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Influence of Skirt Length and Foundation Size on the Bearing Capacity of Circular Foundations Resting on Sandy Soil

Kawther Y. H. Al-Soudany[1*], Nahla M. Salim[2], Luay Y. Hussein[1]

[1] College of Engineering, University of Technology-Baghdad, Baghdad, Iraq.
[2] Department of Civil Engineering, College of Engineering, Al-Naji University, Baghdad, Iraq.

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ABSTRACT

Skirted foundations are an appropriate ground-improvement method for improving the performance of shallow foundations in sandy soils. This paper reports an experimental study on the effect of the skirt length and foundation size on the performance of circular foundations under vertical loading on medium-dense dry sand. Six laboratory model tests were made, of which two were unskirted and four were skirted foundations. Two (2) different diameters of circular footings, 60 mm and 90 mm, were tested with two different lengths of the footing skirts (L/D), 0.5 and 1.0. Terzaghi's criterion, in which the settlement is 10% of the footing diameter, has been used to determine the ultimate bearing capacity. The results showed that skirts significantly improved the load–settlement response, increased foundation stiffness, and increased ultimate bearing capacity. The ultimate load for the footing of diameter 60 mm was increased from 0.167 to 0.304 kN, which is about 82% increase when the footing is skirted with L/D = 1.0. The same trend applied to the 90 mm diameter footing, where the ultimate load went from 0.343 to 0.677 kN, which is about 97% improvement. The bearing capacity of foundations with L/D = 0.5 increased by 29% and 43% for footing diameters of 60 mm and 90 mm, respectively. The experimental results also showed that as the skirt increased in length, the settlement decreased, and the failure mechanisms were more stable and deeper due to the increased soil confinement and passive resistance along the walls of the skirts. Further, all skirts yielded higher failure loads with larger foundation diameters. The study has verified that the length of skirts and foundation size are important parameters that control the performance of circular skirted foundations on sandy soils. The application of skirts is an effective and cost-efficient way to increase bearing capacities, decrease settlement, and enhance shallow foundation stability.

1. Introduction

Shallow foundation performance is mainly influenced by soil's bearing capacity and settlement characteristics. Bulldozing over loose or weak soils can cause structures to have excessive settlement and insufficient load-bearing capacity, posing serviceability and safety concerns. Such issues can be addressed with deep foundations but can be costly, time-consuming, and impactful to the environment. Thus, there has been a growing interest in geotechnical engineering on alternative ground improvement methods to increase the performance of shallow foundations.

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Of these methods, skirted foundations have proven to be a practical as well as cost-effective alternative. A skirted foundation is a traditional footing with vertical or sloping skirts around the periphery of the foundation that extend into the soil and create a confined soil/footing system. This confinement helps to minimize lateral soil movement, enhance embedment depth, and alter the mode of failure, leading to increased bearing capacity and reduced settlement. Skirted foundations were originally designed for offshore structures like suction caissons, subsea systems, and offshore wind turbines but are also being used in onshore structures such as tanks, bridges, and industrial facilities, where they offer high load resistance, stability, and scour protection.

Skirted foundations have consistently been shown to provide improved performance in previous studies. Soil confinement effects on stress distribution and load transfer mechanisms were identified by Gourvenec and Randolph [1] with marked increases in bearing capacity and reduction in settlement. Different failure modes were found by Schneider and Senders [2], who finally found that with deeper penetration of the skirts, the failure surfaces will be deeper and more stable.

Experimental investigations by Tripathy [3] have reported significant improvements in load-carrying capacity for longer skirts and higher soil density, as well as Mahmood et al. [4] who saw an improvement in gypseous soils with deeper failure mechanism.

Moreover, Parmar and Patel [5] have highlighted that the geometry of the skirt, embedment depth and its inclination play a key role in the behavior of the foundation in cohesionless soils. Singh et al. [6] also verified the benefits of skirt depth on settlement and bearing capacity of the foundation, and those of inclined skirts were found to be better because of better confinement.

These results are summarized in recent review studies (2024-2025) which have confirmed that skirting foundations offer significant improvements in both bearing capacity, settlement control and stability under different loading conditions. These studies also indicate that effective performance is achieved with a skirt length/width ratio between 1:1 and 2:1.

Although much research has been conducted, one of the most important issues regarding the behaviour of circular skirted foundations is the combined effect of foundation size and skirt length, especially in the case of vertical loadings in dry sandy soils. The majority of previous studies have examined geometric parameters individually, and have only had a few studies that examined interaction effects between geometric parameters.

This experimental study is therefore carried out to investigate the behavior of circular skirted foundations resting on dry sand under vertical load with special reference to the interaction effects of foundation diameter and skirt length on the ultimate bearing capacity and settlement characteristics of circular foundations. The results are expected to help in gaining better understanding of skirt–soil interaction and provide better design practices in geotechnical engineering.

2. Failure Modes in Soil

The maximum load that the foundation can bear when the stresses generated in the soil under the foundation reach the shear strength of the soil and cause soil failure is what is called the ultimate bearing capacity of the foundation. Soil density, compressibility, strength properties, and foundation embedment ratio (Df/B) are the most important factors influencing the mode of failure. There are three main failure modes: general shear, local shear and punching shear.

The shear failure, which is normally called general shear failure, happens in dense sand and stiff clay and is typically manifested by well-defined failure surfaces that continue upward from the edge of the foundation to the ground surface. In this mode, there is usually a significant load–settlement peak and soil heaving. Local shear failure is the case for medium-density and consistency soils, where the failure surface is not complete, and larger settlements take place prior to ultimate failure. Punching shear failure is normally seen in very loose sands and soft clays where the foundation has minimal lateral movement and no well-defined shear surfaces to the ground surface.

Classical bearing capacity theories generally assume that a general shear failure occurs amongst these failure mechanisms. The skirts of skirted foundations alter the failure mechanism by confining the soil and pushing the failure surface deeper into the soil. Thus, the bearing capacity is increased, and the settlement is reduced when compared to a traditional shallow foundation.

3. Determination of Ultimate Bearing Capacity from Load–Settlement Curves

The interpretation of ultimate bearing capacity from load–settlement test results is an important aspect of foundation analysis. Several criteria have been proposed to define the ultimate load, particularly in cases where a clear failure point is not observed.

According to Terzaghi [7], the ultimate bearing capacity may be defined as the pressure corresponding to a settlement equal to 10% of the foundation width or diameter. This criterion has been widely adopted in laboratory and field investigations of shallow foundations. Another commonly used approach is the tangent intersection method, in which the ultimate load is determined from the intersection of two tangents drawn to the initial and final portions of the load–settlement curve.

Different interpretation methods may yield different values of ultimate bearing capacity. Therefore, it is important to adopt a consistent criterion when comparing experimental results. Lutenegger and Adams [8] evaluated several interpretation methods using model footing tests on sand and concluded that the bearing capacities obtained from the 10% settlement criterion are generally higher than those obtained using the tangent intersection method. Figure 1 illustrates typical methods used to determine ultimate bearing capacity from load–settlement relationships.

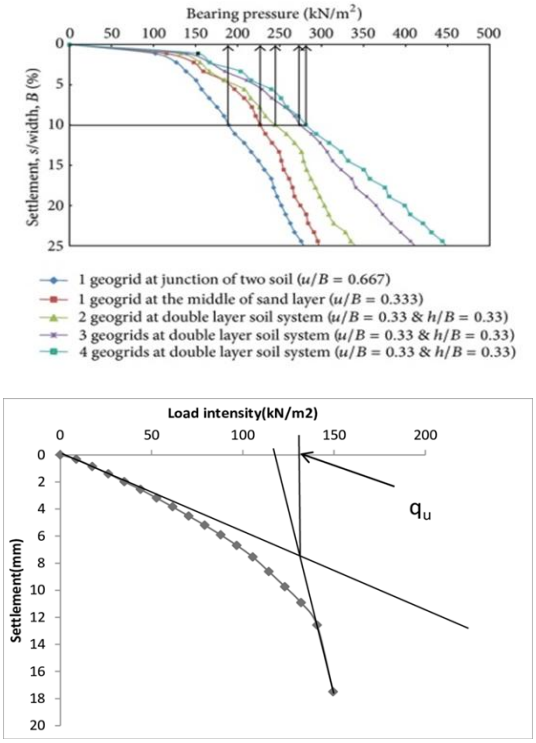

Figure 1. Defining ultimate bearing capacity of shallow foundation from load-settlement test results by using different methods (after Cerato, 2005) [9]

4. Materials and Methods

4.1 Experimental Program

An experimental study was conducted to investigate the behavior of circular skirted foundations resting on dry sand and subjected to vertical loading. A total of six model tests were performed, including two tests on unskirted foundations used as reference cases and four tests on skirted foundations. The investigated variables were foundation diameter and skirt length.

Two circular foundation diameters of 60 mm and 90 mm were considered. For each diameter, it was observed the skirt lengths of 0.5D and D (where D is the foundation diameter). The load–settlement response and ultimate bearing capacity for each foundation configuration was evaluated and compared.

4.2 Materials

4.2.1 Sand

All the experiments were performed on Karbala sand. The sand was cleaned, dried in an oven, and sieved through a 2 mm sieve before testing. Using the Unified Soil Classification System (USCS), the sand was determined to be poorly graded sand (SP). The sand bed was prepared with a relative density of 60%, which is considered a medium-dense condition.

The engineering properties of the sand were obtained from laboratory investigations such as sieve analysis, specific gravity test, and direct shear test. The main properties of the sand are summarized in Table 1.

Table 1. Physical properties of the tested sand.

Property	value	Specification
D10	0.14 mm	ASTM D 422 [10]
D30	0.23 mm	
D50	0.36 mm	
D60	0.41 mm	
Coefficient of uniformity (C_u)	2.93	
Coefficient of curvature (C_c)	0.92	
Specific gravity (G_s)	2.64	ASTM D 854 [11]
Angle of internal friction (Ø)	34°	ASTM D 3080 [12]
Maximum dry unit weight (γ_{dmax})	17.5 kN/m^3	ASTM D 2049-69 [13]
Minimum dry unit weight (γ_{dmin})	14.2 kN/m^3	ASTM D 4254-00 [14]
Relative density of sand during test (D_r)	60 %	-----
Dry unit weight in test (γ_d)	16.02 kN/m^3	-----
Saturated unit weight (γ_{sat})	19.76 kN/m^3	-----

4.3 Foundation Models

Circular steel foundation models with diameters of 60 mm and 90 mm and a thickness of 20 mm were used throughout the testing program.

4.3.1 Skirts

The skirts were fabricated from aluminum cylinders open at both ends. Two skirt lengths were considered, namely 0.5D and D. The skirt diameter was equal to the corresponding foundation diameter, while the skirt thickness was maintained constant at 5 mm for all tests. The skirts were rigidly connected to the foundation models using bolts to ensure monolithic behavior during loading.

4.4 Experimental Setup

The test was performed in a rigid steel container with dimensions of 600 mm × 300 mm (plan) and 350 mm (depth). The size of the containers was chosen to reduce edge influences when loading. The foundation models were subjected to concentric loading using a vertical loading system and settlements were measured using a dial gauge of accuracy 0.01 mm.

4.4.1 Sample Preparation and Testing Procedure

The sand bed was formed in the test container by a layer-by-layer deposition method to obtain a relative density of 60%. The sand was laid in 6 equal layers and lightly compacted to make sure that the soil mass was even. The surface of the soil was carefully levelled after the preparation, and the foundation model was placed.

In the case of the reference tests, the foundation was directly installed on the sand surface. In the case of skirted foundation tests, the skirt was inserted vertically into the excavated sand and firmly attached to the foundation. It was noted that care was taken in the installation to minimize soil disturbance and to have a constant density condition for all tests.

The loads were applied sequentially via a loading rod located in the centre of the specimen, which transmits vertical loading. The loads were applied sequentially via a loading rod at the centre of the specimen that transmits vertical loading. After load increment stabilization, settlement readings were taken. This loading process was continued until a clear failure condition was achieved or until the settlement amount went beyond a pre-defined failure condition. To prevent

the footing from rotating and distribute the stress evenly below the footing, concentric loading was used throughout the test program.

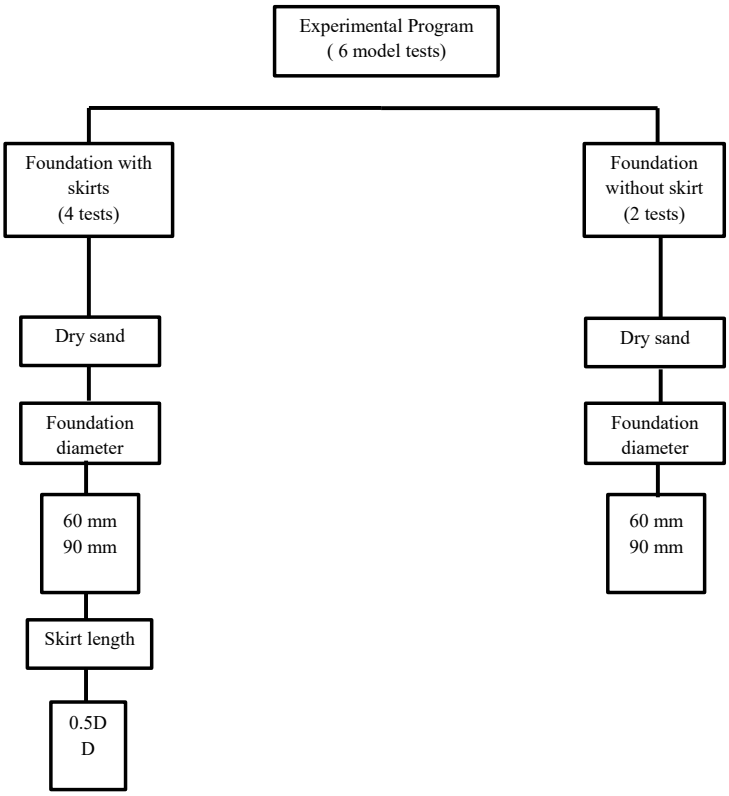

Figure 2. Flowchart for testing program

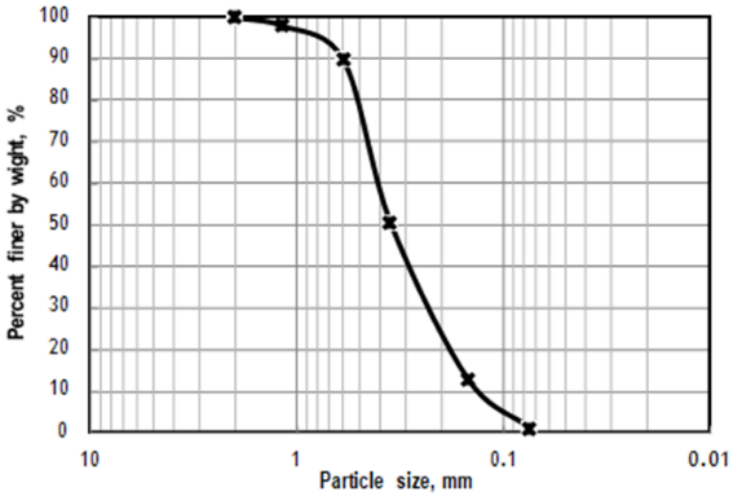

Figure 3. Particle size distribution of the sand

4.4.2 Foundation Models and Skirt Configuration

The circular steel footing models were constructed in sizes 60 mm and 90 mm with a constant thickness of 20 as presented in Figure 4).

Figure 4. Foundation used

4.4.3 Skirt Configuration

The effect of soil confinement in a foundation was studied using aluminum skirts. The skirts were made in the shape of hollow cylindrical pieces of length 0.5D and D (where D is the footing diameter). The two footing diameters, 60 mm and 90 mm, were investigated, and the corresponding skirt diameters were chosen to correspond with the footing diameters. The thickness of the skirt was kept at 5 mm in all tests.

The skirts were firmly connected to the skirts' perimeter using bolts to provide the composite action between the skirts and footings under loading. This allowed the limited soil under the footing to participate in load transfer, increasing the bearing capacity and decreasing the settlement. (Figure 5)

Figure 5. Skirt Configuration used in the present works

As shown in Figure 6, the skirts were securely fastened to the edge of the footing models using bolts, allowing the footing-skirt assembly to behave as a single unit throughout the loading process.

Figure 6. Skirted foundation models

5. Experimental Setup

An experimental program was carried out using a laboratory-scale testing system, which was developed to investigate vertical loading response of skirted foundations. The apparatus consisted of a steel soil container, circular footing models, a raining apparatus of sand to reproduce specimens with control, and a vertical loading system as shown in Figure 7.

Figure 7. Test set-up

5.1 Soil Container

The soil container used was a rigid steel test tank of length 600 mm, width 300 mm and depth 350 mm. The thickness of steel plates used for constructing the tank was 4 mm. Uniform sand layers were obtained during the testing program by providing reference markings at 50 mm intervals.

5.2 Sand Bed Preparation

To achieve a uniform stress distribution in the soil mass and provide a stable base for the test tank, a 50 mm thick gravel layer was first laid at the base of the test tank. The sand sample was then processed in a calibrated layer-by-layer deposition process. The soil was laid in six layers of equal thickness (about 50mm); the target dry unit weight was 16.02 kN/m³. Using γd, max = 17.5 kN/m³, γd,

min = 14.2 kN/m³, and Gs = 2.64, this dry unit weight corresponds to a calculated relative density of approximately 61%, consistent with the target Dr = 60%. . Preliminary calibration tests were performed to determine the placement process necessary to create a uniform density distribution of soil in the soil bed. The experimental results were repeatable and reliable by paying particular attention to deposition conditions, achieving the same layer thickness, and avoiding disturbances during specimen preparation.

5.3 Testing Procedure

A sand bed was prepared in the test tank by using a calibrated deposition procedure and giving a uniform relative density to the specimen depth. Once the desired density was reached, the surface of the sand was levelled carefully to ensure that a smooth and flat testing surface was created.

Vertical loading tests under a series of different loading rates were carried out on circular foundations of diameterS 60mm and 90mm. The footing was located in the middle of the test tank to reduce the boundary effect. Concentric load application was ensured by providing a recess in the middle of the surface of the footing to accommodate the loading rod and to ensure the rod is aligned with the centre of the footing during testing.

Two types of foundation were studied: Unskirted and Skirted foundationS. The footing in the reference tests was installed on the pre-packed sand surface. The aluminum skirts were firmly attached to the footing with four bolts each, above the foundation length of D and 0.5D for skirted tests, creating a single composite structure. A skirted assembly was then carefully placed in the sand excavated vertically without disturbing the adjacent soil and at the desired relative density.

Load was applied incrementally using calibrated weights. Each increment was maintained until the measured settlement was considered stabilized, after which the settlement reading was recorded. The dial gauge had an accuracy of 0.01 mm and a range of 50 mm. The test continued until the load–settlement response reached the predefined settlement criterion or a clear failure response was observed.

The load was applied in sequential increments, with each increment corresponding to approximately 10% of the estimated ultimate bearing load. Each load increment was maintained for approximately 30 min. Settlement readings were taken after the settlement response had stabilized. Settlement was considered stabilized when the rate of settlement was less than 0.01–0.02 mm/min (approximately 0.6–1.2 mm/h). This loading and stabilization procedure was applied consistently throughout the testing program.

Special emphasis was placed on keeping the soils consistent and not disturbing the soil during installation of the footings throughout the testing program. In addition, careful attention was made to ensure that the footing was loaded concentrically, and that the measured response was the correct response of the foundation-soil system to vertical loading.

6. Results and Discussion

6.1 Overview

A series of laboratory model tests was performed to evaluate the performance of circular skirted foundations in medium-dense dry sand under vertical loading. The experimental program comprised six tests, one of which were reference test on an unskirted foundation, and the others were tests on skirted foundations of various lengths. The main goal of the research was to determine the effects of skirt length and foundation diameter on the response of the foundation system in terms of load-settlement behavior, ultimate bearing capacity, and settlement behavior.

The results in this section give a comparative evaluation of the 60 mm and 90 mm diameters with skirt length/diameter ratios of 0.5 and 1.0. Skirted foundations are compared with the responses of traditional shallow foundations to measure the benefits of soil confinement.To quantify the improvement achieved through soil confinement.

6.2 Failure Criterion

The ultimate bearing capacity (q_u) of the tested foundations was calculated using the settlement criterion suggested by Terzaghi (1943) where the failure load is taken as the settlement of the footing is 10% of the footing diameter. This criterion is commonly used in model foundation studies and offers a convenient and uniform means

of judging the performance of various foundation types.

Thus, the ultimate load (Q_u) for each test was defined as the applied load at a footing settlement of 0.1D, where D is the footing diameter.

6.3 Load–Settlement Response

The load–settlement characteristics of circular foundations were then examined using the results of six model tests performed under vertical loading in medium-dense dry sand (RD = 60%). The experimental set-up comprised unskirted foundations (0D) and two different skirt lengths, 0.5D and 1D, on footing diameters of 60 mm and 90 mm, and this allowed an assessment of the effect of skirt length and footing size on the performance.

The load–settlement curves (Figures 8 and 9) clearly show that the stiffness and load-carrying capacity of a skirted foundation are much superior to those of an unskirted foundation. The results show a significant decrease in settlement from the same applied load. At a representative load level of ~40kg, for example, the settlement reduced from ~10-12mm (0D) to 6-8mm (0.5D) and further to ~4-5mm (1D. it is seen to improve progressively with increasing skirt length. The slope of the curve of the load–settlement curve increases with increasing skirt penetration, indicating increased initial stiffness and load transfer characteristics.

The improvement is explained by the confinement effect of the skirts that control the lateral movement of the soil, thus leading to deeper failure mechanisms. Therefore, the greater the volume of soil mobilized, the higher the bearing capacity and the less the soil will deform under the applied load. Also, the effect of footing diameters is observed, as the load resistance will consistently be higher for the 90 mm footing under similar skirt conditions as compared to the 60 mm footing, showing the pronounced scale effect on the overall footing response.

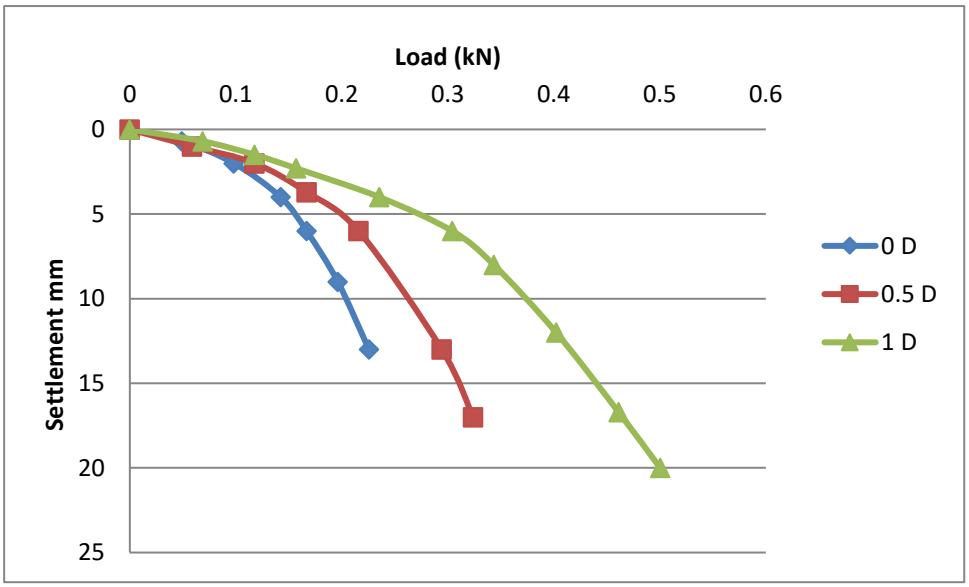

Figure 8. Load vs. foundation settlement relationship for the foundation 60 mm in diameter with skirt resting on dry sand

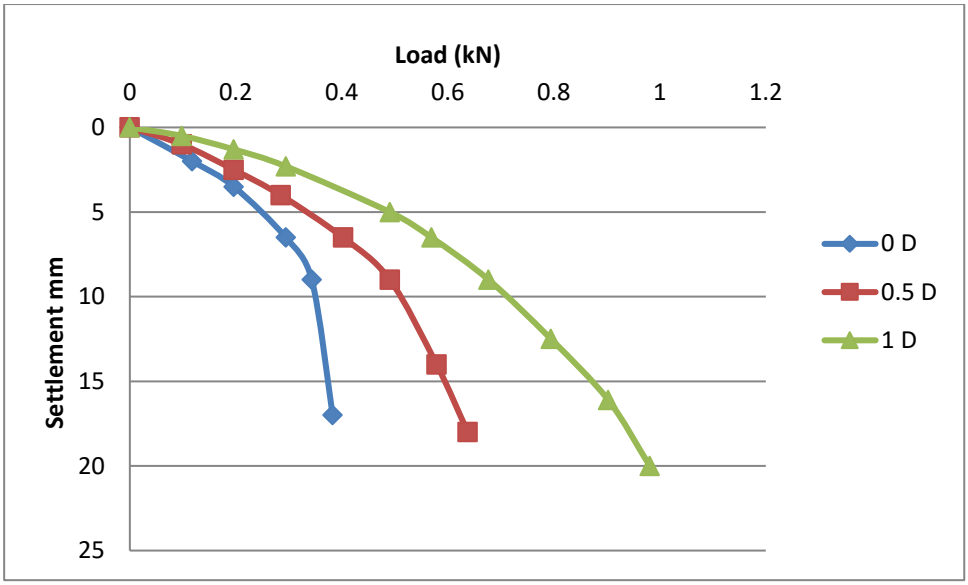

Figure 9. Load vs. foundation settlement relationship for the foundation 90 mm in diameter with skirt resting on dry sand

6.4 Effect of Skirt Length

Experimental results show the effect of skirt length on the foundation performance .In both footing diameters, the longer the skirts were, the higher the load-carrying capacity and the lower the settlement value.

The longer the skirts, the more soil they hold and the deeper the effective embedment depth of the foundation. This results in increased passive resistance of skirt walls and the failure surface moving to deeper and more competent soils. Hence, the foundations with longer skirts were found to have higher stiffness and ultimate loads than the shorter skirts.

This advantage of skirt length was seen consistently for both the diameters of the footing and it is demonstrated that the penetration depth of the skirts is one of the governing parameters that determines the behavior of skirted foundations on sandy soils. From this it is clear that the use of skirts has a marked improvement in the performance of the foundation, especially the load carrying capacity and settlement reduction. The improvement is greater with longer skirts and larger foundation diameters, demonstrating the positive effect of soil confinement and greater effective embedment depth. El Wakil [15] reported significant improvement on the bearing capacity of skirted foundation on sandy soils.

It shows that ultimate loads are significantly increased by the presence of skirts, when comparing load–settlement curves for the two sets of footings at the failure settlement criterion (10% of footing diameter). The unskirted footing failed with an ultimate load of 0.167 kN, whereas the foundation with a skirt length-to-diameter ratio (L/D) of 1.0 was able to sustain an ultimate load of 0.304 kN for the 60 mm diameter footing. In a similar way, for the 90 mm diameter footing, the ultimate load rose from 0.343 to 0.677 kN when L is the same as the diameter of the footing.

The largest increase was recorded for the 90 mm diameter foundation of an L/D ratio of 1.0 where the ultimate load increased by approximately 97% compared to the same unskirted foundation. The reasons for this sizeable improvement are the higher confinement of the soil under the footing and the activation of additional passive resistance along the skirt walls that cause a more deeply developed and stable failure mechanism.

The ultimate load increases for the different skirts as compared with the unskirted foundations (L/D = 0) are summarized in Tables 2 and 3.

The performance improvement of the skirted foundations is mainly due to the confinement of the soil inside the skirts. This confinement restricts the lateral soil movement, enhances the passive resistance of the skirt walls, and encourages a

deeper load transfer mechanism. Hence, the foundation has higher bearing capacity and a lesser settlement than the unskirted foundation.

Table 2. Percent increase in failure load for foundation skirt in dry sand.

L/D ratio	% increase in failure load for different foundation diameter	
	60 mm	90 mm
0.0	-	-
0.5	29	43
1.0	82	97

Table 3. Summary of ultimate load and bearing pressure for all tested configurations.

D (mm)	L/D	Q_u (kN)	q_u (kPa)
60	0	0.167	59.0
60	0.5	0.216	76.3
60	1.0	0.304	107.6
90	0	0.343	54.0
90	0.5	0.491	77.1
90	1.0	0.677	106.4

The effect of the skirt length on the skirted foundations' behavior was studied through a series of model tests, with two different skirt length-to-diameter ratios (L/D = 0.5 and 1.0) for each footing diameter. The experimental results were evaluated by load–settlement relationship and ultimate bearing capacity to quantify the contribution of the increase in the skirt penetration length to foundation performance. The corresponding results are shown in Figure 10).

The findings show that there is a strong increasing trend in the ultimate bearing capacity with an increase in skirt length for both footing diameters. The failure loads of the foundations with L/D = 1.0 were higher than those of the foundations with L/D = 0.5 in all cases, and were greater than those of the unskirted foundations of the same L/D. This is said to be caused by the higher soil confinement and deeper load transfer mechanism achieved with deeper penetration depths of skirts.

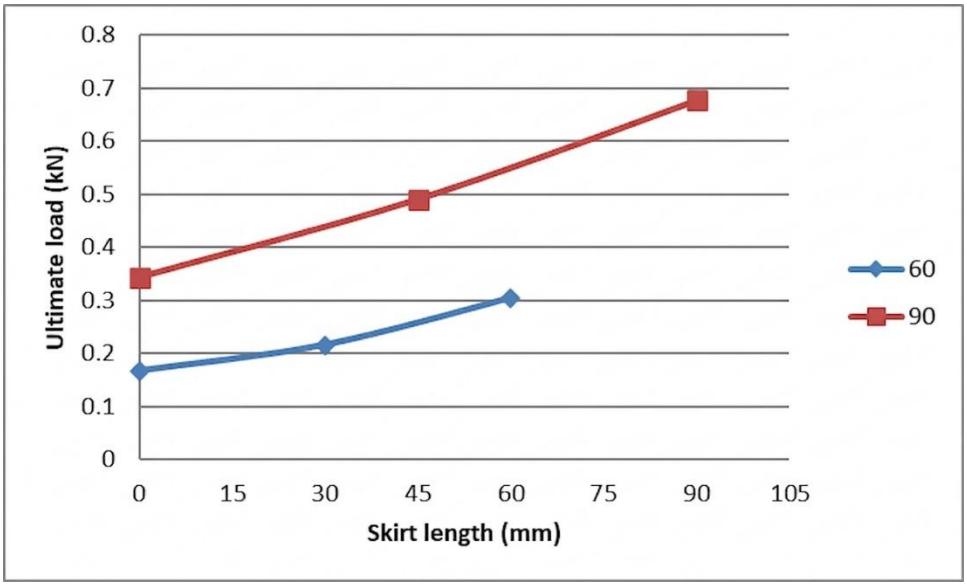

Figure 10. Shows the variation of failure load with respect to skirt foundation length in dry sand.

6.5 Effect of Foundation Size

In the Figure 11) Foundation diameter increased the total ultimate load in every tested skirt configuration. However, comparison of total load alone can be misleading because the footing area increases with D^2. The unskirted 90 mm footing carried 0.343 kN compared with 0.167 kN for the 60 mm footing, while the corresponding bearing pressures were 54.0 and 59.0 kPa. For L/D = 0.5, the pressures were 77.1 and 76.3 kPa, and for L/D = 1.0 they were 106.4 and 107.6 kPa for the 90 and 60 mm footings, respectively.

These results indicate that the increase in total load with foundation size is strongly associated with the larger loaded area. After normalization by footing area, the skirted cases show similar ultimate bearing pressures for the two diameters. Therefore, the present six tests do not justify a broad claim that foundation diameter alone increases unit bearing capacity.

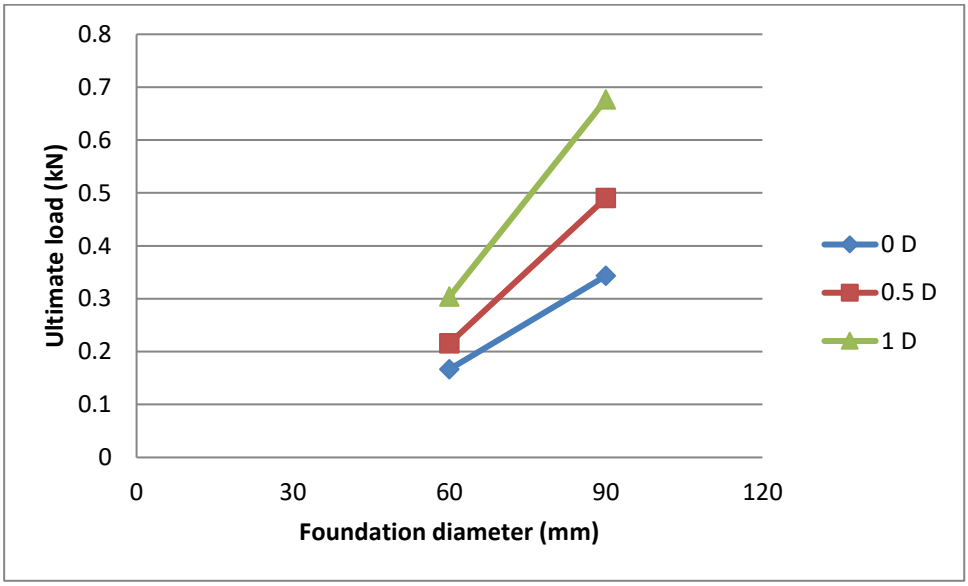

Figure 11. Failure load vs. foundation size in dry sand

7. Conclusions

An experimental study was carried out to examine the response of circular skirted foundations subjected to vertical loading in medium-dense dry sand. Six model tests were conducted in laboratories to investigate the effect of foundation diameter and skirt length on load–settlement response and ultimate bearing capacity. From the experimental results, the following conclusions can be drawn:

Skirts significantly enhanced the performance of shallow foundations by enhancing the ultimate bearing capacity and decreasing the foundation settlement. The better improvement was the longer and wider the skirts, and the greater the footing diameter. At an L/D ratio of 1.0, the carrying capacity increased up to 82% and 97% for the 60 mm and 90 mm diameter footings, respectively.

The skirted foundations were found to be a very effective and practical method for increasing the bearing capacity of foundations on sandy soils. The improvement was determined to be most dependent on the length of the skirt, the size of the foundation, and the nature of the soil upon which it is placed.

The vertical settlement of the tested foundations was reduced by the presence of skirts due to the confinement of soil under the footing and the formation of a deeper load-transfer mechanism. For buildings where settlement control is an important design consideration, skirted foundations might be a viable option.

The ultimate bearing capacity increased with increasing skirt length for a given diameter of footing. The maximum performance was obtained for L/D = 1.0, which means that better soil confinement is achieved at higher penetration depths of the skirts and more passive resistance is mobilized.

It was concluded that the foundation diameter had a significant effect on the load-carrying capacity. For all other skirt combinations, larger footings had higher ultimate loads than smaller footings. The 90 mm diameter footing with a skirt length the same as the footing diameter gave the highest bearing capacity.

Overall, outcomes indicate that the use of skirts can significantly improve the performance of shallow foundations on sandy soils by increasing the foundation bearing capacity, decreasing the foundation settlement, and improving the foundation stability by soil confinement.

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Conflict of interest

The authors declare no conflicts of interest concerning this research.

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Author Contribution

K.Y.H. Al-Soudany: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. N.M. Salim: Writing – review & editing, Validation, Supervision. L.Y. Hussein: experimented, wrote the paper, and worked out almost all of the technical details

AI Declaration Statement

The authors confirm that the manuscript has been written without the assistance of generative AI or AI-based writing tools.

Data availability

Data will be made available on request

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