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Improving Square Skirted Foundations Behavior on Sand

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ORIGINAL STUDY

Improving Square-skirted Foundations Behavior on Sand

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Abstract

Shallow foundations' behavior is enhanced by using skirts to confine the soil beneath the foundation. The bearing capacity and settlement of skirted foundations resting on the sand are influenced by the size of the skirt cell and the shear strength of the sand. Experimental modelling was carried out on an axially square-skirted footing resting on the sand in this study. Plaxis-3D software was used for numerical analysis to support the experimental results. The numerical analysis results validated the experimental results. The outcomes of the study demonstrated that skirts wider than the footing size increased the bearing capacity of skirted foundations. In the case of a skirt-width/foundation-width ratio of 5/3, settlement reduction may well be valued at more than 77%. The enhancement in bearing capacity of the skirted foundation increases with decreasing relative density of sand. The bearing capacity and settlement of skirted foundations with wider skirts are estimated using charts.

Keywords: Bearing capacity, Relative density, Sand, Settlement, Skirted foundation

1. Introduction

The added steel plates -may be concrete-to the surface foundation improves the load-settlement performance of the foundation, because these plates or skirts confine the soil between them (AL-Aghbari and Mohamedzein, 2004). Carried out several tests on surface strip footing resting on the sand to study the influence of the added skirts on bearing capacity. They concluded that the bearing capacity was improved with a ratio of (1.5−3.6) compared with the bearing capacity of surface strip footing without skirts. In experimental studies carried out on strip footing resting on clayey soil (Al-Qaissy and Muwafak, 2013), found that the optimal improvement in bearing capacity occurs at a skirt depth ratio of 0.5 (AL-Aghbari, 2007; AL-Aghbari and Dutta, 2008). Studied the performance of the isolated footings with different shapes -square and circular-resting on sandy soil under a vertical load. They proved that the bearing capacity improved as the skirt-embedded length increased (El Wakil, 2013). Suggested that the effectiveness of the skirts depends on the relative density of the sand. The skirts are more beneficial in case of loose sand. In addition (Eid et al., 2009), performed a numerical analysis on a square footing -with a sheet pile-resting on the sand, and they found that bearing capacity increased as the relative density increased. Parametric studies were undertaken to investigate the effect of skirting pattern, such as inclined skirts on the bearing capacity of skirted foundations resting on sandy soil. The findings revealed a significant enhancement in bearing capacity as the skirt angle increased (Lepcha et al., 2021). The existing literature in the field has been limited in providing sufficient details about skirted foundations where the skirts are wider than the footing size and not connected to the footing. This paper will study the effects of these unique skirt configurations on the performance of the foundation in terms of bearing capacity and settlement. In addition, find out the effect of sand shear strength on these configurations' efficiency. The insights

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gained from this study contribute to advancing the understanding of foundation behavior and offer new perspectives for the design and construction of skirted foundation systems.

2. Testing equipment

Laboratory tests were carried out on a small square footing with a width of 60 mm and a thickness of 20 mm. The skirts used were 2 mm thick. The skirts were 80 and 100 mm wide, with skirt-length/footing-width (*L/B*) values of 0.25, 0.50, 0.75, and 1.00 (see Fig. 1). The load-settlement behavior of a surface foundation with a skirt width wider than the footing width was investigated in twenty-one experiments. The model was placed in the centre of the sand-filled test tank. The applied load was measured using a proving ring with a capacity of 4.5 kN and an accuracy of 0.01 kN. While determining the vertical displacement of the footing, an electronic dial gauge with a capacity of 25 mm and an accuracy of 0.001 mm was employed. The gauges used were meticulously calibrated by the National Institute of Standards (NIS), ensuring their accuracy and traceability (Certificate of Calibration, 2022). The rigid steel test tank had a thickness of 3 mm, an interior diameter of 354 mm, and a height of 550 mm. The test tank was positioned on a moveable cap with a strain rate of 0.1–5 mm/min. The test tank dimensions are sufficient to limit the boundary conditions' impact since the diameter and depth of the test tank are 5.9 and 6.7 times the footing width, respectively (see Fig. 2).

3. Testing procedure

The sand was set in the test tank in five layers, each 80 mm thick. Each layer was compacted until the appropriate relative density, D_r of sand was reached. To maintain layer integrity, the top surface of the layer was levelled and scraped before placing the next layer. Relative densities D_r. of 35%, and 55% were chosen in this investigation to find out the relationship between the efficiency of the wider skirts in enhancing the bearing capacity of surface foundation and the relative density or sand shear strength, as stated in (Eid, 2013). These relative densities indicate that the sand is correspondingly loose, and medium, respectively. The last layer's top surface was levelled, and the skirt model (welded steel plates) was set in the centre. The skirts model was then gradually pushed into the sand at a strain rate of 5 mm/min. The footing model was then placed at the centre of the skirt cell (see Fig. 3). It should be noticed that the skirts and footing models were carefully set to minimize disruption in the sand's relative density. Table 1 lists the parameters of the available sand and materials utilized in the tests. The sand unit weight and void ratio were found at the corresponding relative density. Poisson's ratio was taken at 0.2 which ranged between 0.15 and 0.25 as reported by (Obrzud and Truty, 2020). The proving ring, which was linked to a shaft, was put in the footing's centre. Furthermore, to estimate the vertical displacement of the footing, the electronic dial gauge was positioned on the reference line, which is a steel girder. Before the loading began, both dial gauges were set to zero (see Fig. 4). The loading was gradual with a strain rate of.

1 mm/min as recommended by (Magdy, 2022). According to (Das, 2011), because the foundation was supported by loose sand, the load-settlement curve has no specific value that indicates the ultimate bearing capacity. As a result, the ultimate bearing capacity was chosen to correspond to a 20% settlement, *S* of the footing width, *B*.

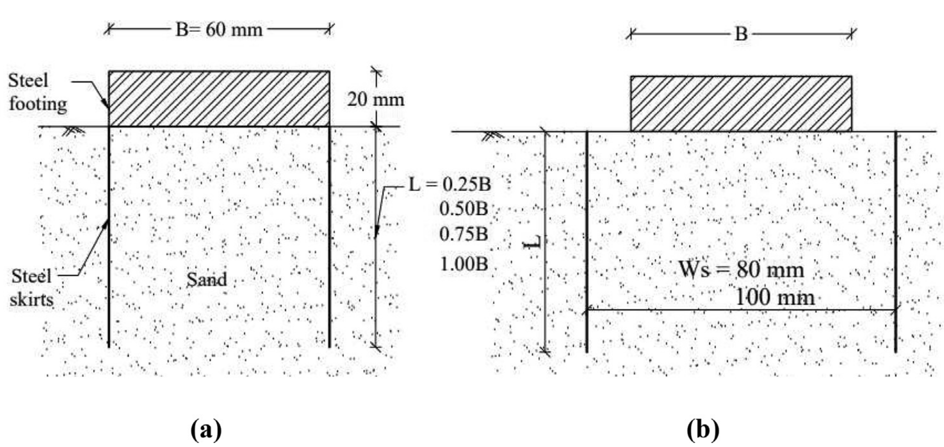

Fig. 1. Square-skirted foundation, (a) skirt width the same of footing width, (b) skirt-width wider than of footing width. B*: footing width,* L*: skirt embedded length, and* Ws*: skirt width.*

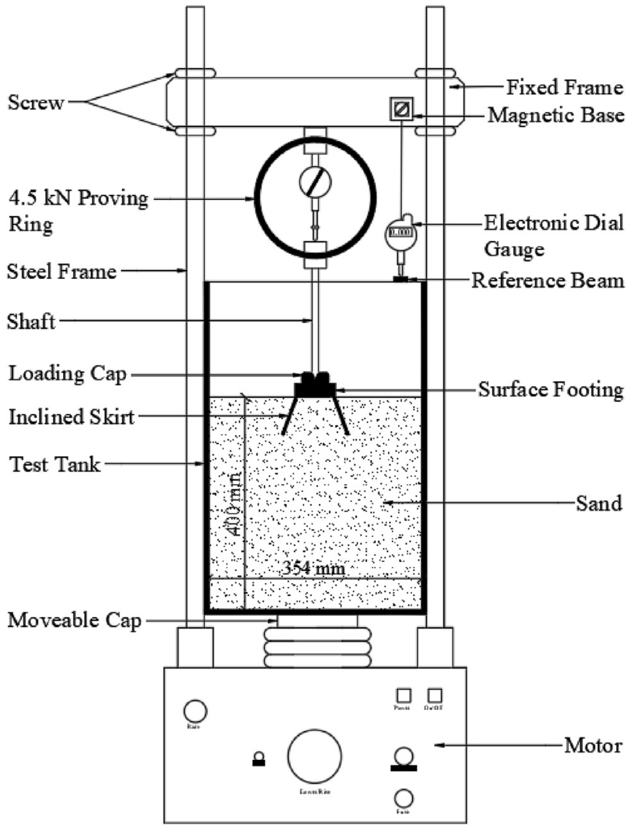

Fig. 2. Schematic view of the apparatus used in the experimental work.

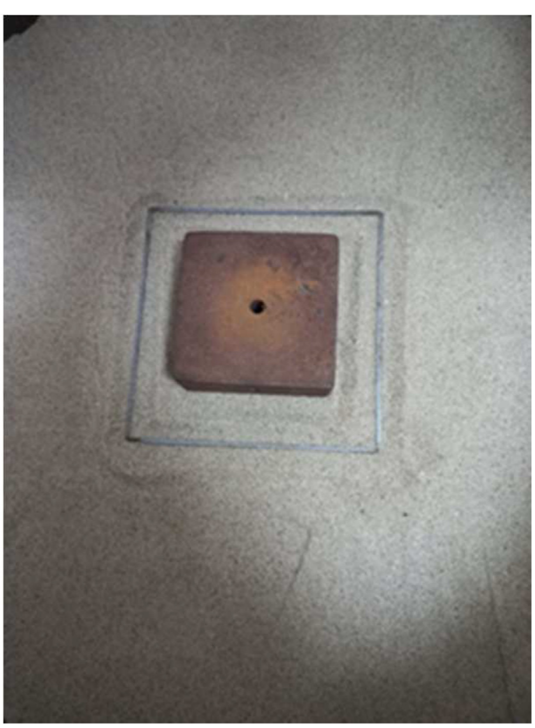

Fig. 3. The final surface of sand after installing the skirt and footing model.

Table 1. Material properties used in the experimental work as reported by (Magdy et al.,2022).

Parameter	Soil	Footing and Skirt (steel)
Unit weight (kN/m^3)	15.60[a], and 16.08[b]	78
Poisson's ratio	0.2	0.2
Void ratio	0.719[a], and 0.667[b]	N/A
Young's Modulus (kN/m^2)	2×10^4	2×10^8
Peak friction angle (degrees)	34.5[a], and 37.5[b]	N/A

[a] sand at relative density 35%.
[b] sand at relative density 55%.

4. Numerical simulation

To confirm the experimental results, three-dimensional finite element analyses were done using the Plaxis-3D software package (Brinkgreve and Broere, 2007) Plaxis-3D is a widely recognized and extensively used software package for geotechnical analysis and finite element modelling.

4.1. Modelling

The finite element method was employed to discretize the soil domain and represent the soil and structural elements. The analysis took into consideration relevant boundary conditions and loadings based on the experimental setup. The distance from the lateral boundary of the model and the distance between the lower bound of the model from the top should be taken sufficient, so that the effects of the boundaries in the numerical model on the results was minimized. The displacement and the stress contours in the numerical software indicate that this distance is sufficient (Maleki et al., 2022), and Maleki and Imani (2022), The constitutive model utilized to describe the behavior of the footing and skirt is the

Fig. 4. Measurement gauges set to zero.

linear elastic models. The Hardening Soil (HS) model was chosen to represent the sand behavior based on its ability to accurately capture the nonlinear behavior of the soil, particularly in terms of soil stiffness and strength as recommended by (Eid, 2013; Schanz et al., 2019). The HS model is a constitutive model used to describe the mechanical behavior of soil. The HS model considers the effects of soil compression, dilation ψ, and hardening (increased stiffness) due to applied loads. In addition to the effects of different factors, such as initial void ratio, initial shear stress, and plastic strains, to capture the complex behavior of soil. According to the HS model, soil stiffness is represented as secant stiffness, E_{50}^{ref}, tangent stiffness, E_{oed}^{ref}, and unloading/reloading stiffness, E_{ur}^{ref}. The additional parameters utilized in the numerical analysis are listed in Table 2. The model consisted of triangular elements to represent different components: the interface, skirt, footing, and sand. The interface and skirt elements were defined with 6 nodes each, while the footing element utilized 10 nodes. For the representation of the sand, 12-node triangular elements were employed. These element configurations were selected based on their suitability for capturing the desired behavior and interactions within the system. The criteria for building the model involved considering the geometry, material properties, and boundary conditions.

4.2. Meshing

Proper mesh generation is essential for obtaining accurate and dependable results from numerical simulations, as it ensures that the model depicts the essential characteristics and behaviors of the system under study. In addition, the quality of the mesh can have a significant effect on the computational efficiency of the simulation, with more efficient and well-structured meshes producing quicker and more accurate results. Consequently, for create meshing in the numerical models, several numerical modellings were created with different mesh dimensions and each time with smaller mesh dimensions until the changes in displacement became too small by modifying the mesh dimensions (Maleki and Mir Mohammad Hosseini, 2022), and Maleki and Nabizadeh (2021). Moreover, for increasing the accuracy of calculations, the density of elements is higher near the foundation. Numerical modellings were carried out on 60 mm surface footing resting on sand with three different mesh sizes, coarse, medium, and fine. Based on Fig. 5, medium mesh size will be chosen with a finer local mesh around the footing.

Table 2. Material properties used in the numerical analysis.

Parameter	Soil	Footing and Skirt (steel)
Material Model	HS	Linear elastic
E_{50}^{ref} (kN/m2)	2×10^4 [a]	N/A
E_{oed}^{ref} (kN/m2)	2×10^4 [b]	N/A
E_{ur}^{ref} (kN/m2)	6×10^4 [c]	N/A
Dilatancy angle (degrees)	4.5 [d]	N/A
Interface strength factor, R_{inter}	0.7 [e]	N/A

[a] Soil secant stiffness as concluded by (Lengkeek, 2003).
[b] Soil tangent stiffness as estimated by (Schanz et al., 2019).
[c] Soil unloading/reloading stiffness as estimated by (Schanz et al., 2019).
[d] Soil dilatancy angle as suggested by (Hong, 2019).
[e] Interface strength factor as reported by (Magdy, 2022).

4.3. Calculation process

Four phases make up the calculation procedure. In the initial phase, initial stresses were assigned based on the K_o Procedure. In the second "skirt" and third phases "footing", the footing, skirts, and interfaces were activated. In the final phase 'loading', the designated displacement was activated, and a plastic analysis was conducted. Importantly, the displacement was reset to zero in the fourth phase so that only the loading phase was considered. By dividing the calculation procedure into these distinct phases, the simulation can be carried out in a structured and systematic manner, ensuring that the results are accurate, dependable, and consistent.

5. Results and discussion

5.1. Verification

In order to validate the proposed models, a comprehensive verification was conducted using both experimental and numerical approaches. The verification focused on a 60 mm square surface footing resting on sand, which served as a representative case for this study. Experimentally, the footing was subjected to vertical loading conditions, and the corresponding bearing capacity and settlement measurements were recorded. The obtained results were then compared with relevant findings from the existing literature (Magdy, 2022). Remarkably, the comparison revealed a high degree of agreement between the experimental data gained and the reported results, demonstrating a strong consistency and reliability. Furthermore, numerical simulations were performed using the proposed models, and the outputs were compared with the corresponding experimental data. Again, a close

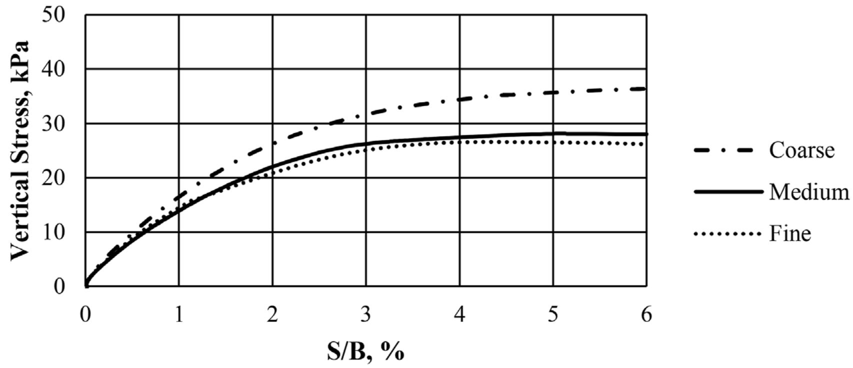

Fig. 5. Surface footing behavior using different mesh sizes.

match was observed, reinforcing the validity and accuracy of the models utilized (see Fig. 6). It can be confidently concluded that the adopted models are suitable for further investigations.

According to the literature, skirts improve the surface foundation behavior. Reference case (Magdy, 2022) of square-surface footing was used to evaluate the improvement in the behavior of square-skirted foundations due to the use of a skirt width wider than the footing width. The impact of having wider skirts will be discussed in the following subsections.

5.2. Bearing capacity

For each test, the load–settlement relationships were plotted. The ultimate bearing capacity was evaluated to the corresponding settlement of 20% of the footing width. The results showed that using a skirt width wider than the footing size enhanced bearing capacity. Bearing Capacity Ratio, *BCR*, will be defined as the ratio of the bearing capacity of the surface foundation with the wider skirt, q_{ws}, to the bearing capacity of the reference case used, q_s, to reflect these improvements. The testing results demonstrate that for the same $L/B = 0.25$ ratio in case of loose sand, the bearing capacity improved by a factor of 3.8 and 2.6 for skirt widths of 80 and 100 mm, respectively (see Fig. 7a). Fig. 7b represents the numerical findings that are in good agreement with the experimental data. The bearing capacity of skirted foundations is affected by the shape and size of the skirt cell (Magdy, 2022; Gnananandarao et al., 2018, 2020). Using a skirt width that is more than the footing width expands the skirt cell size and the effective width, resulting in a reduced stress distribution and higher bearing capacity. The interaction between the skirts and the surrounding soil can influence the load transfer mechanism. The presence of skirts alters the stress distribution within the soil, promoting load transfer to deeper, more competent soil layers. This interaction enhances the overall bearing capacity of the foundation. For L/B less than 1.00, the improvement in bearing capacity is larger when $W_s = 80$ mm than when $W_s = 100$ mm. The reason for this is that in the case

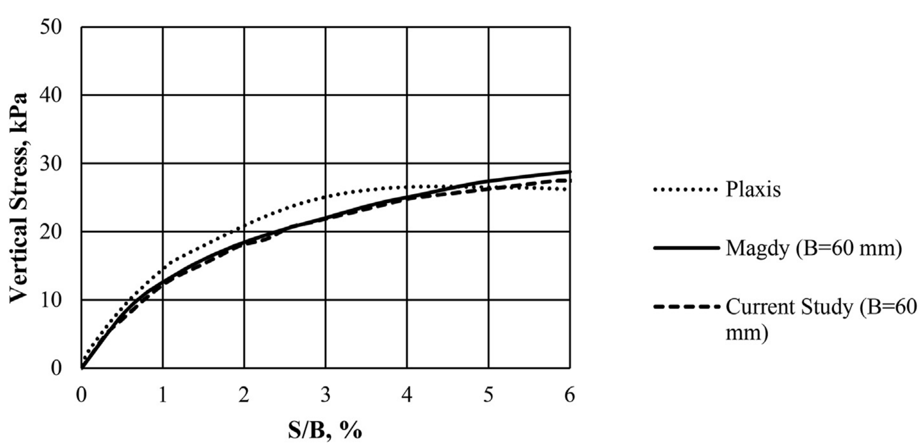

Fig. 6. Comparison of the experimental and numerical results obtained from the verification study.

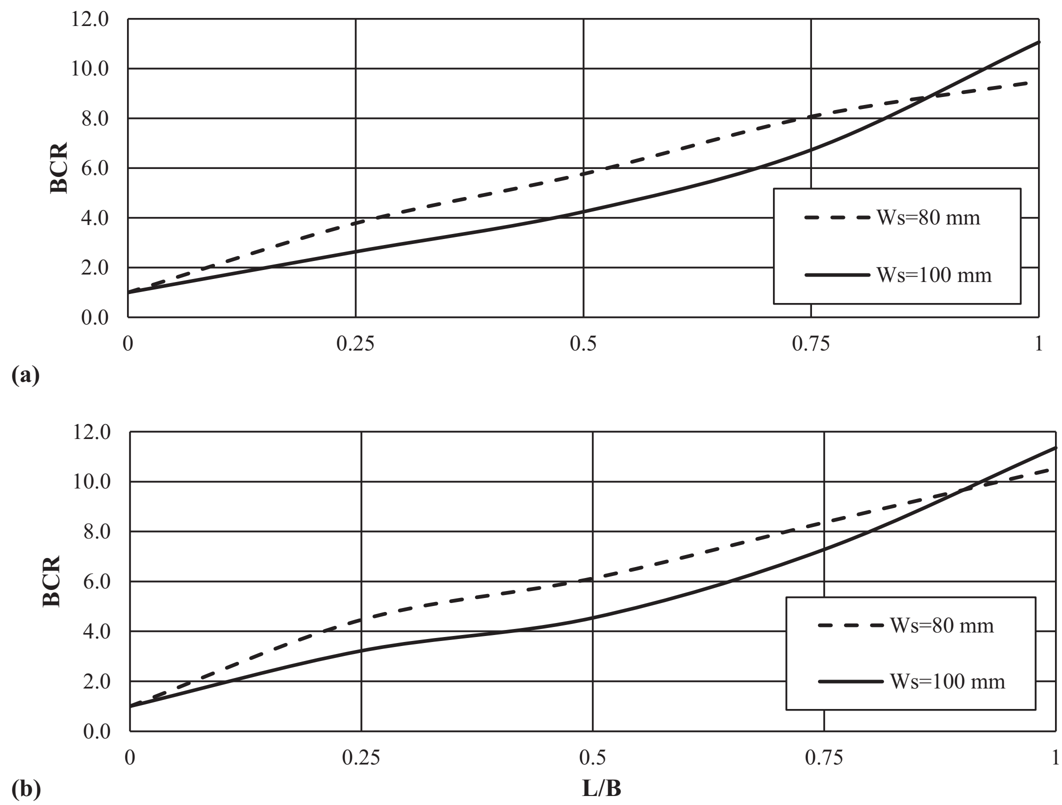

Fig. 7. Effect of using wider skirts on the bearing capacity of the skirted foundations, (a) experimental results, (b) numerical results.

of 80 mm, the sand particles will be confined more quickly during the initial loading phase (Vesic, 1963). Classified the failure mechanisms of surface footings resting on sand into three groups. There are three types of failure mechanisms: general, local, and punching shear failure. These failure mechanisms may not be applicable in the case of the skirted foundation since the footing and the skirt cell work as one unit, pushing the failure mechanism deeper into the soil. Other mechanisms of failure proposed by (Schneider and Senders, 2010) were classified as surface footing, plugged deep, and coring deep failure. Both experimental testing and numerical analyses revealed surface footing failure.

The findings of the numerical investigation also indicate that when L/B is less than 1.00, the increase in bearing capacity is larger for $W_s = 80$ mm compared to $W_s = 100$ mm, as shown in Fig. 8. Fig. 8 illustrates the relationship between the bearing capacity ratio of a surface foundation with wider skirts and the relative density of sand. The observation can be stated that wider skirts reveal higher efficacy when dealing with low relative density, this finding is in accordance (Eid, 2013). The chart presented can be employed for the estimation of q_{ws}, as it employs the relative densities of sand as opposed to their internal friction angles.

5.3. Settlement

To assess the behavior of skirted foundations in terms of settlement in this study, the settlement values of the skirted foundations with wider skirts in case of loose sand, S_{ws}, and the reference cases used, S_s, were estimated. S_{ws} was calculated at a stress level equal to the ultimate bearing capacity, q_s. To represent the improvement in settlement performance, the settlement reduction, S_r term was used. Where S_r denotes the ratio of S_{ws} to S_s ($S_r=S_{ws}/S_s$). In the experimental study, the values of settlement reduction due to the usage of wider skirts are shown in Fig. 9a. Fig. 9b shows the numerical analysis conclusions that somewhat coincide with the experimental results. The increased contact area between the wider skirts and the surrounding soil results in increased frictional resistance, leading to a decrease in settlement. The utilization of wider skirts improves the distribution of the load over a larger area of the soil, consequently mitigating the concentration of stress beneath the foundation. This improved load distribution helps to mitigate excessive soil deformation and settlement. When structures are particularly sensitive to settlement values and excessive settlements become the main aspect of

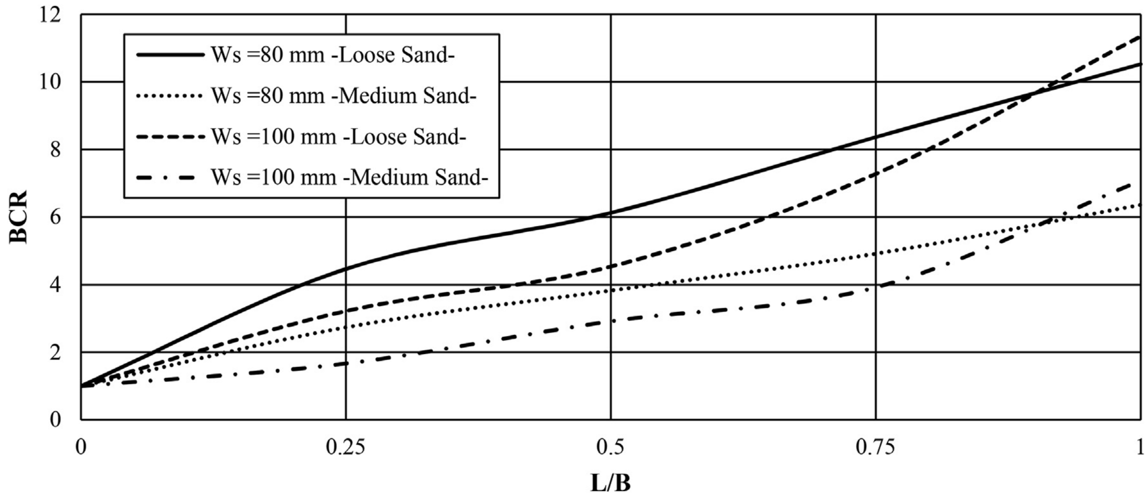

Fig. 8. Effect of sand relative density on wider skirts efficiency.

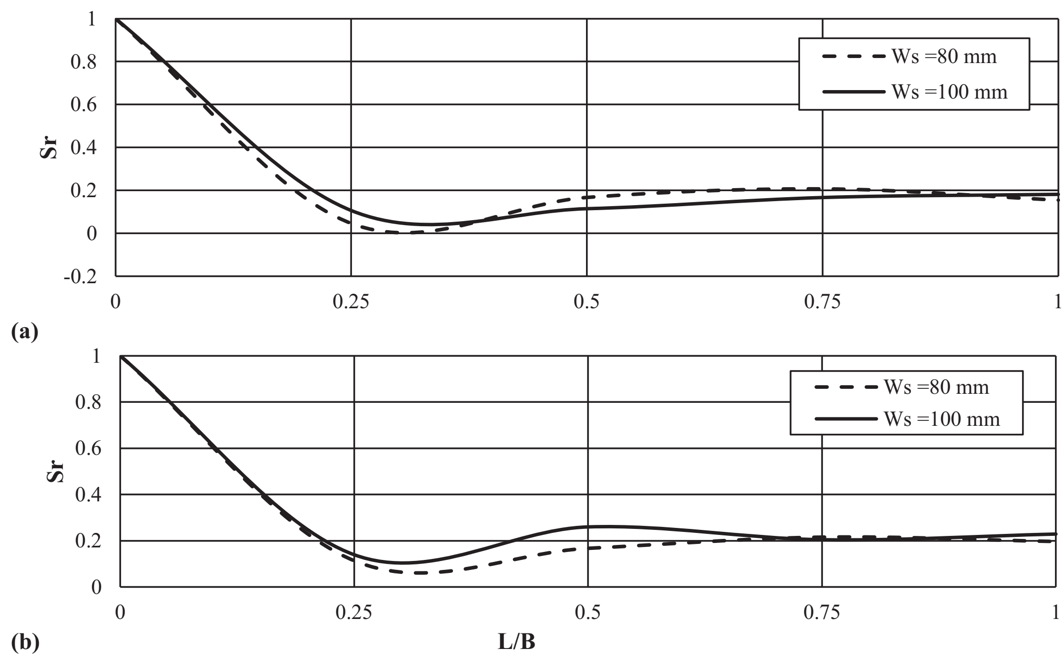

Fig. 9. Effect of using wider skirts on the settlement of the skirted foundations, (a) experimental results, (b) numerical results.

the foundation design process, wider-skirted foundations can be more useful and effective than increasing the size of surface foundations. In these cases, wider-skirted foundations can provide the same allowed bearing capacity with significantly less settlement. The settlement reductions were then estimated using the results of the study's wider-skirted foundation models.

6. Conclusion

Several experimental tests were conducted on surface foundations with wider skirts. The numerical analysis confirmed the test's results. The following findings have been reached.

(1) The results of the study indicate an enhancement in the bearing capacity of the skirted foundations. The presence of wider skirts increases the load-bearing capacity by increasing the size of the skirt cell, resulting in more confined sand beneath the footing.
(2) Additionally, the investigation reveals a significant reduction in skirted foundation settlement compared to traditional skirted foundations with skirts width as the footing width. This

improvement can be attributed to the confinement effect created by the wider skirts, which helps to distribute and control the settlement.

(3) The magnitude of improvement in bearing capacity increases with decreasing sand shearing strength or relative density.

(4) It is important to note that while the study demonstrates positive outcomes, there are certain limitations to consider. The experiments and numerical analyses were conducted under specific soil conditions, geometries, and loading conditions. The findings may vary in different soil types, foundation sizes, and load configurations. Therefore, caution should be exercised when extrapolating the results to other scenarios.

(5) For future research, it is recommended to explore the behavior of skirted foundations under various soil conditions and loading scenarios. Investigating the influence of different skirt geometries, including variations in skirt depth, and angle, would further enhance our understanding of their performance.

(6) Additionally, conducting long-term monitoring and field studies on skirted foundations in real-world applications can provide valuable data on their long-term performance, durability, and maintenance requirements.

NOTATIONS

D_r, relative density of sand; E_{50}^{ref}, secant stiffness of sand; E_{oed}^{ref}, tangent stiffness of sand; E_{ur}^{ref}, unloading/reloading stiffness of sand; R_{inter}, interface reduction factor; S_{ls}, settlement of wider skirted foundation; S_{rs}, settlement reduction; S_s, settlement of skirted foundation; q_{Ls}, bearing capacity of wider skirted foundation; q_s, bearing capacity of skirted foundation; $\varnothing$, peak friction angle of sand; B, footing width; BCR, bearing capacity ratio; L, embedded skirt length; q, bearing capacity of surface foundation; Ws, skirt width and ψ, angle of dilatancy of sand

Author contribution/author credit statement

Study conception or design of the work: Tamer AL-Shyoukhi, Ayman Altahrany, Mahmoud Elmeligy. Visualization: Tamer AL-Shyoukhi, Ayman Altahrany, Mahmoud Elmeligy. Data collection and tools: Tamer AL-Shyoukhi. Data analysis and interpretation: Tamer AL-Shyoukhi, Ayman Altahrany, Mahmoud Elmeligy. Funding acquisition: Tamer AL-Shyoukhi. Investigation: Tamer AL-Shyoukhi, Ayman Altahrany, Mahmoud Elmeligy. Methodology: Tamer AL-Shyoukhi, Ayman Altahrany, Mahmoud Elmeligy. Project administration: Ayman Altahrany, Mahmoud Elmeligy. Resources: Tamer AL-Syoukhi, Ayman Altahrany, Mahmoud Elmeligy. Statistical analysis: Tamer AL-Shyoukhi, Ayman Altahrany, Mahmoud Elmeligy. Software: Tamer AL-Shyoukhi. Supervision: Ayman Altahrany, Mahmoud Elmeligy. Drafting the article: Tamer AL-Shyoukhi. Critical revision of the article: Tamer AL-Syoukhi, Ayman Altahrany, Mahmoud Elmeligy. Final approval of the version to be published: Tamer AL-Syoukhi, Ayman Altahrany, Mahmoud Elmeligy.

Conflicts of interest

Authors declare that there are no conflicts of interest to disclose.

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