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# A study of bearing capacity of skirted octagonal footings resting on different sands

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## ABSTRACT

**Purpose:** After a thorough study of literature it is concluded that the studies related to unskirted/skirted octagonal footings on sand have not yet been investigated. Thus, this paper presents a numerical analysis to assess the ultimate bearing capacity of the unskirted, unskirted-embedded, singly and doubly skirted octagonal footings resting on different sands (S1, S2, and S3). The length of skirt and depth of the embedded footing were varied from 0.0B to 1.5B.

**Design/methodology/approach:** The numerical square and octagonal footing with singly and doubly skirted footing models were developed using Plaxis 3D software.

**Findings:** The results of the doubly skirted octagonal footings ultimate bearing capacity were marginally higher in comparison to the singly skirted footing at all normalised skirt depths as well as for all sands up to a Ds/B ratio 0.25 beyond which the increase in the ultimate bearing capacity in case of doubly skirted footing was appreciable.

**Research limitations/implications:** The results presented in this paper were based on numerical analysis. However, for the actual footings the soil placement and compaction, details of skirt construction and the stress level will be different from the numerical analysis. Further investigations using full-scale numerical models simulating field size footings were recommended to generalize the results.

**Originality/value:** No such study on singly and doubly skirted octagonal shaped footings were conducted so far. Hence, an attempt was made in this article to predict the bearing capacity of those footings using Plaxis 3D.

**Keywords:** Bearing capacity, Sands, Octagonal footing, Unskirted, Unskirted-Embedded, Singly skirted (SS), Doubly skirted (DS)

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METHODOLOGY OF RESEARCH, ANALYSIS AND MODELLING

## 1. Introduction

A major issue in geotechnical engineering is the concept of appropriate economic footings for the safe transmission of loads to soil. A skirted foundation is a continuous semi-deep footing with a thin skirt around the outer part or periphery. These footings are used to support a range of onshore and offshore structures. The skirt forms an enclosure holding the soil to shallow depth and acting as a unit with trapped soil and overlain footing resulting in increased lateral and moment resistance to slipping and overturning. In addition, the soil under the footing can be prohibited from squeezing out and any likely damage because of excavations in the nearby construction works using peripheral skirt. Such footings transfer the load through the end resistance at the tip level as well as through the interface friction generated around the skirt [1]. The fundamental issue in the design of the footing is the determination of the bearing capacity under the loads. Researchers [2-19] have reported the effectiveness of the conventional shaped skirted circular, square, rectangular and strip footing subjected to vertical or inclined loads in recent years through experimental investigations and numerical analysis. Because of economic and architectural reasons, under certain circumstances, footings are required with unusual geometries such as hexagonal and octagonal shapes where the super structure has similar shapes. These footings, as reported by [20] are called multi-edge footings. The paper presents a three-dimensional analysis of the unskirted, unskirted-embedded, singly and doubly skirted octagonal footings on different sands using finite elements.

## 2. Background

Numerical studies on the conventional shaped skirted footings such as strip [2], square [12] and circular [2] have been reported in literature. The failure behaviour of unskirted multi-edge footing resting on sand through a numerical study conducted using FLAC 3D software was reported by [21]. Laboratory tests on multi-edge footing resting on sand reported by [20] confirmed that multi-edge footing performance was good than that of square footings of the same width. In addition, [20, 21] reported that improved footing geometry could also lead to increased bearing capacity. Despite the benefits of attaching skirts to conventional footings, [7, 22] recently reported the results of the bearing capacity of the unskirted/skirted multi-edge H-shaped footing resting on sand. In the above analysis, parameters varied were relative density and normalized skirt depth ranging from 30-60% and 0.25-1.5 respectively, and supported the results of [20] for unskirted multi-edge footing. Prediction of ultimate bearing capacity of skirted footing resting on sand using artificial neural network was reported by [23]. More recently, [24] stated that unskirted/skirted plus and double box shaped footing increases the load carrying capacity of sand and improved the overall behaviour of foundation. Additionally, the skirts were connected as evident from the literature to the outer edges or periphery of the footing geometry in order to increase the bearing capacity of the sand. Provision of an additional skirt below the base of the footing will further increase the bearing capacity as per [25]. Further, the sand's friction angle increases with the increase in the particle size of the sand as reported in the literature [26]. Increase in friction angle means increase in the bearing capacity keeping other parameters same. From the literature presented above, it is evident that the studies related to unskirted/skirted octagonal footings on sand have not yet been investigated. Hence, this paper presents the results obtained from numerical study carried out on the unskirted, unskirted-embedded, singly and doubly skirted model of octagonal footings placed on various sands.

## 3. Octagonal footings and finite element model

The numerical model had a dimension of 700 mm long, 600 mm wide and 450 mm high. The thickness of the modelled iron octagonal footing was kept as 10 mm for the analysis. The outer dimension of a square was chosen as 80 mm x 80 mm. As shown in Figure 1, inside this square, octagonal footing was made. In case of singly skirted (SS) and doubly skirted (DS) octagonal footing, the outer skirt was modelled with an iron plate of thickness 5 mm. For the doubly skirted (DS) octagonal footing, the inner skirt made of iron of thickness 2.5 mm was modelled at a distance of 17.5 mm from the inside of the outer skirt, as shown in Figure 1. In both the cases, the outer and inner lengths of the skirt were modelled from 0 mm to 120 mm. Width of the footing is taken as the length of the largest diagonal i.e. 80mm. For the analysis, unskirted, unskirted-embedded, singly and doubly skirted octagonal footings were exposed to concentrated downward vertical load. It was intended to determine the ultimate bearing capacity of the octagonal footings. It is appropriate to mention here that all previous studies conducted by different researchers were performed on conventional skirted footings (strip, circle, square and rectangular). The unskirted, unskirted-embedded, singly and doubly skirted octagonal footings have not yet been researched and published in literature. In order to study their behaviour, three-dimensional finite element analysis was carried out on the unskirted, unskirted-embedded, singly and doubly skirted octagonal footing resting on different sands. Different parameters such as; saturated unit weights S1 (18.83 kN/m$^3$), S2 (19.12 kN/m$^3$), S3 (19.29 kN/m$^3$), unsaturated unit weights S1 (14.38 kN/m$^3$), S2 (14.89 kN/m$^3$), S3 (15.15 kN/m$^3$), Poisson's ratio S1 (0.3), S2 (0.3), S3 (0.3) and dilation angle S1 (3.37°), S2 (6.517°), S3 (9.47°) were used for modelling. The effective size $D_{10}$ and specific gravity of the sands S1, S2 and S3 were 0.14, 0.45, 1.45 and 2.68, 2.67, 2.67, respectively. The granulometry curves for these sands are reported elsewhere [25]. It was reported by [2, 4, 7, 12] that the skirted footings were more effective in loose sand. 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 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 and Young's modulus determined for the sands S1, S2, S3 was 33.37$^o$, 36.52$^o$, 39.47$^o$ and 4.8 MPa, 5.3 MPa and 5.5 MPa respectively. In addition, the sand modules adopted aren't that far apart and had been deemed constant with depth as per [12] for the numerical modelling to account for the lower moduli value at relatively shallow depths. For the study, a Mohr Coulomb model was used as it represents a 'first order' approximation of the behaviour of the sands by estimating a constant average stiffness resulting in faster computations to obtain a first estimate of deformations, whereas the other soil hardening models take more computational time due to the creation of the material stiffness matrix that decomposes in each phase as the report as reported in Plaxis 3D foundation material models manual version 1.5. It is important to note here that poison ratio of cast iron varies from 0.2 and 0.26. For modelling purposes a lower value of 0.2 is therefore adopted. The normalised depth of the skirt ($D_s$/B) and depth of unskirted-embedded footing ($D_f$/B) ranged from 0 to 1.5. The analysis was carried out up to s/B ratio of 20% in order to assess the elasto-plastic behaviour. A robust numerical model, with parametric variations, will solve the problem of performing large numbers of laboratory tests by taking into account the different parameters. Figure 2 presents the numerical model for the skirted octagonal footing on sand. The stress contour '0.1q' (q is the stress applied on the basis of its failure) represents the ultimate significant isobar, beyond which the effect of the stress applied is considered negligible. The dimensions of the model were chosen so that the geometry of the sand boundaries did not cross the necessary isobar. PLAXIS places a variety of general fixities on the limits of the geometry model. In the present study, the bottom boundary of the model is fixed and the ground surface of the model is free in all directions. The boundaries of the vertical model are fixed in the direction of 'x' and 'z' and free in the direction of 'y' with their normal neither in the direction of 'x' nor 'z'. The model was discretized to perform finite element analysis in a smaller number of 15-noded wedge elements. Domain meshing is performed using fully automatic finite elements in the PLAXIS 3D program.

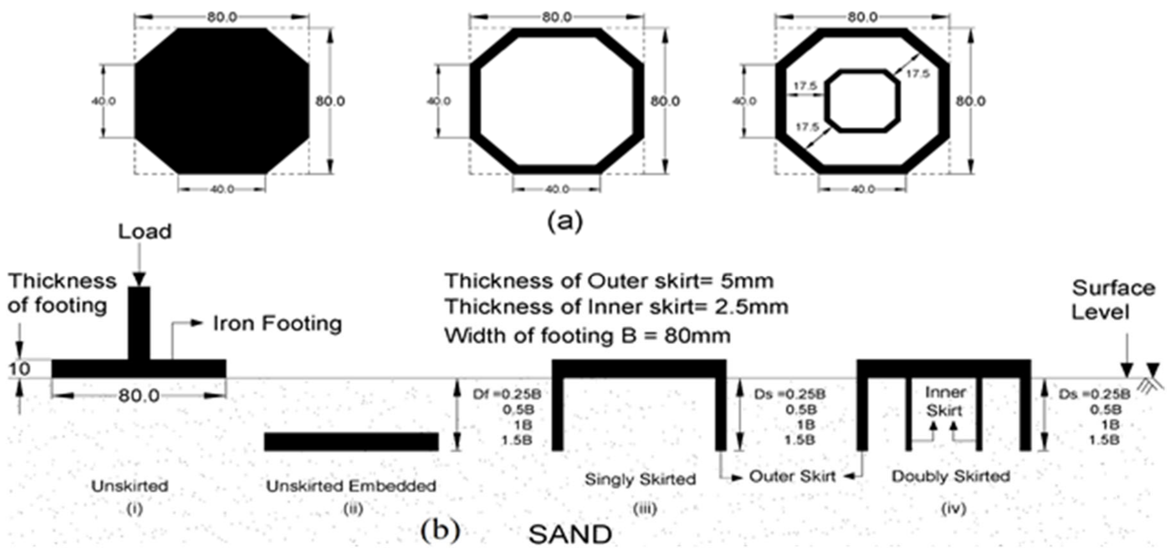


Fig. 1. a) Plan view of octagonal footing and b) Cross-section of footings: (i) unskirted, (ii) unskirted-embedded, (iii) singly skirted (SS) (iv) doubly skirted (DS)

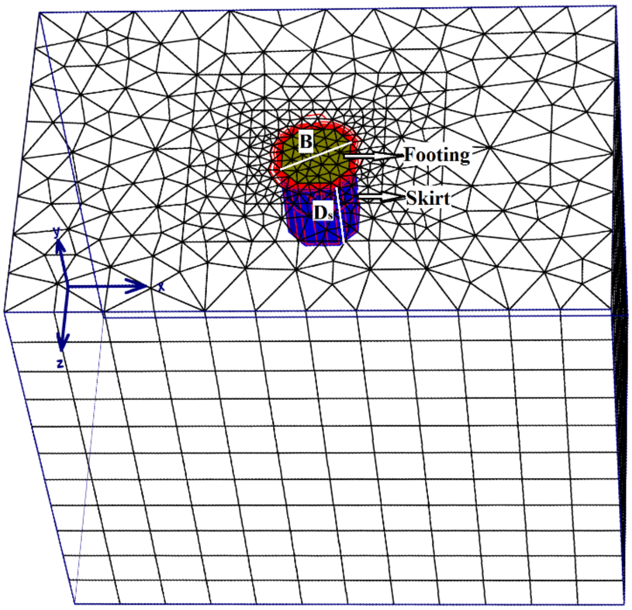


Fig. 2. Model footing and standard mesh used for numerical analysis

There are five popular mesh schemes (i.e. very rough, coarse, moderate, fine, and very fine mesh) that allow the user to refine a field, line, or point further. The standard mesh obtained for the numerical model is shown in Figure 2. The mesh convergence study reveals that increasing the number of elements beyond 8492 does not have any effect on the settlement response of the geometry under consideration. Hence 8492 to 9600 numbers of elements with the average element size of $4.8 \times 10^{-3}$ m has been used in the numerical analysis corresponding to different Ds/B ratio. A very coarse mesh does not capture the domain's key feature responses. However, for any simulation, very fine meshing takes considerable time to determine the optimal mesh configuration. In this analysis, as shown in Figure 2, coarse to fine mesh is used near footing.

## 4. Results and discussions

### 4.1. Bearing capacity of unskirted and unskirted-embedded octagonal footings

The numerically obtained pressure and settlement to width ratio plot for the unskirted and unskirted-embedded octagonal footings resting on different sands are shown in Figure 3. The obtained bearing capacity (corresponding to s/B ratio of 5%) for the unskirted and unskirted-embedded (at different $D_f$/B ratio) octagonal footings is tabulated in Table 1.

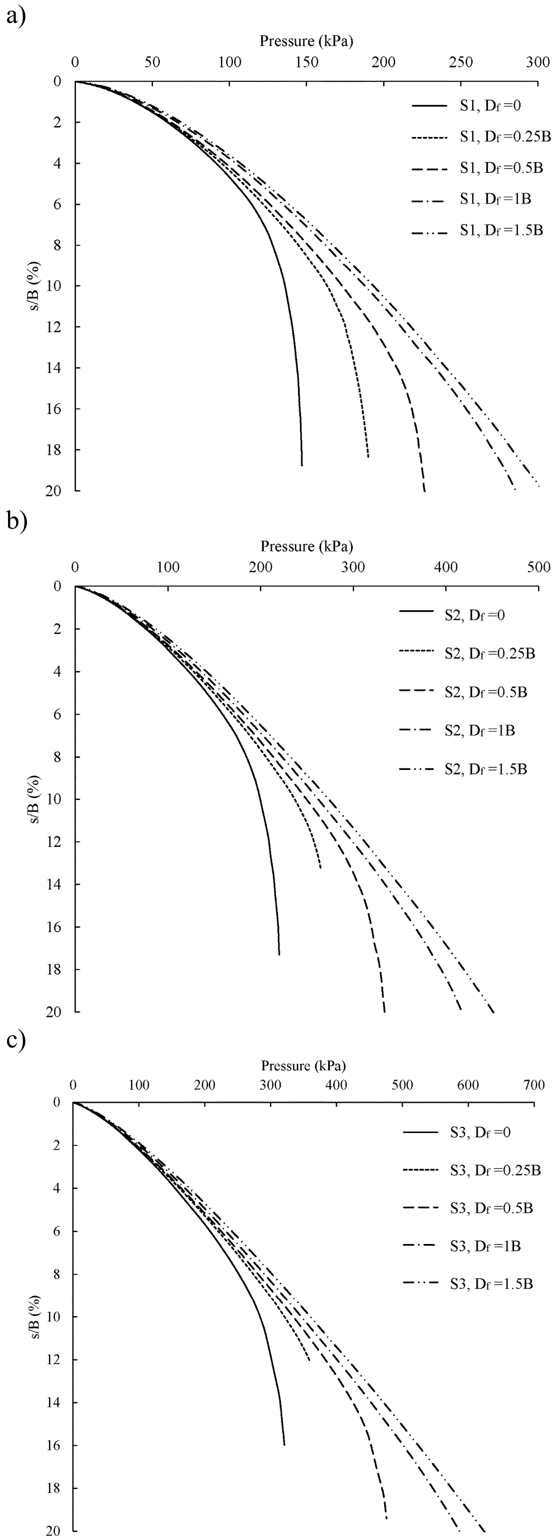


Fig. 3. Pressure-settlement curves for unskirted and skirted embedded footing on sand a) S1, b) S2 and c) S3

Table 1.
Comparison with conventional footing shapes

| Reference | Footing shape | Friction angle, Deg. | Df/B | B or D, mm | δf | Relative density, % | Qult, kPa |
|---|---|---|---|---|---|---|---|
| Present work (S1) | Octagonal | 33.37 | 0 | 80 | - | 30 | 103.75 |
| Present work (S2) | Octagonal | 36.517 | 0 | 80 | - | 30 | 141.95 |
| Present work (S3) | Octagonal | 39.47 | 0 | 80 | - | 30 | 182.35 |
| Ghazavi & Mokhtari (2008) [21] | Square | 38.1 | 0 | 105 | - | 40 | 107.2 |
| Davarci et al. (2014) [20] | Square | 36 | 0 | 100 | - | 25 | 60 |
| Prasanth & Kumar (2017) [27] | Circular | 32.5 | 0 | 75 | - | 30 | 148 |
| Al-Aghbari and Mohamedzein (2018) [6] | Circular | Varied from 39 (medium) to 43 (dense) | 0 | 120 | - | Medium to dense | 70 |
| Present work (S1) | Octagonal | 33.37 | 0.25 | 80 | 22.25 | 30 | 108.98 |
| | | 33.37 | 0.5 | 80 | 22.25 | 30 | 112.35 |
| | | 33.37 | 1 | 80 | 22.25 | 30 | 120.03 |
| | | 33.37 | 1.5 | 80 | 22.25 | 30 | 123.50 |
| Pesent work (S2) | | 36.517 | 0.25 | 80 | 24.34 | 30 | 149.19 |
| | | 36.517 | 0.5 | 80 | 24.34 | 30 | 152.84 |
| | | 36.517 | 1 | 80 | 24.34 | 30 | 159.38 |
| | | 36.517 | 1.5 | 80 | 24.34 | 30 | 165.58 |
| Pesent work (S3) | | 39.47 | 0.25 | 80 | 26.31 | 30 | 192.13 |
| | | 39.47 | 0.5 | 80 | 26.31 | 30 | 195.11 |
| | | 39.47 | 1 | 80 | 26.31 | 30 | 202.00 |
| | | 39.47 | 1.5 | 80 | 26.31 | 30 | 209.82 |
| Al-Aghbari and Mohamedzein (2018) [6] | Circular | Varied from 39 (medium) to 43 (dense) | 0.25 | 120 | 28 | Medium to dense | 112 |
| | | | 0.5 | 120 | 28 | | 148 |
| | | | 0.75 | 120 | 28 | | 217.5 |
| | | | 1 | 120 | 28 | | 238.2 |
| | | | 1.25 | 120 | 28 | | 273 |

Study of Table 1 reveals that the bearing capacity of the unskirted surface octagonal footing was 103.75 kPa, 141.95 kPa and 182.35 kPa, respectively, for the sands S1, S2 and S3. This bearing capacity increased to 108.98 kPa, 149.19 kPa and 192.13 kPa for the sands S1, S2 and S3 respectively for the unskirted-embedded octagonal footing corresponding to $D_f/B$ ratio of 0.25. The bearing capacity further increased to 123.50 kPa, 165.58 kPa and 209.82 kPa for sands S1, S2 and S3 at $D_f/B$ of 1.5. The bearing capacity for the unskirted-embedded octagonal footing at other $D_f/B$ ratio for the sands S1, S2 and S3 is tabulated in Table 1. The present results related to the ultimate bearing capacity of the unskirted and unskirted-embedded octagonal footing were compared with the bearing capacity (obtained experimentally and numerically) of the surface and embedded footings (square and circular) reported in literature [20,21,27].

The relevant comparison of the ultimate bearing capacity is also provided in Table 1. Study of Table 1 reveals that the numerically obtained ultimate bearing capacity in present case for the surface octagonal footing on sand S3 was higher than those reported by [20,21,27]. This was attributed to higher friction angle of sand S3 in comparison to the one reported in literature. Further study of Table 1 reveals that the ultimate bearing capacity for the surface octagonal footing on sand S2 was comparable with the one reported by [27] for circular footing. The ultimate bearing capacity for the surface octagonal footing on sand S1 was comparable with the one reported by [21] for square footing as evident from Table 1. The minor difference in the bearing capacity obtained in the present study with the one reported by [21,27] is attributed to the shape and size of the footing considered for the experimental and numerical study respectively. Further, the present results for the unskirted-embedded octagonal footing on sands S1 (at $D_f/B=0.25$), S2 (at $D_f/B=0.50$) and S3 (at $D_f/B=1.00$) were comparable with the one obtained experimentally for the circular footing by [6]. Therefore, it can be inferred that numerically obtained bearing capacity results confirm the reported results in the literature and can be used as the basis for determining the gain from skirt usage.

### 4.2. Bearing capacity of skirted octagonal footings

In Figure 4, at a skirt depth of 0B, 0.25B 0.5B, 1B and 1.5B shows the numerically obtained pressure and settlement ratio plot at s/B of 5% for the singly and doubly skirted octagonal footings on sands S1, S2 and S3 separately. The bearing capacity obtained at all skirt depths are given in Table 2. Study of Table 1 reveals that the bearing capacity obtained for the unskirted octagonal footing was 103.75 kPa, 141.95 kPa and 182.35 kPa, respectively, for sand S1, S2 and S3. With the provision of single skirt at the periphery of octagonal footing on sands S1, S2 and S3 respectively at a skirt depth of 1.5, this bearing capacity was increased to 138.54 kPa, 187.43 kPa and 266.71 kPa. The bearing capacity further increased to 142.63 kPa, 205.75 kPa and 275.72 kPa for sands S1, S2 and S3 at the same skirt depth with the provision double skirt provided at the periphery as well as below the base of octagonal footing. The trend was similar for all the sands as evident from Table 2. A close examination of Table 2 reveals that the bearing capacity also increases as the skirt depth rises for both singly and doubly skirted octagonal footing. Similar findings were reported based on experimental study for the singly skirted square footing [2,4,7] in literature. Further, the present results related to the ultimate bearing capacity of the skirted octagonal footing were compared with the skirted circular footing reported by [6]. The comparison is also shown in Figure 5.

Study of Table 2 reveals that the ultimate bearing capacity of singly/doubly skirted octagonal footing on sand S1, S2 and S3 were comparable with the one reported by [6] for the circular skirted footing in general at different normalised skirt depths. The minor difference in the ultimate bearing of the singly/doubly skirted octagonal footing may be attributed to the difference in the footing shape, size and relative density of sands used in the study. Comparing the results of singly skirted and doubly skirted footing as shown in Table 2, it is evident that the ultimate bearing capacity for the doubly skirted octagonal footing were marginally higher in comparison to the singly skirted footing at all normalised skirt depths as well as for all sands up to a Ds/B ratio 0.25 beyond which the increase in the ultimate bearing capacity

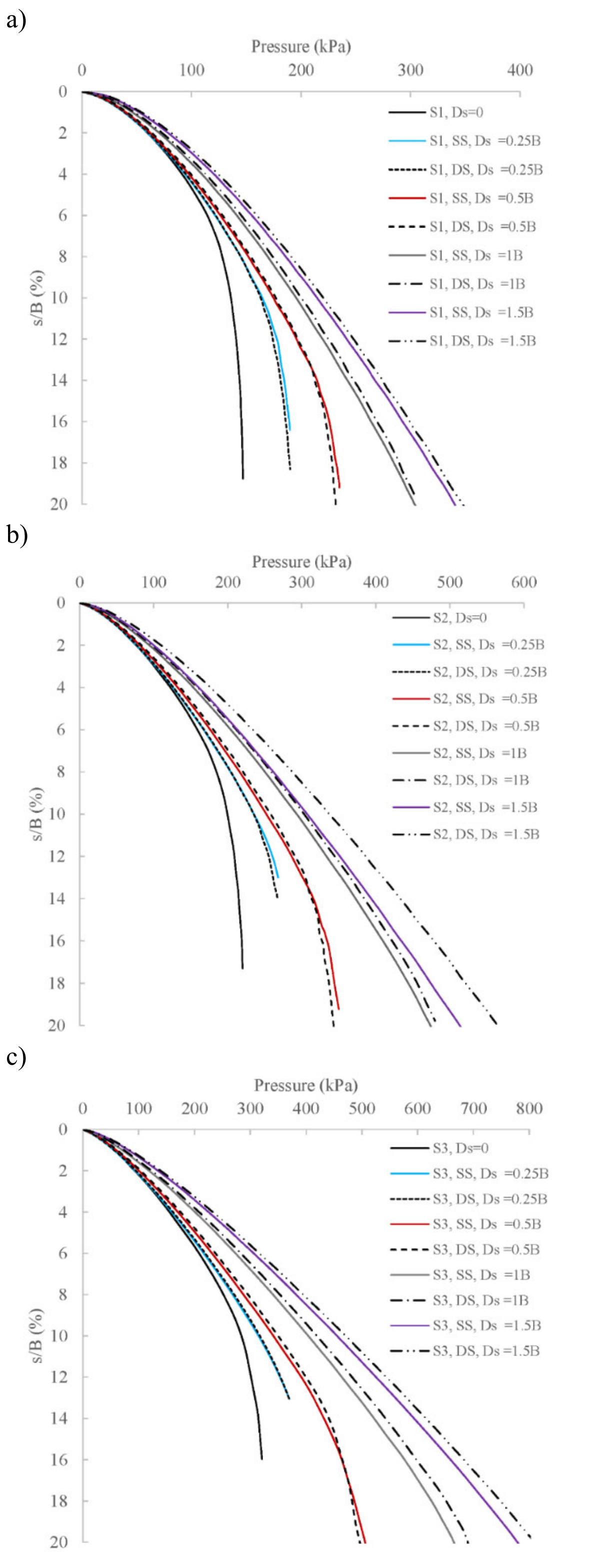


Fig. 4. Pressure-settlement curves for skirted footings on sand a) S1, b) S2, c) S3

Table 2.
Comparison of ultimate bearing capacity of skirted octagonal footing with literature

| Reference | Footing shape | Friction angle, Deg. | Ds/B | B or D, mm | δf = δs | Skin resistance 'Qf' (SS), kPa | Skin resistance 'Qf' (DS), kPa | Relative density, % | Qult, kPa | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | SS | DS |
| Pesent work (S1) | Octagonal | 33.37 | 0.25 | 80 | 22.25 | 0.00058 | 0.00083 | 30 | 108.45 | 108.97 |
| | | 33.37 | 0.5 | 80 | 22.25 | 0.00187 | 0.00288 | 30 | 112.49 | 114.50 |
| | | 33.37 | 1 | 80 | 22.25 | 0.00656 | 0.01065 | 30 | 125.74 | 130.01 |
| | | 33.37 | 1.5 | 80 | 22.25 | 0.01407 | 0.02332 | 30 | 138.54 | 142.63 |
| Pesent work (S2) | | 36.517 | 0.25 | 80 | 24.34 | 0.00060 | 0.00085 | 30 | 147.27 | 147.93 |
| | | 36.517 | 0.5 | 80 | 24.34 | 0.00193 | 0.00298 | 30 | 154.84 | 158.53 |
| | | 36.517 | 1 | 80 | 24.34 | 0.00679 | 0.01103 | 30 | 179.25 | 185.19 |
| | | 36.517 | 1.5 | 80 | 24.34 | 0.01457 | 0.02415 | 30 | 187.43 | 205.75 |
| Pesent work (S3) | | 39.47 | 0.25 | 80 | 26.31 | 0.00061 | 0.00087 | 30 | 188.83 | 190.95 |
| | | 39.47 | 0.5 | 80 | 26.31 | 0.00197 | 0.00303 | 30 | 201.48 | 207.18 |
| | | 39.47 | 1 | 80 | 26.31 | 0.00691 | 0.01122 | 30 | 238.29 | 246.90 |
| | | 39.47 | 1.5 | 80 | 26.31 | 0.01483 | 0.02457 | 30 | 266.71 | 275.72 |
| Al-Aghbari and Mohamedzein (2018) [6] | Circular | 39-43 | 0.25 | 120 | 28 | - | - | Medium state - Dense state | 147.00 | |
| | | | 0.5 | 120 | 28 | - | - | | 194.00 | |
| | | | 0.75 | 120 | 28 | - | - | | 239.00 | |
| | | | 1 | 120 | 28 | - | - | | 271.30 | |
| | | | 1.25 | 120 | 28 | - | - | | 312.00 | |

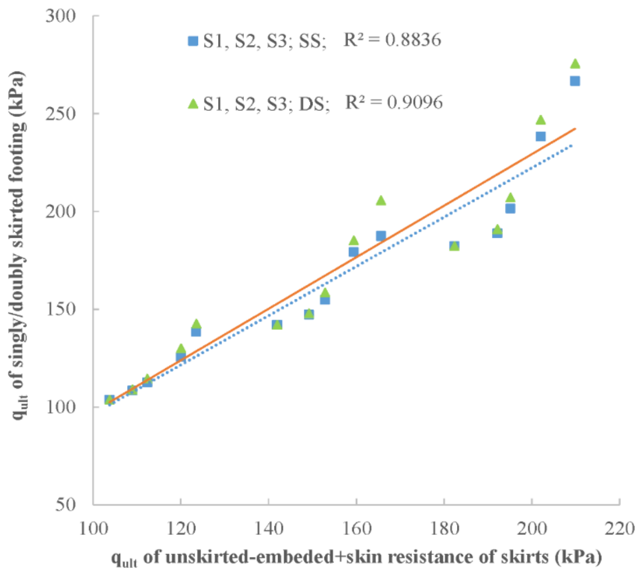


Fig. 5. Comparison of numerically obtained ultimate bearing capacity of singly/doubly skirted octagonal footing with the ultimate bearing capacity of unskirted-embedded plus skin resistance of skirts

in case of doubly skirted footing was appreciable. This is due to the fact that the skirts form an enclosure in which the soil is strictly confined and acts as a unit with the overlain footing to transfer super structural load to the soil basically at the level of the skirt tip. Hence from the above it can be inferred that the provision of double skirt marginally and appreciably benefits at lower and higher Ds/B respectively in increasing the bearing capacity in comparison to the singly skirted octagonal footings.

### 4.3. Failure patterns

Figures 6, 7 and 8 for sands S1, S2 and S3 show the typical failure pattern generated for the unskirted, unskirted-embedded, singly and doubly-skirted octagonal footings corresponding to a normalised skirt depth ($D_s$/B) and unskirted-embedded footing ($D_f$/B) of 0 and 1.5. Figures 6-8 also include the failure pattern for the unskirted and unskirted-embedded octagonal footing. These failure patterns show the total displacement contour, and their significance is to determine the actual displacement under the load. To verify the vertical settlement in the footing design within

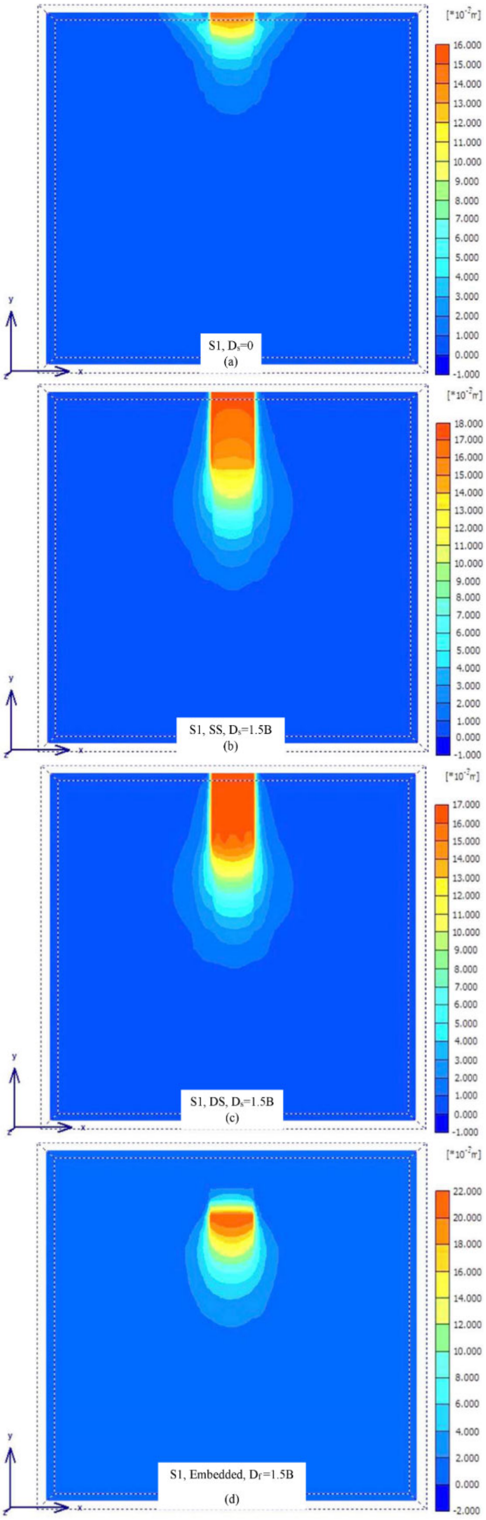


Fig. 6. Failure pattern of the octagonal footing on sand S1: a) unskirted at $D_s$=$D_f$=0; b) singly skirted at $D_s$=1.5B; c) doubly skirted at $D_s$=1.5B; d) unskirted-embedded at $D_f$ =1.5B

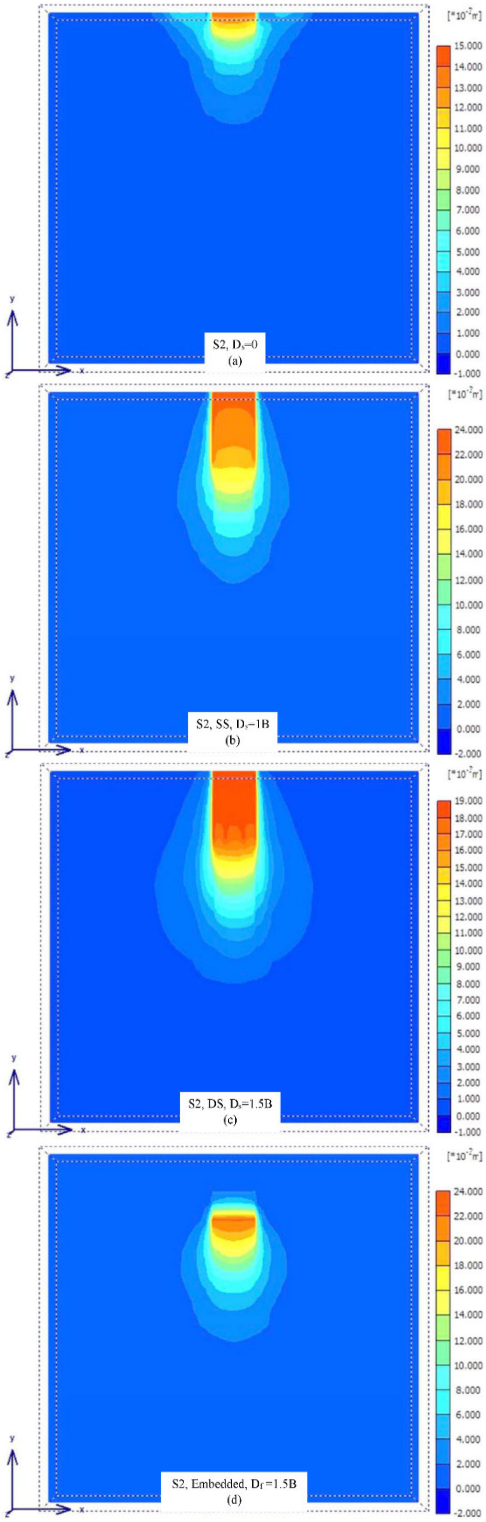


Fig. 7. Failure pattern of the octagonal footing on sand S2: a) unskirted at $D_s$=$D_f$ =0; b) singly skirted at $D_s$=1.5B; c) doubly skirted at $D_s$=1.5B; d) unskirted-embedded at $D_f$ =1.5B

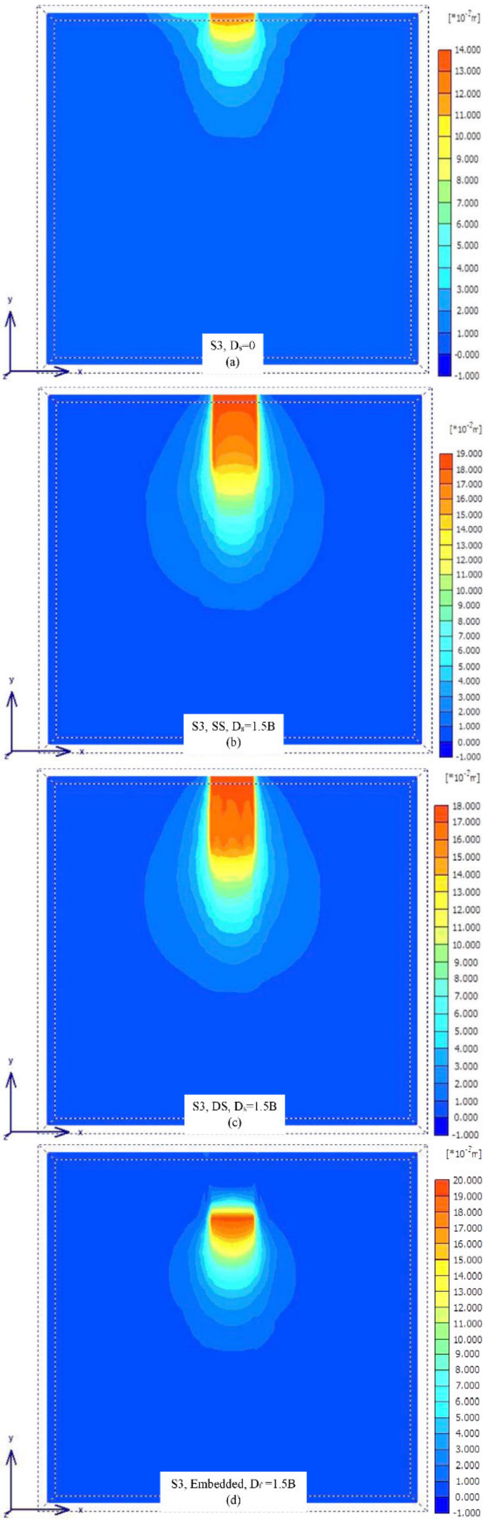


Fig. 8. Failure pattern of the octagonal footing on sand S3: a) unskirted at $D_s$=$D_f$=0; b) singly skirted at $D_s$=1.5B; c) doubly skirted at $D_s$=1.5B; d) unskirted-embedded at $D_f$=1.5B

the acceptable limits, or not under the load, this type of information is needed. For 80 mm x 80 mm unskirted / unskirted-embedded / skirted octagonal footing with vertical load on different sands, Figures 6, 7 and 8 shows output of deformed mesh and vertical settlement distribution. For all cases, the contours of soil settlements along the vertical cross-section of the soil field were shown, and the failure criteria are shown in Figures 6, 7 and 8. Analysis of these figures shows that for sand S3 the isobar size is greater than for sands S2 and S1 at 1.5B skirt depth, suggesting a higher bearing capacity for the footing on sand S3. Furthermore, the study of these figures indicates that the failure pattern remained well defined for the unskirted, unskirted-embedded, singly and doubly skirted octagonal footings corresponding to a skirt depth of 0B, and 1.5B within the selected lateral and vertical distance. That means the chosen problem domain was enough. Similar results were found at other skirt depths for the failure patterns for all sands. The insights gained from the above analysis about the pattern of failure will be useful in the creation of analytical solutions.

## 5. Conclusions

The numerical analysis for the unskirted, unskirted-embedded, singly and doubly skirted octagonal footings subjected to vertical concentric load and resting on different sands is investigated. A series of analysis were performed to assess the behaviour of unskirted, unskirted-embedded, singly and doubly skirted octagonal footings on different sands. From the results and discussion presented above, the following conclusions are drawn:

- Mesh convergence study reveals that increasing the number of elements beyond 8492 does not have any effect on the settlement response of the unskirted, unskirted-embedded, singly and doubly skirted octagonal footings.
- The range of ultimate bearing capacity obtained from the numerical study for the unskirted and unskirted-embedded octagonal footings on different sands were in line with literature.
- The ultimate bearing capacity for the doubly skirted octagonal footing were marginally higher in comparison to the singly skirted footing at all normalised skirt depths as well as for all sands up to a Ds/B ratio 0.25 beyond which the increase in the ultimate bearing capacity in case of doubly skirted footing was appreciable.
- Numerically obtained ultimate bearing capacity of the unskirted-embedded footing plus skin resistance of the skirts was nearly close to the numerically obtained

ultimate bearing capacity of the singly/doubly skirted footing resting on different sands.

- The failure pattern generated supports the observations of the unskirted, unskirted-embedded, singly and doubly skirted octagonal footings with regard to the ultimate bearing capacity on different sands.

The results presented in this paper were based on numerical analysis. However, for the actual footings the soil placement and compaction, details of skirt construction and the stress level will be different from the numerical analysis. Further investigations using full-scale numerical models simulating field size footings were recommended to generalize the results.

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## References

[1] S. Rezazadeh, A. Eslami, Bearing capacity of semi-deep skirted foundations on clay using stress characteristics and finite element analyses, Marine Georesources & Geotechnology 36/6 (2018) 625-639. DOI: https://doi.org/10.1080/1064119X.2017.1361488

[2] V.N. Khatri, J. Kumar, Finite-Element Limit Analysis of Strip and Circular Skirted Footings on Sand, International Journal of Geomechanics 19/3 (2019) 06019001. DOI: https://doi.org/10.1061/(ASCE)GM.1943-5622.0001370

[3] M.Y. Al-Aghbari, Y.E.A. Mohamedzein, A.L.N. Hammad, Potential use of structural skirts towards improving the bearing capacity of shallow footings exposed to inclined loadings, International Journal of Geotechnical Engineering (published online 18.05.2019). DOI: https://doi.org/10.1080/19386362.2019.1617477

[4] G. Sajjad, M. Masoud, Study of the behaviour of skirted shallow foundations resting on sand, International Journal of Physical Modelling in Geotechnics 18/3 (2018) 117-130. DOI: https://doi.org/10.1680/jphmg.16.00079

[5] M.R. Mahmood, M.Y. Fattah, A. Khalaf, Experimental investigation on the bearing capacity of skirted foundations on submerged gypseous soil, Marine Georesources & Geotechnology 38/10 (2020) 1151-1162. DOI: https://doi.org/10.1080/1064119X.2019.1656311

[6] M.Y. Al-Aghbari, Y.E.A. Mohamedzein, The use of skirts to improve the performance of a footing in sand, International Journal of Geotechnical Engineering 14/2 (2020) 134-141. DOI: https://doi.org/10.1080/19386362.2018.1429702

[7] T. Gnananandarao, V.N. Khatri, R.K. Dutta, Performance of multi-edge skirted footings resting on sand, Indian Geotechnical Journal 48/3 (2018) 510-519. DOI: https://doi.org/10.1007/s40098-017-0270-6

[8] V.N. Khatri, S.P. Debbarma, R.K. Dutta, B. Mohanty, Pressure-settlement behaviour of square and rectangular skirted footings resting on sand, Geomechanics and Engineering 12/4 (2017) 689-705. DOI: https://doi.org/10.12989/gae.2017.12.4.689

[9] H. Rezaei, R. Nazir, E. Momeni, Bearing capacity of thin-walled shallow foundations: an experimental and artificial intelligence-based study, Journal of Zehjiang University - SCIENCE A 17/4 (2016) 273-285. DOI: https://doi.org/10.1631/jzus.A1500033

[10] A.E. El-Saied, N.M. Saleh, M.E. El-Mashad, Behavior of circular footing resting on laterally confined granular reinforced soil, Housing and Building National Research Center Journal 11/2 (2015) 240-245. DOI: https://doi.org/10.1016/j.hbrcj.2014.03.011

[11] H.T. Eid, Bearing capacity and settlement of skirted shallow foundations on sand, International Journal of Geomechanics 13/5 (2013) 645-652. DOI: https://doi.org/10.1061/(ASCE)GM.1943-5622.0000237

[12] A.Z.E.L. Wakil, Bearing capacity of skirt circular footing on sand, Alexandria Engineering Journal 52/3 (2013) 359-364. DOI: https://doi.org/10.1016/j.aej.2013.01.007

[13] A.Z.E.L. Wakil, Horizontal capacity of skirted circular shallow footings on sand, Alexandria Engineering Journal 49/4 (2010) 379-385. DOI: https://doi.org/10.1016/j.aej.2010.07.003

[14] H.T. Eid, O.A. Alansari, A.M. Odeh, M.N. Nasr, H.A. Sadek, Comparative study on the behaviour of square foundations resting on confined sand, Canadian Geotechnical Journal 46/4 (2009) 438-453. DOI: https://doi.org/10.1139/T08-134

[15] M.Y. Al-Aghbari, R.K. Dutta, Performance of square footing with structural skirt resting on sand, Geomechanics Geoengineering 3/4 (2008) 271-277. DOI: https://doi.org/10.1080/17486020802509393

[16] F. Villalobos, Bearing capacity of skirted foundations in sand, Proceedings of the VI Congreso chileno de Geotecnia, SOCHIGE, Valparaiso, 2007.

[17] M.Y. Al-Aghbari, Settlement of shallow circular foundations with structural skirts resting on sand, The Journal of Engineering Research 4/1 (2007) 11-16. DOI: https://doi.org/10.24200/tjer.vol4iss1pp11-16

[18] M.Y. Al-Aghbari, Improving the performance of circular foundations using structural skirts, Ground Improvement 10/3 (2006) 125-132.

[19] M.E.L. Sawwaf, A. Nazer, Behavior of Circular Footings Resting on Confined Granular Soil, Journal of Geotechnical and Geoenvironmental Engineering 131/3 (2005) 359-366. DOI: https://doi.org/10.1061/(ASCE)1090-0241(2005)131:3(359)

[20] B. Davarci, M. Ornek, Y. Turedi, Analysis of multi-edge footings rested on loose and dense sand, Periodica Politechnica Civil Engineering 58/4 (2014) 355-370. DOI: https://doi.org/10.3311/PPci.2101

[21] M. Ghazavi, S. Mokhtari, Numerical investigation of load-settlement characteristics of multi-edge shallow foundations, Proceeding of the 12th International Conference of International Association for Computer Methods and Advances in Geomechanics, Goa, India, 2008, 3344-3351.

[22] T. Gnananandarao, V.N. Khatri, R.K. Dutta, Prediction of bearing capacity of h shaped skirted footing on sand using soft computing techniques, Archives of Material Science and Engineering 103/2 (2020) 62-74. DOI: https://doi.org/10.5604/01.3001.0014.3356

[23] R.K. Dutta, R. Rani, T. Gnananandarao, Prediction of ultimate bearing capacity of skirted footing resting on sand using artificial neural networks, Journal of Soft Computing in Civil Engineering 2/4 (2018) 34-46. DOI: https://doi.org/10.22115/scce.2018.133742.1066

[24] T. Gnananandarao, R.K. Dutta, V.N. Khatri, Model studies of plus and double box shaped skirted footings resting on sand, International Journal of Geo-engineering 11/1 (2020) 2. DOI: https://doi.org/10.1186/s40703-020-00109-0

[25] A. Thakur, R.K. Dutta, A study on bearing capacity of skirted square footings on different sands, Indian Geotechnical Journal 50/6 (2020) 1057-1073. DOI: https://doi.org/10.1007/s40098-020-00440-4

[26] M.N. Islam, A. Siddika, M.B. Hossain, A. Rahman, M.A. Asad, Effect of particle size on the shear strength behaviour of sands, Australian Geomechanics 46/3 (2011) 75-86.

[27] T. Prasanth, P.R. Kumar, A Study on Load Carrying Capacity of Skirted Foundation on Sand, International Journal of Science and Research (IJSR) 6/6 (2017) 2231-2235.