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Pressure-settlement behavior of square and rectangular skirted footings resting on sand

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Abstract. The present study deals with the Pressure-settlement behavior of square and rectangular skirted footing resting on sand and subjected to a vertical load through a laboratory experimental study. A series of load tests were conducted in the model test tank to evaluate the improvement in pressure-settlement behavior and bearing capacity of square and rectangular model footings with and without structural skirt. The footing of width 5 cm and 6 cm and length/width ratio of 1 and 2 was used. The relative density of sand was maintained at 30%, 50%, 70%, and 87% respectively. The depth of skirt was varied from 0.25 B to 1.0 B. All the tests were carried out using a strain controlled loading frame of 50 kN capacity. The strain rate for all test was kept 0.24 mm/min. The results of present study reveal that, the use of structural skirt improves the bearing capacity of footing significantly. The improvement in bearing capacity was observed almost linearly proportional to the depth of skirt. The improvement in bearing capacity of skirted footings over footing without skirt was observed in the range of 33.3% to 68.5%, 68.9% to 127% and 146.7% to 262% for a skirt depth of 0.25 B, 0.50 B and 1.0 B respectively. The skirted footings were found more effective for sand at relative density of 30% and 50% than at relative density of 70% and 87%. The bearing capacity was found to increase linearly with footing width for footings with and without skirts. This observation was found to be consistent for footings with different skirt depths and for relative density of sand i.e., 30%, 50%, 70%, and 87%. The obtained results from the study for footing with and without skirts were comparable with available solutions from literature.

Keywords: pressure-settlement; rectangular skirted footing; sand; bearing capacity; relative density

1. Introduction

Most of the civil engineers around the world are in search of an alternative technique for improving the bearing capacity and reducing the settlement of footing resting on soil. There are several ground improvement techniques, but some are expensive and restricted by the site conditions. In some situations they are difficult to apply to the existing foundations requiring the use of underpinning techniques which is expensive. So in this case, structural skirts hold a promise as an alternative technique of improving bearing capacity and reducing settlement of shallow

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foundations. Skirted foundations have been used for a considerable period to increase the effective depth of foundations in marine and other situations where water scour is a major problem. This type of technique of bearing capacity improvement does not require any excavation of soil and is not restricted by the presence of high ground water table. This paper presents an experimental study to evaluate the behavior of square and rectangular skirted footings resting on sand and subjected to vertical load.

2. Background

The design of footing requires two different studies: one deal with the ultimate bearing capacity of soil and other deals with the acceptable limit of settlement. The excessive settlement in footing may induce differential settlement leading to distress in the structure. Binquet and Lee (1975) proposed a theoretical solution for the design of reinforced shallow foundations. The study conducted by Wakil (2013) revealed that the structural skirts are more beneficial in case of footings resting on loose sand as compared to footings resting on medium and dense sand. Mahmoud and Abdrabbo (1989) have studied the effect of vertical reinforcement in the soil on bearing capacity. The study suggested that the bearing capacity could be increased in the range 1.5 to 2.0 times in comparison with unreinforced soil. Al-Alghbari and Mohamedzein (2004) and Wakil (2010) reported that the improvement in the bearing capacity and settlement reduction of footings with structural skirts resting on sand depends on various factors such as the shape of footings, structural properties of skirts, footings, sand and their interface conditions. Bransby and Randolph (1998), Al-Aghbari (2007), Al-Alghbari and Dutta (2008) and Eid (2013) have reported the use of structural skirts in marine and other applications where water scour is a major problem. An extensive software analysis were carried out by Yun and Bransby (2007), Saleh *et al*. (2008), Gourvenec and Jensen (2009), Mana *et al*. (2013), Pusadkar and Bhatkar (2013) in order to validate their model test results. Though the performances of circular, square and strip footings with structural skirts resting on sand have been studied by most of researchers and the behavior of rectangular skirted footing is not thus far contemplated by any researcher, hence in this study the behavior of rectangular footing resting on sand is examined.

3. Test Materials and experimental procedure

Locally available river sand was used in this investigation. The particle size distribution curve of the sand is shown in Fig. 1.

The sand has D_{10} = 0.15 mm, D_{30} = 0.19 mm, D_{50} = 0.22 mm and D_{60} = 0.27 mm. The coefficient of uniformity (C_u), coefficient of curvature (C_c), minimum and maximum dry unit weight of the sand are 1.80, 0.89, 13.06 kN/m^3 and 15.97 kN/m^3 respectively. The specific gravity of sand was found to be 2.67. The sand is classified as poorly graded (SP). In order to find out the friction angle of sand, direct shear test and consolidated drained triaxial tests were conducted at a relative density of 30%, 50%, 70%, and 87% respectively. The normal stress and confining pressure for direct shear test and consolidated drained triaxial test was kept in the range 25 kPa to 200 kPa. The friction angle of sand from direct shear test and consolidated drained triaxial test was found to be 36.5°, 40.1°, 42.05°, 44.6°, 33.4°, 37°, 39.05° and 41.2° for relative density of 30%, 50%, 70%, and 87% respectively. To check the roughness properties of footing and interface, shear test was carried out using the direct shear assembly. The steel plate of size 6 cm × 6 cm × 1.5 cm

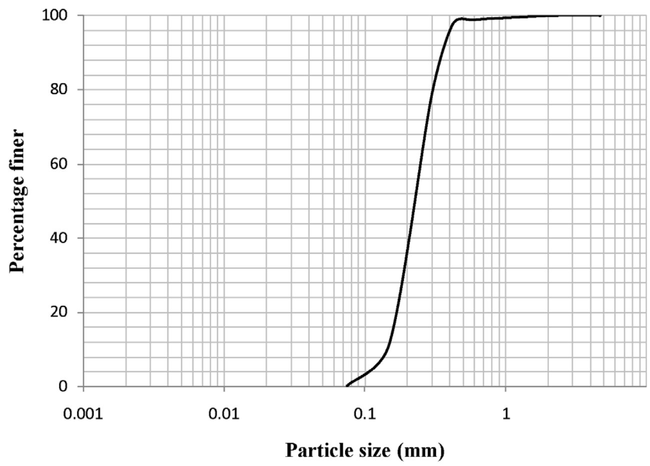

Fig. 1 Particle size distribution curve of the sand

was kept to the lower half of shear box and the upper half was filled with sand and the test was conducted over the same normal stress range. The frictional angle between steel and sand was found to be 22°, 24.2°, 25.5° and 26.9° for relative density of 30%, 50%, 70%, and 87% respectively.

A laboratory setup consisting of test tank, pluviator, loading mechanism and data acquisition system was used to study the pressure-settlement behavior of rectangular skirted footing resting on sand. Four footings of sizes 5 cm × 5 cm, 10 cm × 5 cm, 6 cm × 6 cm and 12 cm × 6 cm were used in the present study. The footing used in this investigation was made of steel plate with a thickness of 1 cm. Steel plates with a thickness of 0.5 cm were used to the model skirts. Skirts were connected to each side of the footing base. The depth of the skirt (D_s) was selected as 0.25 B, 0.5 B, and 1.0 B where B is the width of the footing. The footing with and without skirts are shown in Fig. 2.

The experimental investigation was carried out in a model test tank made of Perspex sheet and stiffened with a steel frame. The inner dimension of the test tank was 70 cm × 45 cm × 60 cm to accommodate the footing and to avoid the boundary effects leading to the development of additional stresses and strains in the sand. The sand preparation was done carefully in order to maintain the relative density of 30%, 50%, 70% and 87% respectively. The sand bed was prepared in the test tank of size 70 cm × 45 cm × 60 cm (l × b × h). Before the preparation of sand bed, the test tank was placed on the Universal testing machine (U.T.M.). The sand was filled up to

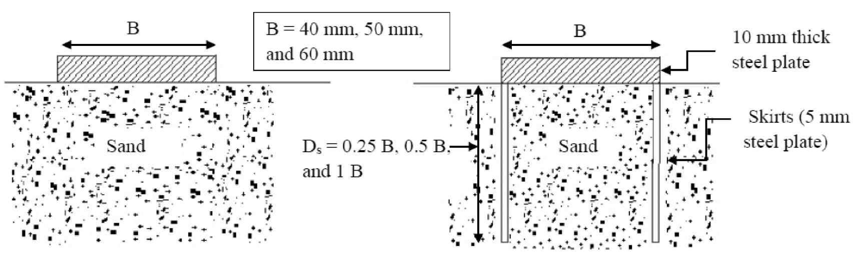

Fig. 2 Schematic diagram of rectangular footing (a) without skirt; and (b) with skirt

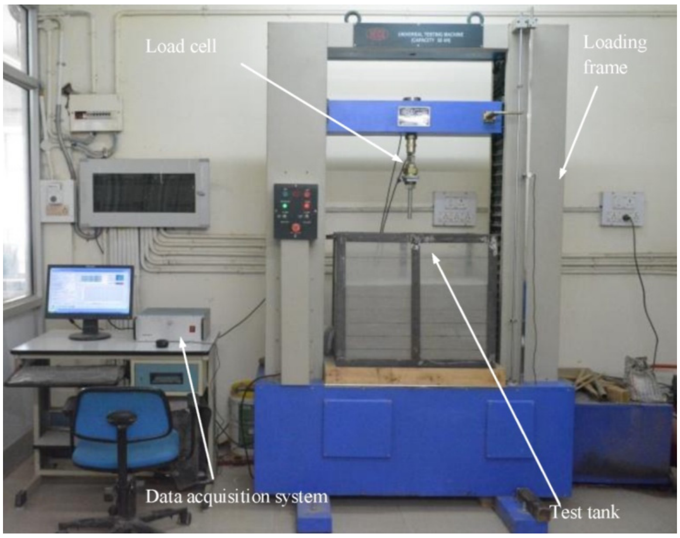

Fig. 3 Complete setup of testing program

a height of 42 cm in 6 cm layers each that is in seven equal layers. The mass of sand required to fill each layer was calculated on the basis of volume of each layer and unit weight corresponding to given relative density. The unit weight of the sand corresponding to relative density of 30%, 50%, 70% and 87% are 13.87 kN/m^3, 14.44 kN/m^3, 15.04 kN/m^3, and 15.54 kN/m^3 respectively. The sand for each layer was poured into the tank from a constant height and compacted to achieve the required relative density. The number of blows required for compaction was arrived by trial and error. When the sand was filled up to the desired level (up to 42 cm), the surface of the sand was leveled. It was observed that the compaction was not required for the relative density of 30%. The footing without skirt was placed on the predetermined position in the tank and finally the test was conducted. For footing with skirt, the skirted footing was gently pushed into the sand till the bottom of footing is just in contact with the top surface of sand. No heave was observed during such placement procedure. After the placement of each footing, the data recording was set to zero prior to starting load-settlement measurements. The loading was carried out at a strain rate of 0.24 mm/min. The test was carried out till settlement to footing width ratio (s/B) of 30%. Each test was carried out twice to check the repeatability of obtained results. At the end of each test, surface of sand that was involved in failure was removed and replaced by fresh sand at the desired relative density. The depth of this replacement was taken as 3B below the skirts edge level. The complete setup of loading frame is shown in Fig. 3.

4. Results and discussions

The present study aims at the analysis of Pressure-settlement behavior of rectangular footing with and without skirts resting on sand. A comparison of bearing capacity in various cases is also carried out. An attempt is also made on bringing out the effect of footing size, and relative density on bearing capacity of skirted foundation. Accordingly, detailed discussions are provided in subsequent sections.

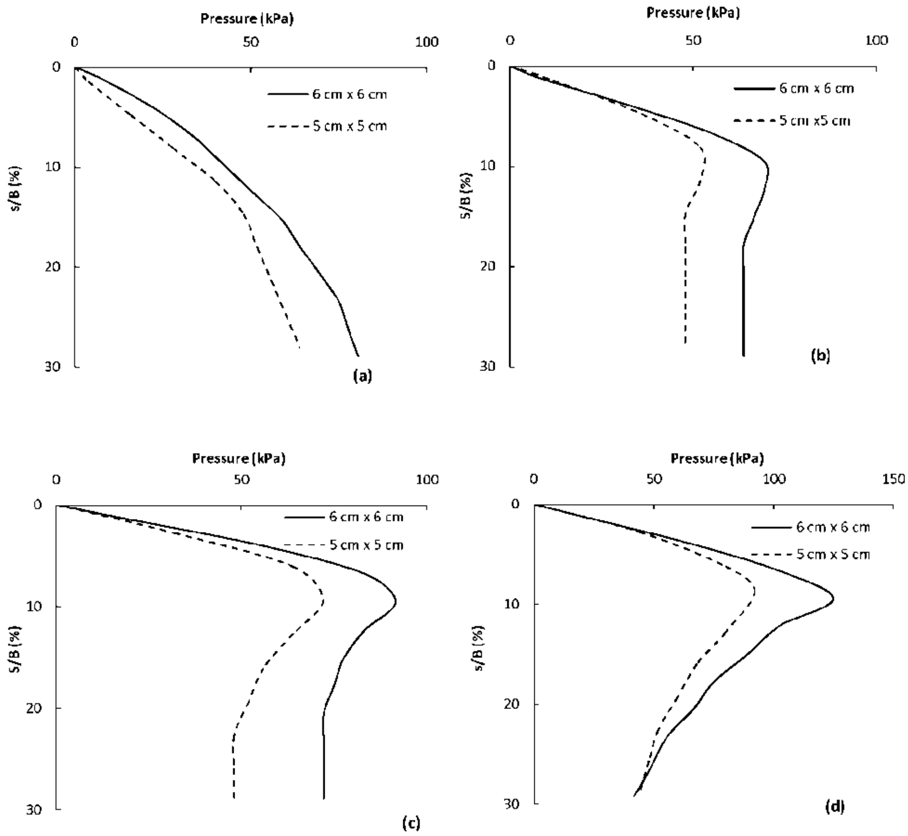

Fig. 4 Pressure-settlement behavior of square footing without skirt for relative density of (a) 30%; (b) 50%; (c) 70%; (d) 87%

4.1 Pressure-settlement behavior of footings without skirt

The load tests were carried out on the plate alone (that is footings without skirts). The relevant Pressure-settlement curves for footings with L/B = 1 and L/B = 2 and relative density of 30%, 50%, 70% and 87% are shown in Figs. 4 and 5 respectively.

From these curves it can be seen that irrespective L/B ratio and relative density a clear peak pressure point is observed for relative density of 50%, 70% and 87% for different width of footing (that is 5 cm and 6 cm). It implies that a general shear failure is evident in all the cases for relative density of 50%, 70% and 87% respectively. But in the case of relative density of 30%, a clear peak pressure was not observed. The peak pressure is observed at about s/B of 10% in almost all the cases. It can also be observed that for a given relative density, with increase in footing size, the pressure at any non dimensional settlement increases. Also with the relative density constant, the pressure at any given settlement has been found to increase with increase in footing size. This observation was consistent for all the footing sizes tested. As anticipated with increase in relative density from 30% to 50%, 50% to 70%, and 70% to 87% the pressure at any given settlement increases with footing width.

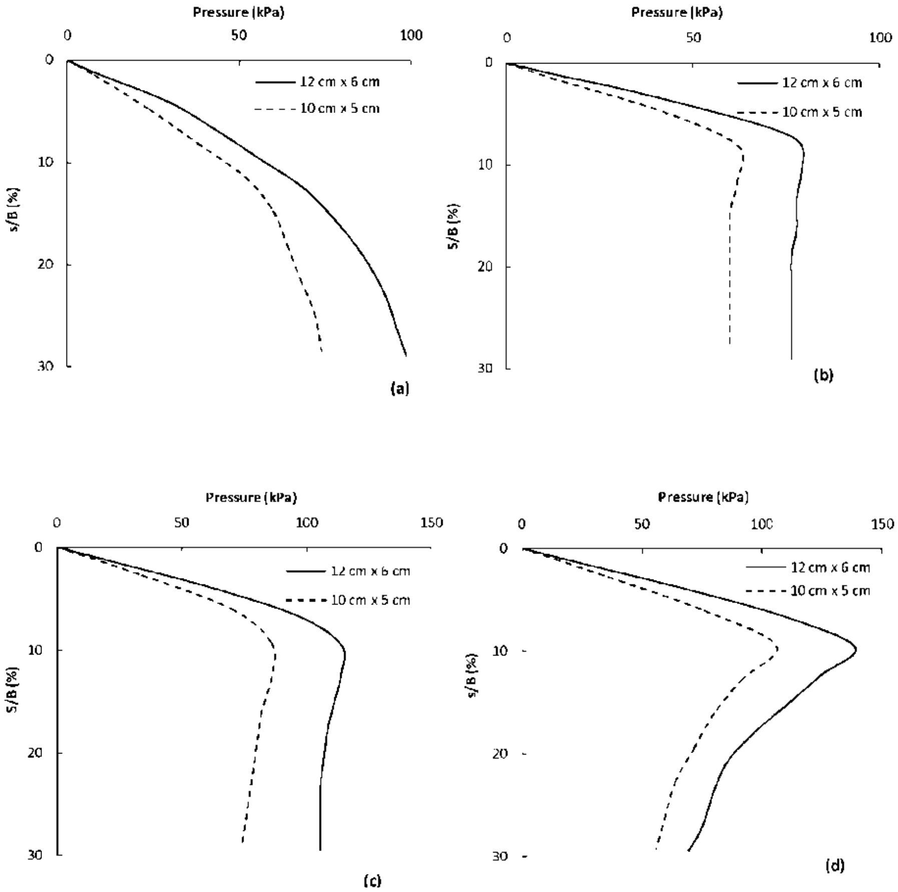

Fig. 5 Pressure-settlement behavior of rectangular footing without skirt for relative density of (a) 30%; (b) 50%; (c) 70%; (d) 87%

4.2 Pressure-settlement behavior of footings with structural skirt

The Pressure-settlement behavior of footings with structural skirts is shown in Figs. 6 and 7 respectively. In the present study, the skirt depth (D_s) is taken as 0.25 B, 0.5 B, and 1.0 B respectively. The study of Figs. 6 and 7 shows a clear break in pressure-settlement curve implies a possibility of general shear failure in sand. This observation is similar to the pressure-settlement behavior of footings without skirts.

The study of this figure further suggests that for a given relative density and L/B ratio, a significant improvement in pressure-settlement behavior is observed for skirted foundation as the skirt depth (D_s) is increased from 0.25 B to 1.0 B. Also the peak pressure is found to increase with the increase of skirt depth. This observation is found consistent for all footing sizes i.e., 5 cm × 5 cm, 10 cm × 5 cm 6 cm × 6 cm and 12 cm × 6 cm. This behavior is expected as the addition of skirts to footing provides a confinement in sand and also intercepts the failure pattern. It leads to an increase in shear strength of sand and also an improvement in pressure-settlement behavior. The study of these figures also shows that with increase in skirt depth from 0.25 B to 1.0 B, the

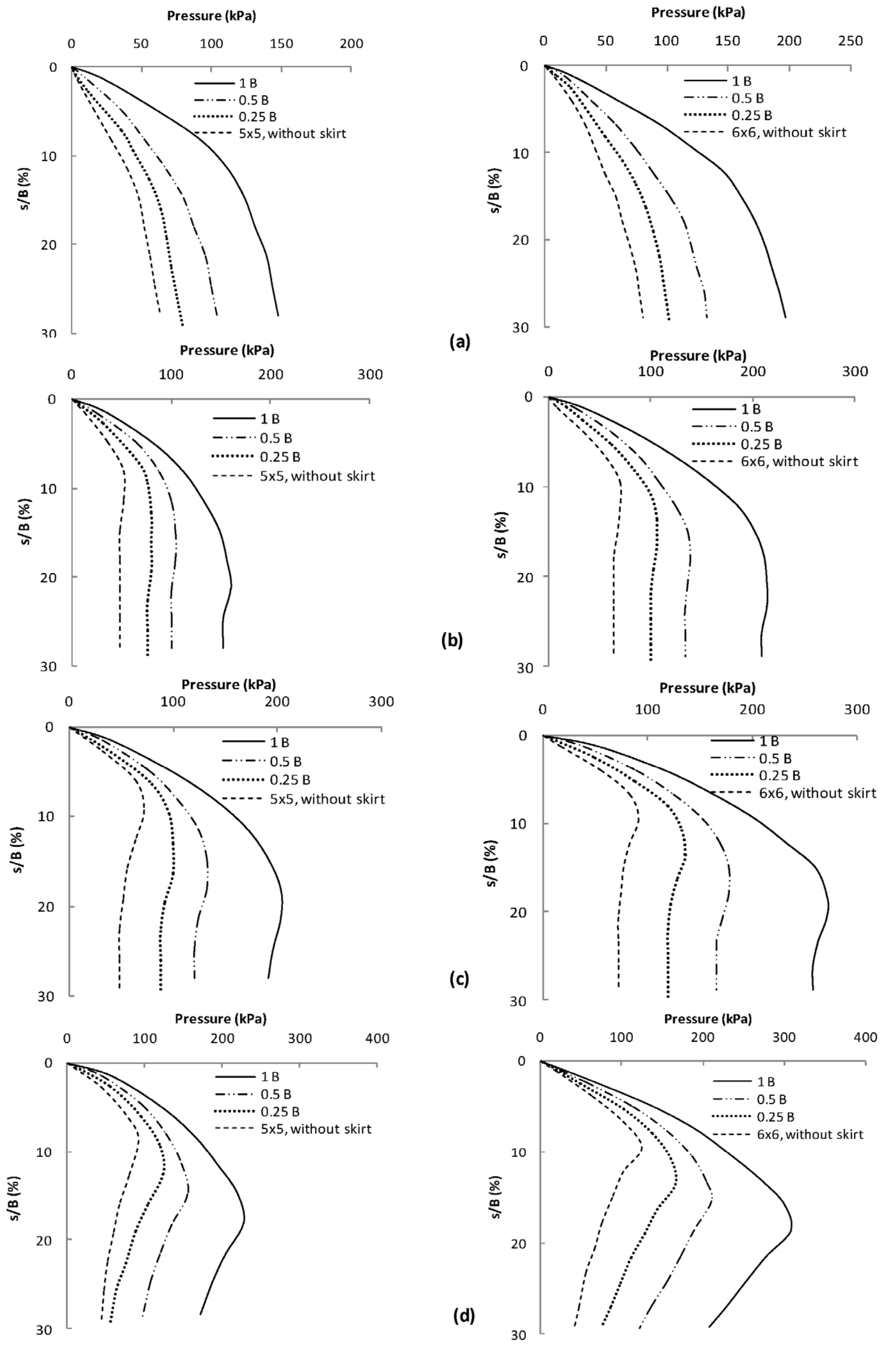

Fig. 6 Pressure-settlement behavior of square skirted footing for relative density of (a) 30%; (b) 50%; (c) 70%; (d) 87%

non-dimensional settlement at peak pressure increases. It means that the increase in skirt depth leads to increase in confinement and hence higher strains are needed to reach the failure in sand.

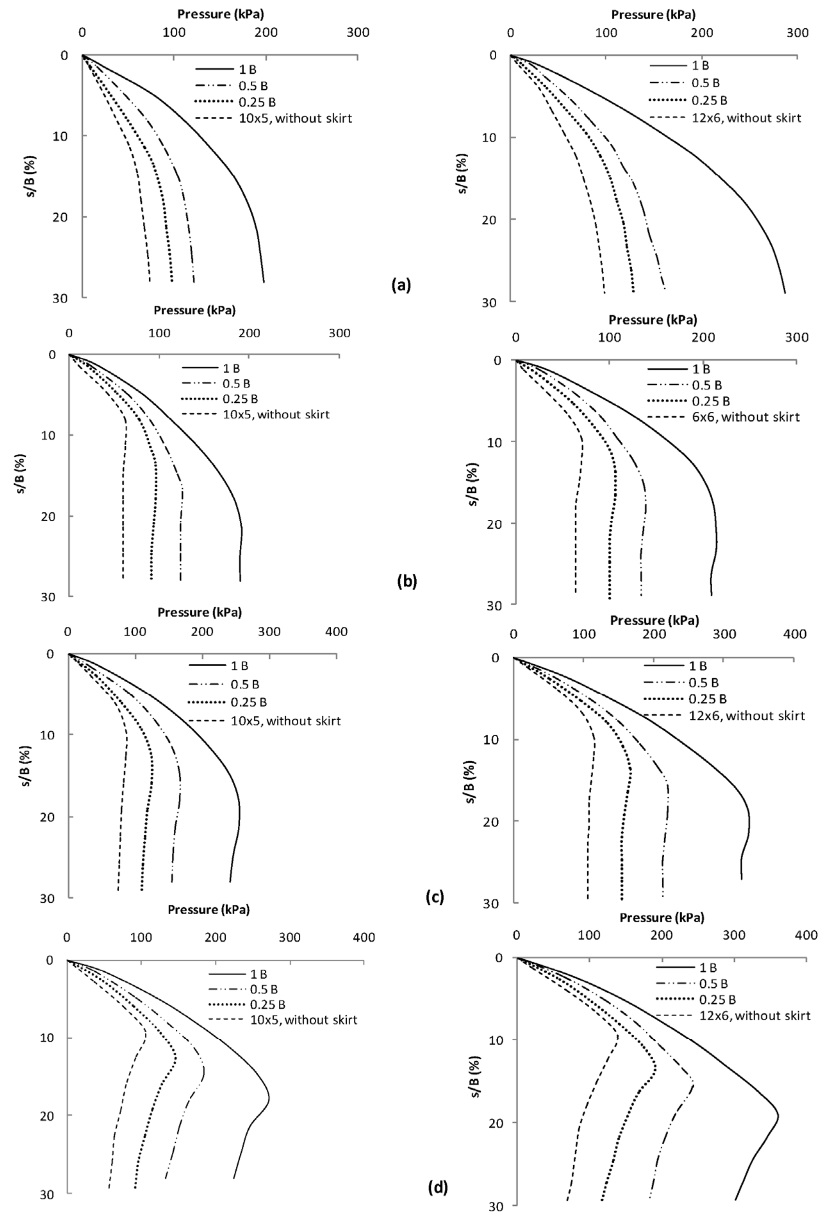

Fig. 7 Pressure-settlement behavior of rectangular skirted footing for relative density of (a) 30%; (b) 50%; (c) 70%; (d) 87%

4.3 Bearing capacity of footings without skirt

The bearing capacity of foundation was calculated from the pressure-settlement curve shown in Figs. 4 and 5. The peak pressure of given load settlement curve was termed as bearing capacity in accordance with the general shear failure criteria. Since peak failure point was not observed in case of 30% relative density, therefore, the bearing capacity was calculated corresponding to *s*/*B* of

Table 1 Bearing capacity of rectangular footing corresponding to s/B of 10%

Footing size (cm)	Bearing capacity (kPa) corresponding to s/B of 10%			
	Relative density (R_d) = 30%	Relative density (R_d) = 50%	Relative density (R_d) = 70%	Relative density (R_d) = 87%
5 cm × 5 cm	34.8	52.0	70.2	88.2
10 cm × 5 cm	47.0	62.0	86.0	103.7
6 cm × 6 cm	43.1	69.4	90.3	120.7
12 cm × 6 cm	60.0	79.2	113.9	137.0

Table 2 Ultimate bearing capacity values for footing without skirt

Footing size (cm)	Bearing capacity (kPa)			
	Relative density (R_d) = 30%	Relative density (R_d) = 50%	Relative density (R_d) = 70%	Relative density (R_d) = 87%
5 cm × 5 cm	36.0	52.0	72.0	92.0
10 cm × 5 cm	47.0	62.0	86.0	106.0
6 cm × 6 cm	44.5	69.4	91.7	125.0
12 cm × 6 cm	60.0	79.2	113.9	138.9

10% as well as by double tangent method. The bearing capacity of rectangular footing corresponding to s/B of 10% and bearing capacity calculated by double tangent method are shown in Tables 1 and 2.

The study of this table reveals that the bearing capacity increases with the increase of footing width and relative density. For example, the bearing capacity of footing with L/B = 2 and relative density of 30% was found to be 47 kPa, and 60 kPa respectively. The bearing capacity of footing for relative density of 30% was determined by double tangent method. For relative density of 50%, the bearing capacity of rectangular footing was observed as 62 kPa and 79.7 kPa respectively. For the same L/B ratio and footing width of 5 cm and 6 cm, the bearing capacity observed was 86 kPa, and 113.9 kPa respectively for a relative density of 70%. The bearing capacity of footings for relative density of 87% was found to be 106 kPa, and 138.9 kPa respectively.

4.4 Effect of skirt depth (D_s) variation on bearing capacity of footings

Here, again the bearing capacity of skirted footing was obtained from the pressure-settlement curves shown in Figs. 6 and 7. From this figure it can be observed that for given L/B ratio, the bearing capacity of footing not only varies with footing width (B) but also varies with the depth skirt (D_s). The study of Figs. 6 and 7 indicates a significant improvement in bearing capacity of footing with the introduction of skirt. For example the bearing capacity of rectangular footing without skirt for B = 6 cm, L/B = 2 and R_d = 50% is observed as 79.7 kPa which increased to 120.3 kPa with an addition of skirt 0.25 B depth. The bearing capacity further increased to 245.8 kPa as the skirt depth increased to 1.0 B. The improvement in bearing capacity with respect to footing without skirt is calculated as 52.6% and 210.5% for a skirt depth of 0.25 B and 1.0 B respectively. A similar trend has been observed for other footing width 5 cm, L/B ratio 1 and relative density (30%, 50%, 70% and 87%) tested. The Tables 3 and 4 provides values of percentage improvement

Table 3 The percentage improvement in bearing capacity of skirted footing corresponding *s*/*B* of 10%

Footing size (cm)	Improvement in bearing capacity (%) corresponding to *s*/*B* of 10%				
	Skirt depth (D_s)/ Width (B)	Relative density (R_d) = 30%	Relative density (R_d) = 50%	Relative density (R_d) = 70%	Relative density (R_d) = 87%
5 cm × 5 cm	0.25	31.9	47.4	36.9	36.8
	0.5	74.6	81.9	63.4	58.6
	1.0	196.4	137.1	123.9	104.8
10 cm × 5 cm	0.25	31.2	36.7	30.9	24.9
	0.5	78.6	64.2	66.0	50.8
	1.0	178.3	110.8	124.7	92.9
6 cm × 6 cm	0.25	37.5	36.1	42.9	28.5
	0.5	79.7	60.1	72.4	50.4
	1.0	192.9	134.8	130.4	90.2
12 cm × 6 cm	0.25	41.7	42.4	31.3	19.9
	0.5	71.3	84.1	52.5	37.8
	1.0	184.5	122.0	104.2	74.8

Table 4 The percentage improvement in ultimate bearing capacity of skirted footings with respect to footing without skirts

Footing size (cm)	Improvement in bearing capacity (%)				
	Skirt depth (D_s)/ Width (B)	Relative density (R_d) = 30%	Relative density (R_d) = 50%	Relative density (R_d) = 70%	Relative density (R_d) = 87%
5 cm × 5 cm	0.25	61.1	53.9	38.9	34.8
	0.5	125.0	100.0	83.3	69.6
	1.0	233.3	207.7	183.3	147.8
10 cm × 5 cm	0.25	61.7	54.8	44.2	37.7
	0.5	113.1	103.2	93.0	75.0
	1.0	257.5	209.7	195.3	156.6
6 cm × 6 cm	0.25	68.5	52.0	48.5	33.3
	0.5	127.0	100.0	93.9	68.9
	1.0	262.0	208.0	197.0	146.7
12 cm × 6 cm	0.25	66.7	52.6	46.3	38.0
	0.5	125.0	103.5	92.7	75.0
	1.0	250.0	210.5	193.9	160.0

in the bearing capacity of rectangular skirted footings with respect to footing without skirts.

The same procedure (i.e., bearing capacity corresponding to *s*/*B* of 10% and by double tangent method) was followed for calculating the bearing capacity of rectangular skirted footing for relative density of 30%. From these tables it can be seen that the percentage improvement in the bearing capacity with the addition of skirt of depth 0.25 B, 0.5 B and 1.0 B lies in the range of 33.3%

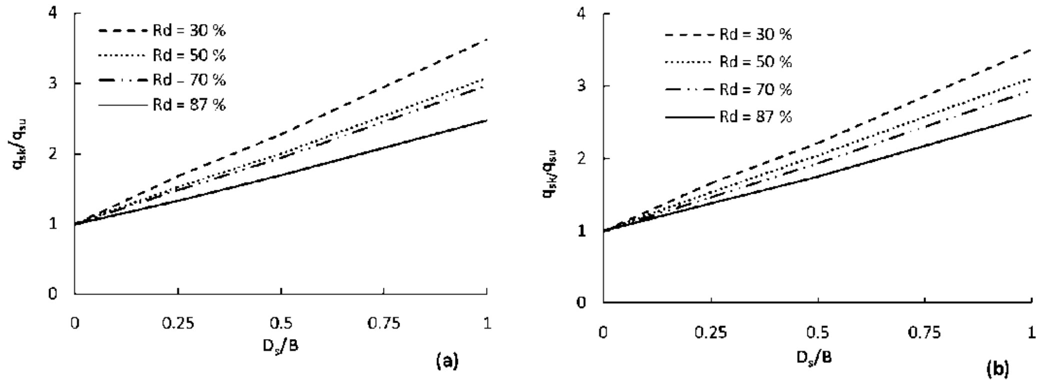

Fig. 8 q_{sk}/q_{su} versus D_s/B for (a) square footing (6 cm × 6 cm); and (b) rectangular footing (12 cm × 6 cm)

to 68.5%, 68.9% to 127% and 146.7% to 262% respectively.

4.5 Effect of relative density on bearing capacity ratio

The effect of relative density on bearing capacity of skirted footings can be assessed by defining a new term in this study named as bearing capacity ratio. The bearing capacity ratio can be defined as the ratio of bearing capacity of footing with skirts to the bearing capacity of footing without skirt. The variation of bearing capacity ratio with non-dimensional skirt depth for L/B of 1 and 2 and relative density is provided in Fig. 8. In this figure q_{sk} and q_{su} are the ultimate bearing capacity of footings with and without skirt respectively. From this figure it can be concluded that the irrespective of skirt depth and L/B ratio, the improvement in bearing capacity of skirted footing is greater for sand with a relative density of 30% than for a relative density of 50%, 70% and 87%. The difference in bearing capacity ratio is quite significant for skirt depth of 1.0 B. So from the present study it can be confirmed that the provision of skirt is more effective in sand of low relative density.

4.6 Effect of footing width on bearing capacity

In the present study footings with a width of 4 cm, 5 cm and 6 cm are used for load testing to investigate the possibility of size or scale effect on bearing capacity of skirted footings. It is well known fact that the peak friction angle is dependent on confining pressure in loose, medium dense and dense sand due to the presence of dilatancy effect (Fukushima and Tatsuoka 1984, Bolton 1986, Ueno *et al*. 1998, Hettler and Gudehus 1989, Maeda and Miura 1999, Lancelot *et al*. 2006). The peak friction angle at low confining pressure is higher compared to friction angle at high confining pressure. In the small scale laboratory test the generated pressure is low as compared to pressure below field size footings. Hence the friction angle generated in laboratory test is higher than mobilized friction angle at failure for field case. Therefore the bearing capacity measured in laboratory when extrapolated for field generally overestimates the actual bearing capacity of field size footings. This is referred to as size or scale effect on bearing capacity. The present study tries to analyze this scale effect on the bearing capacity of skirted footings. The variation of bearing capacity of skirted footings with the footing width is provided in Figs. 9 and 10 for square and rectangular footings for relative density of 30%, 50%, 70% and 87% respectively.

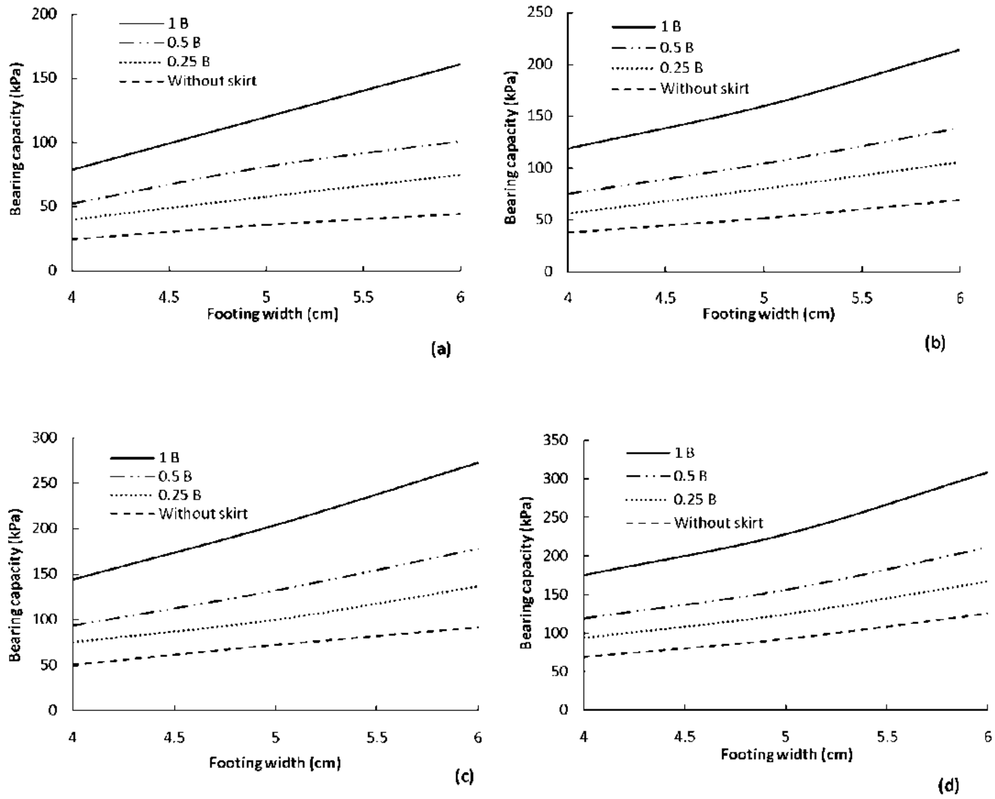

Fig. 9 The variation of bearing capacity with footing width for square footings for relative density (R_d) of (a) 30%; (b) 50%; (c) 70%; and (d) 87%

From these figures it can be noticed that the bearing capacity of footing varies almost linearly with footing width for the given L/B ratio, skirt depth (D_s) and relative density of sand. It implies that for the load tests performed, the scale or size effect was not observed. Hence for the sand used in the present study the bearing capacity of field size footings can be approximated suitably by linear extrapolation without much of error. However for the other cases where the dependency of friction angle of sand on confining pressure is significant, it is quite likely that that the bearing capacity will be dependent on the size of footing even with the presence of skirts.

5. Comparison of present result with literatures

The present results related to bearing capacity of footing without skirt resting on sand are compared with the well-established bearing capacity formulae (Meyerhof 1963, Vesic 1973 and IS-6403 1981). To find out the bearing capacity of footing in accordance with these formulae a triaxial friction angle was used for square footings and a direct shear friction angle was used for the other cases. It should be noted that for the estimation of bearing capacity of rectangular footings the friction angle under triaxial condition is not strictly applicable and hence direct shear friction angle which will simulate a plane strain friction angle in an approximate manner is followed. It is observed that the triaxial friction angle for a relative density of 30%, 50%, 70% and

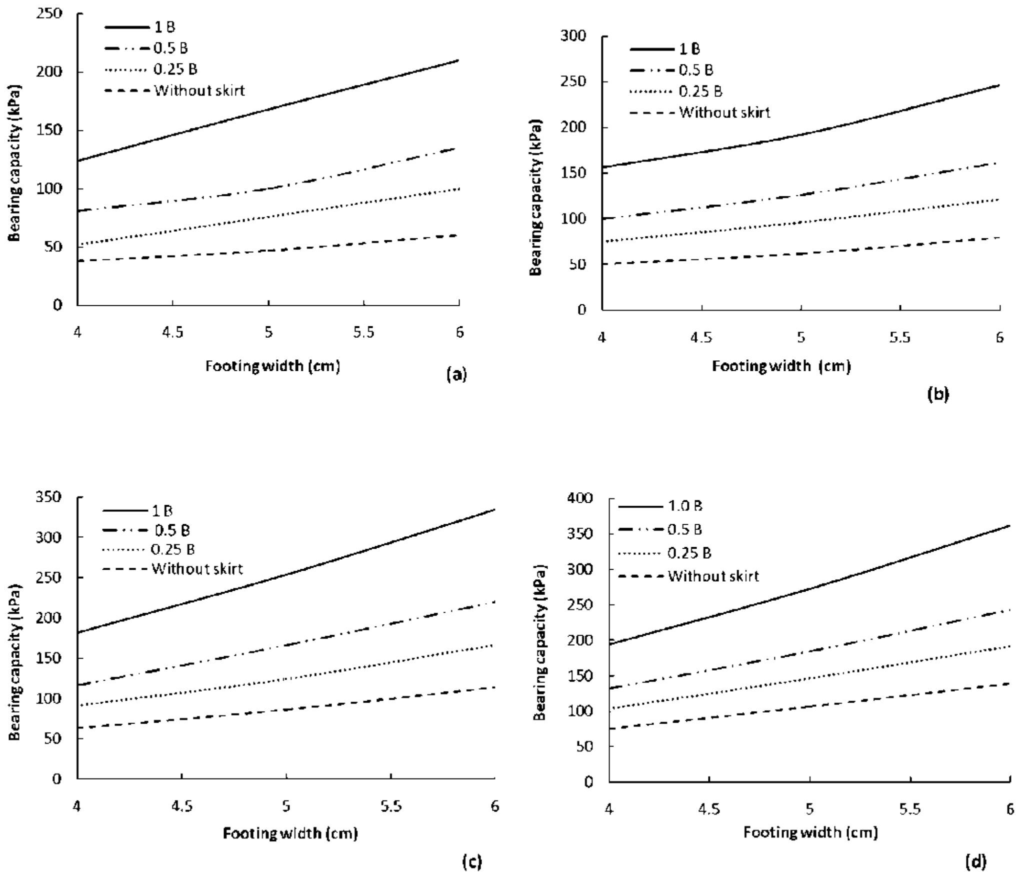

Fig. 10 The variation of bearing capacity with footing width for rectangular footings for relative density (Rd) of (a) 30%; (b) 50%; (c) 70%; and (d) 87%

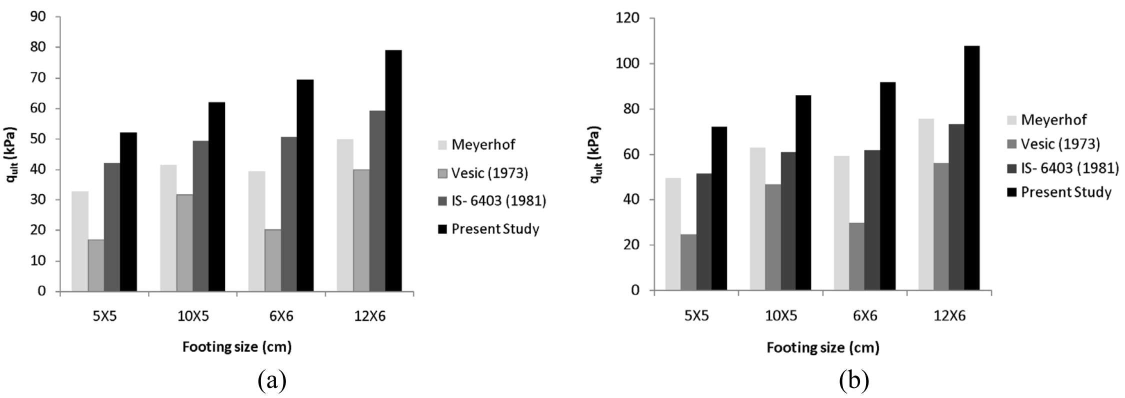

Fig. 11 Comparison of observed bearing capacity with literature for relative density of (a) 50%; (b) 70%

87% were observed as 33.4°, 37°, 39.05°, and 41.2° respectively whereas the direct shear friction angle were observed as 36.5°, 40.1°, 42.05°, and 44.6° respectively. The relevant comparison is

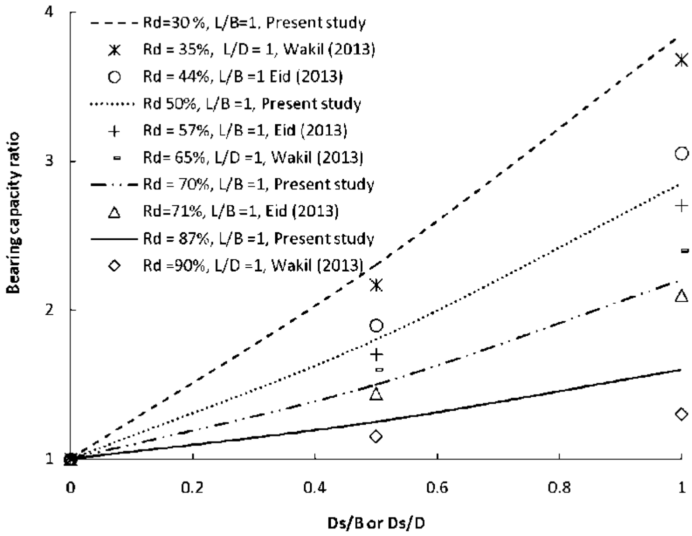

Fig. 12 Comparison of the present results of skirted footings with literature

provided in Fig. 11.

In the present study, the comparison of present result with literatures is shown for relative density of 50% and 70% only. From the Fig. 11, it is observed that the observed bearing capacity of rectangular footings is higher than those predicted by formulae's in all the cases.

The bearing capacity of footings with skirt is compared with available solutions from the literature. For the purpose of comparison the bearing capacity of skirted footing is normalized by the bearing capacity of footing without skirt. This bearing capacity ratio in various cases is compared with literature. The present results of square footing with a relative density of 30% is compared with the result of Wakil (2013) for circular footing with a relative density of 35% and for relative density 50% are compared with the results of Eid (2013) with a relative density of 44% and 57%. Similarly the results of square footing corresponding to 70% relative density are compared with the results of Wakil (2013) for circular skirted footing and with relative density of sand as 65% and that of Eid (2013) for square skirted footing and with relative density of sand as 71%. At last the present study result of square footing with a relative density of 87% is compared with the result of Wakil (2013) for circular footing with a relative density of 90%. The relevant comparison is shown in Fig. 12.

The present results seem to be in good agreement with the available solutions in literature. The comparison of present results with literature further reaffirms the fact that the improvement in bearing capacity of skirted footing reduces with increase of relative density of sand. It should be noted that the literature for comparing the results of rectangular footing was not available for the selected relative density of sand.

6. Conclusions

The behavior of rectangular footing with structural skirt resting on sand and subjected to vertical load through an experimental study is investigated. A series of tests were conducted in a model test tank to evaluate the behavior of rectangular footing with and without structural skirt.

From the results and discussion presented above, the following conclusions are drawn:

(1) The observed bearing capacity of footing without skirts was quite comparable with available theories.
(2) An increase in bearing capacity was observed with the provision of skirt.
(3) The bearing capacity of rectangular skirted footing was found to increase with increase in the depth of skirt.
(4) An improvement in bearing capacity up to 262% was observed for skirted footing over the bearing capacity of footing without skirt.
(5) The non-dimensional settlement at peak pressure was found to increase with increase in depth of skirt.
(6) The bearing capacity of rectangular footing was found to increase almost linearly with footing width for both footing with and without skirt.
(7) The results obtained from the present study suggest that the skirted footings are more effective for sand at low relative density.

The skirted footing resting on sand can be considered as an alternative to the ground improvement of loose sand.

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Notations

The following symbols are used in this paper:

L = length of rectangular footing;

B = width of rectangular footing;

D_s = depth of structural skirt;

L/B = footing length to footing width ratio;

s/B = settlement to footing width ratio;

q_{su} = bearing capacity of rectangular footing without skirt;

q_{sk} = bearing capacity of rectangular footing with skirt;

R_d = relative density of sand;

Φ = peak friction angle of sand;

C_u = coefficient of uniformity; and

C_c = coefficient of curvature.