Journal of Engineering

journal homepage: www.joe.uobaghdad.edu.iq

Volume 29 Number 3 March 2023

Experimental Study on the Behavior of Square-Skirted Foundation Rested on Gypseous soil Under Inclined Load

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ABSTRACT

This work investigates experimentally the effect of using a skirt with a square foundation of 100 mm width resting on dry gypseous soil (i.e., loose soil with 33% relative density), and subjected to an inclined load. Previous works did not study the use square skirted foundation rested on gypseous soil and subjected to inclined load. The investigated soil was brought from Tikrit city with 59% gypsum content. Standard physical and chemical tests on selected soil were carried out. Model laboratory tests were carried out to determine the effect of using a skirt with a square foundation on the load-settlement behavior of gypseous soil and subjected to inclined load with various Skirt depth (Ds) to foundation width (B) ratio Ds/B (0,0.5,1, and1.5). The results show that using a skirt with a square foundation improves load-carrying capacity and reduces settlement of foundation rested on loose gypseous soil and the amount of improvement increase with increasing skirt depth to foundation width Ds/B. Bearing capacity improved by about (193) %, and Settlement ratio (S_r) reduced from (1) % for square foundation without a skirt to (0.14) at Ds/B, equal to 1.5 at θ =0° with the y-axis (Where θ is the inclination angle of the applied load); and bearing capacity improved by about (162) % for the square skirted foundation with Ds/B, equal to 1.5 and θ =15° with the y-axis.

Keywords: Skirted foundation, Inclined load, Bearing capacity, Settlement ratio.

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Peer review under the responsibility of University of Baghdad.
https://doi.org/10.31026/j.eng.2023.03.03

Article received: 15/09/2022
Article accepted: 02/10/2022
Article published: 01/03/2023

دراسة تجريبية لتصرف الأساس المربّع ذو الحواف على التربة الجبسية تحت حمل مائل

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الخلاصة

يتضمن هذا البحث دراسة تجريبية لتحديد تأثير إستخدام الحواف مع أساس مربع عرضة 100 ملم يستند على تربة جبسية جافة (التربة مفككة بكثافه نسبية 33%) وتم تعرضها لحمل مائل. لم يتم التطرق في البحوث السابقة إلى دراسة استخدام الاساس المربع ذو الحواف مع التربة الجبسية وتسليط حمل مائل. لذلك من الضروري دراسة تأثير استخدام الأساس المربع ذو الحواف مع التربة الجبسية الجافة. التربة المستخدمة في البحث تم اخذها من مدينة تكريت نسبة الجبس فيها تساوي 59%. تم إجراء إختبارات معملية نموذجية لتحديد تأثير إستخدام الحواف مع الاساس المربع على سلوك التربة الجبسية وتعرضها لحمل مائل وكانت نسبة عمق الحواف إلى عرض الأساس Ds/B مساوي إلى (0,0.5,1.0,1.5). نتائج الفحوصات بينت إستخدام الحواف مع الأساس المربع الموضوع على تربة جبسية مفككة يحسن قدرة تحمل التربة ويقلل الهبوط فيها , مقدار التحسين يزداد بزياده نسبة عمق الحواف إلى عرض الأساس Ds/B. مقدار تحمل التربة إزداد بنسبة (193)% والهبوط قل Sr من (1)% للأساس المربع بدون حواف إلى (0.14)% عندما تكون نسبة Ds/B مساوية إلى 1.5 عند زاوية ميلان حمل مساوية إلى صفر(θ =0°, الحمل مركزي) (θ هي زاويه ميلان الحمل المسلط). وتم تحسين قدرة التحمل بمقدار (162)% للأساس المربع مع نسبة Ds/B مساوية الى 1.5 و زاوية ميلان الحمل المسلط مساوية إلى (θ =15°) درجة من المحور الصادي.

الكلمات الرئيسية: أساس ذو حواف, حمل مائل, قدرة التحمل, نسبة الهبوط.

1. INTRODUCTION

Gypseous soil is considered one of the most dangerous soil to deal with and build on. Gypseous soil covers (1.5%) of the world's surface area and more than 21% of Iraq's area (**Al-Busoda and Al-Rubaye, 2015).** The problems of weak soils, such as low bearing capacity and settlement of foundations under relatively light loads, make many civil engineers develop and apply various methods to improve poor soil conditions. Improvement techniques are used in different civil engineering applications to enhance soil performance **(Hussein et al., 2019; Al-Baidhani and Al-Taie, 2019; Al-Baidhani and Al-Taie, 2020; Al-Naje et al., 2021).** With the development of modern and various soil improvement methods, skirt foundation behavior has received renewed attention**.** Skirted foundations became widely used in weak soil deposits to support various structures such as renewable energy, gas industry, and turbines. These structures are often subjected to different vertical, horizontal, and inclined loading resulting from wind, water, earthquakes, etc. It is essential to ensure this foundation's stability under various loading conditions.
The skirted foundation considers an alternative technique to used pile in off-shore, jacket, and wind turbine structures for improving bearing capacity and reducing settlement. The

term "Skirt "can be defined as one or more walls surrounding the foundation, connected to the lower part of the foundation, and working as a single unit with the foundation that confines the soil between the walls and transfers load from the structure to soil. Skirts are thin vertical or inclined structural walls made of steel or concrete **(Thakare and Shukla, 2016)**. Skirts' side/s reduce sliding failure. The skirt is used with a shallow foundation of rectangular, square, and circular shapes. This foundation is cost-effective because it uses fewer materials and installation mechanisms and saves time. These foundations gradually replace the costly foundation. Researchers studied the behavior and performance of skirted foundations through numerical and analytical studies. Many studies on skirted foundations occur with various foundation types (circular, square, triangular, etc.) resting on various soil with varying densities. Previous studies on using skirted foundations are given in **Table 1**.

Table 1. Previous studies on using skirted foundation

Author	Description of work
Yun and Bransby, 2003	Used geotechnical tests and compared the results with surface foundation tests; the result shows that the increases in skirt depth lead to an increase in bearing capacity.
Yun and Bransby, 2007	Investigate the response of the strip skirted foundation subjected to vertical, horizontal, and flexural loading rest on sandy soil; the result shows that when the depth of the skirted foundation increased to about 3 to 4 times that of a plain foundation, the failure of the foundation changed from sliding to rotation.
Martinezi et al., 2008	The behavior of shallow circular skirted foundation under compression and tension load was investigated experimentally; the results show up-lift pressure reduced when using a skirt with foundation compared with using foundation without a skirt.
Azzam and Nazir, 2010	Studied the bearing capacity of circular footing resting on clay soil; the footing was with and without skirts. The study shows that the bearing capacity at the failure of the footing can improve by using circular footing with skirts.
Renanigsih et al., 2017	Study the behavior of a circular skirted foundation rested on sand soil and subjected to vertical load; the results show that increased skirt depth improved bearing capacity up to 470% due to confining soil under the circular foundation.
Al-Aghbari et al., 2020	Investigate the use of skirts with circular footing subjected to a vertical load and rested on sandy soil to improve the bearing capacity and reduce settlement; the results show that the settlement was reduced by 17%, and the bearing capacity improved up to 510% for a skirt with depth equal 1.25 B.

Thakur and Dutta, 2020	Use numerical and experimental studies to study the behavior of a hexagonal skirted foundation rested on sandy soil; the results show that using a double skirt with a hexagonal footing improves load-carrying capacity compared with using a single skirt with footing. **Fig. 1**.
Abdulhasan, et al., 2020	Studied the performance of skirted circular shallow footings resting on sandy soil, and an inclined load is applied; the results show that using a skirted foundation improves the bearing capacity and reduces settlement.

Figure 1. Double and single hexagonal skirted foundations rested on sandy soil **(Thakur and Dutta, 2020)**.

2. GYPSEOUS SOIL

A large area of the earth's surface covered with soil was exposed to a significant decrease in bulk volume when the water reached it, such as collapsing soil. One of the essential collapsible soil is named gypseous soil. Gypseous soil is one of the most complex problematic soil, which challenges geotechnical engineers **(Mohsen and Al-Busoda, 2022)** to identify problems and solve them for safe buildings (**Al-Busoda, 1999; Al-Busoda and Hussein, 2013; Al-Busoda and Khdeir, 2016; Al-Taie et al. 2019)**
Gypseous soils are found in arid and semi-arid regions when the rain rate is more diminutive than the evaporation rate. It is located in Russia, Spain, Armenia, and the United States of America and covers more than (20%) of the Iraq area. Gypseous soils have a large bearing capacity and very low compression in the dry state. This soil is known as "metastable" or collapsible soil (**Al-Bosoda, 2008; Hassan and Al-Busoda, 2022)**
Collapsible soils can be found in hot climate weather regions when the rain rate is less than the evaporation rate, which is unsatisfactory for infiltrating gypsum from the soil, and more

gypsum is deposited continuously due to groundwater evaporation. The natural occurring of collapsible soil from:

- Debris flow (e.g., Alluvial fan materials).
- Sediments of windblown (e.g., loess).
- High salt content cemented metastable soils (e.g., sabkha).
- Residual soil.
- Non-engineered or poor compaction with low moisture or waste.

3. MATERIALS AND METHOD

3.1 Gypseous Soil

This experimental investigation uses gypseous soil from Tikrit, a "city north of Baghdad" near Tikrit University at 1 m depth. Laboratory tests were conducted to determine the soil's physical and mechanical properties. **Table 2.** shows the physical properties of the used soil.

Table 2. The physical and mechanical properties of soil.

Test	Units	Property	Standard
Natural Water content	(%)	3%	ASTM D 2216
Specific gravity(Gs): With water With Kerosene	……	2.34 2.37	ASTM D 854-02
The angle of internal friction (ø) Soil Cohesion (c)	Degree kPa	36.7˚ 4.263	ASTM D 3080
C_u Cc	- -	7.35 1.23	ASTM D 422
Soil classification	-	SW-SM	ASTM D 2487

3.2 Skirted Foundation Model

A steel skirt of a square shape surrounds the foundation models. The width of the foundation is (100) mm, and the ratio of the depth of the skirt to footing width (Ds/B) values are (0, 0.5, 1, and 1.5) with a thickness of (1mm). The square footing is set above the skirt and works as a single unit—the skirt works to confine gypseous soil under the square foundation. **Fig. 2** shows the shape and dimension of the square-skirted foundation.

3.3 Model Test Container

The manufactured setup consists of a glass container box of (60×60cm) and 60cm high, glass thickness of 10 mm, as shown in **Fig. 3**; the purpose of using the glass container is to allow better observation of soil behavior. Reference markers were used on the sides of the container to help fill the container in a proper way with soil layers.

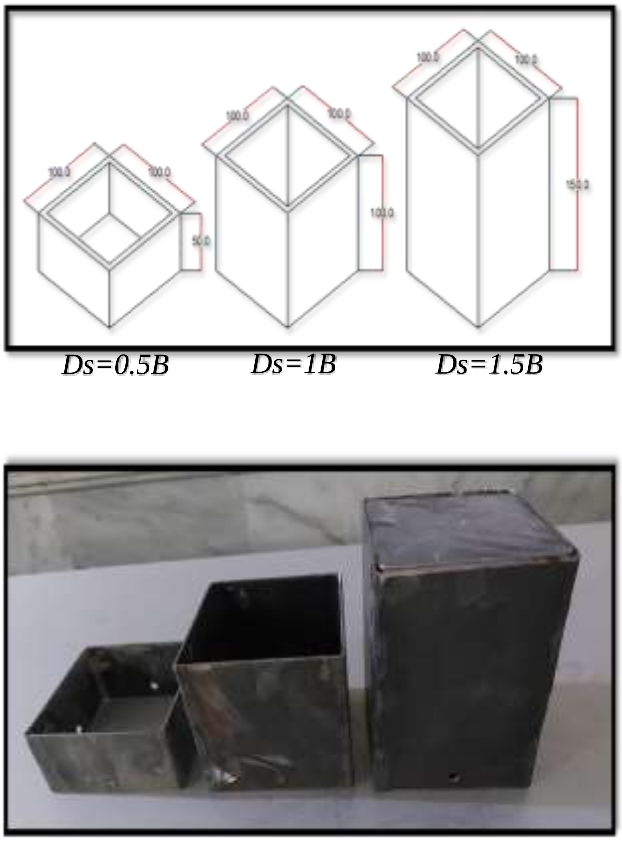

Figure 2. Square-skirted foundation, dimensions in mm.

Figure 3. Glassy Container

3.4 Loading Frame

The loading system consists of a steel arch frame with a mechanical jack of 2 tons attached to the arch frame to apply concentrated, eccentric, and inclined Load. The jack is connected to a load cell SS300-5T to measure the applied Load on the footing. The cell was made from stainless steel with a maximum capacity of 5 tons. Two LVDTs of 75 mm capacity were used. **Fig. 4**.

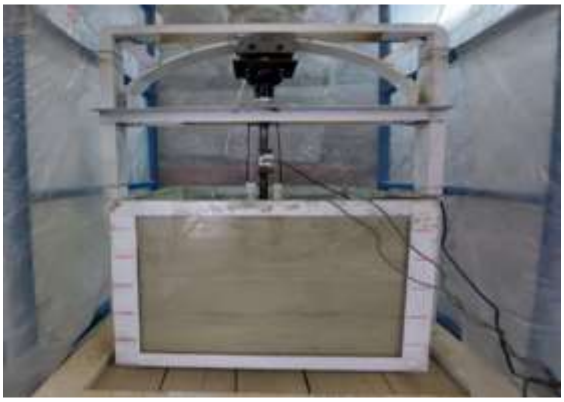

Figure 4. Manufactured Loading Frame System.

4. EXPERIMENTAL TEST PROCEDURE

4.1 Preparation of Gypseous Soil

Gypseous soil was prepared to fill the container by using the raining technique. The raining technique was adopted to achieve a homogenous uniform gypseous soil model with the required relative density; the soil is placed into six equal layers. The sand can rain freely through the air from a specified height with a controlled discharge rate. Different relative density values are given with different heights; for the tests, the soil was prepared with 33% relative density (i.e., loose gypseous soil).

At first, a square foundation without a skirt is set directly on the surface of the prepared gypseous soil gently; then, the Load is applied until failure occurs. For the skirted foundation, the skirt was placed during the raining process at a required depth; the soil continued to be placed inside the container. After filling the container, the foundation is placed at the top of the skirt; the two LVDT is also placed at an equal distance, then the inclined Load with an angle of inclination equal to (0,5,10,15) degrees from vertical (i.e., with y-axis) is applied **Fig. 5.** Different skirt depth of (0.5B, 1B, and 1.5B) was used where B was foundation width. Care was taken when placing the foundation and skirts to avoid any change in the relative density.

Figure 5. Inclined Load Application.

5. RESULTS AND DISCUSSION

5.1 The Behavior of Square Skirted Foundation Subjected to Inclined Load

To evaluate the behavior of the square foundation with and without a skirt and subjected to an inclined Load, a series of (16) physical laboratory model tests were carried out on the square foundation (100) mm width rested on loose dry gypseous soil. The skirts used have a varied depth-to-foundation width ratio (Ds/B) equal to (0, 0.5, 1, and 1.5). The square foundation is set above the skirt, and an inclined load with (0, 5, 10, and 15) degree inclination angle with vertical (i.e., with y-axis) was applied. **Figs. 6 to 9** show the results of model tests.

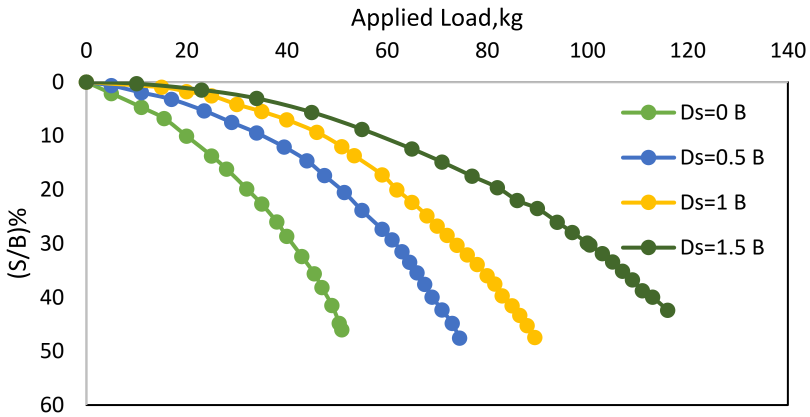

Figure 6. Load-Settlement/foundation width ratio (S/B) behavior of square skirted foundation with (100) mm width rested on dry gypseous soil at θ=0° with the y-axis.

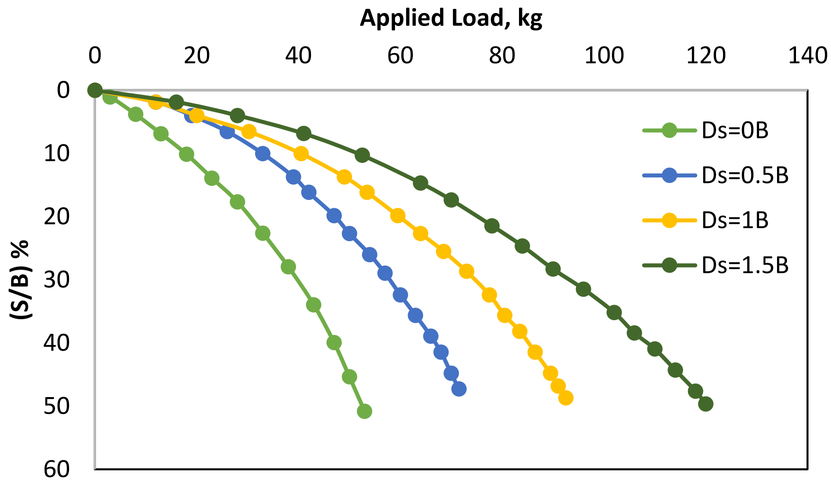

Figure 7. Load-Settlement/foundation width ratio (S/B) behavior of skirted foundation with (100) mm width rested on dry gypseous soil at θ=5° with the y-axis.

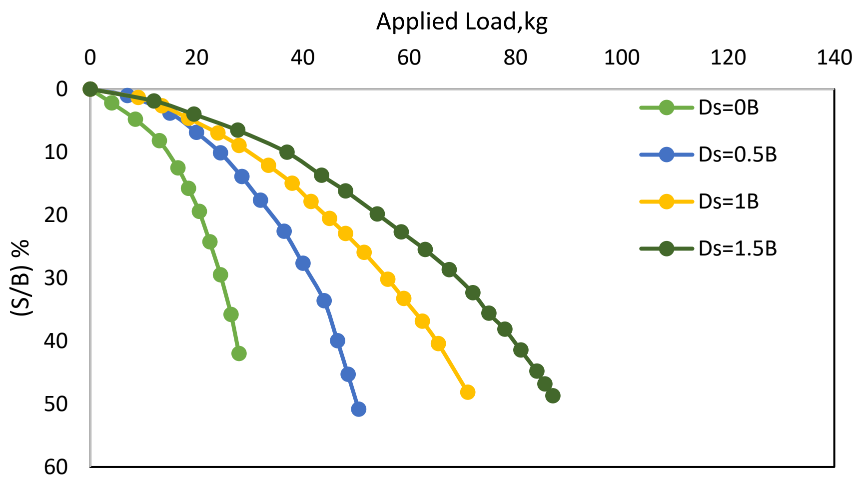

Figure 8. Load-Settlement/foundation width ratio (S/B) behavior of square skirted foundation with (100) mm width rested on dry gypseous soil at θ=10° with the y-axis.

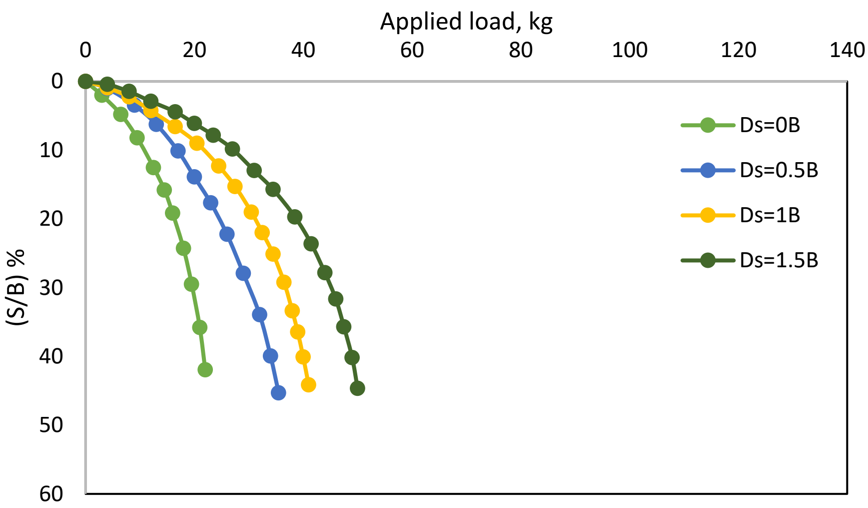

Figure 9. Load-Settlement/foundation width ratio (S/B) behavior of skirted foundation with (100) mm width rested on dry gypseous soil at θ=15° with the y-axis.

Test results show that using skirts with a square foundation improves load-carrying capacity and reduces foundation settlement rested on loose gypseous soil. At 10% of foundation width bearing capacity increases and settlement decreases with increasing skirt depth to foundation width ratio (Ds/B). Load-carrying capacity improved from (10.5) kg for foundations without a skirt to (27) kg at Ds/B, equal to 1.5 at θ =15° with the y-axis. Bearing capacity improved by about (193) %, and the Settlement ratio (S_r) reduced from 1 % for a square foundation without a skirt to (0.14) at Ds/B, equal to 1.5 at θ =0° with the y-axis. General test results show that using a square-skirted foundation increases bearing capacity and reduces settlement. Improvement of Load carrying capacity and settlement reduced with increasing skirt depth to foundation width ratio (Ds/B).

5.2 Effect of Increasing Skirt Depth

To evaluate the effect of increasing skirt depth (Ds) on soil behavior, four different skirt depths were used with the square foundation (100) mm width. The depth of the skirt (Ds) is equal to (0, 0.5, 1.0, and 1.5) of foundation width (B). To evaluate the effect of increasing skirt depth, the improvement in Load carrying capacity was expressed by using a non-dimensional parameter called improvement ratio (IR). 'Improvement ratio' can be defined as the ratio of the failure Load of the skirted foundation to the failure load of the foundation without skirt at the same relative density. It should be noted (IR=1) for foundations without a skirt (i.e., Ds/B=0). **Fig.10** shows the effect of increasing skirt depth on the improvement ratio (IR) rested on dry gypseous soil with 33% relative density (i.e., loose gypseous soil).

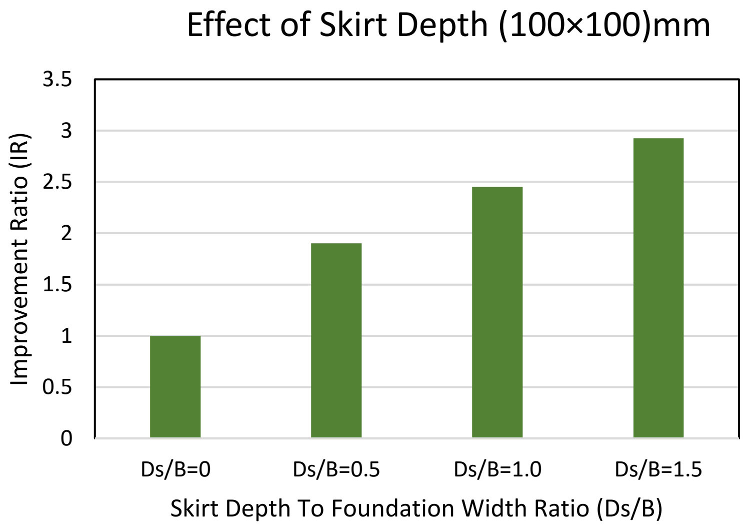

Figure 10. Variation of improvement ratio (IR) with Ds/B ratios of the foundation of 100mm width resting on dry gypseous soil.

The results show that increasing skirt depth causes a more significant improvement in the improvement ratio (IR). As skirt depth to foundation width (Ds/B) increases, the foundation becomes deeper, foundation depth increases, and the improvement ratio increases. These results agreed with the results of **(Abd Ali et al. 2018; Abdulhasan et al. 2020).**

5.3 Effect of Skirted Foundation on Settlement

One of the essential characteristics that must be analyzed when using gypseous soil is the analysis of settlement characteristics, the settlement of a square foundation with a skirt (Ss) and without a skirt (S_0) resting on gypseous soil. To compare the results of the test and knowing the reduction in settlement due to using a skirt with a square foundation of (100) mm width, a dimensionless parameter is used called 'Settlement Ratio" (S_r); this parameter can be defined as the ratio of settlement of the square foundation with a skirt to the settlement of foundation without skirt at a constant load. Three loads have been chosen to compare the settlement results of foundations with and without a skirt in dry soil conditions at different load levels; these loads were selected before load failure of the square foundation without a skirt (i.e., Ds/B= 0). It should be noted that the settlement ratio (Sr) is equal to 1 for a foundation without a skirt. Settlement results of the square foundation with (100) width resting on (dry) gypseous soil at different skirt lengths are summarized in **Table 3**.

Table 3. Settlement ratio (Sr) for a square-skirted foundation with different skirt depths.

Foundation Type	Ds/B	Load, kg	Settlement of foundation with 100mm width, mm		S_r
			Ss	S_0	
Square Skirted Foundation	0.0	10	2.92	-	1
		15	5.3	-	1
		20	9.8	-	1
	0.5	10	1.19	2.92	0.407
		15	2..12	5.3	0.4
		20	3.84	9.8	0.392
	1.0	10	0.64	2.92	0.219
		15	1.32	5.3	0.249
		20	1.95	9.8	0.2
	1.5	10	0.49	2.92	0.168
		15	0.774	5.3	0.146
		20	1.372	9.8	0.14

Test results show that using a skirt with the square skirted foundation reduces settlement and improves Load carrying capacity. The settlement ratio decreases with increasing skirt depth and increasing applied Load. The settlement ratio decreased from (1) for the square foundation without a skirt to (0.14) for the square foundation with a depth of skirt to foundation width (Ds/B) equal to (1.5). The results are compared with **(Al-Aghbari, et.al, 2020).**

6. CONCLUSIONS

Tests aim to study the load and settlement behavior of square-skirted foundations resting on dry gypseous soil and subjected to an inclined Load. The following points summarize the conclusions of the tests:

1- Bearing capacity improved, and settlement decreased when using a skirt with a square foundation rested on loose gypseous soil.

2- Load carrying capacity improved from (10.5) kg for foundations without a skirt to (27) kg at Ds/B, equal to 1.5 at θ =15°. The best improvement in load-carrying capacity and reducing settlement occurs when using a skirted foundation with Ds/B equal to 1.5.

3- Bearing capacity improved by about (193) % at Ds/B, equal to 1.5 at θ =0° with the y-axis. Also, the bearing capacity improved by about (162) % for the skirted foundation with Ds/B, equal to 1.5 and θ =15° with the y-axis. The lower improvement in bearing capacity is when

using a square foundation without a skirt, and the best improvement occurs when Ds/B is equal to 1.5.
4- Settlement ratio (S_r) reduces from (1) % for square foundation without a skirt to (0.14); the settlement decrease about 186% when skirt depth to foundation width Ds/B, equal to 1.5 at θ =0° with the y-axis.

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