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Numerical Analysis of Square and Circular Skirted Footings Placed on Sand using PLAXIS 3D Software

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Abstract

This paper presents the numerical analysis of square and circular skirted footings placed on different sands using the PLAXIS 3D software. The numerical analysis is done using the Mohr-coulomb (M-C) yield criteria. The size of the footings is considered as 100 mm for both the square and circular footings. The three different friction angles (Ø) of sand 36˚, 40˚, and 42˚ are used to study the effect of sand compactness. The depth of the skirt (h) varies from 0B to 2B (B is the width of the footing). The surface roughness between skirt-sand and footing-sand is considered partially rough and completely rough. The interface friction factor (δ) for a partially rough and fully rough interface is taken as 2/3Ø and Ø. All the tests are conducted by applying a prescribed displacement (s/B) of 20% of the footing size. The results obtained from the present work reveal that the inclusion of structural skirts with the footings appreciably increases the bearing capacity and reduces the settlement of the footing by increasing the skirt depth. The results obtained show that the skirted footing is found to be more effective in loose sand compared to dense sand in increasing the bearing capacity. The numerical analysis results are also verified with the experimental results available in the literature and multiple regression model. This work shows that the prediction of the accuracy of the results is quite good with the experimental results and the generated regression model.

1. Introduction

Geotechnical engineers are in search of various soil stabilization techniques to improve the strength of weak soil, and increase its bearing capacity. There are several ground improvement techniques investigated by many researchers but they are found to be expensive for large construction projects or in some cases their implementation is also difficult. Alternatively, using skirts at the foundation periphery is a prominent method to increase the bearing capacity and decrease the settlement of footing. Skirted foundations are a better replacement for deep foundations due to their easy installation and low installation cost. The skirted foundation is more effective for marine structures and does not restrain by the presence of high groundwater levels [1-5]. Skirted footing considerably enhances the bearing capacity, and reduces the settlement of the foundation bed. Improvement in bearing capacity of the skirted footing depends upon several factors including structural properties of skirts, soil characteristics and interface friction between soil, skirt, and footing [6-10]. There were many experimental studies done by various researchers to study the impact of the skirted footing on increasing the bearing capacity and reducing the settlement of the foundation bed [6, 11, 9, 12-15, 10, 5, 16-19]. An equation has proposed to calculate the bearing capacity of skirted strip foundation by [6]. The results of [11, 13] have revealed that

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the enhancement in bearing capacity of skirted foundation depends upon the depth of skirt and relative density of sand. The enhancement in bearing capacity value of skirted foundation is close to the pier foundation of same width and depth [13]. The lateral load carrying capacity of skirted footing increases with increase in the skirt depth reported by [9]. The behaviour of skirted footing depends upon sand relative density and the length of skirt to footing diameter ratio reported by [12]. Skirted footings are more beneficial for sand having low relative density compare to high relative density of sand reported by [14]. A physical model testing on circular skirted foundation resting on sand conducted by [10]. The results have shown that the bearing capacity is increased by 5.0 times and settlement is reduced up to 8.0 times compared with the foundation without skirt. The effect of skirted foundation on the bearing capacity of submerged gypsum soil has studied by [5]. The study suggested that the confinement of soil inside the skirt lead to increase the bearing capacity. The enhancement in the bearing capacity lies in the range of 1.92-2.27. Many studies were also reported for the skirted footing using different footing shapes [15-20]. The comparative behaviour of square and H shape skirted footing on the bearing capacity studied by [15], reporting that the progression of the shear zone between the multiple edges of H shape skirted footing leads to passive force generation in other parts, and hence, more load is required to bring the soil to failure stage. The behaviour of hexagonal shape double skirted footing on the bearing capacity of different types of sand has studied by [16]. The authors reported that double skirted arrangement marginally increased the bearing capacity. The comparative behaviour of embedded square and E-shaped skirted footing behaviour on the bearing capacity enhancement of the foundation bed reported by [20]. For design purposes, quick computations are required to study the influence of various key parameters. In that case, one cannot depend only upon the experimental studies. The numerical modelling approach not only makes it easier to do calculations quickly but also offers a scientific representation of the findings that are obtained. Many researchers study the effect of skirted footings by using numerical modelling approach [21-22, 16, 23, 20, 24-25]. The behaviour of multi-edge footings placed on sand by using FLAC 3D has analysed by [21]. The behaviour strip and circular skirted footing using finite element analysis has studied by [22]. The bearing capacity of strip footing resting on cohesionless slope using lower and upper bounds of finite element limit analysis (FELA) has evaluated by [23]. The behaviour of skirted footing on layered soil using the FEM modelling has reported by [24, 25]. The results of the analysis revealed that the bearing capacity increased with increasing the skirt depth. For the same skirt depth, the bearing capacity of circular footing was found to be greater than the strip footing. Hence, according to the reported studies, it is observed that the inclusion of skirt with shallow footings can be a better and more economical method for increasing the bearing capacity of the foundation bed. In this study, three-dimensional FEM-based PLAXIS software was used to investigate the bearing capacity of square and circular skirted footing placed on the sand having different friction angles. A detailed numerical analysis has been conducted by altering the depth of the skirt, friction angle of the sand, and roughness of the interface between skirt-sand-footing. The aim of the present work is to investigate the comparative behaviour of square and circular footing with structural skirt using numerical analysis. The numerical analysis results were also verified with the experimental results reported in the literature. Further, multiple regression analysis has been done for both footing shapes with different parameters used in this work to check the accuracy of the results obtained.

2. Problem description and material properties

Finite element analysis was conducted to analyse the behaviour of shallow footings with skirts resting on sand subject to concentric vertical loading using the PLAXIS 3D foundation software. Square and circular footing of size 100 mm with variable skirt depth is used for the analysis. Three different friction angles (Ø) of sand 36°, 40°, and 42° are used in the present work. The unit weight (γ) of sand corresponding to these friction angle values were taken as 16 kN/m^3, 17.5 kN/m^3, and 18 kN/m^3 as per the range recommended by [26]. Young's modulus (E) for sand was calculated using the relation given by [27] corresponding to the standard penetration resistance (N) values as 1200 (N + 6) kPa. The N values were taken corresponding to the friction angle values as per [28]. The values of the dilation angle (Ψ) for sand were calculated using the relation Ψ = Ø – 30 for different values of friction angle of sand as per [29]. The values of Poisson's ratio (μ) varied from 0.3 to 0.35 as per the range recommended by [30]. The detailed material parameters used in the present work are summarized in Table 1. Steel material is used for the modelling of skirt and footing. The detailed material parameters used for skirt and footing are summarized in Table 2. The depth of the skirt used in the analysis is varying from 0B to 2B. Here, B is referred for (1) width of the square skirted footing and (2) diameter of circular skirted footing. The thickness of the skirt plate and footing is taken as 3 mm and 5 mm. To investigate the influence of the surface roughness between skirt-sand and footing-sand, two different interface strength factors were used corresponding to the friction angle of sand. For a partially rough interface, the value of the interface friction factor is taken as 0.67 Ø and for a rough interface, the value of the interface strength factor is the same as the friction angle of sand.

Table 1. Properties of sand used in the numerical analysis.

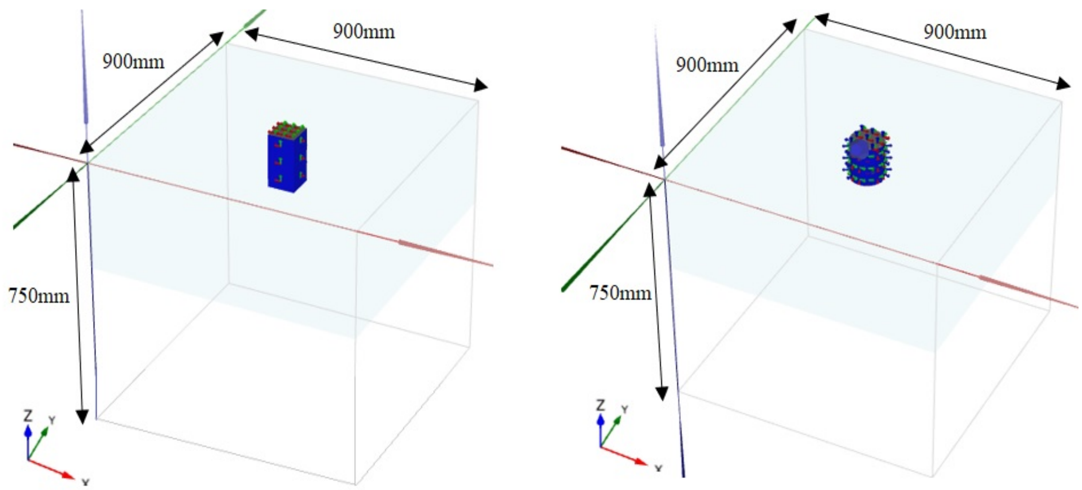
Properties	Sand 1	Sand 2	Sand 3
Friction angle (Ø)	36˚	40˚	42˚
Unit weight, γ (KN/m^3)	16	17.5	18
Cohesion, c (kPa)	0	0	0
Young's modulus, E (MPa)	34.6	51.8	65
Dilation angle (Ψ)	6˚	10˚	12˚
Poisson's Ratio (υ)	0.3	0.33	0.35

Table 2. Material properties used for skirt and footings.

Properties	Values
Material	Steel
Unit weight (kPa)	78.5
Young's modulus E, (MPa)	210000
Poisson's ratio, μ	0.2

3. Finite Element Model and Boundary Condition

The geometric models for square and circular footings with structural skirts having different embedded depth in sand has been developed by the PLAXIS 3D software, as presented in Figure 1. The modelling of sand surrounding the skirts has been done by using the borehole option in PLAXIS 3D by taking suitable plan dimensions. The plan dimension of the sand layer was taken as 900 mm × 900 mm × 750 mm. According to the Boussinesq's stress theory, the stress contour '0.1q' represents the maximum isobar beyond, in which the applied stress effect is considered insignificant. The dimensions of model geometry were chosen such that the outer isobar did not intersect the model boundaries. To avoid the boundary effect, the distance of the foundation edges from the finite element mesh boundary was set to be 4B in length and breadth and 6B in depth. To incorporate the real ground conditions, the numerical model has been employed with standard fixity conditions. The vertical side of the model was restricted from the horizontal movement and the base was fixed in all the three translational and rotational degrees of freedom.

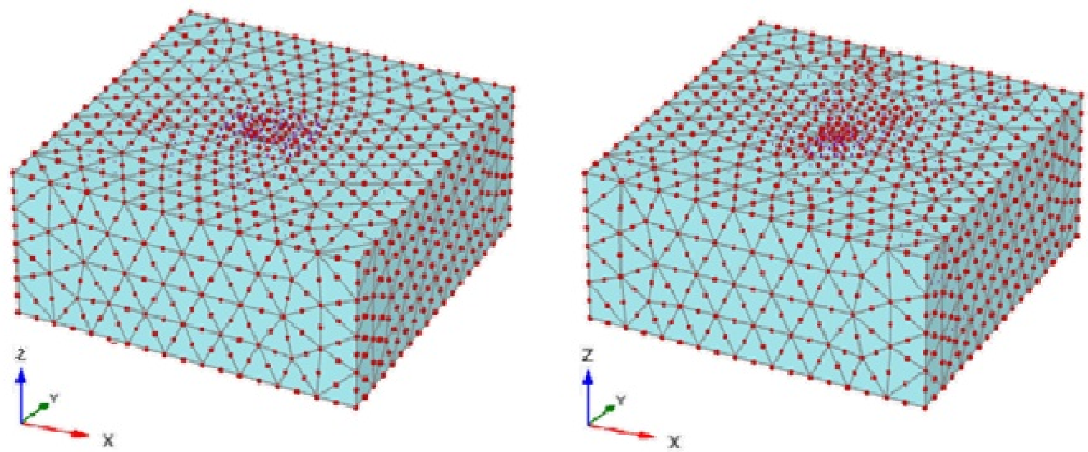


(a) (b)

Figure 1. Numerical models of footings with skirt (a) Square (b) Circular.

4. Finite Element Mesh and Material Model

In the present work, the finite element analysis is performed by modelling the soil element by using 10-node tetrahedral elements, and plate elements are modelled using 6-node triangular elements. The meshing of the domain has been done by using fully automatic mesh generation provided in the PLAXIS 3D program [31-33]. There are usually five different meshing schemes available such as very coarse, coarse, moderately coarse, fine, and very fine, which allow the users to refine a particular area, around a point or line. Generated mesh obtained for numerical models of square and circular skirted footings are shown in Figure 2. A very coarse mesh is not able to collect the important characteristic behaviour of the particular model, resulting in inaccuracy in the obtained data, whereas a very fine mesh takes excessive computational time for the analysis, and chances of accumulation of numerical errors result in inaccuracy in the obtained results. Therefore, it is necessary to undertake a convergence analysis to obtain the optimal mesh arrangement for every simulation model. The mesh convergence analysis concludes that the optimum number of elements is obtained as 7357. Further, increasing the number of elements does not create much difference. Hence, 7357 to 9087 number of elements with 4.2×10^{-3} m or less have been used in the numerical analysis varying with the different depth of the skirts. The modelling of the sand has been done by using Mohr-coulomb (M-C) material model. The M-C model is better suitable for cohesionless soil. The M-C model shows the first-order estimation of the cohesionless soil by calculating the constant stiffness values. This allows the faster computations of the obtained deformations, whereas the other soil models take more computation time due to the formation of the material stiffness matrix that gets decomposed in every step, as reported in the PLAXIS 3D manual, version 1.5.



(a) (b)

Figure 2. Generated mesh for numerical models (a) Square (b) Circular.

5. Results and Discussion

This section presents the numerical analysis results of square and circular footings with structural results placed on different sands by considering different parameters such as skirt depth, interface friction factor between skirt-sand-footing, and friction angle of sand. The results are reported in terms of pressure versus footing settlement ratio (s/B, %). The bearing capacity ratio (BCR) and percentage reduction in settlement (PRS) were further used to discuss the effectiveness of the structural skirt in enhancing the performance of the shallow footings.

5.1. Pressure-settlement plots for square and circular footing

The pressure-settlement plots of square and circular footings with/without structural skirts for different types of sand are presented in Figures 3 and 4. The interface between the skirt-sand and footing-sand was considered partially rough and fully rough. For a partially rough interface, the interface strength factor was considered as 2/3Ø and for a completely rough interface, the interface strength factor was considered as Ø. All the results were reported at a prescribed displacement of s/B = 20%. As we can see that, for unreinforced soil having friction angles 40° and 42° a clear peak is observed on pressure settlement curves for both square and circular footings. The peak was observed at settlement ratio of 8-10% of the footing width, indicating the general shear failure of the footing bed, and for 36° friction angle, clear peak was not observed. The obtained results from the numerical analysis revealed different plots for pressure-settlement behaviour, hence different methods were used to calculate the bearing capacity. If the definite peak in the curve is visible, then the ultimate bearing capacity is considered equivalent to the peak pressure. If the peak pressure is not clearly observed, then the ultimate bearing capacity is computed by using the double tangent method or a minimum value corresponding to a 10% settlement ratio. In the double tangent method, the ultimate bearing capacity is considered at the intersection of the tangent drawn from the initial and final points of the curve. The pressure-settlement response of the footings with the structural skirts continuously improved with increasing the skirt depth from 0B to 2B. The increase in pressure-settlement response takes place due to the confinement of sand inside the skirt. Due to the confinement of sand, the skirted footings behave as a single unit same as pier foundation, so that the development of failure zone limited to the bottom of skirt due to increase in overburden pressure and of the soil. The bearing capacity values of square footing stands higher than that of circular footing in all the cases. It is due to more confining area in case of square footing compares with circular footing for the given footing dimension. The bearing capacity values obtained for square and circular footings for partially rough and completely rough interface are presented in Tables 3 and 4.

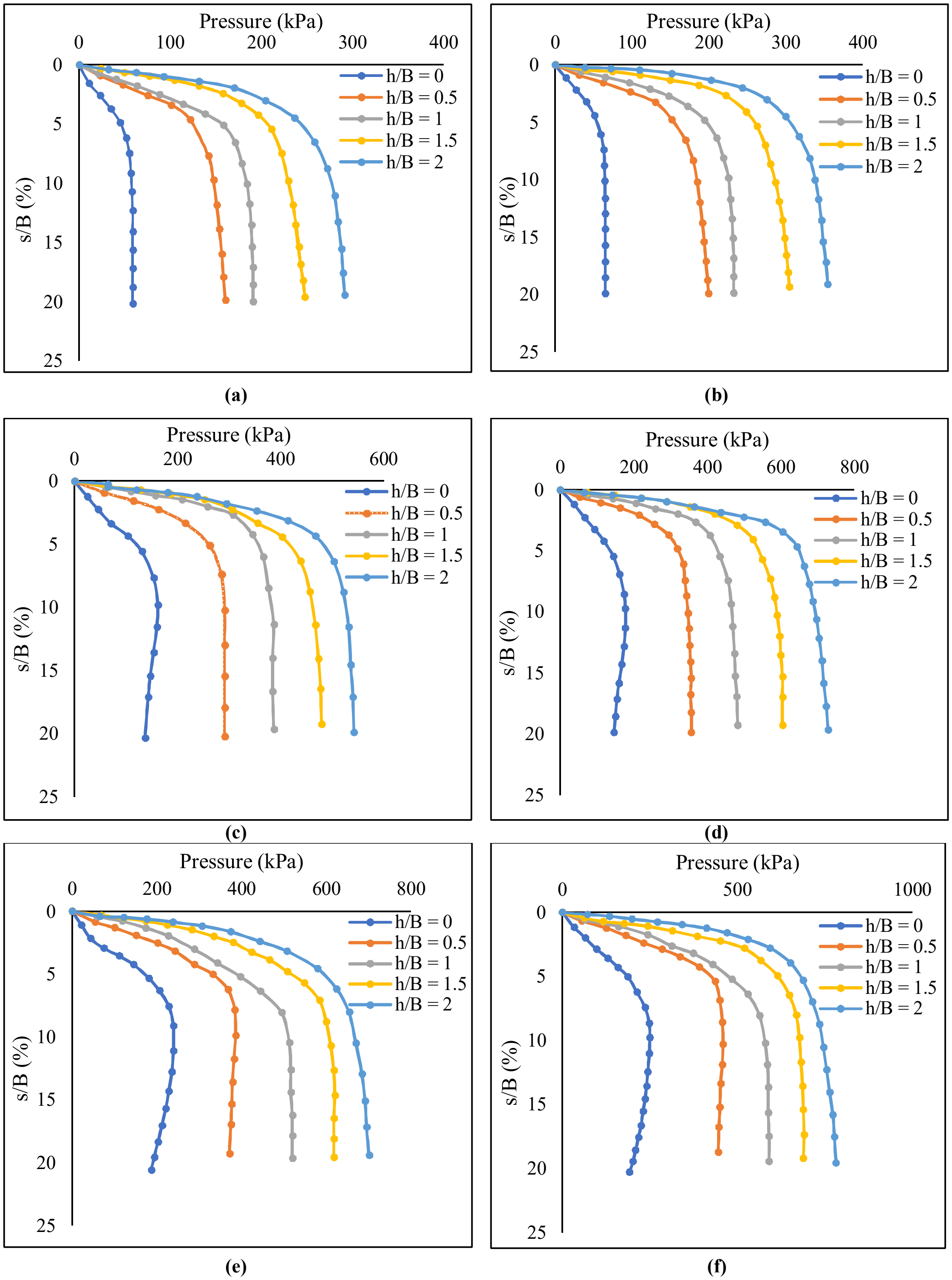


Figure 3. Pressure-settlement plots for square footings (a, c, e) partially rough (b, d, f) rough interface.

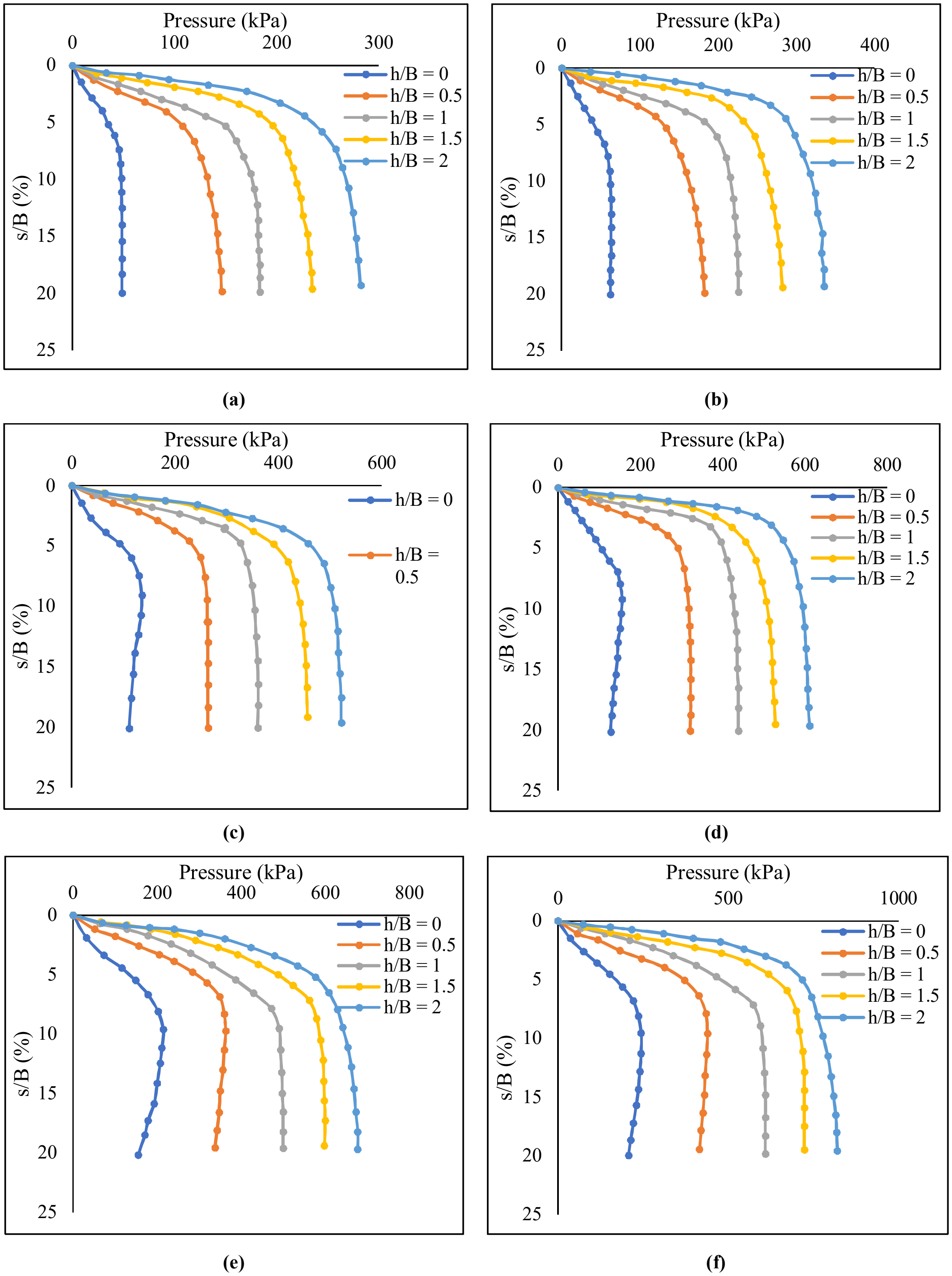


Figure 4. Pressure-settlement plots for circular footing (a, c, e) partially rough (b, d, f) rough interface.

Table 3. Bearing capacity values for square footings.

h/B	Bearing capacity (kPa)					
	Ø = 36°		Ø = 40°		Ø = 42°	
	Partially rough	Rough	Partially rough	Rough	Partially rough	Rough
0	56.12	64.24	159.23	173.23	238.91	247.43
0.5	151.37	184.91	285.16	334.4	385.52	458.75
1	183.72	223.55	377.22	456.07	515.83	565.94
1.5	232.14	271.92	458.82	572.62	617.60	668.68
2	282.32	330.14	533.81	681.40	680.31	738.17

Table 4. Bearing capacity values for circular footings.

h/B	Bearing capacity (kPa)					
	Ø = 36°		Ø = 40°		Ø = 42°	
	Partially rough	Rough	Partially rough	Rough	Partially rough	Rough
0	48.11	56.96	135.44	152.51	214.59	237.03
0.5	135.14	169.67	262.45	320.51	362.91	439.85
1	173.07	222.57	355.73	425.65	494.32	595.0
1.5	221.11	268.19	443.87	509.29	595.73	710.33
2	267.17	321.71	515.18	597.05	657.34	778.41

5.2. Percentage reduction in settlement

The inclusion of skirts with the footings is not only effective in increasing the bearing capacity but also is very effective in reducing the settlement of the footing. The reduction in the settlement of the footings with the inclusion of skirts can be expressed by using the terms percentage reduction in settlement (PRS), which is expressed as:

$$PRS = \frac{So-Sr}{So} \times 100 \quad (1)$$

where s_o is the settlement of unreinforced footing corresponding to the ultimate bearing capacity (Q), and s_r is the settlement of reinforced footing corresponding to the pressure equal to the ultimate bearing pressure of the unreinforced footing. The PRS values obtained for square and circular skirted footings placed on different sands for the partially rough and rough interface are presented in Tables 5 and 6. From the obtained results, it is observed that the reduction in the settlement increases with increasing the skirt depth. Due to higher skirt depth, the friction factor between the skirts and surrounding soil increases resulting in greater resistance offered to the footing settlement with the load increment. The maximum PRS value is obtained for square footing with the rough interface at a skirt depth h/B = 2B and Ø = 36°. It observes that for the consideration of settlement criteria the skirted footing is found to be effective in loose sand. The provision of skirts is very effective where the settlements become the governing factor for the design. In those cases, skirted foundation is very effective in reducing the settlement without increasing the size of the footing.

Table 5. Percentage reduction in settlements for square footings.

h/B	Percentage reduction in settlement (PRS, %)					
	Ø = 36°		Ø = 40°		Ø = 42°	
	Partially rough	Rough	Partially rough	Rough	Partially rough	Rough
0.5	81.74	82.49	75.66	79.34	69.75	77.08
1	84.78	89.71	81.73	85.04	74.5	82.04
1.5	91.97	93.38	89.50	91.38	85.68	89.82
2	95.67	96.07	92.01	94.07	90.01	92.94

Table 6. Percentage reduction in settlements for circular footings.

h/B	Percentage reduction in settlement (PRS, %)					
	$Ø = 36^{\circ}$		$Ø = 40^{\circ}$		$Ø = 42^{\circ}$	
	Partially rough	Rough	Partially rough	Rough	Partially rough	Rough
0.5	74.81	77.78	69.34	72.94	61.73	70.36
1	79.38	83.64	75.31	79.08	69.21	76.71
1.5	85.71	88.97	81.33	85.87	77.23	82.72
2	89.88	94.21	85.48	92.17	85.71	89.32

5.3. Effect of increasing depth of skirt

To investigate the effect of skirt depth, numerical analysis was performed using different depth ratios (h/B) of skirts such as 0.5B, 1B, 1.5B, and 2B for both the square and circular footing models. The plots of bearing capacity ratio in terms of different skirt depths having partially rough and rough interface friction factors for both square and circular footing models are presented in Figure 5. From the obtained results, it is clearly observed that the provision of skirts with shallow foundations significantly increases the bearing capacity of the foundation bed. The maximum improvement in bearing capacity is obtained by increasing the skirt depth up to 2B. The enhancement in the bearing capacity is attributed due to an increase in the confinement of sand inside the skirt with increasing the skirt depth. Due to this, the whole assembly of the skirted footing behaves as a single unit like pier and pile foundation and the failure zone was limited at the bottom of the skirt tip due to the overburden pressure applied by the soil. Furthermore, with increasing the depth of the skirt additional frictional resistance is offered by the inner and outer periphery of the skirt and surrounding soil during the application of load. From the given results, it is observed that the maximum improvement in bearing capacity is observed for sand having $Ø = 36^{\circ}$ with the rough interface between skirt-footing-sand for h/B = 2B. The presented results show that the inclusion of skirt with the footings tends to increase the bearing capacity up to 5.6 times compared to the footings without skirts. [7] has reported an improvement in bearing capacity ratio ranges from 1.5–8.1 for circular skirted footings placed on sand having relative density 64%. [13] has reported an improvement in bearing capacity ratio for square skirted footings placed on sand having relative density 45% ranges from 2.2–5.6. The alteration in bearing capacity ratio was observed on comparing the present study results with the previous studies reported in literature. The reasons for these alterations in results is due to different test conditions such as materials used for skirt and footing, roughness factor between footing-skirt-soil, and properties of the soil used for the analysis.

5.4. Effect of interface roughness

To investigate the effect of surface roughness between footing-sand and skirt-sand, two different interface roughness factors for partially rough and rough interfaces were used in the present numerical study. The friction factor for partially rough and rough interfaces was taken as 2/3Ø and Ø, where Ø is the friction angle of sand. The variation in bearing capacity ratio for different skirt depth for partially rough and rough interfaces are presented in Figure 6. The friction angle of the sand varied from 36°-42°. Based on the friction angle of the sand the interface friction factors for the partially rough interface were varied from 24°-28° and for the fully rough interface, the interface friction factors were considered similar to the friction angle of the sand. The analysis of results reveals that the average increment in the bearing capacity ratio was found to be 7-9% for the rough interface. In case of highly rough interface, friction between skirt-sand offers greater resistance for the settlement of the footing during the application of load and for higher interface friction between footing-sand resist the lateral mobilization of the sand particles below the footing during the load application results in higher bearing capacity ratio obtained compared to partially rough interface between skirt-sand and footing-sand.

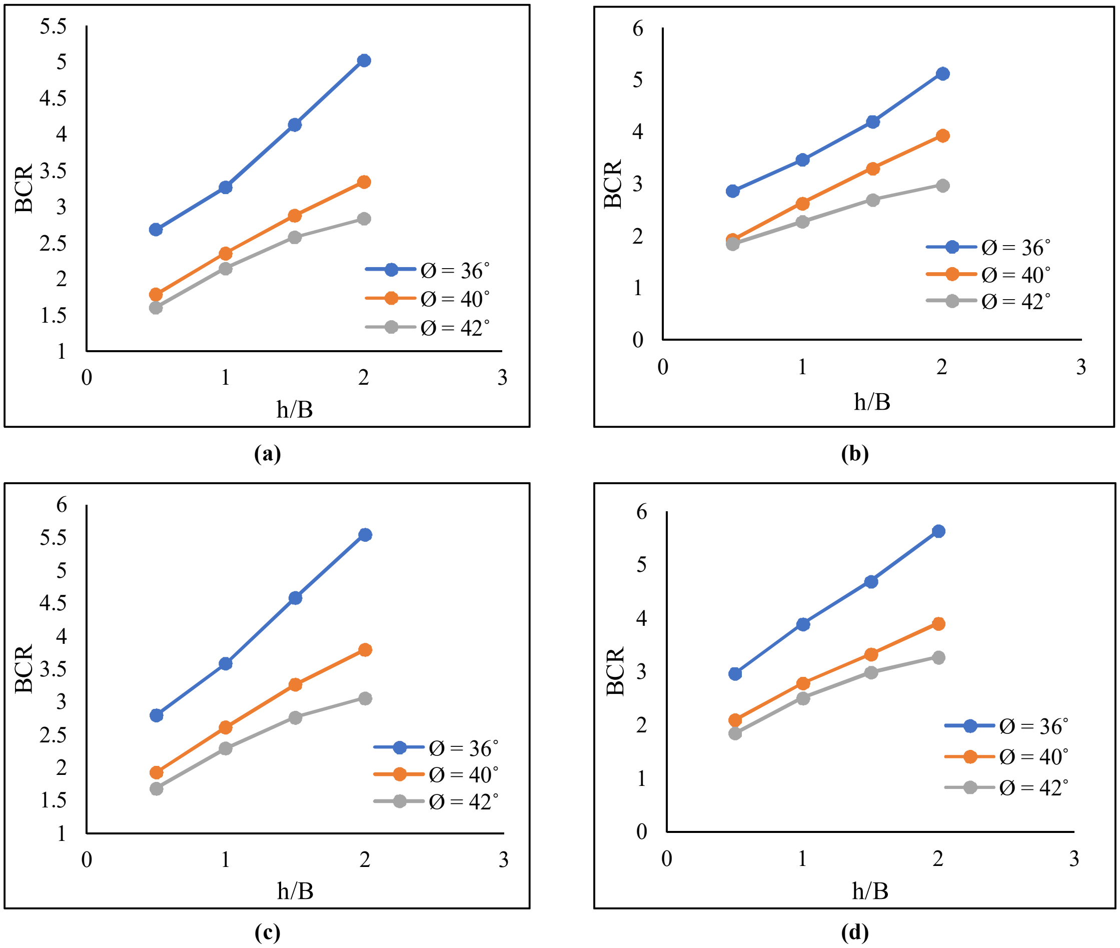


Figure 5. Variation of bearing capacity ratio in terms of depth of skirt for different friction angle of sand (a) square partially rough (b) square fully rough (c) circular partially rough (d) circular fully rough.

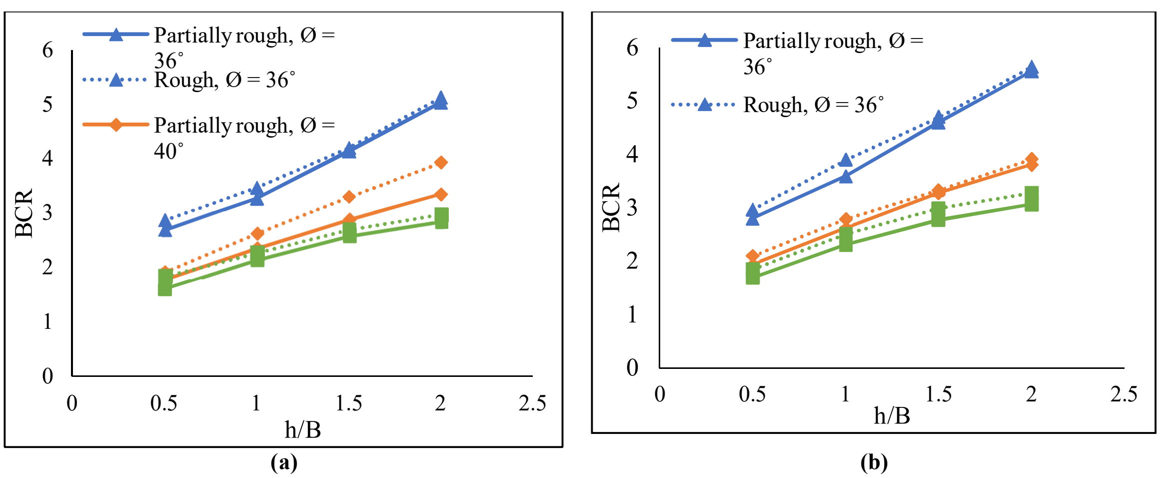


Figure 6. Variation of bearing capacity ratio in terms of different skirt depth for different interface roughness (a) square footing (b) circular footing.

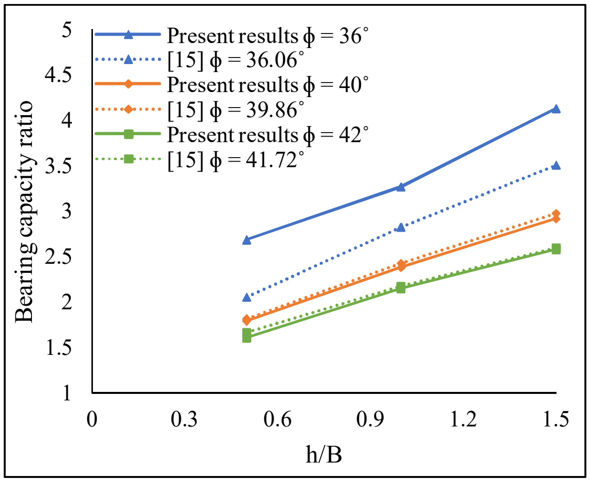
5.5. Software validation

The results obtained from the numerical analysis of square and circular footings without skirts for different friction angles of sand for partially rough and rough interface roughness factors are compared with the bearing capacity formulae [34-37]. The relevant comparison of the results for ultimate bearing capacity are presented in Table 7. From the comparison of results, it can be seen that the ultimate bearing capacity values obtained by the numerical analysis in the present study were higher than the predicted formulae for both footing shapes. This was because the higher mobilized friction factor is developed due to the settlement of footing on the application of load. Due to the settlement of the footing, leads to the densification of sand surrounding the footing and results in increasing the friction factor of the sand. Hence, a higher bearing capacity is observed in the present study compared with the theoretical formulae.

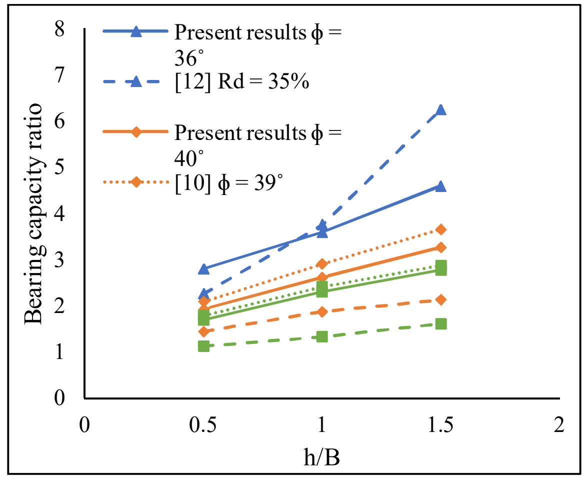
The present study results for square and circular footings with structural skirts are compared with the experimental studies reported in the literature in terms of bearing capacity ratio for different depths of skirts. For square footing, the results are compared with the experimental study reported by [15] for different friction angles of sand. The present study results having friction angles 36°, 40°, and 42° are compared with 36.06°, 39.86°, and 41.72° friction angles obtained at the relative densities of 30%, 50%, and 60%, respectively. The footing-sand and skirt-sand interfaces are considered partially rough for the comparison of results. The comparison of results for square footing is presented in Figure 7(a). From the results shown in the figure, it is observed that the bearing capacity ratio for 36° friction angle of sand is found to be higher than the experimental study, and for 40° and 42°, the results are in good agreement with the experimental results of [15]. For circular footings, the results are compared with the experimental work reported by [12] and [10] for circular skirted footing. In the study of [12], the relative density of sand varied from 35% to 90%. The friction angle corresponding to these relative densities is not mentioned. For the comparison of results, the friction angle corresponding to these relative densities was computed using the relation, $Ø = 30 + 0.15R_d$, where R_d is the relative density of sand as per [35]. Further, for the comparison of results, the interface strength factor is considered partially rough. The comparison of results is presented in Figure 7(b). From the comparison of results, it is observed that the numerical analysis results are in good agreement with the results reported by [10] and the results of [12] are almost smaller in all the cases except $L_s/B = 1.5$ for relative density of 35%. It should be mentioned that in the experimental study of [12], the failure load was specified at a settlement ratio of 5% of the footing size. As a consequence of this, the reported bearing capacity was smaller compared to the present study.

Table 7. Comparison of surface square and circular footings with theoretical studies.

Footing shape	Friction angle (Ø)	Bearing capacity (kPa)					
		Present study		[34]	[35]	[36]	[37]
		Partially Rough	Rough				
Square	36°	52.12	64.24	29.60	32.96	36.12	19.04
	40°	158.23	173.23	78.32	107.44	112.99	66.91
	42°	238.91	247.43	157.28	177.49	196.78	97.44
Circular	36°	48.5	56.96	22.70	26.96	31.21	16.04
	40°	135.44	152.51	65.29	87.44	102.81	52.91
	42°	211.43	237.03	129.71	137.49	152.09	87.44



(a)



(b)

Figure 7. Comparison of present study results with literature (a) square (b) circular.

5.6. Multiple regression analysis

The non-linear multiple regression analysis has been performed on the whole dataset for square and circular skirted footing using the DataFit 9.1 software. The equations obtained for square and circular skirted footing are shown below as Equations 1 and 2, and the performance metrics that were computed are reported in Table 8.

$$q_{ult(square)} = 48.75*Ø + 4.08*\delta + 187.85*(h/B) - 1867.59 \quad (2)$$

$$q_{ult(Circular)} = 48.39*Ø + 4.68*\delta + 188.08*(h/B) - 1888.25 \quad (3)$$

Here, Ø is the friction angle of sand, δ is the interface friction factor, h/B is the skirt depth ratios, and q_{ult} is the ultimate bearing capacity for square and circular footings.

Table 8. Performance measures for multiple regression analysis model.

Performance measures	Multiple regression analysis	
	Square	Circular
Correlation coefficient	0.93	0.91
Coefficient of determination	0.9554	0.9415
Mean square error	256750.18	235214.07
Root mean square error	322.41	307.71
Mean absolute error	195.16	190.81
Mean absolute percentage error	32.45	40.14

The coefficient of determination (R^2) was used to determine the degree of adjustment of the regression line to the data, which is defined as the ratio of the sum of squares to the regression to the sum of squares about the mean. As presented in Figure 8, the coefficient of determination (R^2) for square and circular footing is observed as 0.9554 and 0.9415, which indicate that the estimation obtained with the model was quite reasonable. The proposed equations obtained from the multiple regression analysis are helpful to estimate the ultimate bearing capacity of square and circular footing with structural skirts placed on the sand.

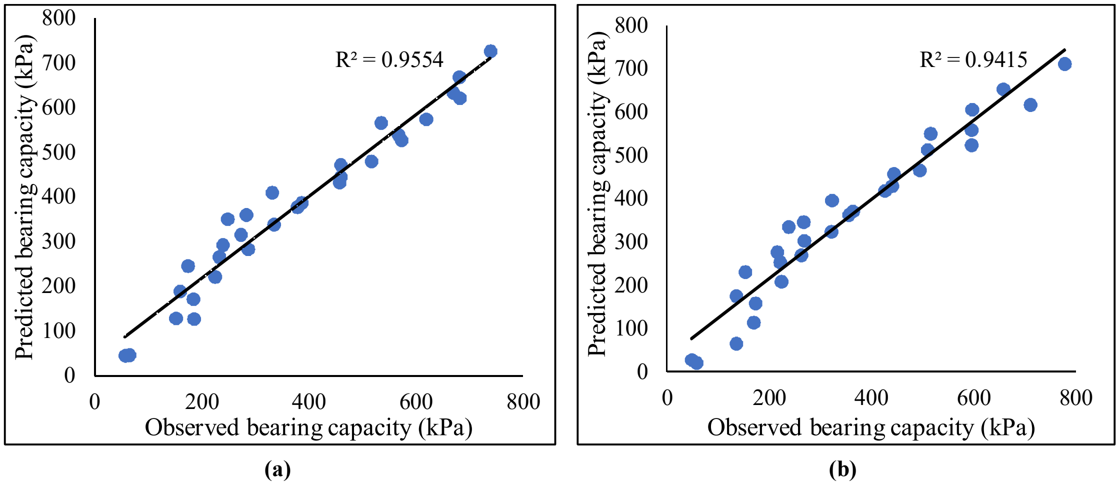


Figure 8. Variation of observed and predicted bearing capacity (a) square footing (b) circular footing.

5.7. Failure pattern

The failure pattern generated from the numerical analysis of square and circular footings corresponding with and without structural skirts is shown in Figures 9 and 10 for different friction angles of sand. The failure pattern shown in the given figures represents the displacement contours corresponding to the given load. The information generated from these types of contours is helpful to check the failure pattern and the permissible settlement of the footing under the given load for design purposes. The given contours are represented at the ultimate bearing capacity of the foundation bed. Analysis of these figures reveals that the size of the isobar is higher in the case of sand having $Ø = 42^{\circ}$ compared to sands having $Ø = 40^{\circ}$ and 36° for both square and circular footing, indicating the higher bearing capacity in the case of sand having $Ø = 42^{\circ}$. From the analysis of these figures, it is observed that the inclusion of structural skirts around the periphery of the footings results in limiting the failure zone below the tip of the skirts and negligible effect is shown at the surface of the foundation bed and increasing the performance of the foundation bed. Furthermore, for all the cases of foundation bed with/without structural skirts, the given contours remained within the specified lateral and vertical boundaries. This signifies that the horizontal and vertical boundaries chosen for the specified problem are adequate.

6. Limitation of Study

The findings of the numerical analysis conducted with the small-scale model are susceptible to scale effects. According to [38], the findings of the small-scale model tests can be used for the prototype case by applying suitable scale factors. To maintain the similarity of the stresses and settlement of the footing, it is required to keep similar geometric dimensions and the same stiffness of the materials between small-scale model and prototype. According to [39], if ‘N’ is the scale factor, then the stiffness of the soil used in the small-scale model is taken as $(1/N)^{\alpha}$ times the stiffness of soil used in the prototype model, where α is the material constant. Similarly, the load calculated in the case of a small-scale model is $(1/N)^{1-\alpha}$ times the load in the prototype model. As a consequence, the extrapolated findings may be used for limited prototype uses. Accordingly, despite the limitations, the small-scale model numerical analysis conducted in the present work is moreover enough to demonstrate the effectiveness of the skirted foundation bed with the different denseness of sand. The findings of the present numerical study are helpful in analysing the general mechanism as well as the failure trends of the results. The results might be used to provide the basic regulations for the design of square and circular footings with structural skirts with the different denseness of sand for the large-scale model tests and generation of the analytical model.

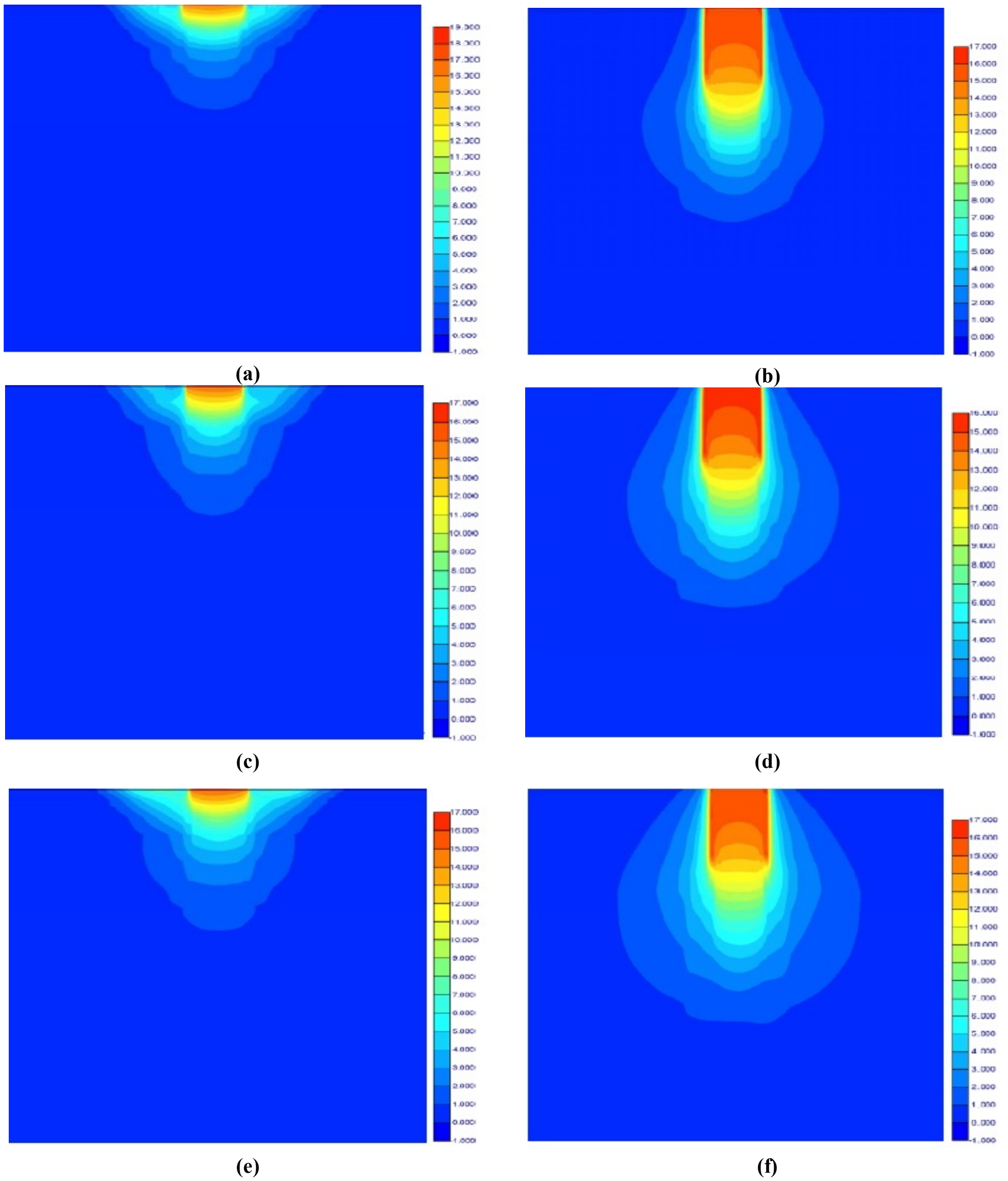


Figure 9. Failure pattern for unskirted (h/B = 0) and skirted (h/B = 2) square footing with different friction angle (a, b) 36° (c, d) 40° (e, f) 42°.

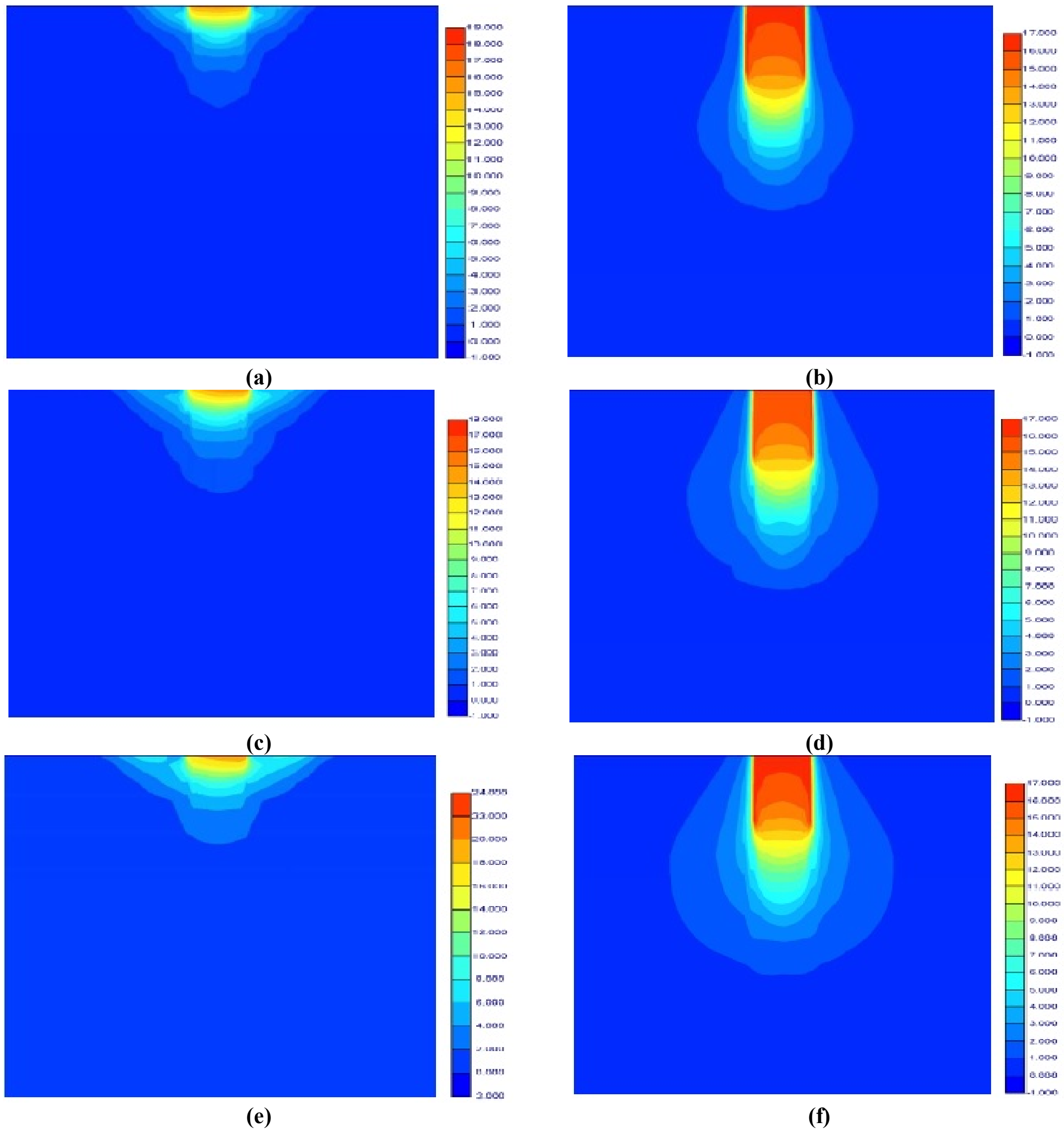


Figure 10. Failure pattern for unskirted (h/B = 0) and skirted (h/B = 2) circular footing with different friction angle (a, b) 36° (c, d) 40° (e, f) 42°.

7. Conclusions

This paper presented the three-dimensional numerical analysis results to describe the mechanism and performance of square and circular footings with structural skirts placed on different sands. The effect of various parameters such as the depth of the skirts, friction angle of the sand, and roughness coefficient between skirt-sand and footing-sand on the bearing capacity were investigated and further validated with the experimental data. Based on the findings, the following conclusions are presented:

- The findings of the numerical analysis performed by three-dimensional PLAXIS software using the Mohr-coulomb (M-C) model correlate well with the experimental results reported in the literature. It shows that the numerical modelling of the skirted foundation system was precisely modelled by using PLAXIS software.
- The results of the numerical analysis confirm that the provision of skirts with footings increases the bearing capacity of the foundation bed. For square footings, the bearing capacity increases from 151.37 kPa to 738.17 kPa, and for circular footings, the bearing capacity increases from 135.14 kPa to 778.41 kPa for different increasing values of skirt depth ranges from 0.5B to 2B.
- The inclusion of skirts with the foundation reduces the settlement of the foundation bed.

The maximum reduction in settlement for square and circular footing was observed as 96.07% and 94.21% for skirt depth equal to 2B.

- For both the cases of square and circular footings, the maximum improvement in bearing capacity is observed for sand having Ø = 36° compared to sands having Ø = 40° and 42°. Hence, the skirted footing is found to be more effective in case of loose sand compared to dense sand
- The effectiveness of the skirted footing increases with increasing the roughness coefficient between skirt-sand and footing-sand.
- The developed equation from the multiple regression analysis for the prediction of ultimate bearing capacity of the skirted footing was quite comparable with the results obtained from the numerical analysis.

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Conflict of interest

The authors declare that they have no conflict of interest.

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تحلیل عددی پایه‌های مربعی و دایره‌ای که روی شن قرار گرفته‌اند با استفاده از نرم‌افزار PLAXIS 3D

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چکیده:

این مقاله آنالیز عددی پایه‌های مربعی و دایره‌ای قرار گرفته بر روی ماسه‌های مختلف را با استفاده از نرم‌افزار PLAXIS 3D ارائه می‌کند. تجزیه و تحلیل عددی با استفاده از معیار Mohr-coulomb (M-C) انجام می‌شود. اندازه پایه‌ها برای هر دو پایه مربع و دایره ۱۰۰ میلی متر در نظر گرفته شده است. از سه زاویه اصطکاک مختلف (Ø) ماسه ۳۶ درجه، ۴۰ درجه و ۴۲ درجه برای بررسی اثر فشردگی ماسه استفاده شد. عمق دامنه (h) از ۰B تا ۲ B متغیر است (B عرض پایه است). اصطکاک سطح بین ماسه دامنی و ماسه پایه تا حدی زبر و کاملاً زبر در نظر گرفته می‌شود. ضریب اصطکاک رابط (δ) برای یک رابط نیمه ناهموار و کاملاً ناهموار به صورت Ø و ۲/۳ Ø در نظر گرفته شد. تمام آزمایش‌ها با اعمال جابجایی (S/B) تجویز شده ۲۰ درصد از اندازه پایه انجام می‌شود. نتایج به‌دست‌آمده از کار حاضر نشان می‌دهد که گنجاندن دامن‌های ساختاری با پایه‌ها، ظرفیت باربری را به میزان قابل‌توجهی افزایش می‌دهد و با افزایش عمق دامن، نشست پایه را کاهش می‌یابد. نتایج به‌دست‌آمده نشان می‌دهد که پایه دامنی در ماسه شل در مقایسه با ماسه متراکم در افزایش ظرفیت باربری مؤثرتر است. نتایج تحلیل عددی نیز با نتایج تجربی موجود در ادبیات و مدل رگرسیون چندگانه تأیید می‌شوند. این کار نشان می‌دهد که پیش‌بینی دقت نتایج با نتایج تجربی و مدل رگرسیون تولید شده کاملاً خوب است.

کلمات کلیدی: آنالیز عددی، PLAXIS، پایه رکابی، موهر-کولب، ظرفیت باربری.