Effect of Footing Shapes and Reinforcement on Bearing Capacity of Three Adjacent Footings

S. S. Saraf and S. S. Pusadkar

Abstract The effect of geogrid reinforcement on bearing capacity was studied on three surface square footings in series. Parameters included under the reinforcement configuration were, length of reinforcement on either side beyond center of footings (Lx), depth of first geogrid layer (u), vertical distance between geogrid layers (h) and center to center distance between three footings (S). Also influence of footing shapes was studied for square, circular and rectangular shape of same cross-sectional area for optimum reinforcement configuration. In order to evaluate these effects, laboratory model tests were conducted at 55% relative density of sand. Bearing capacity of adjacent footings has been observed to be improved by providing geogrid reinforcement layer in the foundation soil under closely spaced footings. It was observed that the reinforcement configurations play a vital role in bearing capacity improvement. It was also observed that bearing capacity of the soil varies with the shape of footings.

Keywords Three footing · Bearing capacity · Geogrid-reinforced sand

1 Introduction

The lowest part of a structure which transmits its weight to the underlying soil or rock is the foundation. The foundation design is aimed at providing a means of transmitting the loads from a structure to the underlying soil without causing any shear failure or excessive settlement of the soil under the imposed loads. Bearing capacity is the supporting power of a soil or rock, which play important role in design of foundation. The bearing capacity may be determined by analytical methods, conducting field and laboratory tests and from the building codes. The scarcity of

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land due to growth in population and built-up area results in construction of heavy high-rise adjacent structures. Because of this, the footings are kept at close spacings and the interferences of footings occur. The interference of foundations may change the behavior, as compared to isolated foundations. The influence of the interference is directly related to the distance between adjacent footings. The soil improvement is necessary when the available soil is weak. The uses of geo-synthetic materials are mostly preferred as soil reinforcement for improving the performance of shallow foundations.

Numerous investigations have been carried out, to study the bearing capacity of two interfering footings on unreinforced sand (Das and Larbi-Cherif 1983; Khan et al. 2006; Kumar and Ghosh 2007; Kumar and Bhoi 2009; Mabrouki et al., 2010; Kouzer and Kumar 2010; Ghosh and Sharma 2010; Ghosh and Kumar 2011; Nainegali and Basudhar 2011; Srinivasana and Ghosh 2013; Nainegali et al. 2013) and reinforced sand (Khing et al. 1992; Al-Ashou et al. 1994; Kumar and Saran 2003; Ghazavi and Lavasan 2008; Ghosh and Kumar 2009; Pusadkar and Saraf 2012a; Ghazavi and Lavasan 2012; Pusadkar and Saraf 2012b; Naderi and Hataf 2014). The results of these research works show a significant improvement in bearing capacity and settlement after providing continuous geogrid reinforcement. It was also observed that the ultimate bearing capacity (UBC) of neighboring footings increases as the spacing between footing decreases. The literatures only show work on the interfering effects of multiple footings on unreinforced sand (Graham et al. 1984; Lee and Eun 2009; Kumar and Bhattacharya 2010; Daud 2012). However, the experimental study on the interfering effects of three adjacent footings on reinforced sand is not available. This reveals that study on the effect of reinforcement configurations, spacing between footings and shape of footings on bearing capacity of three adjacent footing on reinforced sand is the need of the future. In order to evaluate the performance of three adjacent footings on reinforced sand, laboratory experiments to simulate the various conditions of footing were performed and the results were compared for development of knowledge base in this regard.

2 Scope of the Study

From the literature study it was observed that most of the works on the interfering effects of three adjacent footings were for unreinforced sand. Limited information is available for reinforced sand. The main objective of this research work was to experimentally investigate the effect of footing shapes and reinforcement on bearing capacity of three adjacent footings. The effect of geogrid reinforcement on bearing capacity was studied on three surface square footings in series. Parameters included under the reinforcement configuration were length of reinforcement on either side beyond center of footings (Lx), depth of first geogrid layer (u), vertical distance between geogrid layers (h) and center to center distance between three footings (S). The influence of footing shapes was studied for square, circular and rectangular shape of same cross-sectional area for optimum reinforcement configuration. For

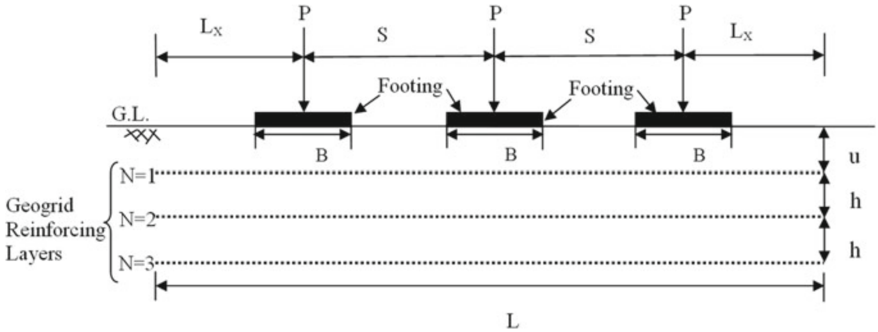


Fig. 1 Layout of geogrid reinforced sand bed

these purposes, extensive laboratory model tests were conducted at 55% relative density of sand for simulating the various conditions of footing. For reinforced sand three geogrid layers (N = 3) were used. Figure 1 shows typical layout of multi-layered geosynthetic reinforced sand bed adopted in the model tests.

3 Material and Experimental Program

3.1 Materials

For the model load tests, cohesionless dry sand (Kanhan Sand) available in Nagpur region of Vidarbha, passing through 2 mm IS sieve and retaining on 1 mm IS sieve was used as the foundation material. The properties of sand used are shown in Table 1.

Commercially available continuous biaxial geogrid in three layers was used for reinforcing the sand bed. Three model footings of square, rectangular and circular shapes were fabricated by using cast iron material of same cross-sectional area. The sizes of footings for square, rectangular and circular shapes were 10 cm × 10 cm,

Table 1 Properties of sand used

Properties	Values
Specific gravity	2.53
Bulk unit weight (kN/m^3)	15.21
Maximum unit weight (kN/m^3)	16.26
Minimum unit weight (kN/m^3)	14.20
Angle of internal friction	34°
Coefficient of uniformity C_u	2.8
Coefficient of curvature C_c	1.37
Effective size D_{10}	0.50

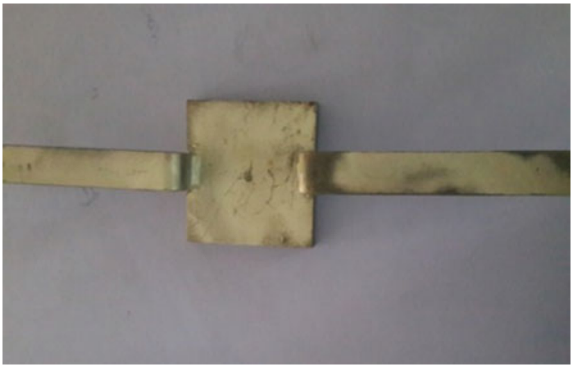


Fig. 2 Model footing

14.1 cm × 7.1 cm and 11.3 cm diameter, respectively. Every footing has a little groove at the center to facilitate the application of load. The base of the model footings was roughened by fixing a thin layer of sand to it with epoxy glue. The footings were provided with the two flanges on two sides of footings to measure the settlement of footing under the action of load with the help of dial gauges as shown in Fig. 2.

3.2 Test Setup

Laboratory plate load test setup consists of a test bed tank and loading frame assembly. The sand beds were prepared in a steel test tank of size 2.5 m × 1.5 m × 0.9 m stiffened at different levels to avoid volume change during preparation of reinforced sand bed. The tank was fabricated using steel plates of 6 mm thickness. A loading frame consisting of two vertical ISMB 200 girders bolted with ISMB 200 horizontal reaction beam for applying the load to the model footing is assembled. The load was applied with manually controlled hydraulic jack bolted on reaction frame. For transferring the symmetrical loads to three footings, load transfer beam of size 800 × 50 × 50 mm having arrangement to change the spacing between footings was fabricated and connected to hydraulic jack. Load on each footing was measured with the help of proving ring placed between footing and load transfer beam. Dial gauges were placed on each flanges of each footing to measure the settlement. The schematic diagram of the experimental setup used for studying the effect of footing shapes and reinforcement on bearing capacity of three adjacent footings is as shown in Fig. 3.

3.3 Testing Procedure

For the load test, initially the tank was filled with the dry sand of 2 mm passing and retaining on 1 mm IS sieve up to 600 mm depth. The sand was poured in the tank by

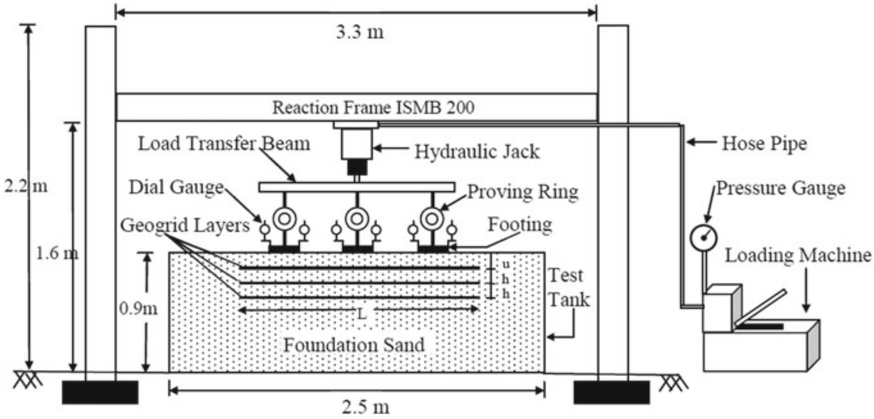


Fig. 3 Schematic diagram of test setup

rainfall technique keeping the height of fall as 25 cm to maintain the constant relative density and average unit weight of 55% and 15.21 kN/m^3, respectively, throughout the bed. The height of fall to achieve the desired relative density was determined a priori by performing a series of trials with different heights of fall. Whenever the sand is deposited up to the desired location of the bottom layer geogrid reinforcement from bottom of footing, the top surface of the sand was leveled and the bottom geogrid reinforcement was placed. Again, the sand was filled over this geogrid reinforcement layer in the tank up to the desired location of the next layer, and similarly, the multi-layered geosynthetic-reinforced sand bed adopted in the model tests, as shown in Fig. 1, was prepared. The prepared top surface of sand was leveled and three surface square footings 10 cm × 10 cm size in series at different spacing are then placed on the prepared reinforced sand bed. The middle footing was placed exactly at the centre of the loading jack to avoid eccentric loading. A manually controlled hydraulic jack installed between the load transfer beam and strong reaction frame, as shown in Fig. 3, was used to provide the required load on the footings. A calibrated proving ring was used to measure the load transferred to the footing. The load was applied in small increments. Each load increment was maintained constant until the footing settlement was stabilized. All the three footings were simultaneously loaded vertically. The vertical displacement of each test footing was measured by taking the average of two dial gauges readings. By gradually increasing the load, a series of tests was carried out so as to monitor the complete load deformation plots till the ultimate failure occurs. Figure 4 shows the actual experimental setup used for load tests.

Fig. 4 Actual experimental setup used

3.4 *Testing Program*

Initially, one model plate load test was conducted on three surface square footings in series resting on unreinforced sand bed, each at varying spacing distance between footings of 1B, 2B and 3B, where B is the width of the footing. After that three different series of model tests (i.e. A–C) were carried out on footings resting on geosynthetic-reinforced sand beds by varying different parameters, such as depth of the top most reinforcement layer from the base of the footing (u), vertical spacing between consecutive layers of reinforcement (h), center to center distance between three footings(S) and length of geogrid reinforcement on either side beyond center of footings (Lx). Table 2 presents the description of each of these series with the parameters used. All the varying parameters are expressed in non-dimensional form in terms of the footing width (B) as u/B, h/B, Lx/B and S/B.

After performing the model load tests mentioned in the Table 2, the optimum geogrid reinforcement configuration (u/B = 0.3, h/B = 0.3 and Lx/B = 3, N = 3)

Table 2 Description of laboratory model test series for reinforcement configuration

Test series	Details of parameters used in tests			
	S/B	L_X/B	h/B	u/B
A	1	4, 3 and 2	0.2	0.2, 0.3, 0.4 and 0.5
			0.3	
			0.4	
B	2	4, 3 and 2	0.2	0.2, 0.3, 0.4 and 0.5
			0.3	
			0.4	
C	3	4, 3 and 2	0.2	0.2, 0.3, 0.4 and 0.5
			0.3	
			0.4	

Table 3 Description of laboratory model test series for different footing shapes

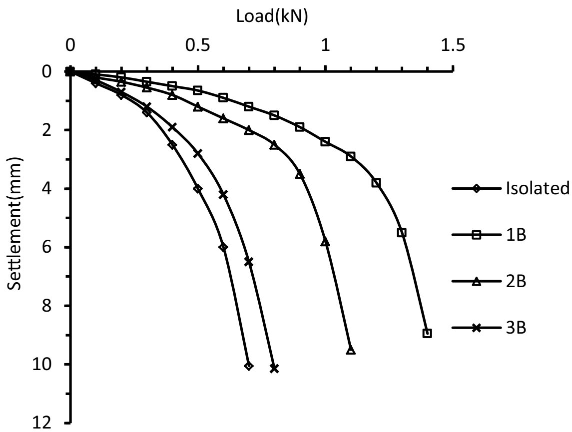
Test series	Details of parameters used in tests		
	Foundation bed type	S/B	Footing shapes
D	Optimum geogrid reinforcement (u/B = 0.3, h/B = 0.3 and Lx/B = 3, N = 3)	1, 2 and 3	Square, circular and rectangular
E	Unreinforced	1, 2 and 3	Square, circular and rectangular

was determined by comparing the results from Figs. 6, 7 and 8. After that, the two different series of model tests (i.e. D and E) were carried out to investigate the effect of footing shapes on bearing capacity of three adjacent footings for square, circular and rectangular shape of same cross-sectional area. Table 3 presents the description of each of these series with the parameters used.

4 Results and Discussion

The load settlement behaviors of footings were determined by conducting a model plate load tests as described in Tables 2 and 3. The load settlement curves were plotted for each case. The ultimate failure load was decided from load settlement curve, and thus ultimate bearing capacity was calculated. The typical load settlement curves for isolated and three square footing in series at different spacing for reinforced sand are as shown in Fig. 5.

Fig. 5 Typical load settlement curves for isolated and three square footings in series at different spacing for reinforced sand



4.1 Bearing Capacity Ratio (BCR)

The performance improvement in terms of the increase in the ultimate bearing capacity due to the provision of geosynthetic reinforcement is quantified through a non-dimensional parameter, the bearing capacity ratio (BCR), which is defined as follows and shown in Eq. (1).

$$B.C.R = \left(\frac{q_{u\,\mathrm{int(reinforced)}}}{q_{u\,\mathrm{int(unreinforced)}}} \right) \tag{1}$$

where $q_{\mathrm{u\ int\ (reinforced)}}$ is the ultimate bearing capacity of an interfering footing on the reinforced sand and $q_{\mathrm{u\ int\ (unreinforced)}}$ is the ultimate bearing capacity of the same footing on unreinforced sand.

4.1.1 Effect of Length of Reinforcement on Either Side Beyond Center of Footing

Figures 6, 7 and 8 show the variation in BCR with the length of reinforcement on either side beyond center of footing for test series A, B and C, respectively. From these figures it can be observed that initially up to Lx/B = 3 the BCR increases rapidly with increase in the length of reinforcement on either side beyond center of footing. After that the improvement in BCR is very marginal. It was also observed that the BCR is maximum for test series A when the ratio of center to center distance between the three footings and width of footing is unity (S/B = 1).

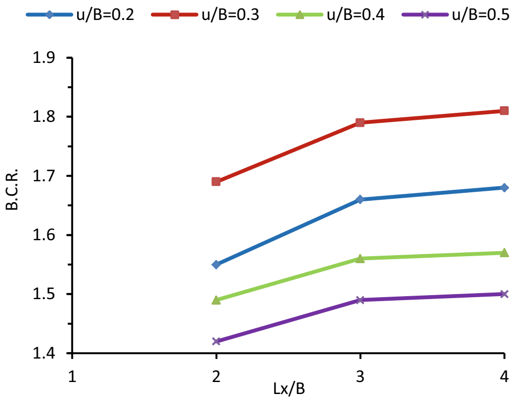
4.1.2 Effect of Depth of First Layer Reinforcement (U/B) and Vertical Distance Between Layers (H/B)

From the Figs. 6b, 7b and 8b, it can be observed that the BCR is optimum when the depth of inclusion of first layer geogrid reinforcements and vertical distance between consecutive layers is 0.3 times the width of footing for all the three test series. It was also observed that the BCR is maximum for test series A when the ratio of center to center distance between the three footings and width of footing is unity (S/B = 1).

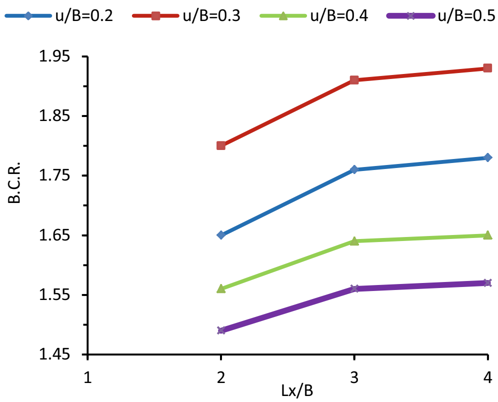
After comparing the variation in BCR with Lx/B for test series A, B and C as shown in Figs. 6, 7 and 8, it was observed that the BCR is optimum for the geogrid reinforcement configuration with u/B = 0.3, h/B = 0.3, Lx/B = 3, and N = 3.

4.1.3 Effect of Footing Shapes

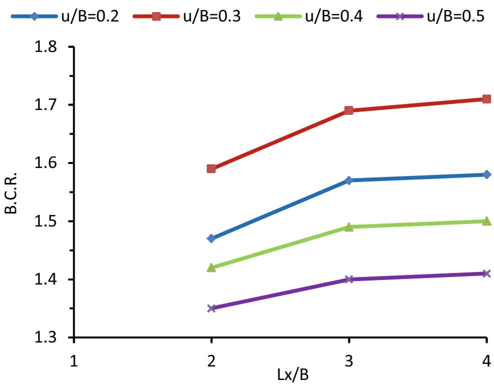
Figure 9a and b shows the variation in UBC with center to center distance between footings for optimum geogrid reinforced and unreinforced sand, respectively. From



(a). Variation of B.C.R. with Lx/B for h/B=0.2

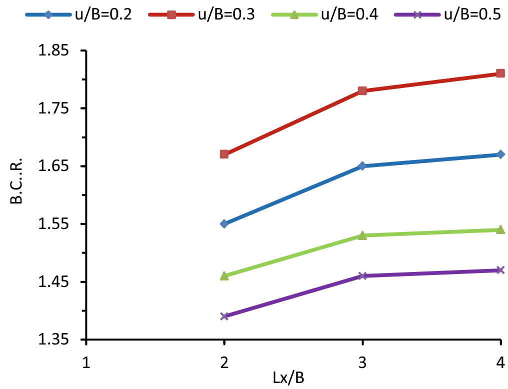


(b). Variation of B.C.R. with Lx/B for h/B=0.3

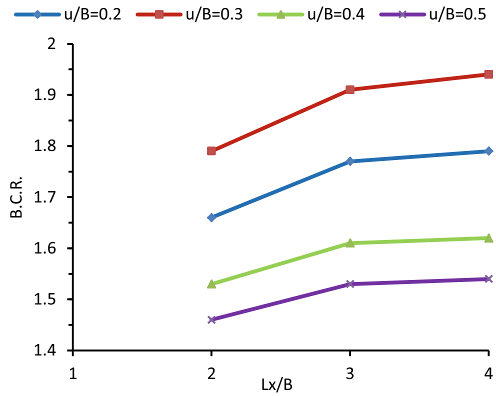


(c). Variation of B.C.R. with Lx/B for h/B=0.4

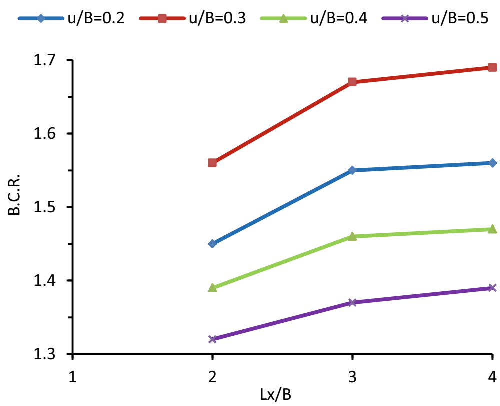
Fig. 6 Test series A for S/B = 1



(a). Variation of B.C.R. with Lx/B for h/B=0.2

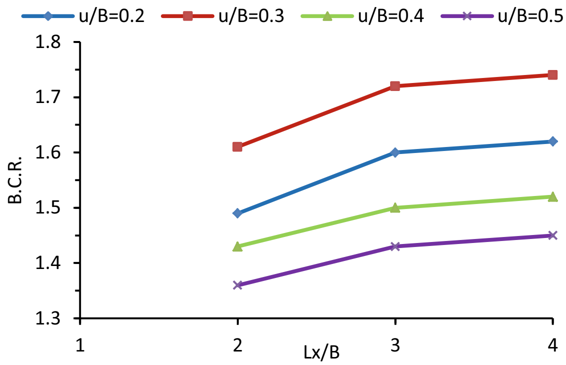


(b). Variation of B.C.R. with Lx/B for h/B=0.3

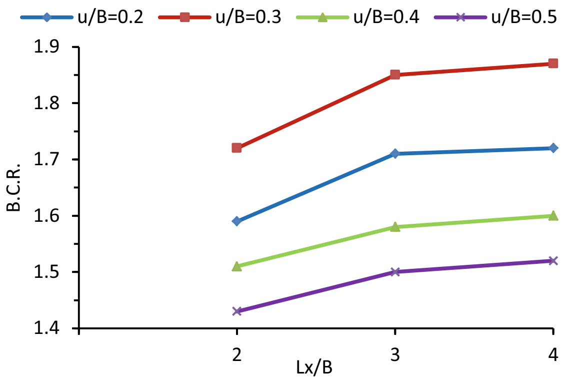


(c). Variation of B.C.R. with Lx/B for h/B=0.4

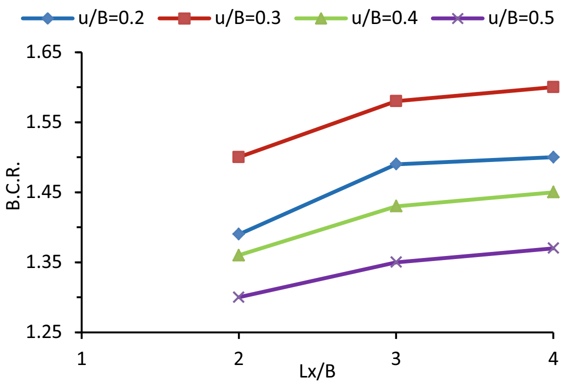
Fig. 7 Test series B for S/B = 2



(a). Variation of B.C.R. with Lx/B for h/B=0.2



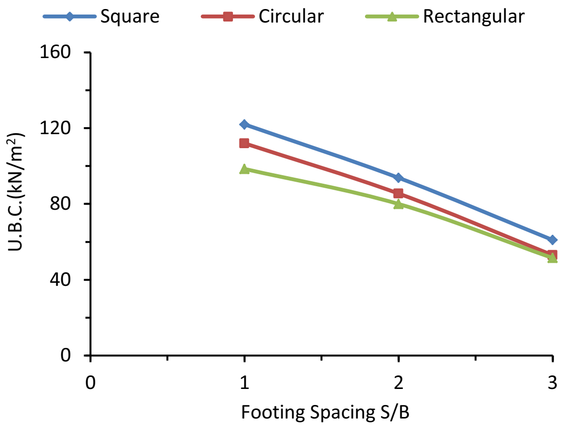
(b). Variation of B.C.R. with Lx/B for h/B=0.3



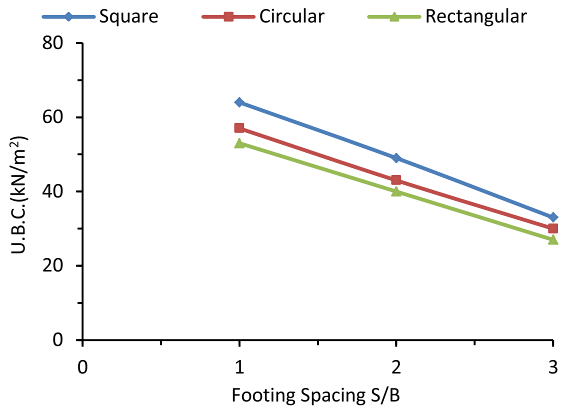
(c). Variation of B.C.R. with Lx/B for h/B=0.4

Fig. 8 Test series C for S/B = 3

Fig. 9 Variation in UBC with center to center distance between footings



(a). Test series D for optimum geogrid reinforced sand



(b). Test series E for unreinforced sand

the results it was observed that for both the test series D and E, the ultimate bearing capacity of square footing is more than the circular and rectangular footing of same cross-sectional area. Also the same trend was observed while finding the optimum geogrid reinforcement for footing spacing (S/B). As the center to center distance between footings decreases the ultimate bearing capacity increases. For all the three shapes it was observed that the UBC of three interfering footing is nearly equal to the UBC of isolated footing for S/B more than three.

5 Conclusions

From the present study, the following conclusions were drawn:

- Reinforcement configuration plays a very significant effect on the behavior of reinforced sand foundation.
- The optimum length of geogrid reinforcement on either side beyond center of footing is three times the width of the footing (Lx/B = 3).
- The optimum depth of first layer geogrid reinforcement is 0.3 times the width of the footing (u/B = 0.3) and the optimum vertical distance between geogrid reinforcing layers is also 0.3 times the width of the footing (h/B = 0.3).
- The ultimate bearing capacity of square footing is more than the circular and rectangular footing of the same cross-sectional area.
- The bearing capacity of interfering footing on unreinforced and reinforced sand increases as spacing decreases.
- A considerable improvement in bearing capacity and settlement has been observed by providing geogrid reinforcement layers in the foundation soil.
- When the footings are placed at a distance more than three times the width of the footing, there is no interference.

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