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Study of bearing capacity of skirted irregular pentagonal footings on different sands

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ABSTRACT

Purpose: The paper presents an experimental and numerical study to evaluate the bearing capacity of unskirted, singly and doubly skirted irregular pentagonal footings on different sands (S1, S2, S3) at a relative density of 30 %. The skirt depth of the footing was varied from 0.0B to 1.5B (B is the width of the square footing).

Design/methodology/approach: The experimental and numerical study of the singly and doubly skirted irregular pentagonal footing resting on sands was modelled in a test tank and Plaxis 3D software respectively.

Findings: The results of this study reveal that the bearing capacity was higher for the skirted irregular pentagonal footings on sand S3 followed by sand S2 and S1. The lowest percentage improvement for the singly skirted footing on sand S3 was 18.51% at a $D_s/B = 0.25$ whereas the highest improvement was 90.81% at a $D_s/B = 1.50$ for the singly skirted footing on sand S2. The highest percentage improvement for the doubly skirted footing on sand S2 was 95.13% at a $D_s/B = 1.5$ whereas the lowest improvement was 23.70% at a $D_s/B = 0.25$ the doubly skirted footing on sand S3. The results further revealed that the numerically obtained bearing capacity was marginally higher in comparison to the one obtained experimentally for the footings on all sands. Further, the experimental results validated the results obtained numerically with an average deviation of 8%. The percentage improvement in the bearing capacity was higher for the irregular pentagonal footing resting on sand S2 in comparison to sand S3 and S1. The settlement response of the irregular pentagonal footings is unchanged by increasing the number of elements beyond 7700. Both the experimental and numerical studies revealed a linear elastic behaviour at $D_s = 0.5B$, while the experimentally obtained pressure-settlement ratio plot shows a clear failure at $D_s = 1B$ and 1.5B.

Research limitations/implications: The results presented in this paper were based on the experimental and numerical study conducted on small scale model footings. However, for the actual footings, further study is recommended using full-scale field size footings to generalize the results.

Originality/value: No experimental and numerical studies on singly and doubly skirted irregular pentagonal footings were conducted so far. Hence, an attempt was made in this article to predict the bearing capacity of these footings experimentally and using Plaxis 3D respectively.

Keywords: Bearing capacity, Sands, Friction angle, Pentagonal footing, Singly skirted, Doubly skirted

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PROPERTIES

1. Introduction

The design of the foundation requires the estimation of bearing capacity of the footings to a reasonable accuracy to affect the economy as a whole. Traditionally, the shallow footings with square, circular and rectangular shapes were used in the practice of geotechnical engineering. Under certain circumstances, however, due to economic and architectural reasons, footings are needed with unusual geometries (Pentagon Memorial, located southwest of the Pentagon in Arlington County, Virginia, is a permanent outdoor memorial) in which the super structure has similar shapes. As reported by [1,2], such footings were called multi-edge footings. Numerical analysis was performed by [3] using FLAC 3D to analyse the sand's failure behaviour under the multi-edge shallow footing. Laboratory tests were carried out by [2] on the multi-edge footings and confirmed that the bearing capacity of the multi-edge footing was higher than the bearing capacity of the square footing with the same width. Laboratory tests on the multi-edge H-shaped skirted footing were conducted by [4]. The results of this study revealed that the multi-edge H-shaped skirted footing has shown an improved bearing capacity compared to the square skirted footing. In view of the above, a detailed study of the laboratory on the model unskirted, singly and doubly skirted irregular pentagonal footings placed on different sands followed by a three-dimensional finite element analysis of the same is presented in this paper.

2. Background

It has been established the effectiveness of skirted footings such as strip [5-7], square [4, 8-12], circular [7, 13-24] and rectangular [12] that have been subjected to vertical or inclined loads in recent years through experimental investigations. Skirted footing numerical studies such as strip [7], square [10] and circular [7,24] have been carried out in literature. The above studies concluded that the skirted footings increase the bearing capacity with the increase in footing/skirt roughness (ii) square skirted bearing capacity was similar to the pier foundation bearing capacity of the same size (iii) circular skirted bearing capacity was higher than the skirted strip at the same depth of the skirt (iv) skirted footings on loose sand were more beneficial than those resting on medium or dense sand. Bearing capacity can also be achieved through improved geometry reported by [2,3]. According to [25], the use of skirts decreases the settlement caused by machine vibration, and the percentage decrease is influenced by the density of the soil and the frequency of vibration. Further, based on the computational analysis for both variations in the internal caisson compartment structure and the soil shear strength profile, it was concluded by [26] that the geometry induces major changes in the soil failure mechanisms as compared to a plain skirted mat. Despite the advantages of attaching skirts to conventional footings, [4] recently reported a study on multi-edge H-shaped footing with and without skirts on sand by varying the relative density and normalised skirt depth from 30 % to 60 % and 0.25 to 1.5 respectively and confirmed the results of [2] for the unskirted multi edges footing. More recently, [27] stated that unskirted/skirted plus and double box shaped footing increases the load carrying capacity of sand and improved the overall behaviour of foundation. Provision of an additional skirt below the base of the footing will further increase the bearing capacity as per [28]. A numerical as well as experimental study to determine the ultimate bearing capacity of unskirted, singly and doubly skirted hexagonal footings on different sands were reported by [29]. The novelty of this work is that till date no systematic study related to irregular pentagonal footing is available in literature. These types of footings are sometimes required for the architectural reason or for the construction of pentagon memorial. The present study presents the laboratory results obtained from the model irregular pentagonal unskirted, singly skirted (SS) and doubly skirted (DS) footings on different sands and the same were compared to the one obtained from the numerical study.

3. Materials used and experimental methods

This study uses different sands (designated as S1, S2 and S3). The effective size and specific gravity of the sands S1, S2 and S3 were 0.14, 0.45, 1.45 and 2.68, 2.67, 2.67 which were determined as per [30] and [31] respectively. The grain size distribution curves are reported elsewhere [29].

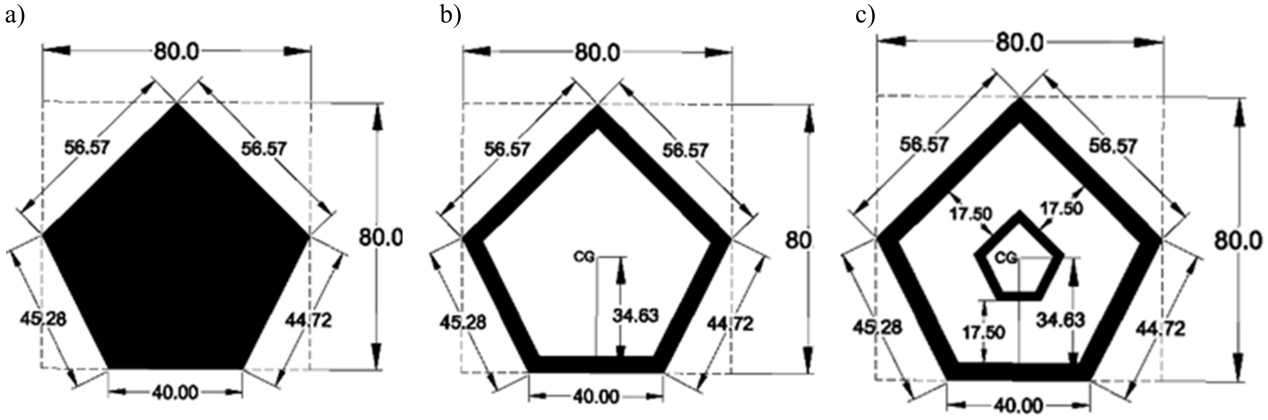

Fig. 1. Plan view of irregular pentagonal footing (a) unskirted (b) singly skirted (c) doubly skirted

Keeping the above in view, the friction angle of all the sands at a relative density of 30% were determined through consolidated drained triaxial tests as per [32] were performed on a specimen of 38 mm in diameter and 76 mm in height. The cell pressure applied varied between 25 kPa and 200 kPa. The angle of friction determined for the sands S1, S2, S3 was 33.37°, 36.52°, 39.47° respectively. The Young's modulus (corresponding to 50 % of the peak stress) for the sands S1, S2, S3 obtained from the stress- strain curves were 4.8 MPa, 5.2 MPa, 5.5 MPa respectively corresponding to a confining pressure of 50 kPa. The test set-up consists of a test tank (700 mm x 450 mm x 600 mm, made from the perspex sheet and further stiffened with a steel frame), pluviator, loading mechanism and data acquisition system to study the pressure settlement behaviour of unskirted/skirted pentagonal (singly and doubly) footings on sands. The footings were made of a 10 mm thick, mild steel sheet. The outer dimension of a square was selected as 80 mm x 80 mm. Inside this square, as shown in Figure 1, irregular pentagonal footing was built. The outer skirt of this pentagonal footing was made of a 5 mm thick steel plate and welded for the singly skirted footing around its outer edge. Another skirt made of a 2.5 mm thick mild steel plate was welded around the periphery at a distance of 17.5 mm from the inside of the outer skirt as shown in Figure 1. For both cases, the outer and inner depth of the skirt varied from 0 mm to 120 mm. The test tank size was maintained to prevent the restricting effects that would otherwise result in additional stresses and strains being generated in the sand. To prepare the sand bed, the tank was filled with eight equal layers of 60 mm each up to 480 mm height. Because the skirted footings were as reported in literature [7,18,20] more effective in loose sand. In view of this, all experiments were carried out at a relative density of 30% for all sands and were carried out up to a settlement ratio (s/B) of 20%. The sand weight corresponding to a given relative density was obtained by knowing the unit weight and the volume of the soil for each layer's preparation. Then the sand was poured from a constant height to fill the layer and compacted by hand using a wooden rammer of 6 N. The S1, S2 and S3 unit weight was maintained at 14.38 kN/m^3, 14.89 kN/m^3 and 15.15 kN/m^3 respectively in the test tank. The test was performed on the prepared sand bed using a 50 kN capacity and 5 kN strain-controlled loading frame and load cell respectively. All tests were performed using a 0.24 mm/min strain rate. To test the unskirted irregular pentagonal footing, the model footing was placed on the surface of the prepared bed. The plunger was brought into contact with the metal ball placed on top of the irregular pentagonal footing at the centre of gravity as shown in Figure 2 and then the load test was carried out. In the case of singly and doubly irregular pentagonal skirted footing after [12] and [4] the footing was placed into the sand by inserting the load until the base of the footing starts to hit the top surface of the sand. As reported for the footings by [12] and [4], heaving was not observed after this procedure around the footing. This means that the marginal densification of sand around the skirt's edge may not have a significant impact on the overall bearing capacity of the footing. Study then proceeded similar to the unskirted irregular pentagonal footing. Every test was performed three times and approximately similar results were obtained during each study, which meant that three tests should be adequate to replicate the repeatability of the results obtained. At the end of each test, the sand layer involved in failure was removed and replaced by fresh sand and the replacement depth was taken as 3B below the edge of the skirts as per [4,10,12]. For both the experimental and numerical studies, It's worth noting that if the clear peak in the curve is visible, the bearing capacity corresponding to the peak pressure is used. If the peak pressure in the plot could not be found, the bearing capacity was calculated using a double tangent method or the minimum of those corresponding to at least 10% of the settlement ratio as per [4].

Fig. 2. Placement of skirted irregular pentagonal footing on the sand bed

4. Numerical study

4.1. Problem definition and model parameters

A singly and doubly skirted irregular rigid pentagonal footing is placed over different sands with a horizontal surface of the ground. The plan view of the footings is shown in Figure 1. The various parameters used for the modelling are tabulated in Table 1. It is pertinent to mention here that for the experimental work, unsaturated sands were used in the test tank. But for the modelling the values of unsaturated as well as saturated unit weights were required in the PLAXIS software for the analysis. The interface strength factor was considered unity as mentioned in Table 1 for all cases. Cast iron has a Poisson ratio ranging from 0.2 to 0.26 as per [29]. As a consequence, a lower value of 0.2 is used for modelling. To compensate for smaller values of moduli at relatively shallow depths, the sand moduli S1 (4.8 MPa), S2 (5.2 MPa), and S3 (5.5 MPa) corresponding to a 50 kPa confining pressure is assumed to be constant with depth for numerical modelling as per [10]. For the study, a Mohr Coulomb model was used because it represents a ‘first order' approximation of the sands behaviour by estimating a constant average stiffness, resulting in faster computations to obtain a first estimate of deformations, while other soil hardening models take more computational time due to the formation of material stiffness matrix, which is decomposed in every phase as stated in the Plaxis 3D foundation material models manual version 1.5.

Table 1.
Properties used for modelling

Properties	S1	S2	S3
Saturated unit weight of soil, kN/m^3	18.83	19.12	19.29
Unsaturated unit weight of soil, kN/m^3	14.38	14.89	15.15
Internal friction angle (ϕo) at a relative density of 30%	33.37	36.52	39.47
Assumed Poisson’s ratio	0.3	0.3	0.3
Young’s modulus (E) of soil, MPa	4.8	5.2	5.5
Angle of dilatancy ($\psi = \phi - 30$), Deg.	3.37	6.517	9.47
Interface strength factor	1	1	1
Young’s modulus (E) of footing, GPa	210	210	210
Assumed Possion's ratio of footing	0.2	0.2	0.2

The footing is subjected to vertical downward concentric load. It is necessary to determine the ultimate bearing capacity (q_u) for: (i) 33.37°, 36.52° and 39.47° friction angles for sands S1, S2 and S3 respectively (ii) normalised skirt depth (D_s/B) varied from 0 to 1.5 (iii) Two different types of irregular pentagonal skirted footing (singly and doubly) as shown in Figure 3. Past researchers have done numerous works on singly skirted (strip, circular and square) footings, but they have not yet studied the singly and doubly skirted irregular pentagonal footings. Three-dimensional finite element analysis was performed to study the behaviour of an irregular unskirted, singly and doubly skirted pentagonal footing on different sands. A validated numerical model, including parametric variations, can solve the complexity of performing large numbers of laboratory experiments by taking into consideration the variations of different parameters.

4.2. Finite element meshing and boundary conditions

Typical numerical model for the irregular pentagonal skirted footings on the sands is shown in the Figure 4.

It is appropriate to mention here that the numerical model's outer boundary and the size of the footing were kept the same as used for the experimental study in order to avoid size or scale effect [33-34]. The stress contour '0.1q' (q is the stress applied due to its failure) is the ultimate significant isobar, beyond which the stress effect applied is considered negligible. The dimensions of the model were

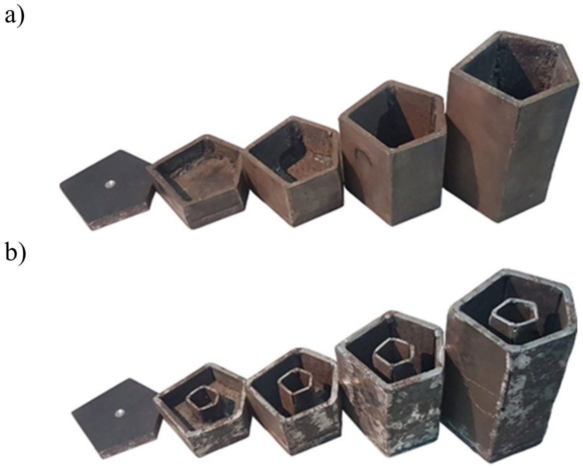

Fig. 3. Pentagonal footings (a) singly skirted (b) doubly skirted

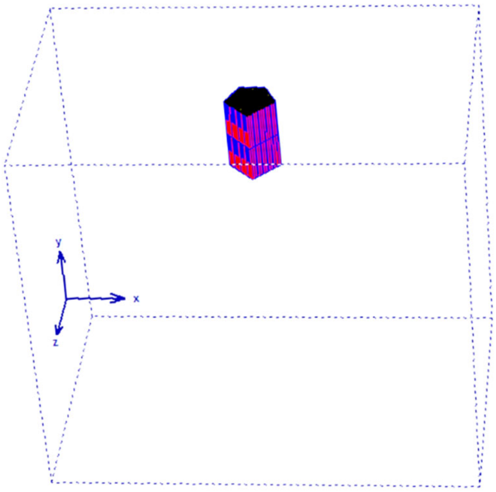

Fig. 4. Numerical model for the pentagonal skirted footing on sand

chosen in such a way that the geometry of the sand model boundaries did not cross the appropriate isobar. Increasing the number of elements beyond 7700 has no effect on the settlement response of the irregular pentagonal footings as confirmed by the mesh convergence study. Hence 7700 to 12000 numbers of elements with the average element size of 4×10^{-3} m has been used in the numerical analysis corresponding to different D_s/B ratio, where D_s and B are the skirt depth and width of the footing respectively. For the boundary conditions, PLAXIS automatically imposes a number of general fixities on the geometry model's boundaries. The model's bottom boundary is fixed in the present study and the model's ground surface is free in all directions. Vertical model boundaries are fixed in X and Z direction and free in Y direction with their normal neither in X nor in Z direction. The design has been discretized in a smaller number of 15-noded wedge elements to perform finite element analysis. Domain meshing is performed on the basis of fully automatic finite elements in the PLAXIS 3D program. There are five common meshing schemes (i.e. very rough, coarse, medium, fine, and very fine mesh), thus allowing the user to refine an area, line, or point further.

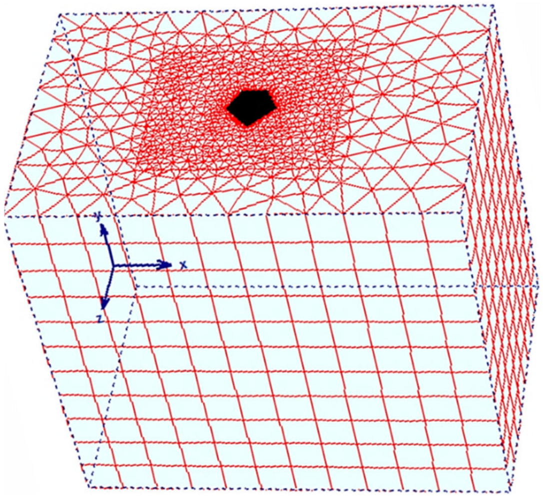

Fig. 5. Standard mesh used for numerical model

Figure 5 shows the standard mesh obtained for a numerical model. A very coarse mesh does not capture the domain's important characteristic responses. Besides optimally fine meshes, there are chances of numerical error accumulation, resulting in inaccuracy in the knowledge obtained. However, very fine meshing involves considerable computational time in order to decide the optimum mesh configuration for any simulation device. In this study, coarse to fine mesh is used near footing as shown in Figure 5.

5. Results and discussions

5.1. Bearing capacity of unskirted, singly skirted and doubly skirted irregular pentagonal footings

The experimentally obtained typical pressure and settlement ratio plot for the unskirted and singly skirted irregular pentagonal footings on sands S1, S2 and S3 are shown in Figure 6 corresponding to different skirt depths. The curves for the doubly skirted irregular shaped pentagonal footings are shown in Figure 7 for sands S1, S2 and S3 respectively.

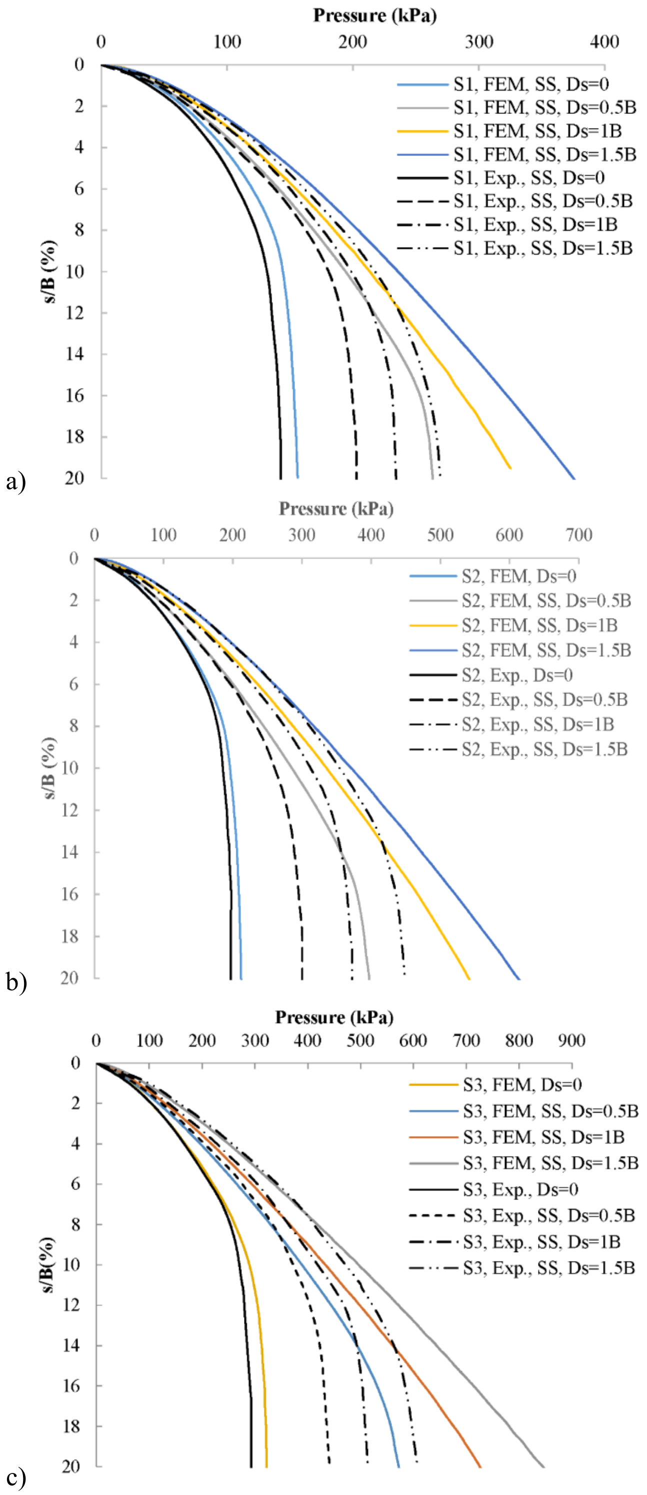

Fig. 6. Experimentally and numerically obtained pressure settlement ratio plot for the unskirted and singly skirted irregular shaped pentagonal footing on sand (a) S1 (b) S2 (c) S3 at a skirt depth (D_s) of 0B, 0.5B, 1B and 1.5B

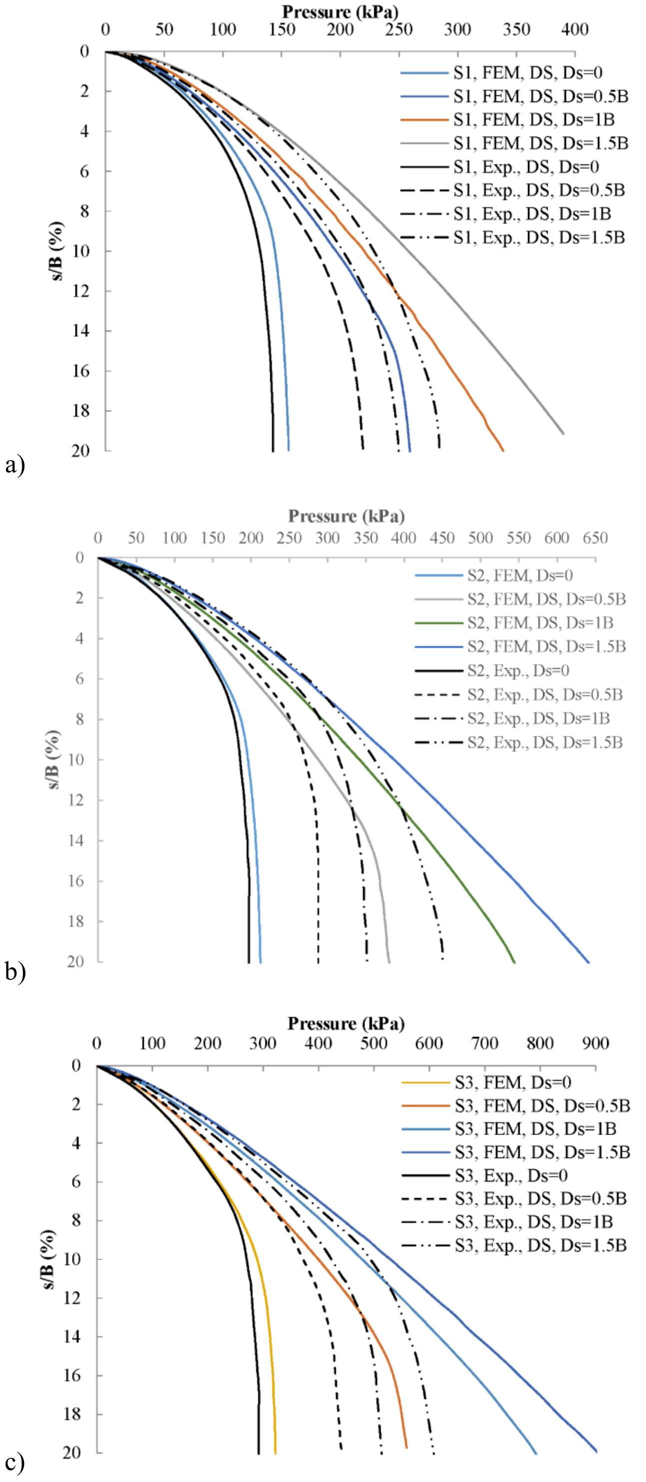

Fig. 7 Experimentally and numerically obtained pressure settlement ratio plot for the unskirted and doubly skirted irregular shaped pentagonal footing on sand (a) S1 (b) S2 (c) S3 at a skirt depth (D_s) of 0B, 0.5B, 1B and 1.5B

Table 2.
Bearing capacity of the unskirted, singly and doubly skirted Irregular pentagonal footing

D_s/B	Bearing capacity, kPa					
	S1		S2		S3	
	ϕ' =33.37°		ϕ' =36.52°		ϕ' =39.47°	
	D_{10} =0.14		D_{10} =0.45		D_{10} =1.45	
	Singly skirted	Doubly skirted	Singly skirted	Doubly skirted	Singly skirted	Doubly skirted
0.00	131	131	185	185	270	270
0.25	161	164	228	243	320	334
0.50	180	183	259	270	371	375
1.00	196	200	312	315	420	423
1.50	216	228	353	361	470	492

Table 3.
Numerically obtained bearing capacity of unskirted, singly and doubly skirted irregular pentagonal footings

Ds/B	Bearing capacity (kPa)					
	S1		S2		S3	
	ϕ' =33.37°		ϕ' =36.52°		ϕ' =39.47°	
	D10 =0.14		D10 =0.45		D10 =1.45	
	Singly skirted	Doubly skirted	Singly skirted	Doubly skirted	Singly skirted	Doubly skirted
0.00	145	145	196	196	289	289
0.25	171	174	246	255	355	359
0.50	192	195	285	290	389	400
1.00	212	220	334	342	433	480
1.50	235	258	370	389	500	532

These figures also include the curves for the unskirted irregular shaped pentagonal footings as well as curves obtained from the numerical study. The bearing capacity values obtained experimentally and numerically are given in Table 2 and Table 3 respectively. Table 2 study shows that the bearing capacity of the unskirted irregular pentagonal footing was 131 kPa, 185 kPa and 270 kPa respectively for sands S1, S2, and S3. For the singly skirted irregular pentagonal footing at a skirt depth of 1.5B for sands S1, S2 and S3 respectively, this bearing capacity was increased to 216 kPa, 353 kPa and 470 kPa. The bearing capacity further increased to 228 kPa, 361 kPa and 492 kPa for sands S1, S2 and S3 at the same skirt depth for the doubly skirted irregular pentagonal footing. Similar trend of the bearing capacity at other normalised skirt depths (D_s/B) was observed as shown in Table 2. Further, study of Table 2 reveal that the bearing capacity was higher for the irregular pentagonal footings on sand S3 followed by sand S2 and S1. This could be attributed to the higher placement density of sand S3 in comparison to sands S2 and S1 in the test tank resulting higher bearing capacity for the former.

Comparing the results of singly skirted and doubly skirted footing as shown in Table 2, it is evident that the bearing capacity for the doubly skirted irregular pentagonal footing was higher in comparison to the singly skirted footing at all normalised skirt depths as well as for all sands. This is attributed to the fact that the additional skirt forms an enclosure in which soil is strictly confined and works at the level of the skirt tip as a unit with the overlain foundation to transfer superstructure load to soil. This implies that the provision of doubly skirt marginally benefits the increase in the bearing capacity in comparison to the singly skirted footings. Study of Table 3 indicates that the bearing capacity of the unskirted irregular pentagonal footing was 145 kPa, 196 kPa and 289 kPa respectively for S1, S2 and S3 sands. For singly skirted irregular pentagonal footing at a normalised skirt depth of 1.5 for sands S1, S2 and S3 respectively, this bearing capacity value was increased to 235 kPa, 370 kPa and 500 kPa. The bearing capacity increased further to 258 kPa, 389 kPa and 532 kPa for sands S1, S2 and S3 at the same normalised skirt depth for the doubly skirted irregular pentagonal footing. Similar trend was observed as evident from Table 3 for the increase in the bearing capacity at other normalised skirt depths. Further, study of Table 2 and Table 3 reveal that the bearing capacity obtained numerically was higher for the singly and doubly irregular pentagonal skirted footings in comparison to the one obtained experimentally on all sands. A close

Table 4.
Percentage improvement in the experimentally obtained bearing capacity of singly and doubly skirted irregular pentagonal footing

D_s/B	Percentage improvement					
	S1		S2		S3	
	ϕ' =33.37°		ϕ' =36.52°		ϕ' =39.47°	
	D_{10} =0.14		D_{10} =0.45		D_{10} =1.45	
	Singly skirted	Doubly skirted	Singly skirted	Doubly skirted	Singly skirted	Doubly skirted
0.25	22.9	25.19	23.24	31.35	18.51	23.7
0.5	37.4	39.69	40	45.94	37.4	38.88
1	49.61	52.67	68.64	70.27	55.55	56.66
1.5	64.88	74.04	90.81	95.13	74.07	82.22

Table 5.
Percentage improvement in the numerically obtained bearing capacity of singly and doubly skirted Irregular pentagonal footing

D_s/B	Percentage improvement					
	S1		S2		S3	
	ϕ' =33.37°		ϕ' =36.52°		ϕ' =39.47°	
	D_{10} =0.14		D_{10} =0.45		D_{10} =1.45	
	Singly skirted	Doubly skirted	Singly skirted	Doubly skirted	Singly skirted	Doubly skirted
0.25	17.93	20	25.51	30.1	22.83	24.22
0.5	32.41	34.48	45.4	47.95	34.6	38.4
1	46.2	51.72	70.4	74.48	49.82	66.08
1.5	62.06	77.93	88.77	98.46	73.01	84.08

examination of the data for the effective size (D_{10}) and friction angle of the sands along with the bearing capacity for the unskirted, singly and doubly skirted irregular pentagonal footings as shown in Table 2 and Table 3 indicates that the bearing capacity of the unskirted, singly and doubly skirted irregular pentagonal footings increased as the effective size and friction angle of the sand increased. The percentage improvement with respect to the unskirted footing both for the experimentally as well as numerically obtained bearing capacity were tabulated in Table 4 and Table 5 respectively. Study of Table 4 reveals that the lowest percentage improvement for the singly skirted footing on sand S3 was 18.51 % at a D_s/B = 0.25 whereas the highest improvement was 90.81 % at a D_s/B = 1.50 for the singly skirted footing on sand S2. Further study of Table 4 reveals that the highest percentage improvement for the doubly skirted footing on sand S2 was 95.13 % at a D_s/B = 1.5 whereas the lowest improvement was 23.70 % at a D_s/B = 0.25 for the doubly skirted footing on sand S3. Barring few exceptions, similar trend of improvement in the bearing capacity was observed for the numerical study as evident from Table 5. Hence from the above it can be concluded that the bearing capacity of the unskirted, singly and doubly skirted irregular shaped pentagonal footings increased as the effective size and the friction angle of the sand increased. The percentage improvement in the bearing capacity was higher for the irregular pentagonal footing resting on sand S2 in comparison to sand S3 and S1.

Comparison

The pressure and settlement ratio plot for the irregular shaped pentagonal unskirted/singly/doubly skirted footing obtained experimentally and numerically are shown in Figure 6 and Figure 7. These figures reveals a linear elastic behaviour corresponding to D_s = 0.5B both for the experimental and numerical study. However, at D_s= 1B and 1.5B, the experimentally obtained pressure-settlement ratio plot indicates a clear failure as evident from these figures. But the pressure settlement plot obtained from the numerical study as evident from these figures corresponding to D_s= 1B and 1.5B, indicates a linear elastic behaviour. This different behaviour is attributed to the fact that the constitutive models implemented using commercially available finite element software such as PLAXIS provide the analysis based on the isotropic yield surface and the elasto-plastic nature of the sand, whereas in the experimental study, sands show a non-linear stress-strain behaviour at very small strains. Yet linear elasticity will continue to play an important role in solving these problems, due to its suitability. Further, in the present study, the properties derived from the non-linear stress-strain curves obtained experimentally for different sands were used in the numerical analysis. In the absence of data for the irregular pentagonal skirted footings in literature, it was thought to compare the results of the experimental study with the one obtained numerically. The results of the comparisons of the bearing capacity at different normalised skirt depths for the unskirted, singly and doubly skirted irregular pentagonal footings are shown in Figure 8.

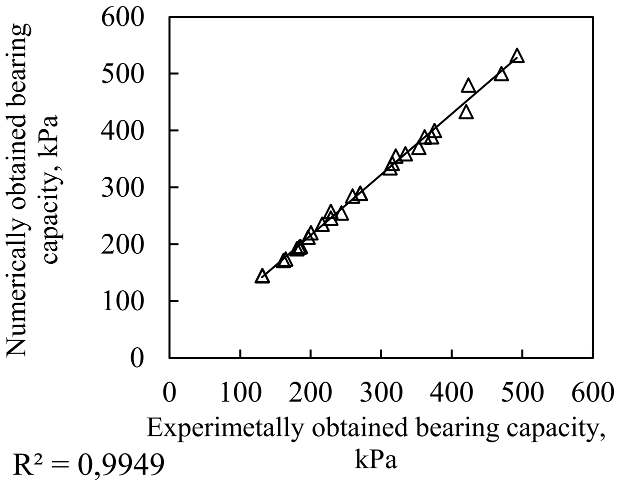

Fig. 8. Comparison of experimentally and numerically obtained bearing capacity

Study of Figure 8 reveals that the experimentally and numerically obtained values of bearing capacity for the unskirted, singly and doubly skirted irregular pentagonal footings indicates a good fit with $R^2 = 0.9949$. Further, the minimum and maximum deviation in the experimentally obtained bearing capacity with respect to the one obtained numerically was about 3% and 9.8% with average deviation of 8% for all the irregular pentagonal footings. It can therefore be assumed that the results obtained numerically are confirmed by the experimental results and can be used as the basis for evaluating the gain to be obtained from skirt use.

5.2. Displacement contours

The typical displacement contours generated from the present numerical analysis for the singly and doubly skirted irregular pentagonal footings corresponding to a normalised skirted depth of 0 and 1.5 are shown in Figure 9 to Figure 11 for sands S1, S2 and S3.

These figures also include the displacement contours for the unskirted irregular pentagonal footing. These displacement contours show the total contour of the displacement and their importance is to assess the actual displacement under the load. This type of information is required in order to verify the vertical settlement in the footing design within the acceptable limits or not under the load. Study of these figures reveals that for sand S3, the size of the isobar is larger in

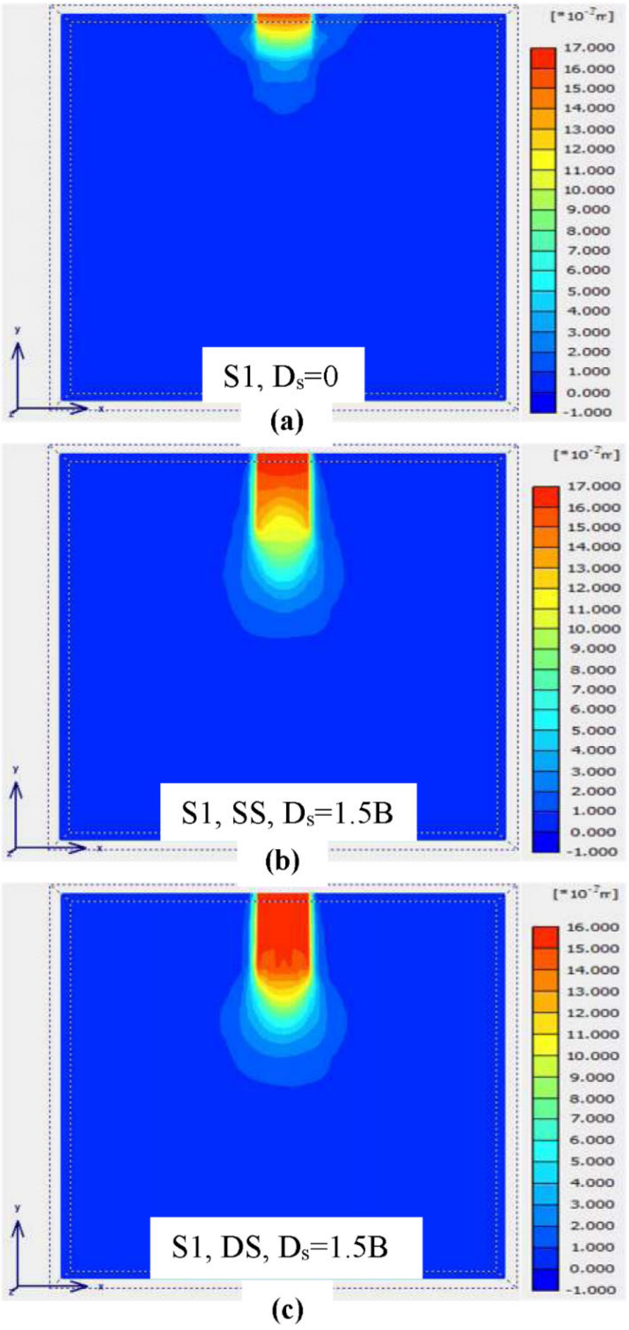

Fig. 9. Displacement contours of the irregular pentagonal (a) unskirted (b) singly skirted (c) doubly skirted footing on sand S1 at a skirt depth of 0B and 1.5B

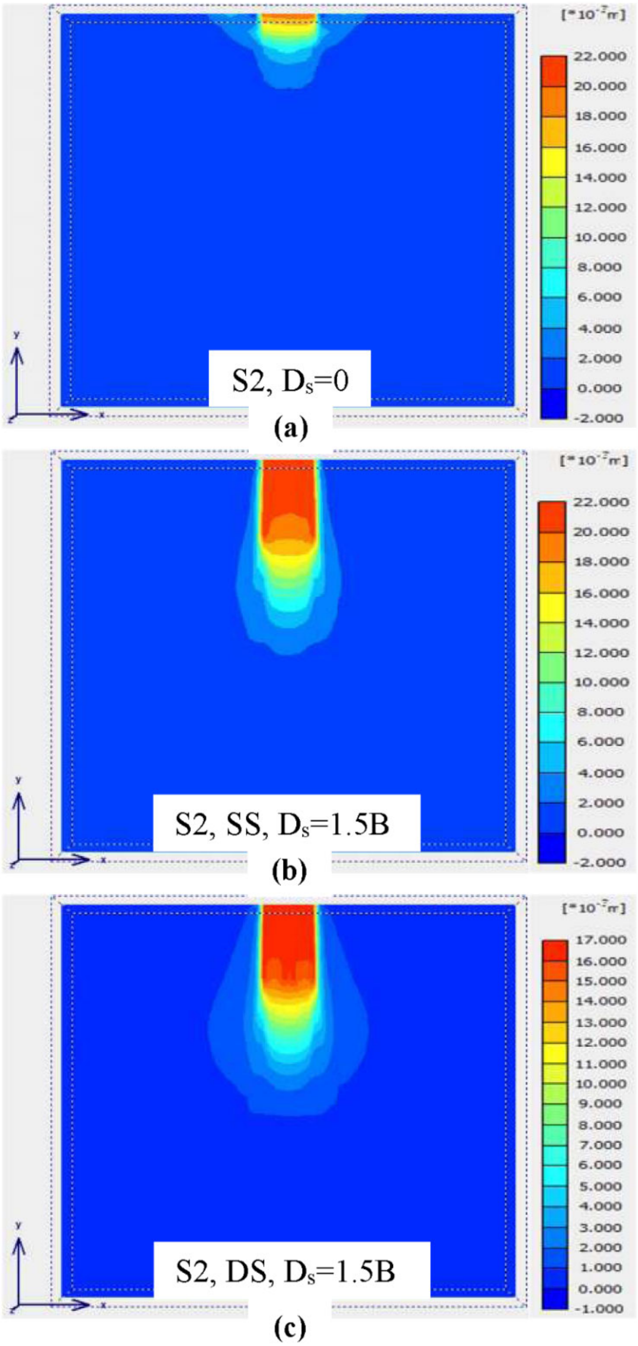

Fig. 10. Displacement contours of the irregular pentagonal (a) unskirted (b) singly skirted (c) doubly skirted footing on sand S2 at a skirt depth of 0B and 1.5B

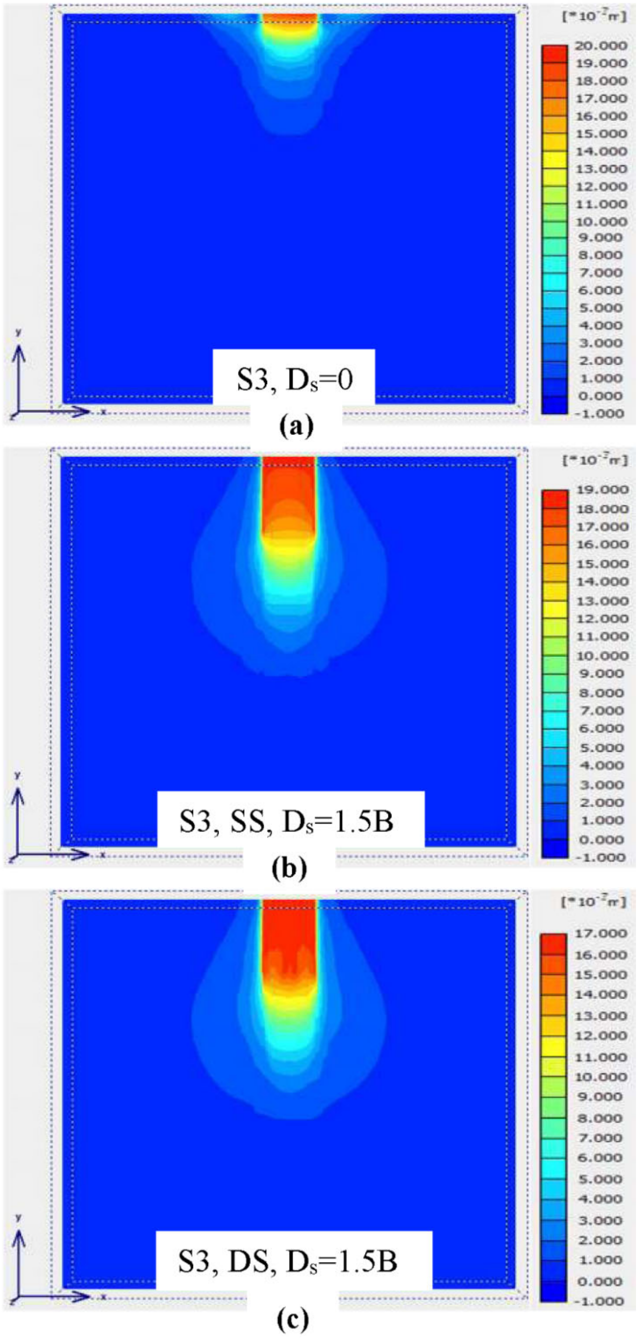

Fig. 11. Displacement contours of the irregular pentagonal (a) unskirted (b) singly skirted (c) doubly skirted footing on sand S3 at a skirt depth of 0B and 1.5B

comparison to sands S2 and S1 at a skirt depth of 0.5B and 1.5B indicating higher bearing capacity for the footing with sand S3. Further, study of these figures reveal that the displacement contours remained well contained within the selected lateral and vertical extent for the unskirted, singly and doubly skirted irregular pentagonal footings corresponding to a skirt depth of 0B, 0.5B and 1.5B. It means that it was sufficient for the chosen problem domain. Similar observation for the displacement contours were noticed at other skirt depths and for all the sands used in this investigation. The insights gained from the above study on the displacement contours will be useful for developing analytical solutions.

6. Conclusions

The experimental and numerical analysis of unskirted, singly and doubly skirted irregular pentagonal footings subjected to vertical concentric load on different sands is investigated. In a test tank and numerical study to assess the unskirted, singly and doubly skirted irregular pentagonal footings on different sands, a series of tests and analysis were performed. From the results and discussion presented above, the following conclusions are drawn:

1. The settlement response of the irregular pentagonal footings is unchanged by increasing the number of elements beyond 7700.
2. The bearing capacity was higher for the skirted irregular pentagonal footings on sand S3 followed by sand S2 and S1.
3. As the effective size and the friction angle of the sand increased, the bearing capacity of the unskirted, singly and doubly skirted irregular shaped pentagonal footings increased.
4. Similar to the one obtained experimentally for the footings on all sands, the numerically obtained bearing capacity was slightly higher.
5. The lowest percentage improvement for the singly skirted footing on sand S3 was 18.51 % at a $D_s/B = 0.25$ whereas the highest improvement was 90.81 % at a $D_s/B = 1.50$ for the singly skirted footing on sand S2.
6. The highest percentage improvement for the doubly skirted footing on sand S2 was 95.13 % at a $D_s/B = 1.5$ whereas the lowest improvement was 23.70 % at a $D_s/B = 0.25$ the doubly skirted footing on sand S3.
7. The percentage improvement in the bearing capacity was higher for the irregular pentagonal footing resting on sand S2 in comparison to sand S3 and S1.
8. The provision of doubly skirt marginally enhances the bearing capacity compared to the singly skirted irregular pentagonal footings.
9. The findings of the tests confirmed the numerical results with an average deviation of 8%.
10. Both the experimental and numerical studies revealed a linear elastic behaviour at $D_s = 0.5B$, while the experimentally obtained pressure-settlement ratio plot shows a clear failure at $D_s = 1B$ and 1.5B.
11. The generated displacement contours supports observations on the bearing capacity on different sands of the unskirted, singly and doubly skirted irregular pentagonal footings.

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