ORIGINAL RESEARCH

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Model studies of plus and double box shaped skirted footings resting on sand

Tammineni Gnananandarao¹, Rakesh Kumar Dutta^{1*} and Vishwas Nandkishor Khatri²

*Correspondence:
rakeshk Dutta@gmail.com
¹ National Institute
of Technology, Hamirpur,
Himachal Pradesh Pin No:
177005, India
Full list of author information
is available at the end of the
article

Abstract

The paper presents the investigation on the model unskirted/skirted footings (plus and the double box) on sand. Skirt depth, sand relative density, footing interface condition and skirted footing type were varied parameters. Skirt depth (D_s) varied in this investigation was from $0.25 B$ to $1.5 B$ (B , footing width). The results show that the footing geometry and the skirt increased the bearing capacity and improved the overall behaviour. The results further revealed that the lowest percentage improvement for the square shaped footing with $D_s/B = 0.25$ was 26.08% at a relative density of 60%, whereas the highest improvement for the double box shaped footing with $D_s/B = 1.50$ was 364.12% at a relative density of 30%. The settlement reduction factors with the use of skirt from this investigation ranged from 0.16 to 1.0 and depended on the pressure applied and the depth ratio of the skirt. Finally, for the settlement reduction factor, an empirical equation was developed. This expression can be used to calculate the settlement of the plus and double box shaped skirted footings on sand.

Keywords: Plus and double box skirted footing, Sand, Bearing capacity, Interface condition, Relative density, Settlement

Introduction

Civil engineers are always looking for innovative techniques for reducing the settlement and improving the bearing capacity of the subsoil. A large number of such techniques are available in literature. These techniques are costly, limited by the site condition and are difficult to apply to the existing footings in certain circumstances. In this context, skirted footings offer an alternative method which can be applied for the shallow footings. Skirted footings are generally constructed with steel or concrete. Such footings have a raft with a thin wall along its edge towards the subsoil. The skirt enters into the soil under the footing, making an enclosure where the soil is firmly confined. Inside the skirts, the confined soil acts as a single unit to transfer the structural load from the bottom edge of the skirt to the subsoil. Skirted footings can be used as an alternative to surface, pier and pile foundations for offshore structures, wind turbines, oil platforms, and jacket structures as reported by Byrne et al. [1]. The unskirted/skirted model plus and double box shaped footings were therefore used in the present work to study their behaviour through laboratory tests. Such unconventional geometry in certain cases is

required for static, economical and architectural reasons. Finally, their behaviour is compared with the conventional square shaped footing.

Background

For the successful performance of the footing, there are two independent criteria required to be satisfied with regard to under lying soils. The first one is that the pressure on the underlying soil should not exceed the bearing capacity and the second one is that the footing should not settle beyond acceptable limit. Reinforcing of soils began with the effort of Vidal [2]. This technique is now considered as a promising method for improving the bearing capacity and the reducing the settlement below the foundation soils. The study reported by Al-Aghbari and Mohamedzein [3] and El Wakil [4] concluded that the addition of skirt to shallow foundation can be considered as an alternative technique for improving the bearing capacity and reduction of settlement. The authors further added that the condition of the interface also effect the pressure-settlement behaviour of the skirted footing on sand. Further, it was concluded by researchers [4–8], that the skirts were more useful for the footing having a concern for the water scour. Researchers [8–13] performed the analysis using software for validating their model test result. Eid [8] reported that the settlement and the bearing capacity of the skirted footing were nearly equal to that of the pier foundations with similar width and depth. El Wakil [14] reported that the bearing capacity of the footing was directly and inversely proportional to the skirt depth and the relative density respectively of the sand. The use of skirts for improving the load-settlement response of circular footing on reinforced sand was explored by Elsaied et al. [15]. Based on 23 laboratory small scale model tests, it was concluded placing geogrid layers below the skirted footing improves the bearing capacity up to 7.5 times in comparison to the unconfined case. On similar lines with previous research studies, Sajjad and Masoud [16] examined the behaviour skirted circular footing on sand and reported an increase in bearing capacity and reduction in settlement up to 5 times and 8% with respect to footing without any skirt. Al-Aghbari and Mohamedzein [17] and Al-Aghbari et al. [18] demonstrated the applicability of skirts in improving the performance of shallow footings subjected to vertical and inclined loading respectively. By means of small-scale laboratory model studies, Mahmood et al. [19] extended the use of circular skirted footing in submerged gypseous soil and reported an improvement in the bearing capacity in the range of 1.92 to 2.27. Ghazavi and Mokhtari [20] and Davarci et al. [21] reported that the enhancement in the bearing capacity and decrease in the settlement of the footing can also be attained by improving its geometry. However, the use of uncertain geometry (plus and double box shape) of the skirted footings with a vertical concentric load has not been studied yet in the literature.

Materials and methods

This study uses Beas river sand whose grain size distribution curve and the properties are shown in Fig. 1 and Table 1 respectively. The sand having a specific gravity of 2.67 was used in this study and was classified as per IS-1498 [22] as a poorly graded (SP) sand. Consolidated drained triaxial test on a specimen (3.8 cm dia. and 7.6 cm height) was conducted to determine the friction angle of the sand. The confining pressure applied was within the range of 24.53 kPa to 196.20 kPa. Figure 2 shows the stress–strain and

Table 1 Physical properties of sand

Description	Value
Effective grain size, D_{10} (mm)	0.15
D_{30} (mm)	0.18
Medium grain size, D_{50} (mm)	0.20
D_{60} (mm)	0.22
Coefficient of uniformity, C_u	1.46
Coefficient of curvature, C_c	0.98
Classification	SP
Maximum dry unit weight (kN/m^3)	15.97
Minimum dry unit weight (kN/m^3)	13.06
Specific gravity	2.67

p' – q' plots for the sand. From the p' – q' plot, the friction angle for the sand was 36.06° and 41.72° , respectively, at a relative density of 30% and 60%.

The test setup consists of a test tank, a mechanism to apply a strain-controlled load and a system to acquire data. This test setup was used to conduct laboratory plate load test for the square, plus and the double box shaped unskirted/skirted footing on the sand. The dimensions of the both unskirted and skirted footings are as shown in Fig. 3. The footing (made from a steel plate of 1 cm thick) was used in this study. Steel plates (0.5 cm thick) were used to the model the skirt. Skirt was welded along the periphery of the footing under the base. The variation in the skirt depth (designated as D_s) was kept from $0.25 B$ to $1.5 B$. Dimensions of the square, double box and plus shaped footing were kept $L = B = 8$ cm. For the plus shaped footing, the flange thickness was kept as 2.6 cm. The footings with and without skirt are shown in Fig. 3. A Perspex sheet made test tank which was further strengthened with a steel frame was used in this study. This tank was used to carry out the experimental study. In order to

avoid the boundary effect which leads to additional stress and strain in the sand, the test tank has to be made with dimensions of 70 cm $\times$ 45 cm $\times$ 60 cm to accommodate the footing. The sand was poured in layers of 6 cm thickness in the test tank. To ensure homogeneity of the sand, for each layer of rise, three calibrated steel bowls

were kept in each layer. Compaction was done manually using a wooden rammer weighing 0.6 kg for achieving the desired relative density (30% and 60%). The relative density was restricted up to 60%, due to lack of load cell capacity to withstand further higher bearing pressure. On the universal testing machine, the tank was placed. The sand was filled in eight equal layers of 6 cm each up to a height of 48 cm. The requisite dry mass of the sand to fill a 6 cm layer was calculated using a unit weight at a relative density to be achieved in the tank as well as the volume of each layer. The unit weight and relative density of the sand was used in the present study in between 14.09 kN/m³ to 14.96 kN/m³ and 30%, to 60% respectively. The sand corresponding to each layer of 6 cm was poured into the test tank. Then, the desired relative density was achieved manually using the wooden rammer weighing 6 N. The required blow count for each layer of 6 cm was obtained by trial and error. Then the top surface of the prepared sand bed was levelled using sharp straight steel plate, and the model footing was then placed on the compacted sand surface and then the test was carried out. The skirted footing was mounted by moving the footing with skirt into the already prepared sand bed by applying compression with universal testing machine on the top surface of the footing till its bottom touches the top of the prepared sand bed, when positioning the skirted footing no heave was observed. The data recording was set to zero immediately upon positioning the skirted footing before the beginning of the load-settlement measurement and the load was applied to the skirted footing using a strain rate of 0.24 mm/min. The test was continued up to a (s/B) ratio of 30%. In order to ensure the replication of the test results, every test in the test tank was repeated twice. At the end of each test, a sand layer up to $3B$ was removed from the base of the skirt edge and the same was replaced with the fresh sand and the desired relative density. The replacement of the sand depth ($3B$ below the skirt edge level) was considered as per Eid et al. [23].

Results and discussions

Unskirted footing's bearing pressure and bearing capacity

The standard plot of 30% and 60% vertical pressure with settlement ratio for all unskirted footings is shown in Fig. 4. It is appropriate to mention here that the bearing capacity corresponding to the peak pressure is taken if the clear peak was observed in the curve. If the peak pressure in the plot was not found, the bearing capacity was taken as the minimum of that corresponding to at least 10% of the settlement ratio or obtained using a double tangent method. The calculated bearing capacity at different relative density and interface condition is presented in Table 2. It is also important to mention here that because of the same area, the bearing capacity of the square and double box footing was observed the same. A study Table 2 reveals that the bearing capacity increases with the change in the condition of the interface from partially rough to rough. For example, the bearing capacity was 65.50 kPa, 65.50 kPa and 74.29 kPa respectively in the partially rough interface condition for the square, double box and plus shaped footing at a relative density of 30% whereas for the rough interface condition, the bearing capacity was 73.30 kPa, 73.30 kPa, and 91.43 kPa respectively for the square, double box, and plus shaped footings. The results were further analyzed and compared to the multi-edge footing's advantage over the square footing. To this end, the ultimate bearing capacity

Fig. 4 Pressure-settlement ratio plot for all the surface footings with interface (a) partially rough (b) rough

Table 2 Bearing capacity of unskirted footings at different interface condition

Rd (%)	Ultimate bearing capacity (kPa)							
	Partially rough interface				Rough interface			
	δ	Square	Plus	Double box	δ	Square	Plus	Double box
30	22.9	65.50	74.29	65.50	36.46	73.30	91.43	73.30
60	27.32	228.31	231.43	228.31	40.66	268.93	270.00	268.93

(q_{skp}) of the plus shaped unskirted footing at a given relative density was normalized at the same relative density with the ultimate bearing capacity (q_{su}) of the square footing. The results are tabulated in Table 3. This table shows that the ratio (q_{skp}/q_{su}) for the present unskirted plus shaped footing falls between the results reported by Davarci et al. [21]. It is appropriate to mention here that Davarci et al. [21] reported the ratio (q_{skp}/q_{su}) corresponds to sand at a relative density of 25% and 75% and the footing area of the plus shaped was 104 cm². The footing area used in the current study was 35 cm² and the relative sand density was 30% and 60%. The study of Table 3 suggests that the ratio (q_{skp}/q_{su}) decreases with the increase in the relative density of the sand. This observation was found consistent with the one reported by Davarci et al. [21]. This can therefore be inferred that experimental results validate the reported results in the literature and can be used as the basis for determining the benefit to be obtained from skirt usage.

Skirted footing's bearing pressure

The variation of vertical pressure with settlement ratio is shown in Figs. 5 and 6 for all skirted footings for different D_s/B ratio corresponding to the relative density of 30% and 60%. Study of Figs. 5 and 6 reveals that the vertical pressure increases with the increase in D_s/B ratio from 0.25 to 1.5 for the given relative density. The increase in vertical pressure can be attributed to (i) the containment effect provided by skirts which may lead to increase in shear strength of sand locally (ii) the overburden pressure of sand present between base of the skirt up to the top of footing which changes the behavior of footing from shallow for a footing without skirt to the embedded for skirted footing and (iii) the skin friction generated at skirt-soil interface. Needless to say, the double box footing results with skirt reveal that adding the skirt between the square skirted footing (double box footing) also improves the sand's vertical pressure. Figures 5, 6 also show that the skirted plus and double box footings were more effective in improving vertical pressure than the skirted square footings.

Influence of skirt depth on bearing capacity

The pressure-settlement ratio plots were used to calculate the footing bearing capacity shown in Figs. 5 and 6 with a skirt depth ratio of 0.25 and 1.5 corresponding to a relative density of 30% and 60%. The procedure reported by Khatri et al. [24] and Gnananandarao et al. [25] was followed for determining the bearing capacity. The experimental bearing capacity of the square, plus and double box shaped footings were tabulated in Table 4. Based on the above, the experimental bearing capacity was noted for the rough interface as 106.20 kPa and 230 kPa for the square footing, 125.71 kPa and 290.00 kPa for the plus shaped footing and 133.00 kPa and 304.00 kPa

Table 3 Comparison of present (q^{skp}/q^{su}) with the one reported in literature

Relative density (%)	q_{skp}/q_{su}	References
25	1.44	Davarci et al. [21]
30	1.24	Present work
60	1.10	Present work
75	1.06	Davarci et al. [21]

for the double box footing corresponding to D_s/B of 0.25 and 1.50 respectively. The percentage improvement corresponding to a relative density of 30% and 60% is tabulated in Table 5. This table reveals that the percentage improvement in bearing

Table 4 Bearing capacity of skirted footings before and after deduction of the skin friction for partially rough and rough interface

Rd (%)	D _s /B	Ultimate bearing capacity (kPa) before and after deduction of the skin friction											
		Partially rough interface						Rough interface					
		Square		Plus		Double box		Square		Plus		Double box	
		Before	After	Before	After	Before	After	Before	After	Before	After	Before	After
30	0.25	106.2	106.15	125.71	125.66	133	132.95	114	113.86	137.14	137	147	146.86
	0.5	135	134.90	160	159.90	170	169.90	140	139.72	177	176.72	188.77	188.49
	1	186	185.80	225	224.80	238	237.80	191	190.43	250	249.43	258	257.43
	1.5	230	229.70	290	289.70	304	303.70	235	234.15	320	319.14	326	325.15
60	0.25	312.5	312.44	313.43	313.37	314.06	314.00	339.06	338.97	340	339.91	342.19	342.10
	0.5	382.81	382.70	385.71	385.60	387.5	387.39	409.38	409.20	411.43	411.25	412.5	412.32
	1	497.72	497.51	503	502.79	509.16	508.95	546.08	545.72	548.57	548.21	552.53	552.17
	1.5	593.95	593.64	623	622.69	633.39	633.08	640.2	639.67	646	645.47	653	652.47

Table 5 Percentage improvements in bearing capacity of square, plus and double box shaped skirted footings

Footing shape	Improvement in bearing capacity (%)				
	D_s/B	Relative density (Rd) = 30%		Relative density (Rd) = 60%	
		Partially rough	Rough	Partially rough	Rough
Square	0.25	62.14	55.53	36.87	26.08
	0.50	106.11	91.00	67.67	52.22
	1.00	183.97	164.67	118.00	103.06
	1.50	251.15	226.06	160.15	138.05
Plus	0.25	91.92	87.09	36.88	26.43
	0.50	144.27	141.47	67.67	52.99
	1.00	243.51	241.06	118.00	103.98
	1.50	342.75	336.56	160.15	140.21
Double box	0.25	103.05	100.55	37.56	27.24
	0.50	159.54	157.53	69.72	53.39
	1.00	263.36	251.98	123.01	105.45
	1.50	364.12	344.75	177.42	142.81

capacity for the skirted footing compared to unskirted footings at a relative density of 30% for the partially rough interface was 62.13% and 251% for the square footing, 91.92%, and 342.75% for the plus shaped footing, and 103.05% and 364.12% for the double box footing corresponding to D_s/B of 0.25 and 1.50 respectively. The bearing capacity was slightly higher for the plus and double box shaped skirt footings when compared to the skirted square footing as like unskirted footings. Finally, among the three footings, the lowest percentage increase in bearing capacity was 26.08%, corresponding to 60% of the relative density for the square shaped footing ($D_s/B = 0.25$), while the highest improvement was 364.12%, corresponding to 30% of the relative density for the double box footing ($D_s/B = 1.50$). It can be concluded that the skirts were most effective with partially rough interface and resting on low relative density sand to improve the bearing capacity.

Influence of skirt depth on bearing capacity ratio with respect to relative density

The effect of skirt depth on the bearing capacity ratio (BCR , ratio of skirted plus and double box footing bearing capacity to unskirted square footing bearing capacity) is shown in Fig. 7 for square, plus and double box shaped footing. Figure 7 shows that the increase in bearing capacity ratio was higher for the relative density of 30% compared to 60% relative density and regardless of skirt length, footing shape and sand footing interface. From the BCR values, the bearing capacity of the plus and the double box shaped footings can be calculated using the bearing capacity of the unskirted square footing. Before generalising the above statement, more research is needed on prototype of these kinds of footings. Finally, highest BCR was observed at $D_s/B = 1.50$ corresponding to a relative density of 30% which implies that provision of skirt was more effective in low relative density sand regardless of the shape of the footing.

Fig. 7 Variation of bearing capacity ratio and with skirt depth ratio for the footing, **a** square; **b** plus; **c** double box

Influence of skirted footing shape on bearing capacity

To separate the effect of skirted footing shape, skirt skin resistance was calculated as like deep (pile) foundation i.e. $Q_s = \sigma_{avg} K \tan \delta A_s$ where A_s is the surface area of the skirt. The earth pressure coefficient (K) was assumed corresponding to at rest condition which is $1 - \sin \phi$. The skin resistance was divided by footing plan area to provide bearing pressure on account of skin friction. This additional bearing pressure was subtracted from the bearing capacity of the footings obtained experimentally in the laboratory. The bearing capacity after the deduction for the skirted square, plus and double box shaped footings were also given in Table 4 both for the partially rough and rough interfaces at a relative density of 30% and 60%. The study of this table reveals that when compared to the skirted square footing, the skirted plus and double box shaped footings have shown improved bearing capacity. For example, at a relative density of 30%, the bearing capacity for the square shaped skirted footing at a D_s/B of 0.25 was 106.15 kPa after deduction of skirt skin resistance for the partially rough interface whereas the bearing capacity was increased to 125.66 kPa and 132.95 kPa just by changing the shape of skirted footing to plus and double box. Similar observations were noted at other relative density and skirt depth ratio. This improvement in the bearing capacity was entirely due to the skirted footing shape effect. The contribution for the skin resistance was almost negligible as evident from Table 4 for the square, plus and the double box shaped footings. Further research is suggested to equate the skin resistance obtained theoretically with the one obtained experimentally which was beyond the scope of the current study as the experiments were not carried out in this study for the embedded skirted footings. However, the analysis data on embedded footing by Lyamin et al. [26] and skirted footing by Khatri and Kumar [27] based on finite elements limit analysis suggests that the skin friction generated by skirts increases the BCR up to 20% for rough strip footing and 30% for rough circular footing.

Settlement reduction factor

From the pressure settlement ratio plot, the settlement corresponding to a pressure of 25 kPa to 200 kPa for footing with (S_s) and without (S_f) skirt was determined. To describe and compare the results, the settlement reduction factor (SRF , S_s to S_f ratio) was used. For the unskirted/skirted square footings, a total of 300 data points collected from the pressure settlement ratio plot were used. The data collected has not been presented in this article due to its vast amount. From the data point of the square footing, an equation was proposed using non-linear multiple regression analysis to predict the SRF for the square footing.

$$SRF_{Squarefooting} = e^{(1.32r\phi - 0.09 \frac{D_s}{B} + 0.03\sigma + 69.44)} \quad (1)$$

The statistical parameters such as coefficient of determination (R^2), modified multiple determination coefficient (adjusted $R_{adjusted}^2$), standard error (SE) and confidence level (CL) for Eq. (1) are respectively 0.91, 0.83, 0.17 and 95%. Using the “ F ” and “ t ” measures, respectively, the importance of the multiple regression coefficients as a

Fig. 8 Plot between targeted and predicted settlement reduction factor for **a** partially rough interface; **b** rough interface

whole and the value of the multiple regression coefficients are conducted. From both checks all the parameters are found viz. D_s/B , σ , ϕ and r important to the model. The r value for the rough and rough interface condition for the skirted footing were 0.83 and 1.00 respectively. The SRF for the plus and double box shaped footings was correlated to the SRF of the square footing and the coefficient obtained from this analysis was 0.99 and 0.98 for the multi-edge plus and the double box shaped skirted footing and the obtained expression were as given below as

$$SRF_{\text{Plus shaped footing}} = 0.99 \times SRF_{\text{Square footing}} \quad (2)$$

$$SRF_{\text{Double box shaped footing}} = 0.98 \times SRF_{\text{Square footing}} \quad (3)$$

Fig. 9 Comparison of *SRF* with literature

A comparison of the predicted settlement reduction factor (*SRF*) with the one obtained experimentally is shown in Fig. 8. This figure reveals that the coefficient of determination (R^2) for different cases falls in the range of 0.902 to 0.978 indicating a good fit. Further, Fig. 8b reveals that the experimental and predicted values of *SRF* for all the footings with partially rough interface falls inside the $\pm 20\%$ lines whereas few of the values obtained for the *SRF* for all the footings with rough interface falls outside the $\pm 20\%$ lines as evident from Fig. 8a. Further, the average deviation in the predicted *SRF* with respect to the one obtained experimentally was about 8% for all the footings. In order to validate the *SRF* obtained from Eq. (1), the results were compared with the *SRF* of circular and square skirted footing calculated from the data reported by Al-Aghbari and Mohamedzein [17] and Eid [8] respectively. The results are shown in Fig. 9. Study of this figure reveals that the variation is $\pm 10\%$. It implies that the proposed equation can be used for reliable prediction of settlement reduction in case of skirted footings.

Conclusion

The behaviour of unskirted/skirted square, plus and double box shaped footing on sand with a concentric vertical load through a laboratory model study was investigated. In a model test tank, a total of 60 model tests were performed to measure improved bearing capacity and reduced settlement of a square, plus and double box footing with and without skirt. The following conclusions are drawn from the preceding:

1. Skirt and footing geometry increased the bearing capacity and improved pressure settlement behaviour.
2. The lowest percentage improvement was 26.08% at a relative density of 60% in plus shaped footing with $D_s/B=0.25$ whereas the highest improvement was 364.12% at a relative density of 30% with $D_s/B=1.50$.
3. In all situations, the increase in the bearing capacity was more in the case of partially rough interface footing than in the case of rough interface footing. Nonetheless, for

the loose sand, the geometry along with the skirt attached to the footing may be an alternate technique for ground improvement.

4. In terms of the settlement reduction factor of the square footing which can be used to estimate the settlement of the plus and double box shaped footing with skirt and resting on sand, an empirical equation for the settlement reduction factor for the plus and double box shaped footing is suggested.
5. Depending on the pressure applied and the skirt depth ratio, the settlement reduction factors obtained for footing with skirt were in the range of 0.16 to 1.0.

Abbreviations

L : Footing length; B : Footing width; B : Flange/web thickness of plus footing; D_s : Depth of the skirt; s : Settlement of the footing; q_{skp} : Bearing capacity of the plus shaped footing with skirt; q_{su} : Bearing capacity of the square footing without skirt; R_d : Relative density of sand; Φ : Friction angle of the sand; C_u : Uniformity coefficient of the sand; C_c : Coefficient of curvature of the sand; σ : Stress (kPa) applied on the footing; r : Coefficient of roughness; Q_s : Skirt skin resistance; σ_{avg} : Overburden pressure; K : Earth pressure coefficient at rest; δ : Interface friction (between footing and sand); A_s : Surface area of the skirt; S_s : Settlement of the footing with skirt; S_f : Settlement of the footing without skirt; F and t : Model accuracy measures; R^2 : Coefficient of determination; $R^2_{adjusted}$: Modified multiple determination coefficient.

Authors' contributions

All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interest.

Author details

¹ National Institute of Technology, Hamirpur, Himachal Pradesh Pin No: 177005, India. ² Indian Institute of Technology, Dhanbad, Jharkhand, India.

Received: 23 April 2019 Accepted: 31 January 2020

Published online: 12 February 2020

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