d/B=0.3, 0.5, 1.0, 2.0	Geotextile
9	D_r=85% & X/B=2.0	d/B=0.3, 0.5, 1.0, 2.0	Geotextile
A	Tests on non-reinforced sand slope D_r=60%	X/B = 0.0, 1.0, 2.0	Soil-nail row
B	D_r=60% & X/B=0.0	b /B = 1.0, 1.5, 2.0	Soil-nail row
C	D_r=60% & X/B=1.0	b /B = 1.0, 1.5, 2.0	Soil-nail row
D	D_r=60% & X/B=2.0	b /B = 1.0, 1.5, 2.0	Soil-nail row

3.2 Effect of Embedment Ratio On Bearing Capacity

A series of tests were performed for various d/B (0.3, 0.5, 1, and 2) by keeping X/B (0, 1, and 2), and gradient of the slope face (2H: 1V) constant. The tests were carried out with one type of reinforcement, that is, non-woven geotextile.

Variations of BCR and S/B against d/B are shown in Figs. 4a and 4b, respectively. From the results of Figs. 4a and 4b, the addition of geosynthetic reinforcement obviously improved the performance of the footing by increasing bearing capacity and reducing settlement of the system. An optimum d/B could be observed. For d/B greater than this value, BCR and S/B are at a minimum. The optimum d/B depends on the edge distance X/B in such a way that d/B increases as X/B increases. The optimum d/B is 0.5 when X/B=1, and 1.0 when X/B=2. The efficiency of the reinforcement on bearing capacity and peak settlement seems to decrease significantly. The performance of reinforced slope becomes rather minimal, as reflected by both BCR and S/B approaching unity. Figure 4a shows that adding a single layer increases BCR from 1.06 to 3, depending upon the d/B and the X/B. From Figure (4b) it was found that adding single layer decreases the settlement (S/B) depending upon the depth ratio (d/B), the edge distances (X/B).These results are highly consistent with the model test results obtained by Selvadurai and Gnanendran (1989) who presented their findings for an experimental modeling and an investigation on the reinforcing efficiency of geogrids in stabilizing soil slope subjected to loading.

The behavior described in the previous paragraph can be explained by the "deep footing effect" as suggested by Huang *et al.* (1994). A section of the reinforced zone, where a relatively large reinforcement force was developed, behaves like rigid footing and transfers a major part of the footing load to a deeper zone. This load-transfer mechanism seems to reach its optimum when d/B is approximately 0.5 for X/B=1 and 1.0 for X/B=2.

At larger depths of embedment, the contribution to the load-transfer mechanism caused by the presence of the reinforcement is reduced significantly. For d/B≥1, this explanation seems to be consistent with the experimental results of Selvadurai and Gnanendran (1989), and Huang *et al.* (1994). These researchers proved that bearing capacity of a footing on a sloped fill structure can be improved by more than 50% by incorporating geogrid reinforcement. Ultimate bearing capacity and the optimum location for the geogrid reinforcement occur at a depth between 0.5 and 0.9 times the width of the foundation. The location of the geogrid layer at a depth greater than twice the width of the footing does not lead to any improvement in either load-bearing capacity or stiffness characteristics of the footing on a sloped fill.

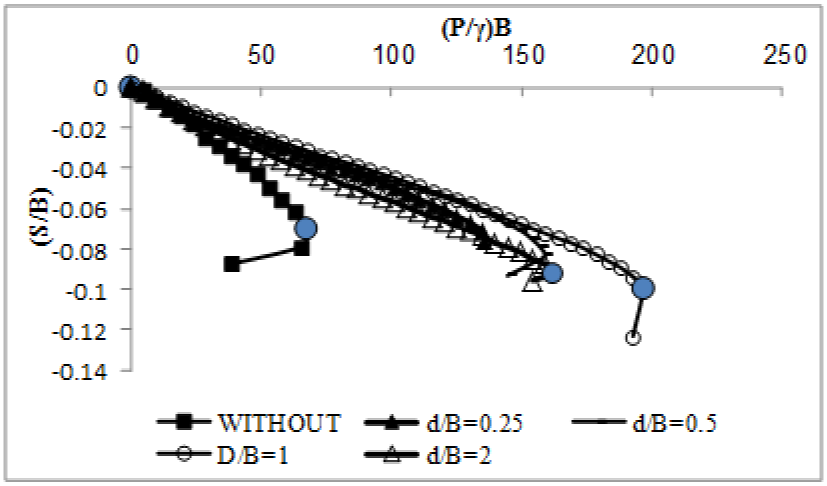


Figure 3 Variation normalized stress versus settlement

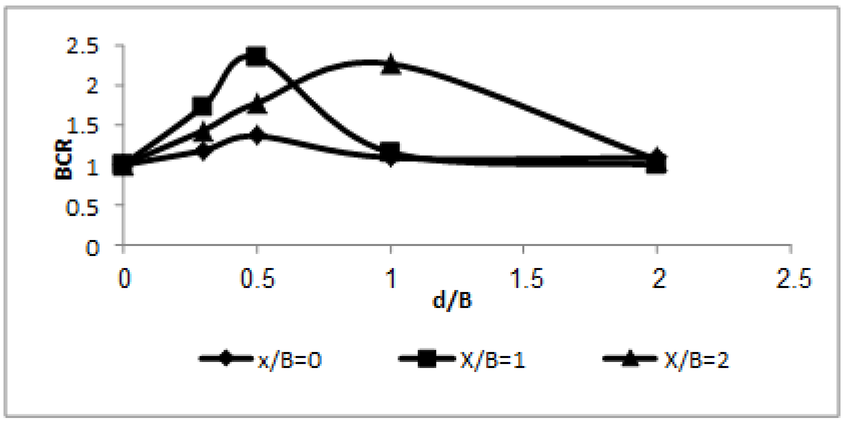


Figure 4a Variation of bearing capacity with depth

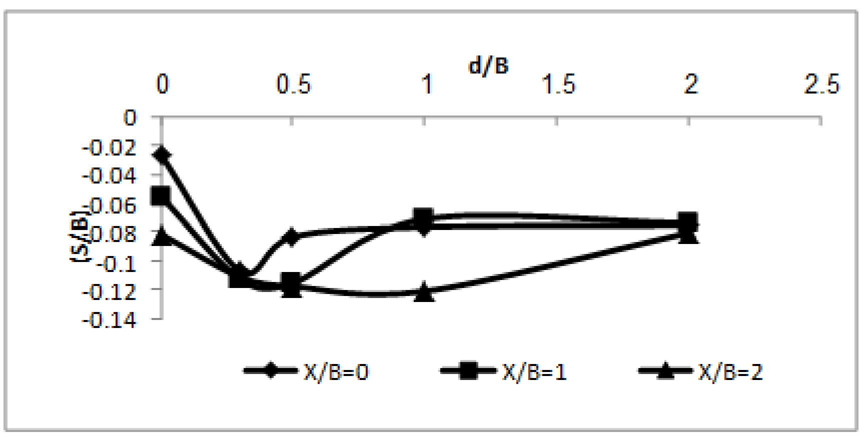
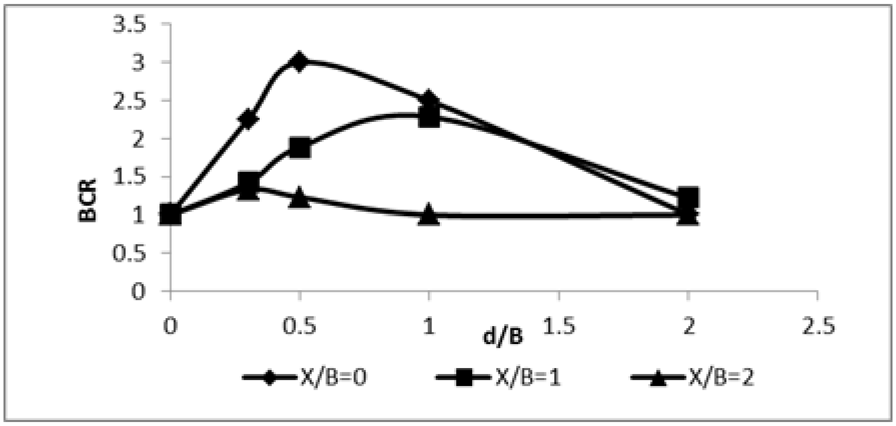


Figure 4b Variation of bearing capacity with settlement

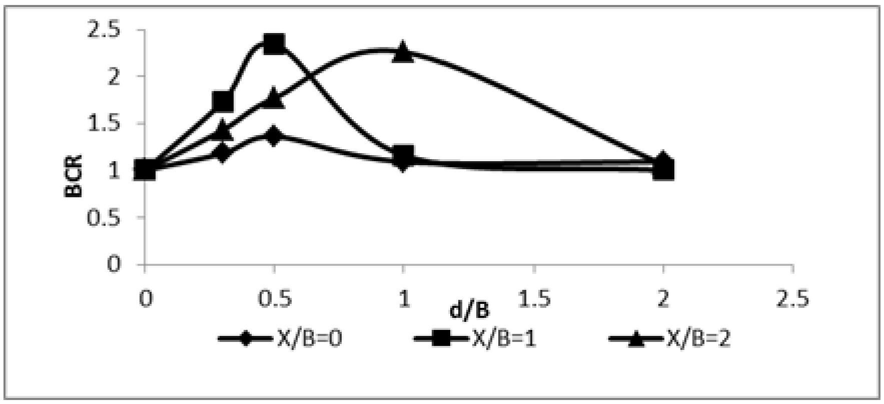
Figure 5 was plotted to investigate the effect of d/B on BCR. The Figures 5a, 5b, and 5c illustrate that BCR increases as d/B increases up to d/B =0.5, wherein BCR reaches its peak value irrespective of D_r and L/B. These relationships show that maximum BCR was reached at the most effective d/B of 0.5. These results conform to those of Yoo (2001) for single geogrid-reinforced sand.

3.3 Effect of Edge Distance of the Footing on BCR

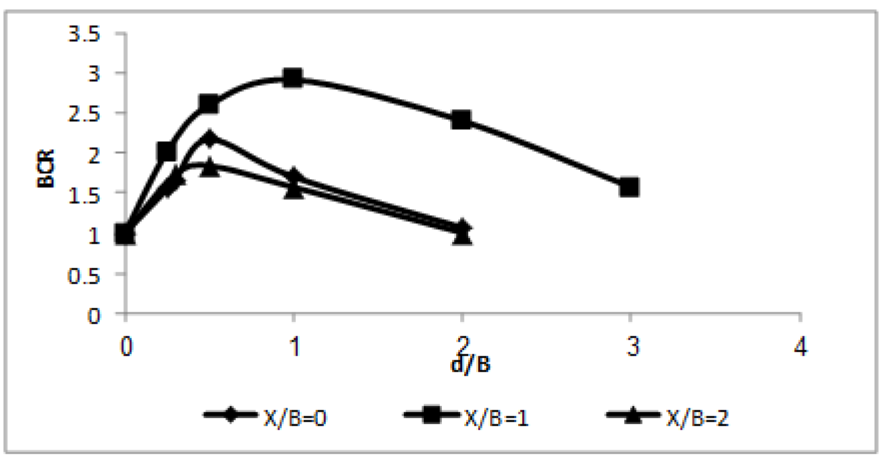
The second series of tests was performed for three different X/B values on both reinforced and unreinforced slope (2H:1V), corresponding to X/B= 0.0, 1.0, and 2.0. The d/B was kept constant at an optimum value of d/B=0.5 in case of X/B=1, and d/B=1.0 in case of X/B=2, as determined from the earlier series of tests.



(a) D_r=60%



(b) D_r=70%



(c) D_r=85%

Figure 5 Variations of bearing capacity with depth for various sand densities

Results clearly indicate that for both reinforced and unreinforced slopes, ultimate bearing capacity increases with increasing edge distance. At an edge distance of 2B, ultimate bearing capacity of a footing on sloping ground approaches that of a footing on a level surface in both reinforced and unreinforced cases. The effect of slope is minimized when the footing is placed at an edge distance more than two times the width of the footing. Furthermore, as shown in Figure 6a, 6b and 6c ultimate bearing capacity of a footing on a reinforced slope is considerably higher than that of a footing on unreinforced slope at any given edge distance. This result reflects the beneficial effect of reinforcement in improving bearing capacity of the footing of a slope. Results of bearing capacity of strip footing on unreinforced sandy slope in this study indicate that bearing capacity increases as X/B increases.

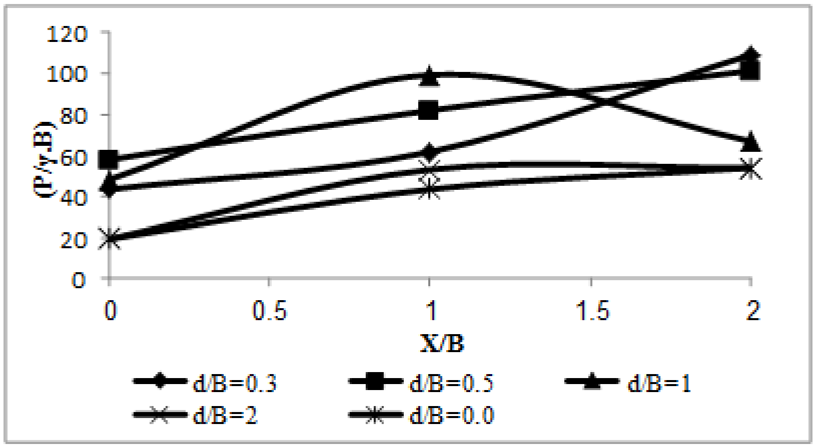
3.4 Soil Nail-Stabilized Sand Slope

Improvement in footing response caused by slope stabilization through soil nails at different locations relative to slope crest b and edge distance of the footing X were investigated. Bearing capacity improvement factors (BCR) along with footing S/B were used to present test results.

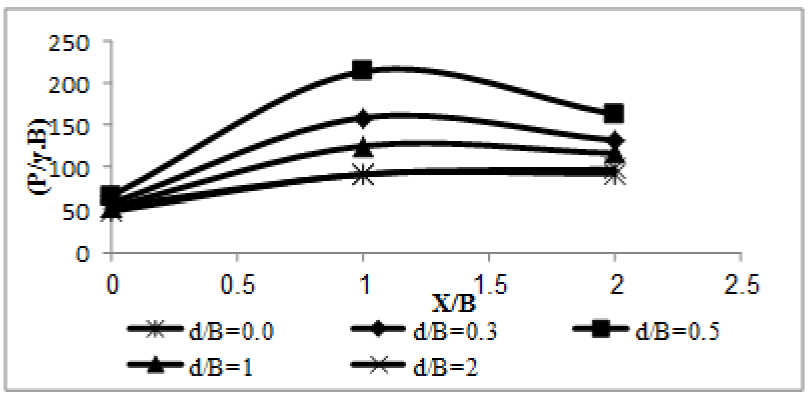
3.5 Effect of the Location of Nail Row

The (P/γ.B)-S/B relationships of strip footing on soil nailing were plotted in Figures 7a, 7b, and 7c. From these figures, a significant effect for the embedding row nailing into sandy soil obviously exists. To study the effect of the location of nails on the behavior of strip footing on sand, three different embedment ratios (1.00, 1.50, and 2.00) were tested for three different groups of X/B (0.0, 1.0, and 2.0). For each group, the distance between the edges of the strip footing to the edge of the crest.

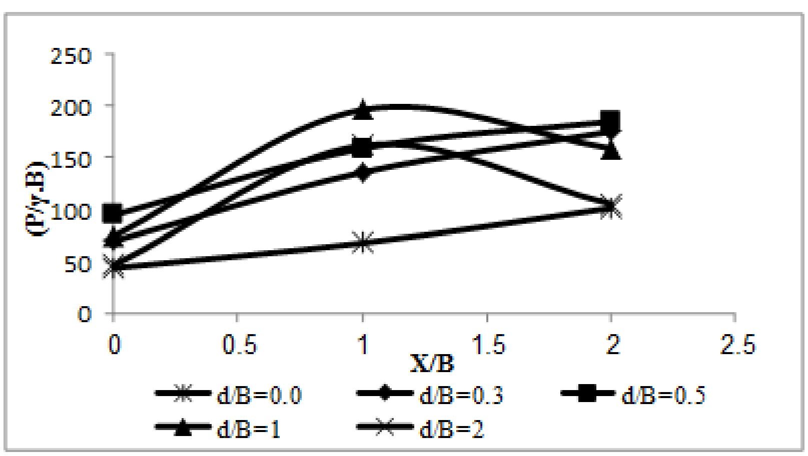
Figure 8 presents variations of BCR with normalized nail row location (b/B). The figure shows that when the nail is placed nearer to the slope crest, bearing capacity response of the footing is much better than anywhere else. The same trend is confirmed by different series of studies carried out using different edge distances of the footing. Any position far from that location may increase overall stability of the slope but will not prevent or decrease lateral deformations of soil particles under the footing and near the slope.



(a) D_r=60%

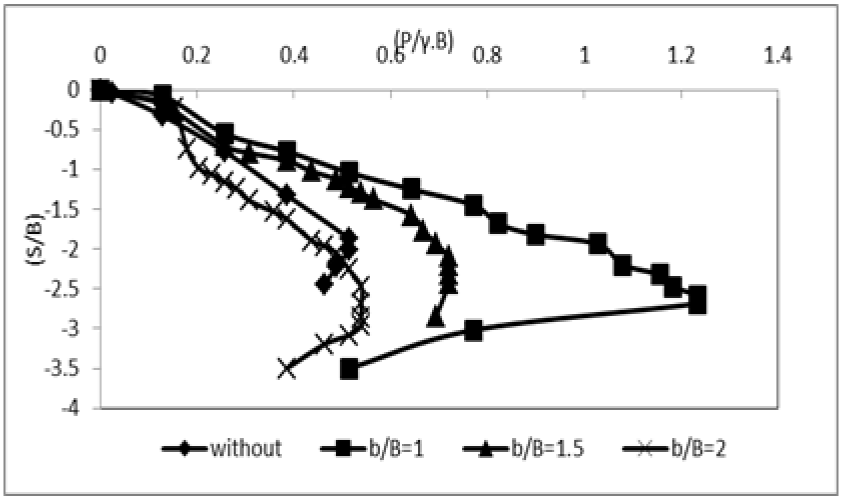


(b) D_r=70%

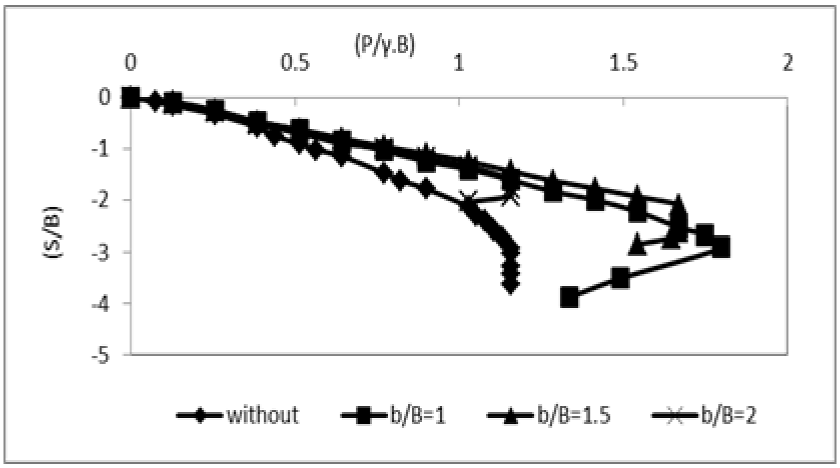


(c) D_r=85%

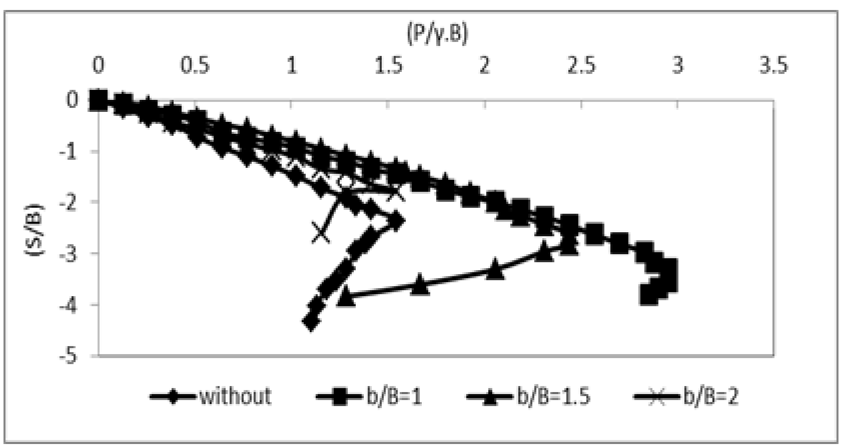
Figure 6 (P/γ.B) versus (X/B) at various sand densities



(a) X/B=0



(b) X/B=1



(c)X/B=2

Figure 7 (P/γ. B) versus (S/B) at various edge distances

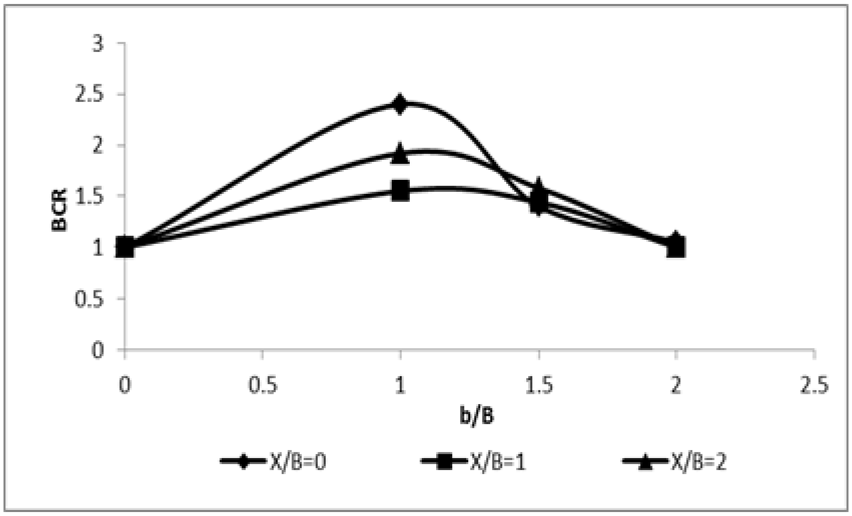


Figure 8 Variations of BCR with normalized nail-row location (h/B=10)

3.6 Effect of Edge Distance of the Footing

Three series of tests were performed on sand slope stabilized by nail rows placed at the slope crest (b/B=1.0, 1.5, and 2.0) to determine the effect of edge distance of the footing at X= 0, 1, and, 2. Variations in BCR with normalized strip footing of slope crest distance for different nail-row location are plotted in Figure 9. Row nailing increased BCR from 1.05 to 2.40 according to the location of b/B and X/B. The highest improvement in bearing capacity occurred when footing was placed at X/B=0.

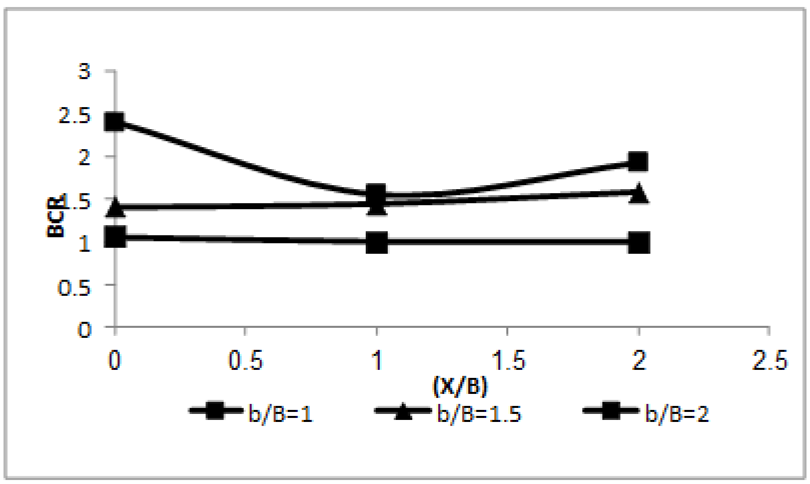


Figure 9 Variations of BCR with normalized strip footing of slope crest distance for different nail row locations

3.7 Comparison of Geotextile and Soil-Nailing Stabilized Slope

A comparison between bearing capacity improvements of the footing for the two methods is shown in Figure 10. The location of geotextile or soil nails, and the position of the footing are the same. The effect of geotextile stiffness (made of fiber) and soil nail stiffness (made of steel) was considered to be relatively low. Soil nail stiffness appears to have little effect on the overall soil nail-slope stability (El Sawwaf, 2007). Figure 10 clearly confirms the expected trend that geotextile has better effect on footing behavior than a row of soil nails. This effect is much more pronounced for higher heights of geotextile because resistance of geotextile increases as the size of the embedded part of the geotextile increases in stable layers of soil.

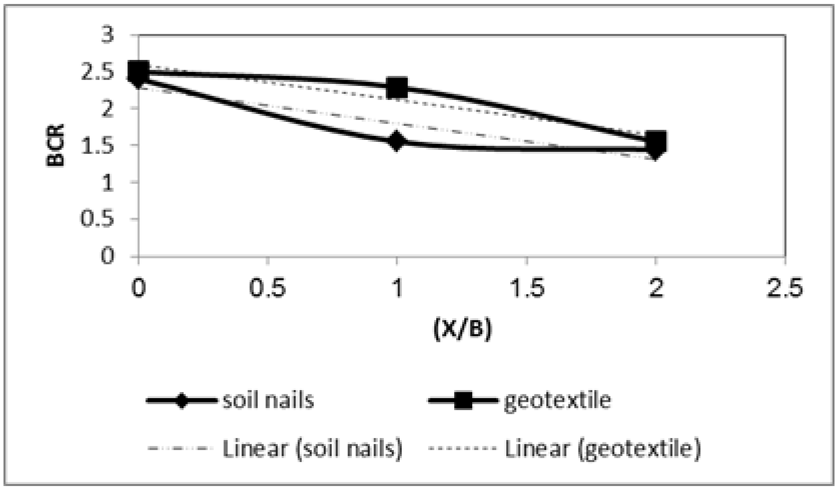


Figure 10 Comparison of BCR with geotextile and soil nails

■4.0 CONCLUSIONS

From the conducted laboratory tests, the use of geotextiles is shown to be effective in improving bearing capacity of sand. Other conclusions are detailed as the following:

- Stabilizing earth slope using a row of soil nails or geotextile has a significant effect on improving bearing capacity of a strip footing supported on sandy soil on a slope.
- BCR varied from 1.06 to 3.0 depending on the d/B.
- The most effective d/B was found to be 0.5 irrespective of the relative density of sand or the X/B. The effect of reinforcement on bearing capacity was more pronounced in soil samples with lower relative density.
- Row nailing increased BCR from 1.05 to 2.40, according to the location of b/B and X/B.
- Overall improvement when using geotextile to stabilize earth slope was much better than when using soil nails.
- The optimal location of a row of soil nails or a geotextile is at the slope crest when considering bearing capacity improvements instead of overall stability of the slope.

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