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Effect of Load Eccentricity on the Performance of Skirted Square Shallow Foundations in Dry Sandy Soils

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ABSTRACT

The research evaluates the influence of load eccentricity on square shallow foundation behavior when embedded in dry sandy soil at a relative density of soil =30% with and without skirts. Laboratory model tests analyzed a 10 × 10 cm foundation under one central load condition (E/B = 0, where E is the load eccentricity and B is the foundation width) and three eccentric load conditions (E/B = 0.04, 0.08, and 0.16). Three skirt lengths were examined: 0.5B, 1B, and 1.5B. The results showed that skirted foundations significantly enhanced bearing capacity and reduced settlement compared to unskirted ones. The maximum improvement in bearing capacity occurred under central loading with a skirt length of 1.5B, where the Bearing Capacity Ratio (BCR) reached 4.4 times. Under the highest eccentricity (E/B = 0.16), the BCR decreased to 3.95 times. Settlement was also effectively reduced, with the Settlement Reduction Factor (SRF) reaching 0.921 under central loading and remaining as high as 0.85 under eccentric loading. The results confirm that skirted foundations improve the bearing capacity and reduce settlement of shallow foundations on sandy soils under both central and eccentric loads.

Keywords: Skirted foundation, Eccentric load, Bearing capacity improvement, Settlement.

1. INTRODUCTION

The connection between structures and supporting soil relies on foundations as the essential element ensuring the safety and stability of buildings and infrastructure. With increasing construction activities in weak soil regions such as loose sands and soft silts, it has become critical to develop efficient solutions for improving foundation performance **(Das, 2015).** Although methods like mechanical compaction, chemical grouting, and geosynthetic reinforcement have been widely used to enhance soil strength **(Han, 2015),** the geometry of the foundation and how it responds to applied loads—especially eccentric and inclined ones—often play a more significant role than soil treatment alone.

Skirted foundations have emerged as a practical solution that enhances the behavior of shallow foundations by improving load-bearing capacity and reducing settlements under

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vertical, horizontal, and moment loads. Initially adopted for offshore platform stabilization in the 1960s, skirts have been increasingly applied to shallow foundations on sandy soils, offering benefits under both central and eccentric loading **(Gourvenec and Randolph, 2010; Tripathy, 2013).** Understanding the behavior of foundations under eccentric loading, caused by uneven load distribution, wind, waves, and seismic actions, is essential because such loads result in tilting, increased displacement, and reduced bearing capacity. Therefore, recent research has focused on how skirts can mitigate these negative effects and improve stability.

Several researchers have studied the performance of skirted foundations under eccentric, inclined, and lateral loads. (**Singh et al., 2007; Sargazi and Hosseininia, 2017; Ali and Al-Saidi, 2024**) showed that eccentric loads reduce bearing capacity and increase foundation displacement and rotation. Improvements such as geogrid reinforcement and soil confinement help reduce these adverse effects. Further investigations revealed that increasing skirt length improves bearing capacity and settlement control, especially in loose soils **(Eid, 2013; Golmoghani-Ebrahimi and Rowshanzamir, 2013; Khatri et al., 2017; Al-Aghbari and Mohamedzein, 2018; Sajjad and Makarchian, 2018).** Also, skirt shape plays a significant role: circular skirts perform better than square ones in terms of bearing capacity, and double skirts are more effective than single skirts in reducing settlement (**Gnananandarao et al., 2018; Gnananandarao et al., 2020; Magdy et al., 2022; Gnananandarao et al., 2023).** T-shaped skirts have also shown better results than H-shaped ones in some studies. The performance of skirted foundations is highly influenced by the characteristics of the surrounding soil. High-friction coarse-grained soils enhance bearing capacity **(Thakur and Dutta, 2020a; Thakur and Dutta, 2020b),** while inclined skirts improve lateral resistance and stability in sloped terrains **(Azzam and Farouk, 2010; Mohammadizadeh et al., 2023).** However, increased slope steepness reduces skirt effectiveness.

Also, the skirts demonstrate better bearing capacity and reduced settlement performance when foundations experience inclined or eccentric loading conditions **(Al-Aghbari et al., 2019; Shukla, 2022; Al-Shyoukhi et al., 2023; Basha and Eldisouky, 2023; Alhalbusi and Al-Saidi, 2024).** In partially saturated soils, matric suction enhances bearing behavior, but full saturation reduces particle cohesion, causing capacity loss **(Mahmood et al., 2022).** In gypsum soils, skirts with L/D ratios between 0 and 2 optimize bearing performance, although excessive depth leads to soil over-confinement and shear strength reduction **(Mahmood et al., 2018; Mahmood et al., 2019; Abd-Alhameed and Al-Busoda, 2023)**. The use of geogrid skirts with horizontal reinforcement further improves performance. Numerical analyses using PLAXIS 3D have demonstrated that skirted foundations significantly reduce differential settlement and increase safe excavation depth, even under unbalanced loading conditions **(Ahmed et al., 2024a; Ahmed et al., 2024b).** Alternative solutions like belled piles and drainage systems have also shown effectiveness in resisting uplift and controlling groundwater effects **(Fattah et al., 2018; Jebur and Ahmed, 2020; Al-Qaisee et al., 2020; Ali and Karkush, 2021; Ibrahim and Karkush, 2023).**

Although there were many studies about skirt foundations, a noticeable gap exists in understanding how the geometry and internal configuration of skirted foundations influence their performance under eccentric vertical loads. Most previous studies have focused either on skirt depth or skirt material behavior under central loading, with limited attention to the combined effect of foundation shape and load eccentricity. Moreover, experimental studies on square foundations with skirts, especially under varying eccentricity ratios, are still scarce. The study aims to experimentally investigate the effect of skirts on the bearing capacity, settlement, and overall stability of square shallow foundations resting on dry clean sand under eccentric vertical loads, with eccentricity ratios ranging from 0.04B to 0.16B. The novelty of this work lies in providing the first systematic laboratory assessment of square skirted foundations under a range of eccentricity ratios, enabling direct comparison between skirted and unskirted foundations. The main contribution is the development of practical design insights for improving the performance of shallow foundations in sandy soils subjected to eccentric loading, which can be directly applied in geotechnical engineering practice.

2. EXPERIMENTAL SETUP AND INSTRUMENTATION

The experimental program aimed to study the bearing capacity and settlement response of skirted square foundations embedded in sandy soil. The laboratory setup consisted of a steel test tank and model foundations with different skirt depth features and sand compacted to achieve target relative densities. The mechanical loading system applied load under different conditions while precise LVDT and data acquisition systems monitored settlement response to ensure accurate soil-foundation interaction measurement.

2.1 Testing Tank

It was fabricated with dimensions of 60 × 60 × 60 cm to perform the experimental work. dimensions were selected to minimize boundary effects and simulate realistic conditions for model foundation testing, according to Bossinq's approach **(Bowels,1997)**. The tank was constructed from 3 mm thick steel plates to provide sufficient strength and rigidity. One face of the tank was made of reinforced glass to allow clear observation of soil behavior during loading.

2.2 Footing and Skirt Used

The research utilized a 10×10 cm shallow square steel footing model with 5 mm thickness. Based on this thickness and material properties, the footing behaves as a rigid foundation during loading. In addition, it was used steel skirts with 3mm thickness that extended from the footing at three different depths (0.5B, 1.0B, and 1.5B), where B represents the footing width, to improve soil confinement and load-bearing capacity. The design structure enabled researchers to study skirt depth variations on foundation performance in sandy soil. **Fig. 1** illustrates the skirt used in the study.

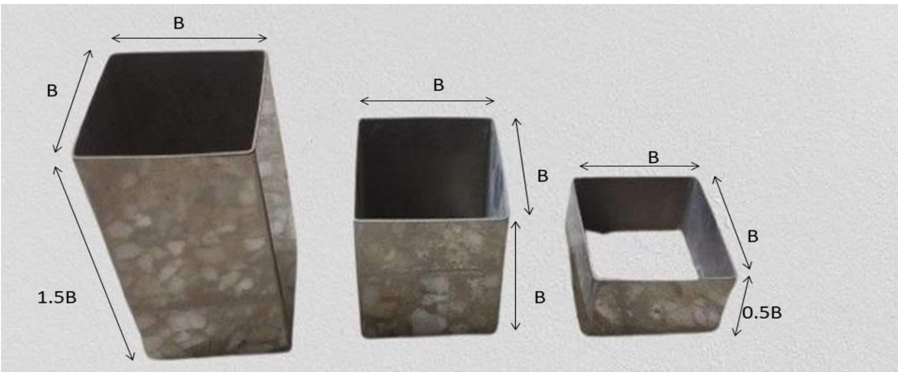

Figure 1. Skirted foundation models showing different lengths

2.3 Dry Pluviation Technique

The sand raining device is specifically designed to prepare sand with a controlled relative density for geotechnical testing purposes. The device consists of a metal box with dimensions of 60 cm in length, 10 cm in width, and 55 cm in height, suspended vertically by strong metal wires. The fall height is manually controlled via a pulley system, allowing precise adjustment of the relative density. The device also features adjustable gates to regulate the sand flow, ensuring a uniform deposition while minimizing particle segregation. This simple and reliable design enables the creation of sand layers with precise relative densities in controlled laboratory environments. **Fig. 2** illustrates the components of the sand rainfall device used in the study.

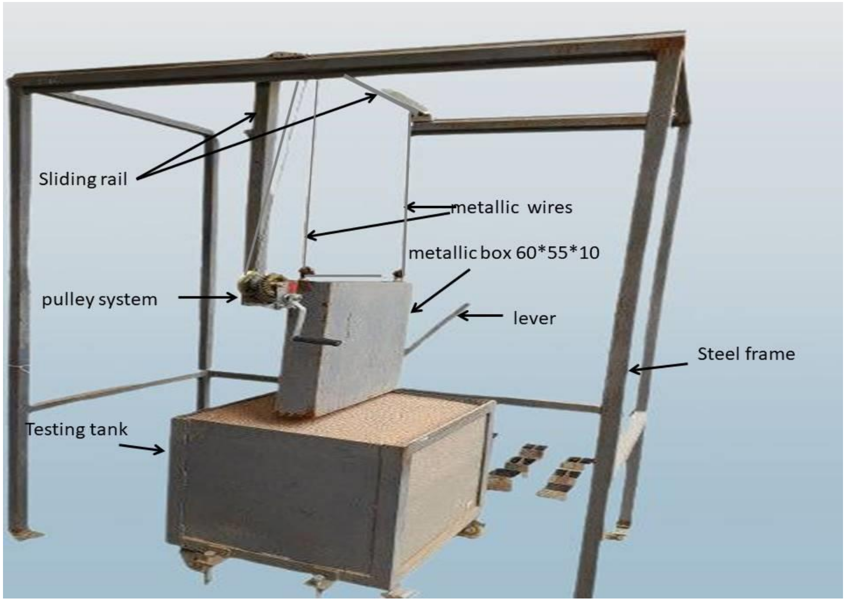

Figure 2. Raining device for controlled sand deposition in foundation testing

2.4 Loading System

The experimental loading system functions to manage foundation model load applications during experimental procedures. The system consists of a 140 cm tall, 80 cm wide steel frame with 4 mm thick steel plates for strength and rigidity. A reinforced steel arch supports a manually operated hydraulic jack which applies vertical and inclined loads to simulate field conditions. A precision load cell with 1-ton capacity precision measures the applied load to provide continuous force monitoring during testing. The system provides simple operation and precise load control, and minimal deviation to achieve consistent test results**. Fig. 3** illustrates the loading system used in the study.

2.5 Instrumentation and Measurements

The integrated instrumentation system provided precise monitoring of skirted foundation behavior during load tests. A digital load indicator linked to a 1-ton load cell monitored the load application throughout the testing period. The foundation base displacement measurements were obtained using two Linear Variable Differential Transformers (LVDTs) which provided 0.01 mm precision to detect small movements on both sides of the foundation base. The data acquisition system performed automatic measurement recording which produced load-settlement curves at regular time intervals. The combination of exact measurement tools with data logging systems produced dependable experimental results for further analysis.

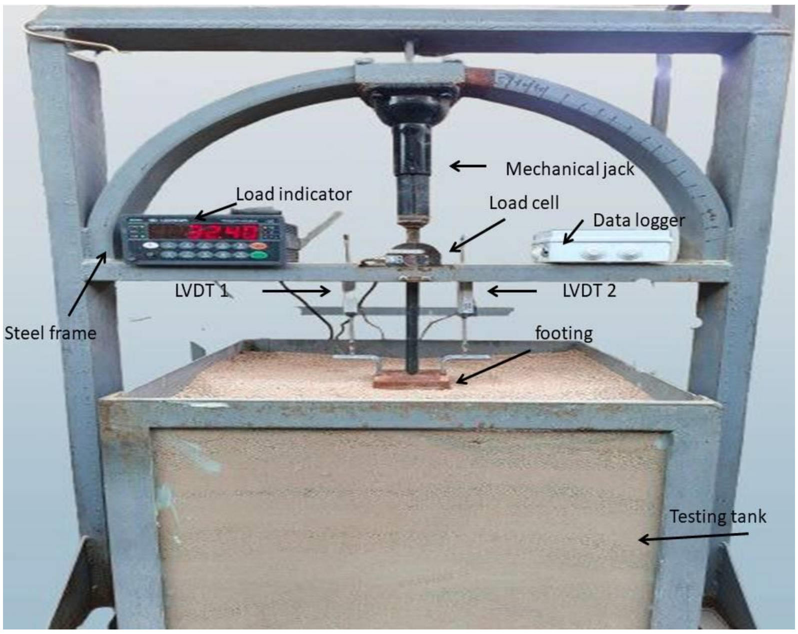

Figure 3. Loading system for foundation testing

2.6 Properties of Sand

The research utilized sand samples which were obtained from Karbala Governorate. The sand underwent washing and drying procedures before undergoing multiple laboratory tests to establish its physical characteristics. The grain-size distribution curve appears in **Fig. 4.**

The specific gravity (Gs) of the sand sample was determined to be 2.67 through **(ASTM D854-14, 2014)** testing. The **(ASTM D422-63, 2007)** testing revealed that D10 measured 0.238 mm, while D30 reached 0.52 mm and D60 reached 1.37 mm. The calculated coefficient of uniformity (Cu) reached 5.75, and the coefficient of curvature (Cc) reached 0.829.

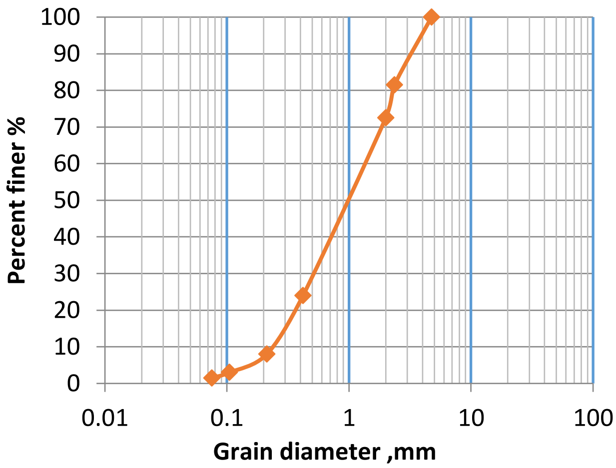

Figure. 4 Sand grain – size distribution curve

The maximum dry unit weight of the sand reached 18.00 kN/m^{3}according to **(ASTM D4253-16, 2016),** and the minimum dry unit weight reached 15.89 kN/m^3 according to **(ASTM D4254-16,2016).** The dry unit weight reached 16.47 kN/m^3 when testing the material at a relative density (D_r) of 30%. The direct shear test according to **(ASTM D3080-11, 2011)** revealed that the internal friction angle (∅) of the sand reached 32 when the relative density (D_r) was set to 30%. The Unified Soil Classification System (USCS) based on **(ASTM D2487-17, 2017)** classified the sand as poorly graded sand (SP).

2.7 Testing Procedure

The experimental tests were designed to evaluate the effect of increasing skirt length on the bearing capacity and settlement behavior of square foundations in sandy soil under eccentric load. The tank was filled with sand in 10 cm thick layers using the raining technique to achieve the required relative density 30% at the beginning of each test. After reaching the target level, the skirt foundation model was placed at the center of the tank and filled internally with sand using the same method. The footing plate was then positioned directly above the model, and eccentric loads were applied gradually, maintaining each load increment for two minutes to allow settlement stabilization. The two-minute holding period was selected based on monitoring the settlement readings during the test; load increments were applied only after the displacements had nearly stabilized, indicating that immediate settlement had occurred. This approach ensures that each loading stage reflects a stable behavior before proceeding to the next load increment, which is consistent with common practices in small-scale model testing in laboratory settings. The system measured both load and settlement with precise LVDT and load cell sensors, which transferred data automatically through a dedicated data acquisition system (data logger). The study generated performance curves through plotting applied load against measured settlement after finishing all loading stages, which enabled a detailed analysis of the foundation behavior with different eccentric loads.

3. RESULTS AND DISCUSSION

3.1 Effect of Load Eccentricity and Length of Skirt on the Performance of Skirted Shallow Foundations

The effect of load eccentricity on square shallow foundations, both skirted and unskirted, embedded in sandy soil was investigated through laboratory experiments. The testing program included four loading scenarios: one with a central load (E/B = 0) and three with eccentric loads corresponding to E/B values of 0.04, 0.08, and 0.16, where B represents the foundation width of 10 cm. Each condition was tested using foundations both with and without skirts, and three skirt lengths were used: 5 cm, 10 cm, and 15 cm. The ultimate bearing capacity was determined using Terzaghi's (1943) failure criterion, which considers failure to occur when settlement reaches 10% of the foundation width. This widely adopted approach in geotechnical research ensures consistency and reliability in identifying the onset of shear failure in sandy soils.

Under central loading, the foundation without a skirt failed at a stress of 32 kPa. When skirts were added, the bearing capacity improved significantly, reaching 70 kPa, 103.5 kPa, and 141.1 kPa for skirt lengths of 5 cm, 10 cm, and 15 cm, respectively, indicating that skirts enhance performance under centrally applied loads. Similar improvements were observed under eccentric loading. At E/B = 0.04, failure stress increased from 28 kPa without a skirt to 57.5 kPa, 87.5 kPa, and 120 kPa with skirts of increasing length. At E/B = 0.08, the bearing capacity rose from 25 kPa to 47 kPa, 75 kPa, and 103.8 kPa as the skirt length increased. At the highest eccentricity of E/B = 0.16, the foundation failed at 20 kPa without a skirt, while skirted configurations achieved 35 kPa, 57.5 kPa, and 79 kPa for skirt lengths of 5 cm, 10 cm, and 15 cm, respectively.

The results clearly show that the use of skirts effectively mitigates the reduction in bearing capacity caused by eccentric loading. Increasing the skirt length consistently leads to improved performance of shallow foundations in sandy soils. This enhancement is due to better soil confinement beneath the foundation, reduced lateral soil displacement, and the mobilization of additional passive resistance. These mechanisms provide deeper overall stability, delay shear failure, and allow the foundation to support greater loads. However, the effectiveness of the skirts diminishes as eccentricity increases, mainly due to increased tilting of the foundation and non-uniform settlement caused by additional moments and uneven stress distribution. The stress–settlement relationships for each eccentricity level are illustrated in **Figs. 5 to 7**.

The Bearing Capacity Ratio (BCR) serves to measure the improvement from skirt integration into shallow foundations through the following Eq. (1). The Bearing Capacity Ratio (BCR) calculates the improved bearing capacity (q_{SK}) in relation to the unimproved bearing capacity (q_{USK}) through the following formula:

$$BCR = \frac{q_{SK}}{q_{USK}} \tag{1}$$

q_{SK}: The bearing capacity of sand soil for skirted footing
q_{USK}: The bearing capacity of sand soil for the un- skirted footing

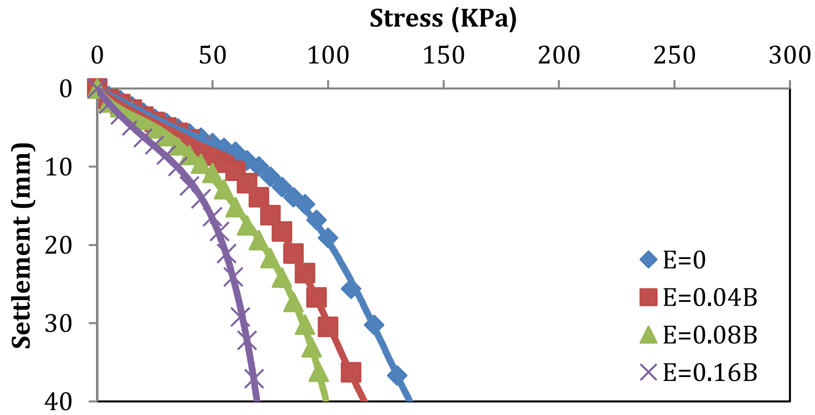

Figure 5. Stress-settlement relationship for skirted foundation with varying skirt eccentricities at L=0.5B

The maximum dry unit weight of the sand reached 18.00 kN/m^{3}according to **(ASTM D4253-16, 2016),** and the minimum dry unit weight reached 15.89 kN/m^3 according to **(ASTM D4254-16,2016).** The dry unit weight reached 16.47 kN/m^3 when testing the material at a relative density (D_r) of 30%. The direct shear test according to **(ASTM D3080-11, 2011)** revealed that the internal friction angle (∅) of the sand reached 32 when the relative density (D_r) was set to 30%. The Unified Soil Classification System (USCS) based on **(ASTM D2487-17, 2017)** classified the sand as poorly graded sand (SP).

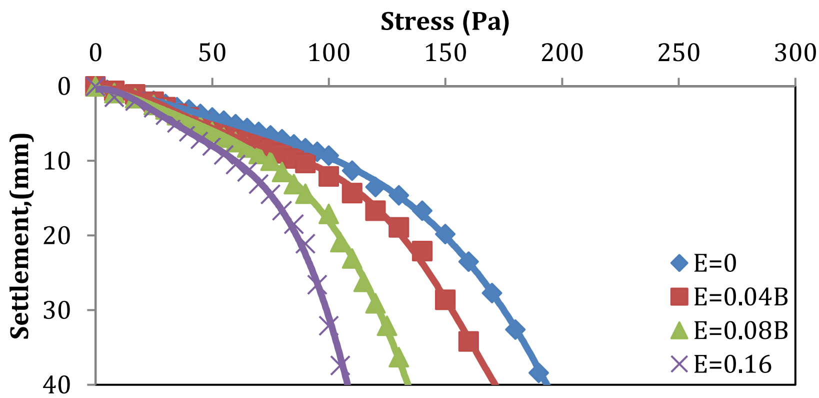

Figure 6. Stress-settlement relationship for skirted foundation with varying skirt eccentricities at L=1B

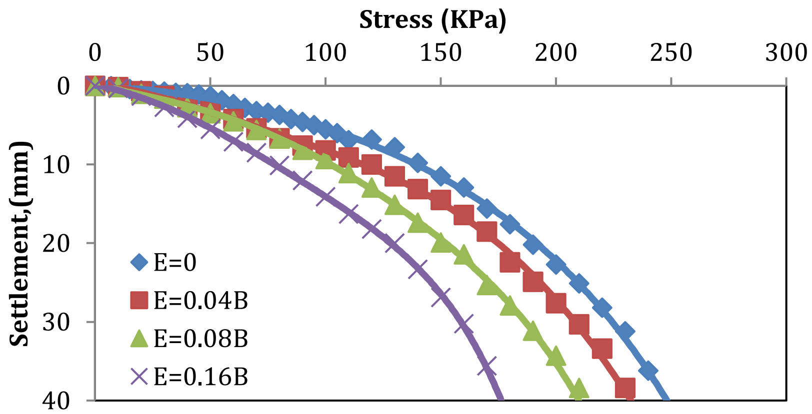

Figure 7. Stress-settlement relationship for skirted foundation with varying skirt eccentricities at L=1.5B

The results in **Table 1** demonstrate that shallow foundation performance improves when skirts are implemented. The bearing capacity increases substantially when skirt length increases because the soil receives improved lateral confinement. The soil confinement provided by longer skirts enhances passive resistance while minimizing lateral soil movement, particularly when the load is off-center. The longer skirts prove effective at stabilizing foundations because they reduce capacity loss at higher eccentricities before shear failure occurs.

Table 1. BCR for skirted foundations with different lengths and eccentricity ratios.

E/B(Eccentricity Ratio)	Skirt Length (B)	BCR
0	0.5	2.18
	1	3.23
	1.5	4.4
0.04	0.5	2.05
	1	3.125
	1.5	4.28
0.08	0.5	1.88
	1	3
	1.5	4.152
0.16	0.5	1.75
	1	2.87
	1.5	3.95

3.2 Effect of Skirted Foundation on Settlement

Table 2 presents the results of how skirted foundations minimize settlement in sandy soil when subjected to different eccentric loading scenarios. The Settlement Reduction Factor (SRF) served to measure this improvement.
The (SRF) is calculated using the following formula:

$$SRF = \frac{S_{USk} - S_{Sk}}{S_{USk}} \quad (2)$$

S_{USk}: The settlement of sandy soil for un-skirted footing at failure stress
S_{Sk}: The settlement of sandy soil for skirted footing at the same stress.

Higher SRF values indicate greater effectiveness in reducing settlement. The SRF values increased with increasing skirt length at central loading (E/B = 0) until reaching 92.1% at 1.5B. The observed settlement reduction patterns followed the same pattern under eccentric loading conditions. The settlement reduction factor (SRF) increased from 0.528 when the skirt length was 0.5B to 0.882 when it reached 1.5B for E/B = 0.04. The settlement reduction effectiveness of skirts remained significant for both E/B = 0.08 and E/B = 0.16 eccentricities, with maximum SRFs reaching 0.87 when the skirt length reached 1.5B. The research demonstrates that skirt implementation leads to settlement reduction and longer skirts enhance this effect, yet produce slightly reduced efficiency when the loading becomes more eccentric.

Table 2. SFR for skirted foundations with different lengths and eccentricity ratios

E/B (Eccentricity ratio)	Skirt length (B)	SFR
0	0.5	0.532
	1	0.744
	1.5	0.921
0.04	0.5	0.528
	1	0.72
	1.5	0.882
0.08	0.5	0.49
	1	0.71
	1.5	0.87
0.16	0.5	0.44
	1	0.7
	1.5	0.85

4. CONCLUSIONS

Based on the experimental results and analysis, the following conclusions can be drawn

1. Skirted foundations significantly improve bearing capacity, especially under central loading. With skirt lengths (0.5B, B, and 1.5B), the Bearing Capacity Ratio (BCR) increased, reaching up to 4.4 at 15 cm.
2. Load eccentricity reduces BCR. At E/B = 0.16, BCR decreased to 3.95 for the 1.5B skirt, though all skirt lengths still outperformed un-skirted foundations.
3. Skirts also reduced settlement. The Settlement Reduction Factor (SRF) reached 0.921 for the 1.5B skirt under central loading, and up to 0.87 under eccentric loads.

4. Longer skirts provided better confinement, delayed shear failure, and increased resistance in sandy soils under all loading scenarios.
5. Skirted shallow foundations, particularly those with longer skirts, offer a practical and effective solution for improving foundation performance under both central and eccentric loading—especially where controlling settlement is critical.

NOMENCLATURE

Symbol	Description	Symbol	Description
B	Width of footing, cm	Gs	Specific gravity of soil solids
BCR	Bearing Capacity Ratio	D_r	Relative Density, %
Cc	Coefficient of curvature	SRF	Settlement Reduction Factor
Cu	Coefficient of uniformity	Ø	Internal friction angle (°)
D10	Effective grain size, mm	q_{SK}	The bearing capacity of sand soil for skirted footing, kPa
D30	Grain size at 30% finer, mm	q_{USK}	The bearing capacity of sand soil for the un-skirted footing, kPa
D60	Grain size at 60% finer, mm	S_{USk}	The settlement of sandy soil for un-skirted footing at failure stress, mm
E	Load eccentricity, cm	S_{Sk}	The settlement of sandy soil for skirted footing at the same stress, mm
E/B	Eccentricity ratio		

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Credit Authorship Contribution Statement

Yousif Jawad Tieh: Conceptualization, Methodology, Investigation, Writing – original draft
Mahmood D. Ahmed: Supervision, Validation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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تأثير انحراف الحمل على أداء الأساسات السطحية المربعة المزودة بتنورة في الترب الرملية الجافة

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الخلاصة

تقيّم هذه الدراسة تأثير انحراف الحمل (اللامركزية) على سلوك الأساسات السطحية المربعة المدفونة في تربة رملية جافة ذات كثافة نسبية 30%، مع وجود تنورة (skirts) وبدونها. أُجريت اختبارات نموذجية مخبرية على أساس بمقاس 10 × 10 سم تحت حالة حمل مركزي واحدة (E/B = 0 ، حيث E تمثل انحراف الحمل و B عرض الأساس)، وثلاث حالات حمل لامركزية E/B= (0.04، 0.08، 0.16). تم اختبار ثلاثة أطوال للتنورات وهي: B 0.5 و 1B و1.5 B أظهرت النتائج أن الأساسات المزودة بتنورة حسّنت بشكل كبير قدرة التحمل وقللت من الهبوط مقارنةً بالأساسات بدون تنورة. كان التحسن الأقصى في قدرة التحمل تحت الحمل المركزي مع طول تنورة B1.5، حيث بلغ معامل زيادة قدرة التحمل (BCR) 4.4 مرات. تحت أعلى انحراف(E/B = 0.16) ، انخفض المعامل إلى 3.95 مرات. كما تم تقليل الهبوط بشكل فعال، حيث بلغ معامل تقليل الهبوط (SRF) 0.921 تحت الحمل المركزي وبقي مرتفعًا حتى 0.85 تحت الأحمال اللامركزية. تؤكد النتائج أن الأساسات المزودة بتنورة تحسن قدرة التحمل وتقلل الهبوط للأساسات السطحية على التربة الرملية تحت الأحمال المركزية واللامركزية.

الكلمات المفتاحية: الأساس المزود بالأكمام، الحمل اللامركزي، تحسين قدرة التحمل، الهبوط.