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Pressure settlement ratio behavior of plus shaped skirted footing on sand

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Abstract

The paper presents the results of the pressure-settlement ratio behaviour of plus shaped footing with and without skirt resting on sand. The study was carried out by varying the normalised skirt depth, relative density of sand and interface condition of the footing with sand. The results of this study revealed the improvement in the pressure-settlement ratio behaviour, bearing capacity and decrement in the settlement with the addition of the skirt to the plus shaped footing. The lowest and highest bearing capacity ratio observed was 1.26 and 3.90 corresponding to a relative density of 60 % and 30 % and at a normalised skirt depth of 0.25 and 1.50 respectively. Finally, the results obtained from this study were compared with the results of the H shaped skirted footing reported in literature.

Keywords: Plus shaped footing, bearing capacity, normalised skirt depth, interface condition, relative density.

1. Introduction

Traditionally square, circular and rectangular footings were used in geotechnical engineering to transfer the load of the super structure safely to the foundation soil. In present day era, multi storey buildings with asymmetric plan (E, N, T and H shape in plan) are being constructed in urban and metropolitan areas globally due to their attractive aesthetic appearance, economic and architectural reasons. For the construction of such asymmetric plan shaped buildings, similar shape of the footing is required. These shapes of the footings were termed as multi-edge footings (Jaiswal and Sengupta, 2017; Dawarci et al 2014). Further, laboratory test on the model footings with different geometries (Plus shape, H-shape and T-shape footings) was performed by Dawarci et al(2014)and reported that the bearing capacity of these multi-edged footings was slightly greater than the bearing capacity of the square footing having similar width. Numerical study to observe the failure behaviour of the soil beneath Plus, T and H shaped footing was conducted by Ghazavi and Hadiani (2005) and reported the development of shear zones in between the multi edges results in the generation of the passive force in the other parts and thus require more load to extend the shear zone in larger areas to bring the soil to the failure stage. Further, along with the use of multi-edge footings to increase the bearing capacity, research efforts were directed towards the use of skirt with the traditional footings(Al-Aghbari and Mahamedzein (2004); Al-Aghbari (2007); Al-Aghbari and Dutta (2008); Wakil (2010); Eid (2013); Khatri et al (2017)). These studies suggested that the use of skirt leads to significant increase in bearing capacity at a given pressure and it's use was more beneficial in loose sand than in medium dense or dense sand. Recently, Gnananandarao et al (2018) reported the performance of H-shaped footing on sand by varying the relative density in the range of 30 %-60 %. The obtained result by Gnananandarao et al (2018) confirmed the observations of Dawarci et al(2014) with regard to multi-edge footings and further justifies the findings of Khatri et al (2017) on the use of skirted footings. However, there is a lack of research with regard to plus shaped footing with skirt in literature. In the present paper, the results of the pressure-settlement ratio behaviour of the plus shaped footing with and without skirt resting on sand were discussed. The obtained results were further compared with the H shaped footing with skirt reported by Gnananandarao et al (2018).

2. Materials used and experimental procedure

The investigation was carried out on locally available sand in Hamirpur, Himachal Pradesh, India. The sand had a specific gravity of 2.67. The sand has D_{10} = 0.15 mm, D_{30} = 0.18 mm and D_{60} = 0.22 mm. The coefficient of uniformity (C_u), coefficient of curvature (C_c), minimum and maximum dry unit weight of the sand are 1.46, 0.98, 13.06 kN/m^3 and 15.97 kN/m^3 respectively. Accordingly the sand was classified as poorly graded (SP) in accordance with IS 1498 (1970). The sand was washed prior to experimental study in order to remove the organic matter and fines. It was reported by Prasanth and Kumar (2017)that the highest bearing capacity for the circular footing was observed at a normalized skirt depth of 2.0 and a relative density of 30 % in comparison to the circular footing without skirt at the same relative density and the normalised skirt depth. It was reported by Wakil (2013) that the skirts attached to the circular footing were more beneficial for the sand having relative density less than 65 %.

Therefore, the relative densities were varied from 30 % to 60 % in this investigation keeping in view the observations reported above in literature for the circular footing. The sand had a friction angle of 36.06°, 38.64°, 39.86°, and 41.72° corresponding to a relative density of 30 %, 40 %, 50 % and 60 % respectively and were determined using consolidated drained triaxial test. Steel plate of thickness 10 mm and 5 mm were used to prepare the plus shaped footing and the skirt respectively. The steel plate was cut into plus shapes to prepare the footings. To the periphery of the plus shaped footing, skirt was accurately welded under the base. Further, normalised skirt depths adopted for the study of traditional footings in literature (Al-Aghbari and Mahamedzein (2004); Al-Aghbari (2007); Al-Aghbari and Dutta (2008); Wakil (2010); Eid (2013); Khatri et al (2017); Gnananandarao et al (2018); Prasanth and Kumar (2017); Wakil (2013);Al-Aghbari, Mohamedzein (2006))were in the range of 0.05 to 2. Hence, the normalised skirt depth varied in this study was from 0.25 to 1.5. The flange width (B) and overall depth (L) for the plus shaped footing were kept 80 mm each. Thickness of the flange and the web of the plus shaped footing were 26 mm each. The area of the multi-edge plus shaped footing was 3500 mm^2. The schematic of the plus shaped footing with and without skirt was shown in Figure 1. The footing and the skirt was made rough by gluing the sand particles to the base of the plus shaped footing as well as to the inner surfaces of the skirt whereas no such sand particles were glued to the base of the plus shaped footing as well as to the inner surfaces of the skirt for the partly rough condition. The interface friction angle determined from the direct shear test for the partly rough condition and corresponding to a relative density of 30 %, 40 %, 50 % and 60 % were 22.90°, 23.61°, 24.51° and 27.32° respectively whereas for the rough condition, the interface friction angles were 36.46°, 38.07°, 39.03°, 40.66° corresponding to a relative density of 30 %, 40 %, 50 % and 60 % respectively. The tests were performed in a test tank having dimensions 700 mm × 450 mm × 600 mm. To prepare the sand bed, the tank was filled with 8 equal layers of 60 mm each up to a height of 480 mm.

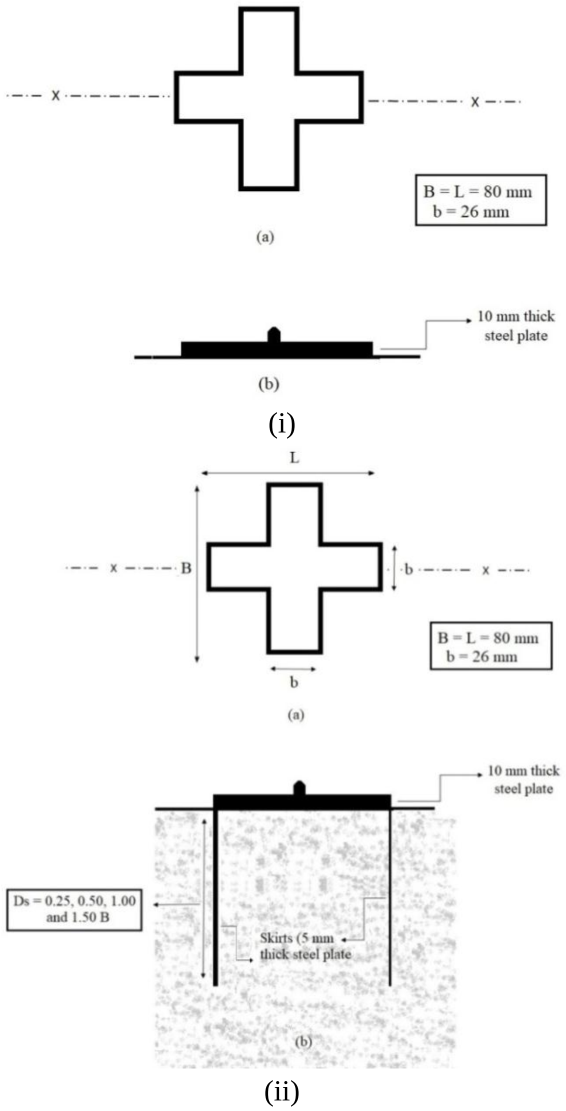

Fig. 1. Plus shaped footing (i) without skirt (ii) with skirt where
(a) plan and (b) cross section along x-x.

For the preparation of each layer, the weight of the sand corresponding to a given relative density was arrived by knowing the unit weight and the volume of the layer. The sand was then poured from a constant height to fill the given layer and was compacted manually using a wooden rammer of 6 N. The number of required blows for compaction, for a given relative density, was arrived by trial and error.

It was ensured that the difference in measured relative densities was within ± 1 %. The test on the prepared sand bed was performed with a strain controlled loading frame of 50 kN and with an employment of load cell of 5 kN capacity. All the tests were carried out at strain rate of 0.24 mm/min. For testing plus shaped footing without skirt, the model footing was placed on the surface of the prepared bed.

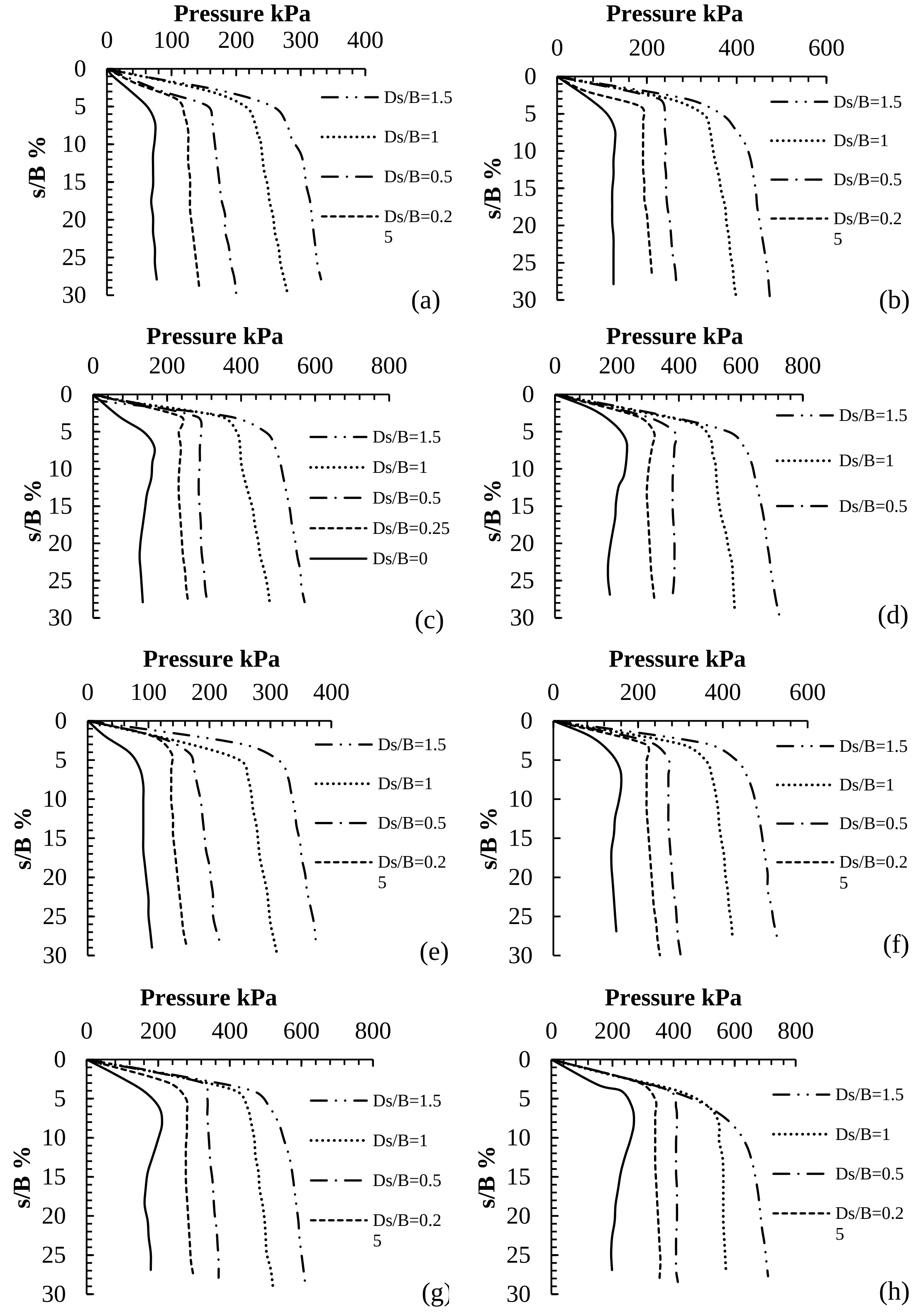

Fig. 2. Pressure-settlement ratio of plus shaped footing with partly rough (a-d) and completely rough (e-h) interface and with relative density of 30% (a, e), 40% (b, f), 50% (c, g) and 60% (d, h).

The plunger for the load application was brought in contact with the metal ball placed on the top of the plus shaped footing at the centre of gravity and the load test was continued thereafter. In case of plus shaped footing with skirt, the footing was pushed in to the sand by applying the load till the footing base was just in contact with the top surface of the sand. No heave around footing was noticed by such placement procedure as reported by Khatri et al (2017) for the traditional footing. It implies that the marginal densification of the sand around the skirt periphery may not have significant effect on the ultimate bearing capacity of the footing.

The test was then continued similar to the plus shaped footing without skirt. All the tests were carried out up to s/B ratio of 30 %. For each of the test, the load-settlement observations were recorded digitally with a data-logger. Each test was performed thrice in order to ensure the repeatability of the test results.

Table 1
Bearing capacity for the plus shaped footing at different normalised skirt depth and relative density

Relative density (%)	Normalised skirt depth (D_s/B)	Bearing capacity (kPa)	
		Partly rough	Rough
30	0.00	74.29	91.43
	0.25	125.71	137.14
	0.50	160.00	177.00
	1.00	225.00	250.00
	1.50	290.00	320.00
40	0.00	128.57	160.00
	0.25	191.43	220.00
	0.50	240.00	271.43
	1.00	335.00	372.00
	1.50	415.00	462.00
50	0.00	165.71	210.57
	0.25	237.14	280.00
	0.50	291.43	341.14
	1.00	390.00	456.00
	1.50	489.00	549.00
60	0.00	231.43	270.00
	0.25	313.43	340.00
	0.50	385.71	411.43
	1.00	503.00	548.57
	1.50	623.00	646.00

3. Results

3.1 Pressure-settlement ratio behaviour of plus shaped footings with and without skirt

The pressure-settlement ratio curves for the plus shaped footing with and without skirt were presented in Figure 2. Study of Figure 2 revealed that addition of skirt to the plus shaped footing improved its pressure-settlement ratio behaviour. For example, from Figure 2, a clear peak was observed corresponding to a relative density of 40 %, 50 % and 60 % both for the partly rough as well as rough condition for the plus shaped footing without skirt indicating a general shear failure. The average settlement ratio at failure for the plus shaped footing without skirt was about 8 % both for the partly rough as well as rough condition as evident from Figure 2.

Table 2
Bearing capacity ratio for the plus shaped footing at different normalised skirt depth and relative density

Relative density (%)	Normalised skirt depth (D_s/B)	Bearing capacity ratio (BCR)	
		Partly rough	Rough
30	0.00	1.00	1.00
	0.25	1.69	1.50
	0.50	2.15	1.94
	1.00	3.03	2.73
	1.50	3.90	3.50
40	0.00	1.00	1.00
	0.25	1.49	1.38
	0.50	1.87	1.70
	1.00	2.61	2.33
	1.50	3.23	2.89
50	0.00	1.00	1.00
	0.25	1.43	1.33
	0.50	1.76	1.62
	1.00	2.35	2.17
	1.50	2.95	2.61
60	0.00	1.00	1.00
	0.25	1.35	1.26
	0.50	1.67	1.52
	1.00	2.17	2.03
	1.50	2.69	2.39

This implies that the observed behaviour was independent of the roughness condition of the plus shaped footing without skirt. This observation was consistent with the literature Gnananandarao et al (2018) with regard to the H shaped footing. With the addition of the skirt to the plus shaped footing, the clear peak observed in the pressure settlement ratio curve corresponding to a relative density of 40 %, 50 % and 60 % as evident from Figure 2 gradually vanished with the increase in the normalised skirt depth from 0.25 to 1.5 indicating a local shear failure. This is attributed to the fact that with the increase in the normalised skirt depth of the plus shaped footing; the failure pattern becomes localized below the tip of the skirt. The observed behaviour with regard to plus shaped skirted footing was independent of the roughness condition of the base as well as inner surfaces of the skirt. This observation was consistent with the literature Gnananandarao et al (2018) with regard to the H shaped footing. A close examination of the Figure 2 further reveals that at a given pressure, a lesser settlement ratio was observed for the plus shaped skirted footing in comparison to the plus shaped footing without skirt. This observation was consistent at all the relative density, the normalised skirt depth and the roughness condition.

3.2 Effect of skirt depth on the bearing capacity

The bearing capacity of the plus shaped footing was determined from the pressure-settlement ratio curve as shown in Figure 2. The bearing capacity was taken corresponding to a peak pressure or a pressure corresponding to s/B of 10 % whichever occurs earlier. Additionally if the clear peak was not visible in the pressure-settlement ratio curve, then the bearing pressure was obtained using double tangent method and was adopted as peak pressure and the same was compared with the pressure corresponding to s/B = 10%. The bearing capacity for the plus shaped footing without skirt was tabulated in Table 1.

Table 3
Bearing capacity of multi-edge H shaped footing with and without skirt
(after Gnananandarao et al. 2018)

Normalised skirt depth (Ds/B)	Rd	Bearing capacity (kPa)	
		Partly rough	Rough
0	30%	87.76	106.12
0.25		136.73	159.18
0.5		171	197.96
1		248	270
1.5		312	335
0	40%	138.78	171.43
0.25		210.2	242.86
0.5		259.18	298.71
1		352	400.54
1.5		440	490
0	50%	171.43	214.29
0.25		248.98	285.71
0.5		302.04	344.9
1		414	462
1.5		510	566
0	60%	236.73	273.47
0.25		320.41	348.98
0.5		393.88	418.37
1		513.04	561
1.5		640	660

For the plus shaped footing with skirt, the bearing capacity was expressed in the form of a ratio by dividing it’s magnitude with the bearing capacity of the plus shaped footing without skirt. The bearing capacity ratio (BCR) at different relative density and normalised skirt depth was shown in Table 2.

Study of this table reveals that the addition of a skirt to the plus shaped footing resulted in a significant improvement in the bearing capacity ratio both for the partly rough and rough condition. For instance, the bearing capacity ratio of the partly rough and rough condition of the plus shaped footing resting on sand having a relative density of 30 % and normalised skirt depth of 0.25 was 1.69 and 1.50 respectively. With the increase in the normalised skirt depth to 1.5, the bearing capacity ratio of the plus shaped footing increased to 3.90 and 3.50 respectively at the same relative density. Further, from Table 2, the bearing capacity ratio of the partly rough and rough condition of the plus shaped footing resting on sand having a relative density of 60 % and normalised skirt depth of 0.25 was 1.35 and 1.26 respectively. With the increase in the normalised skirt depth to 1.5, the bearing capacity ratio of the plus shaped footing increased to 2.69 and 2.39 respectively at the same relative density. It is pertinent to mention here that the bearing capacity for the plus shaped footing without skirt was higher for the rough condition in comparison to the partly rough condition. This higher bearing capacity for the plus shaped footing under rough condition was attributed to higher interface friction between the plus shaped footing and the sand in comparison to the partly rough condition and thus requiring more load to bring the sand to failure. Further, the BCR of the plus shaped footing under rough condition was marginally smaller than the BCR of the partly rough plus shaped skirted footing for a given relative density of the sand and the skirt depth as evident from Table 2. Table 2 also reveals that the highest benefit of providing the skirt to the plus shaped footing was derived for the case of partly rough skirted footing at a relative density of 30 %. This observation was consistent with the literature (Al-Aghbari (2007); Al-Aghbari and Dutta (2008); Al-Aghbari, Mohamedzein (2006)) with regard to the traditional shaped skirted footings. Further study of Table 2 reveals that the bearing capacity ratio decreased with the increase in the relative density of the sand corresponding to given normalised skirt depth. This observation was consistent at both the roughness condition.

Table 4
Bearing capacity ratio of multi-edge H shaped footing with and without skirt

Normalised skirt depth (Ds/B)	Rd	Bearing capacity ratio	
		Partly rough	Rough
0	30%	1.00	1.00
0.25		1.56	1.50
0.5		1.95	1.87
1		2.83	2.54
1.5		3.56	3.16
0	40%	1.00	1.00
0.25		1.51	1.42
0.5		1.87	1.74
1		2.54	2.34
1.5		3.17	2.86
0	50%	1.00	1.00
0.25		1.45	1.33
0.5		1.76	1.61
1		2.41	2.16
1.5		2.97	2.64
0	60%	1.00	1.00
0.25		1.35	1.28
0.5		1.66	1.53
1		2.17	2.05
1.5		2.70	2.41

3.3 *Comparison with literature*

The comparison was attempted for the plus shaped skirted footing with the one available in literature for the H shaped skirted footing. The bearing capacity for the H shaped skirted footing for the partly rough and rough condition reported by Gnananandarao et al (2018) was shown in Table 3. The values reported in Table 3 were used to calculate the bearing capacity ratio. The calculated bearing capacity ratio for the H shaped skirted footing were shown in Table 4. Study of Tables 2 and 4 reveal that the bearing capacity ratio for the plus shaped footing was higher in comparison to the H shaped footing at all relative density and normalised skirt depth despite the fact that the plan area (4900 mm^2) of the H shaped skirted footing was more than the plan area (3500 mm^2) of the plus shaped skirted footing. The trend was same irrespective of the roughness of the footing. The higher bearing capacity ratio in case of plus shaped skirt footing in comparison to the H shaped skirted footing was attributed to the fact that the bearing capacity of the H shaped footing without skirt was higher than the bearing capacity of the plus shaped footing without skirt. Therefore, the improvement in the bearing capacity ratio of the plus shaped footing with the addition of skirt was slightly higher than that of the H shaped skirted footing. For more insight on this aspect a detailed numerical study with an attention towards failure pattern of both the footing is required.

4. Conclusion

A study on the pressure settlement ratio behaviour of plus shaped footing with and without skirt on sand and subjected to compressive load through a laboratory model study was investigated. Based on the results following conclusions were drawn. For the plus shaped footing without skirt a general and local shear was observed corresponding to relative a density of 40 %, 50 %, 60 % and 30 % respectively. With the addition of skirt to the plus shaped footing, the behaviour changes from general to local. This trend was independent of the roughness condition. The peak observed in the pressure settlement ratio curves for the plus shaped footing without skirt vanished as the normalised skirt depth changed from 0.25 to 1.5. This observed behaviour was independent of roughness condition and was consistent at other relative density. The bearing capacity of the plus shaped skirted footing was about 1.26 to 3.90 times the bearing capacity of the surface plus shaped footing considering the range of other parameters same. Settlement ratio at failure for the plus shaped footing without skirt was about 8 % both for the partly rough as well as rough condition. The bearing capacity of the plus shaped skirted footing was marginally smaller in comparison to the bearing capacity of the H shaped skirted footing. The BCR of the plus shaped skirted footing was slightly higher than the BCR of the H shaped skirted footing.

Notations

L	Length of footing
B	Width of the footing
b	Thickness of flange / web of plus shaped footing
D_s/B	Normalised skirt depth
s/B	Settlement ratio
C_u	Coefficient of uniformity
C_c	Coefficient of curvature
R_d	Relative density

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