A Comparative Experimental Study of Circular Footings on Sand Reinforced with Geogrid and Loosely Skirted Foundations under Eccentric Loading

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Received: 3 June 2025 | Revised: 7 July 2025 and 20 July 2025 | Accepted: 23 July 2025

ABSTRACT

This study conducts a comparative experimental analysis of two soil improvement methods—geogrid reinforcement and skirted foundations—used beneath circular footings on loose sandy soils. While both techniques are well documented, their combined assessment is limited in the existing literature. In this study, sixty-four small-scale physical model tests were conducted in which footings were subjected to concentric and eccentric vertical loads. The results demonstrated that both improvement methods significantly enhance the foundation performance. Loosely cylindrical skirted foundations increase the bearing capacity by confining the soil and reducing the lateral movement; however, geogrid reinforcement performs better. The optimal spacing for geogrid layers (*h*) was 0.4 times the footing diameter, the ideal configuration for loosely cylindrical skirted foundations was a diameter (*Ds*) equal to 1.4*D*, and a length (*Ls*) equal to 1.5*D*. Although smaller skirts are less affected by eccentric loading, they did not show any significant improvement in performance. It was also found that the eccentric loads affect the loosely skirted foundations less than the geogrid reinforcement. Still, the latter generally performs better than the loosely skirted foundations in increasing the load-bearing capacity of the circular footings on sandy soil. The results are significant for the design of towers, heavy infrastructure foundations, and other constructions where the increased load-bearing capacity and reduced settlement are essential.

Keywords-loosely skirted; circular foundation; geogrid; sandy soil

I. INTRODUCTION

Shallow foundations are frequently utilized in buildings, due to their ease of usage and cost-effectiveness; however, the underlying soil's properties can significantly affect their efficiency. Sandy soil's low cohesiveness and high permeability can often cause issues, like significant settlement and reduced bearing capacity. The importance of the foundation design in enhancing the soil stability has become increasingly evident within civil engineering, especially in regions with complex geotechnical challenges. Soil reinforcement is an established method of improving the engineering properties of weak soils. The former is essential in geotechnical engineering, since it enhances the soil stability and strength, particularly in construction projects. Geosynthetics have been widely used in various geotechnical structures, including soil reinforcement for footings, slopes, retaining walls, and roads. This technique incorporates different elements into the soil to enhance its mechanical characteristics and increase its capacity to support structures [1]. Using reinforcing techniques can significantly improve the load-carrying capacity of the soil, which is weak in tension. Geosynthetic soil reinforcement mechanisms offer vertical and lateral soil confinement and wider stress distribution [2]. The geogrid reinforced system reduces the differential settlement and increases resistance. Given that the geogrid reinforcement reduces the lateral deformation, it increases the soil's shear strength, overall strength, and the stability of the associated geotechnical construction [3].

The shear resistance coefficient of the sand–geogrid interface increases as the geogrid mesh size increases [4]. The geogrid reinforcement impact on shallow foundations on sandy soils has been investigated [5]. Square footings supported by geosynthetic reinforced sand are evaluated for their bearing capacity. It has been investigated how various reinforcement parameters, including the type and tensile strength of the geosynthetic material, reinforcement amount, and the layout of geosynthetic layers beneath the footing, affect performance. Research shows that the design and setup of the reinforcement significantly impact the increase in the bearing capacity, more than the tensile strength of the geosynthetic material [6].

Authors in [7] used numerical models to examine the behavior of shallow foundations subjected to long- and short-term earthquakes. It was demonstrated that when a geogrid is used, pseudo acceleration, pseudo velocity, and relative displacement drop logarithmically. The skirted foundation is another technique for improving the characteristics of weak soils. Skirted foundations are utilized in various engineering applications. They are frequently employed in offshore structures, such as wind turbines and oil platforms due to their exceptional resistance to the lateral loads and moments [8]. Geotechnical engineers have explored the features of skirted foundations and how they increase the bearing capacity of weak soils. It has been observed that these foundations improve the load-bearing strength and minimize the risks of settlement and sliding. It has been shown that the skirted foundations can significantly improve the performance of the shallow foundations in various soil types, such as sandy and gypseous soils, by confining the underlying soil and improving the resistance to the lateral forces. The underlying soil is confined by installing vertical skirts around a raft foundation, creating resistance along the skirts' sides. This helps the footing in its preventive role against sliding [9].

Skirted footings can replace the pile driving in weak gypseous soils, which leads to lower construction costs [10]. The skirts significantly increase the ultimate bearing capacity, while extending their length can raise this capacity by up to 4.70 times [11]. The skirt foundations can be constructed from various materials and may be designed as either rigid or flexible (loose). In loosely skirted foundations, skirts are made of a geogrid material to reinforce the soil [12].

The present study examines the effectiveness of loosely skirted square footing on sandy soil. The test results indicate that an increase in the skirt depth leads to a significant rise in the load-bearing capacity. This study also investigates two ground improvement methods that have rarely been evaluated together. It analyzes the effects of geogrid reinforcement and loose skirt foundations on enhancing the properties of sandy soil. Factors, such as geogrid layer spacing and the performance of loose skirt foundations under different loading conditions are explored. This comparative study offers valuable insights for optimizing the foundation solutions in challenging soil conditions.

II. MATERIALS AND EXPERIMENTAL METHODS

A. Materials

The soil utilized in this study is sandy soil taken from the AL-Rashdiya site, northeast of Baghdad. The soil was classified according to the Unified Soil Classification System (USCS) and ASTM D-2487 [13] as poorly graded sand (SP) with a specific gravity of 2.67, based on ASTM D-854 [14]. The maximum and minimum dry unit weights of 1531 kg/m^3 and 1375 kg/m^3, respectively, were obtained according to ASTM D-4253 and ASTM D-4254 [15, 16]. The angle of internal friction ($\emptyset$) was measured by performing a direct shear test based on ASTM D-3080 [17] on sand prepared at a Relative Density (RD) of 30%. The angle of internal friction was found to be 25^o, with an apparent cohesion of 2 kN/m^2.

The chemical properties of the sandy soil employed in this study, which was conducted at the National Centre for Construction Laboratories, were: SO_3, acid = 0.165%, Total Soluble Salts (TSS) = 0.544%, Organic Matter (OM) = 0.108%, and Gypsum content (CaSo4.2H2O) = 0.355%.

The geogrid used in the test was made of Polymer materials with specifications: square mesh type, green color, rib width of 1.6 mm, rib thickness of 1.5 mm, junction thickness of 1.8 mm, and tensile strength of 2.25 MPa. The geogrid was molded into square samples during the test preparation, measuring 354 mm on each side to reinforce the soil. It was formed in the shape of a cylinder with diameters (D_S) of 100 mm, 110 mm, 120 mm, and 140 mm, representing loosely skirted foundation, as shown in Figure 1. This geogrid size is suitable for the miniature model, as it ensures the compatibility with the soil and avoids the excessive stiffness. The skirt employed in this study was made from geogrid, offering less stiffness than other rigid types typically used in other studies.

Fig. 1. Loosely skirted cylindrical foundation.

B. Test Setup

The experimental study was conducted using a physical model with circular footing of 100 mm diameter on loose sandy soil. Figure 2 illustrates the experimental setup [18, 19]. A glass container box of 600 mm × 600 mm × 600 mm size and a tank with width and depth equal to six times the footing's diameter were utilized to ensure the minimum proposed width ($\geq 5D$), preventing the significant boundary effects and enabling the natural failure mechanisms [20]. The glass container is 10 mm thick and is reinforced with 3 mm thick iron plates on the outside to avoid any lateral deformation. It allows a clear observation of the soil behavior and reduces the wall friction. The loading system features an arch frame made of steel with a two-ton mechanical jack, intended to apply both concentrated and eccentric loads. This jack is linked to a load cell made of stainless steel (SS300-1T) that gauges the load on the footing, supporting a maximum one-ton capacity.

A pair of Linear Variable Differential Transformers (LVDTs – MODEL KTR-R-100) capable of measuring 100 mm (maximum linearity error is no more than ±0.1% of the full-scale value) is positioned symmetrically on either side of the jack to monitor the settlement during loading. The load cell is connected to a digital indicator to display the applied load. The load cells and the two LVDTs used in this study were calibrated to ensure that the recorded load-settlement data remained reliable and accurate throughout the experiment. The LVDTs and the digital display are connected to a data logger and an Arduino program, which process and display the test data. This program transmitted LVDT readings and the applied load every second, ensuring an accurate measurement of the soil's response under load.

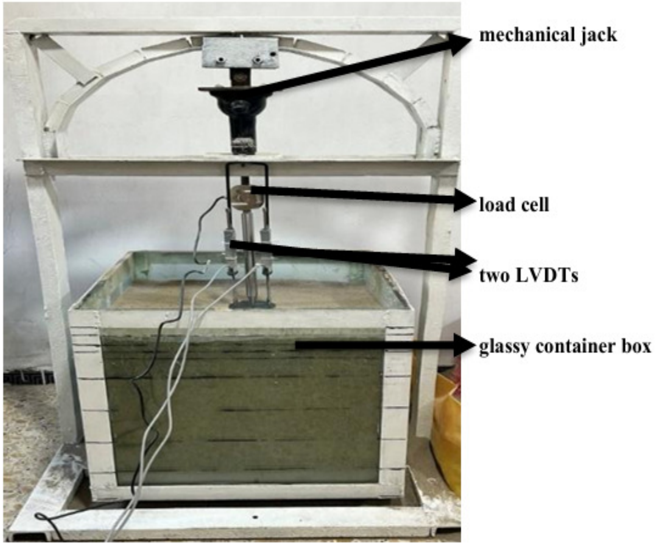

Fig. 2. Experimental setup.

C. Scale Effect

This study tested a 100 mm diameter circular footing in a cubic container. The sand used had a mean particle size (D_{50}) of 0.24 mm. A footing-to-mean particle size ratio (D/D_{50}) f 416.7 was used. This high ratio shows that the footing size is much larger than the average soil grain size. According to the geotechnical modeling guidelines [21], maintaining a large D/D_{50} ratio is essential to reduce the scale effects and ensure that the soil acts as a continuous medium rather than as separate particles.

D. Soil Preparation

The box was filled with a homogeneous layer of sand at the desired density deploying the sand soil raining method, a widely used method for preparing sand samples. In this method, the resulting RD is influenced by factors, such as the Falling Height (HF) and Deposition Intensity (DI). It has been demonstrated that the increased HF is associated with increased RD [22]. Figure 3 shows the drop height corresponding to each sand density that was determined. A clear correlation was observed between the elevation of the drop and increment in the sand density. The height required to achieve a density of 1.42 g/cm^3 at an equivalent RD of 30% was about 10.8 cm. The sand bed was thoroughly prepared, with layers in the container, each leveled with a plate to prevent the disturbances, and with each layer measuring a consistent 10 cm height.

E. Testing Program

An experimental program was designed to examine the effect of different improvement techniques (loosely skirted and reinforced soil) on the behavior of footing under vertical (centric and eccentric) loads.

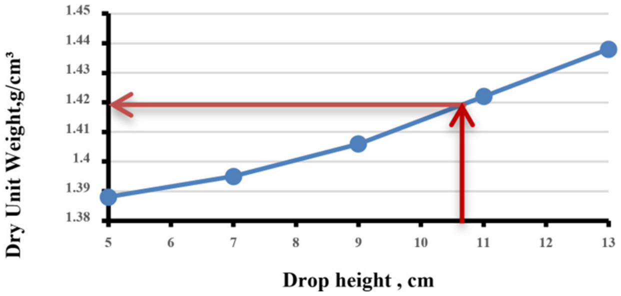

Fig. 3. Density estimation curve for the sand raining method.

The testing program investigated various parameters, including the skirt length, foundation diameter, and the distance between the reinforced layer and the applied load. The footing was subjected to vertical concentric loading with $e/D = 0$ and eccentric loading with $e/D = 0.04$, 0.08, and 0.16. The eccentricity was a fraction of the footing's width ($e/D < 1/6$). These limits help avoid the intolerable stress concentrations that could lead to foundation instability and contact stress between a footing loaded within its middle third area. They also ensure that a tensile zone does not occur and prevent the uplifting of the foundation.

The diameter of the loosely skirted cylinder was 1.0*D*, 1.1 *D*, 1.2 *D*, and 1.4 *D*, not exceeding 1.5*D*, as per Bossinq's approach [20], which states that the loading affects the soil till 1.5*D*. The used skirt lengths (L_S) were 0.5D, 1.0D, and 1.5D based on experimental and theoretical researches [18, 23-25]. It was found that the ratio of the skirt depth to the footing width should be between 0.5 and 2.0. The width of the soil reinforcement (b) was 5*D*, according to [26, 27]. The distance between the layers of the horizontal reinforcement (h) varied at intervals of 0.2*D*, 0.4 *D*, and 0.6 *D*, with a constant first layer distance ($u = 0.25D$) based on the findings of [27, 29-31].

F. Test Procedure

A hydraulic jack monitored using a load cell supported by a reaction beam applied the load of the footing model. The load was applied every 2 min until the settlement became stable, as per the plate load test principle. The settlement was measured using two LVDTs placed at equal distances originating from the center of the footing. The average settlement was considered for the calculation. Geogrid layers were prepared at desired depths before the load application for reinforced sand bed tests. The tank was emptied and refilled after every test to keep similar conditions for each test. The tests were conducted by varying parameters, like the length, diameter of the loose skirts, reinforcing layers spacing, and the magnitude and direction of applied load. Each test was performed twice and the average of the recorded readings were used in the analysis to ensure the accuracy and consistency.

III. RESULTS AND DISCUSSION

Sixty-four tests were performed to examine the relationships load-settlement for surface footing, footing with reinforced soil, loosely skirted footings, and unimproved footings. This includes four tests for circular footings without any improvement, forty-eight for circular footings with skirts, and twelve tests for circular footings with reinforced soil. Two nondimensional parameters, the bearing capacity Improvement Factor (IF) and the Settlement Reduction Factor (SRF) were calculated to quantify the bearing capacity increase resulting from the loosely skirted footing and reinforced soil. IF can be calculated using:

$$\mathrm{IF} = \frac{q_t}{q_{ut}} \tag{1}$$

where q_t and q_{ut} represent the bearing capacity for the treated and untreated soils, respectively [32-34]. Load-settlement curves were utilized to evaluate the load-bearing capacity at a settlement equivalent to 10% of the foundation width [35]. The SRF can be computed using:

$$\mathrm{SRF} = \frac{s_{ut} - s_t}{s_t} \tag{2}$$

where S_{ut} is the settlement of the untreated sandy soil at the footing failure load, and S_t is the settlement of the treated soil at the same load.

A. *The Effect of Loosely Skirted Footing*

The load-settlement behavior of loosely skirted footings under various loading eccentricities was investigated using forty-eight tests, as illustrated in the Figures 4–19. Table I presents the IF and SRF for different skirt diameters and lengths. The influence of the length and diameter of the cylindrical skirted foundation was studied and analyzed using the values of IF and SRF for the sandy soil. The findings demonstrate the impact of applying concentric and eccentric loads on a circular footing, both with and without a skirt. The results highlight how increasing the skirt length and diameter influences the footing's performance.

a) Effect of Skirt Length

First, the effect of using a cylindrical loosely skirted foundation with a diameter equal to the diameter of the circular footing (D_S = 1.0D) and different lengths (L_S = 0.5D, 1.0D, 1.5D) under various loading eccentricities was studied, as depicted in Figures 4-7. The failure load was 21 kg at an ultimate settlement of 10% of the footing diameter, for a circular footing without a skirt under vertical load, as portrayed in Figure 4; however, this value increases to 36 kg, 39.9 kg, and 44 kg when using loosely skirted cylinder lengths 0.5D, 1.0D, and 1.5D, respectively.

The results indicate that an increase in the length of the skirt increases the load-bearing capacity. The IF value increased as the skirt length increased, reaching a maximum (2.095) when the skirt length was 1.5D. The eccentric loads affect the bearing capacity of the circular footing, as it has been indicated that the bearing capacity of a circular footing with and without skirts is considerably reduced with an increase in the eccentricity ratio (e/D). Figures 4-7 demonstrate that the application of skirts significantly decreases the settlement. The SRF increased with the skirt length, reaching a peak of 60% when the skirt length was 1.5D for loosely skirted footings under concentric loading and eccentric loading at e/D = 0.08 and e/D = 0.16.

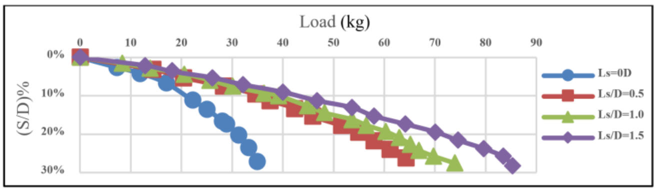

Fig. 4. Load–settlement behavior for loosely skirted footing with D_S = 1.0D at e = 0.

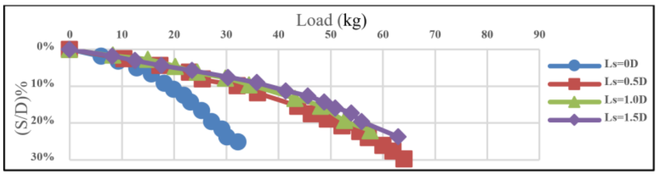

Fig. 5. Load–settlement behavior for loosely skirted footing with D_S = 1.0D at e = 0.04D.

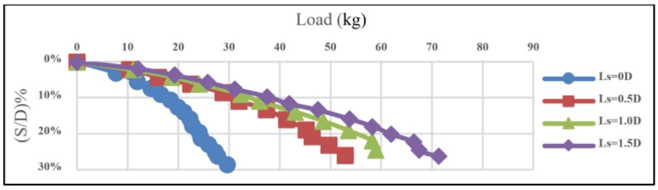

Fig. 6. Load–settlement behavior for loosely skirted footing with D_S = 1.0D at e = 0.08D.

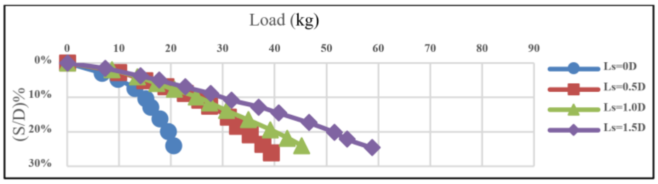

Fig. 7. Load–settlement behavior for loosely skirted footing with D_S = 1.0D at e = 0.16D.

b) Effect of Skirt Diameter

The effect of the cylindrical skirt foundation with various diameters (D_S = 1.1D, 1.2 D, and 1.4 D) and different lengths (L_S = 0.5D, 1.0D, and 1.5D) under varying eccentricities is illustrated in figures 8-19. The failure load for a circular footing without a skirt under vertical load was 21 kg. This value increased to 49.5 kg, 52kg, and 57 kg when D_S was 1.1D, 1.2D, and 1.4D, respectively, with L_S 1.5D. The results suggest that any increase in D_S improves the load-bearing capacity. The IF increased with the skirt diameter, reaching a maximum value of 2.714 at D_S = 1.4D. Figures 8-19 exhibit that using skirts significantly reduces the settlement. It was noted that the SRF steadily decreased as the D_S increased; the SRF ranged from 50% to 70% under various loading eccentricities.

The test results suggest that increasing the diameter and length of the skirt in a loosely skirted design enhances the performance of a circular foundation by improving its load-bearing capacity and reducing the settlement. The reason for this behavior is that resistance loads placed on the circular footing increase with the volume of the soil beneath it. The skirt transfers the load deeper and decreases the lateral movement of the sand particles. These findings are consistent with the observations of [12, 18, 36-39].

The values displayed in Table I were analyzed to determine the variance in IF and SRF, as well as the percentage reduction in IF and SRF, as presented in Table II. The percentage reductions were calculated using:

$$\text{IF}_{\text{Reduction}} = \frac{\text{IF}\ at(e=0D) - \text{IF}\ at(e=0.16D)}{\text{IF}\ at(e=0D)} \times 100 \qquad (3)$$

$$\text{SRF}_{\text{Reduction}} = \frac{\text{SRF}\ at(e=0D) - \text{SRF}\ at(e=0.16D)}{\text{SRF}\ at(e=0D)} \times 100 \qquad (4)$$

TABLE I. IF AND SRF FOR LOOSELY SKIRTED FOOTINGS AND SOIL REINFORCEMENT UNDER CONCENTRIC AND ECCENTRIC LOADING

D		**Loosely skirted footing**							
D_S	L_S	**IF**				**SRF**			
		***e* = 0**	***e* = 0.04*D***	***e* =0.08*D***	***e* =0.16*D***	***e* = 0**	***e* = 0.04*D***	***e* =0.08*D***	***e* =0.16*D***
1.0*D*	0.5*D*	1.714	1.684	1.667	1.600	0.50	0.49	0.48	0.47
	1.0*D*	1.9	1.894	1.889	1.733	0.56	0.54	0.53	0.51
	1.5*D*	2.095	2.053	2.055	2.000	0.60	0.58	0.60	0.60
1.1*D*	0.5*D*	1.809	1.737	1.722	1.700	0.55	0.51	0.50	0.50
	1.0*D*	2.071	2.026	2.000	1.800	0.61	0.53	0.53	0.55
	1.5*D*	2.357	2.315	2.277	1.933	0.65	0.61	0.60	0.57
1.2*D*	0.5*D*	1.905	1.868	1.777	1.733	0.59	0.58	0.57	0.58
	1.0*D*	2.286	2.079	2.055	1.866	0.60	0.59	0.59	0.60
	1.5*D*	2.476	2.421	2.389	2.100	0.68	0.67	0.64	0.63
1.4*D*	0.5*D*	2.190	1.947	1.833	1.667	0.68	0.65	0.63	0.55
	1.0*D*	2.524	2.263	2.222	1.967	0.69	0.60	0.59	0.58
	1.5*D*	2.714	2.526	2.500	2.300	0.70	0.68	0.67	0.66
h		**Soil reinforcement**							
0.2*D*		3.238	3.158	2.805	2.333	0.76	0.70	0.68	0.65
0.4*D*		3.571	3.526	3.416	2.933	0.79	0.78	0.76	0.75
0.6*D*		2.952	2.789	2.611	2.133	0.65	0.60	0.59	0.58

TABLE II. ANALYSIS OF IF AND SRF FOR LOOSELY SKIRTED FOOTINGS AND SOIL REINFORCEMENT UNDER CONCENTRIC AND ECCENTRIC LOADING

D_S	L_S	**Loosely skirted footing**			
		Variance in IF	**IF$_{\text{Reduction}}$ from *e* = 0 to *e* = 0.16*D***	**Variance in SRF**	**SRF$_{\text{Reduction}}$ from *e* = 0 to *e* = 0.16*D***
1.0*D*	0.5*D*	0.0023	6.7%	0.0002	6.00%
	1.0*D*	0.0065	8.8%	0.0004	8.90%
	1.5*D*	0.0015	4.5%	0.0001	0.0%
1.1*D*	0.5*D*	0.0022	6.0%	0.0006	9.10%
	1.0*D*	0.0144	13.1%	0.0014	9.8%
	1.5*D*	0.0378	18.0%	0.0011	12.3%
1.2*D*	0.5*D*	0.0063	9.0%	0.0001	1.70%
	1.0*D*	0.0295	18.4%	0.0000	0.0%
	1.5*D*	0.0283	15.2%	0.0006	7.40%
1.4*D*	0.5*D*	0.0482	23.9%	0.0031	19.1%
	1.0*D*	0.0520	22.1%	0.0026	15.9%
	1.5*D*	0.0287	15.3%	0.0003	5.70%
h		**Soil reinforcement**			
0.2*D*		0.1701	28%	0.0022	14.5%
0.4*D*		0.0858	18%	0.0003	5.10%
0.6*D*		0.1253	28%	0.0010	10.8%

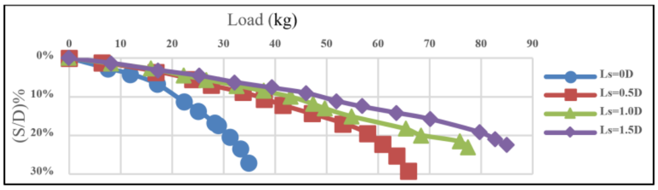

Fig. 8. Load–settlement behavior for loosely skirted footing with D_S = 1.1*D* at *e* = 0.

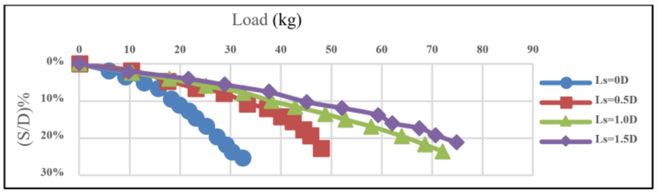

Fig. 9. Load–settlement behavior for loosely skirted footing with D_S = 1.1*D* at *e* = 0.04*D*.

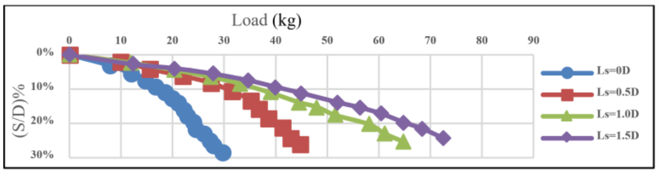

Fig. 10. Load–settlement behavior for loosely skirted footing with $D_S = 1.1D$ at $e = 0.08D$.

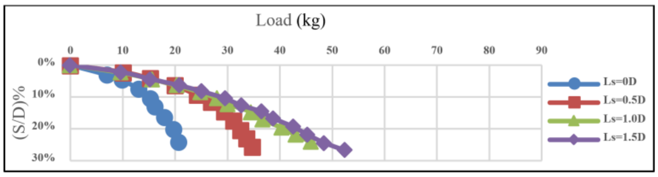

Fig. 11. Load–settlement behavior for loosely skirted footing with $D_S = 1.1D$ at $e = 0.16D$.

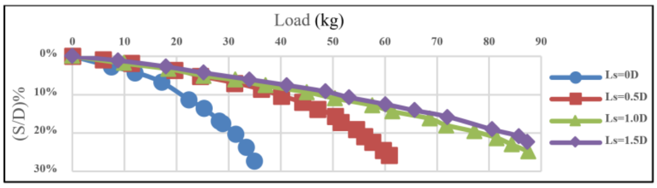

Fig. 12. Load–settlement behavior for loosely skirted footing with $D_S = 1.2D$ at $e = 0$.

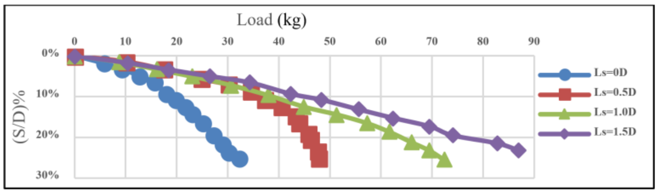

Fig. 13. Load–settlement behavior for loosely skirted footing with $D_S = 1.2D$ at $e = 0.04D$.

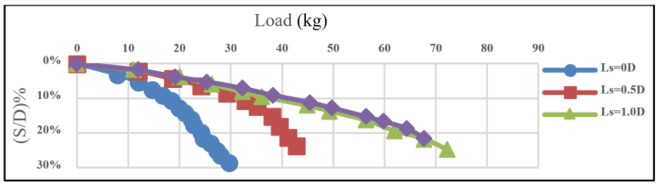

Fig. 14. Load–settlement behavior for loosely skirted footing with $D_S = 1.2D$ at $e = 0.08D$.

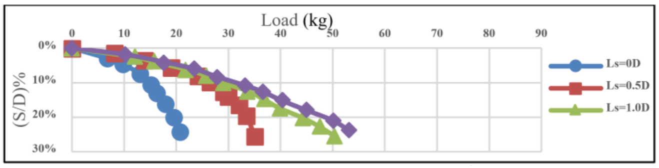

Fig. 15. Load–settlement behavior for loosely skirted footing with $D_S = 1.2D$ at $e = 0.16D$.

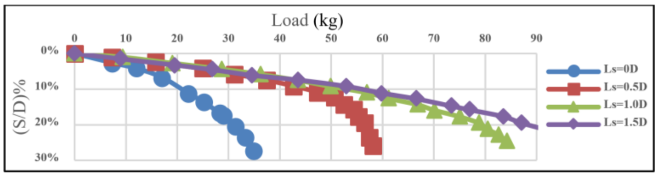

Fig. 16. Load–settlement behavior for loosely skirted footing with $D_S = 1.4D$ at $e = 0$.

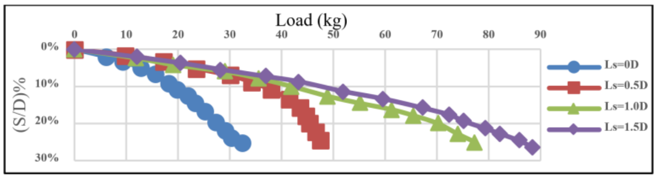

Fig. 17. Load–settlement behavior for loosely skirted footing with $D_S = 1.4D$ at $e = 0.04D$.

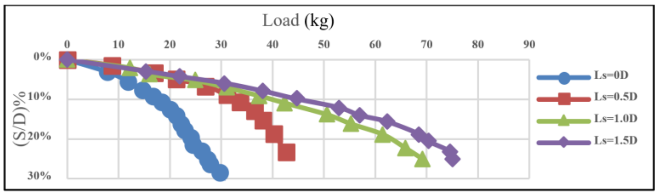

Fig. 18. Load–settlement behavior for loosely skirted footing with $D_S = 1.4D$ at $e = 0.08D$.

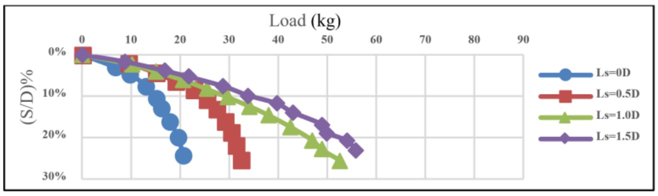

Fig. 19. Load–settlement behavior for loosely skirted footing with $D_S = 1.4D$ at $e = 0.16D$.

The results in Table II show a good consistency, with a low variance across most measurements, indicating accurate calibration and reliable experiment repeatability. The highest maximum reduction in IF (23.9%) and SRF (19.1%) was noted at $D_S = 1.4D$ and $L_S = 0.5D$. In contrast, the lowest reduction was recorded in IF (4.5%) and SRF (0.0% reduction) at $D_S = 1.0D$ and $L_S = 1.5D$. It is worth noting that smaller skirts offer minimal improvements but show a reduced sensitivity to the eccentric loading effects.

Three types of failure mechanisms can be seen in footings: punching shear failure, local shear failure, and general shear failure. For the ultimate load, the ratio of the foundation diameter to depth and the soil's compressibility characteristics determines the type of failure in the soil [40]. The load-settlement behavior observed in Figures 4-19 suggests a potential punching shear failure in the sand, particularly in the foundation without the skirt. However, this failure mode may not occur in skirted foundations. Skirted foundations, which feature skirts that constrain the soil beneath the footing, create intricate and distinct failure mechanisms compared to the ordinary foundations. Due to this configuration, skirted foundations can function as a single, integrated system, enhancing their stability and load-bearing capacity. Types of skirted foundation failure include the surface failure, plugged deep failure, and coring deep failure, influenced by factors, such as the skirt depth and soil properties. The skirts shift the shallow foundation collapse mechanism into deeper and stronger soil layers. Increasing the skirt depth pushes the failure surface further into the soil, potentially interacting with more stable soil layers and improving the overall stability. Extending the failure surfaces into the ground above the foundation offers additional resistance [41]. Similar failure patterns have been observed. Authors in [42, 43] identified a plugged (block) failure mode, indicating that the soil inside the skirt moves as a single unit with the foundation.

B. *Effect of Geogrid Spacing of Reinforced Soil*

In this study, the width of the reinforcement was kept constant at $b = 5D$. The depth of the first reinforcement layer (u) was $0.25D$, and the number of reinforcement layers was N = 3. The load settlement behavior of the circular footing on the strengthened soil under various loading eccentricities was investigated using twelve model footing tests, as illustrated in Figures 20-23. The failure load was 21 kg (at an ultimate settlement of 10% of the footing diameter) for a circular footing without reinforcement at concentric load ($e = 0$); however, this value increases to 68 kg, 75kg, and 62 kg for the distance between the reinforcement layer (h) equal to $0.2D$, $0.4D$, and $0.6D$, respectively.

The study further examined the bearing capacity in relation to the horizontal spacing ratio (h) between successive reinforcement layers. The bearing capacity increased by 54% for $h = 0.4$D at concentric load ($e = 0$) compared to the unreinforced soil, as seen in Figure 20. The optimal spacing between the reinforcement layers was determined to be 0.4 times the footing diameter, which yields the highest IF (3.571, for $e = 0$) under all eccentricities.

When the ratio e/D is lowered, the influence of the soil reinforcement on the load-bearing capacity becomes more pronounced. Additionally, as e/D increases, the IF significantly decreases. The greatest decrease in IF occurred at $h = 0.2D$ and $h = 0.6D$, with a 28% reduction, while the smallest SFR reduction occurred at $h = 0.2D$ (14.5%), as shown in Table II. Under eccentricity, the reinforced soil method exhibits a relatively stable performance. The effect of the eccentricity on the reinforced soil demonstrates that the SRF decreases less sharply than the IF, indicating that IF is more sensitive to the changes in eccentricity than SRF.

Figures 20-23 show that the failure mode changes with varying reinforcement. Without reinforcement, sharp settlement occurs even at low loads, suggesting punching shear failure in unreinforced sand. In case of reinforced soil, the failure is gradual without abrupt settlement. This pattern indicates a general shear failure mode, with geogrid reinforcement improving the load distribution. There are three potential failure mechanisms of reinforced soil failure, based on the tensile strength of the reinforcement and layout. The shear failure occurs when the spacing (u) exceeds $2B/3$. The pull-out failure takes place when spacing (u) is less than $2B/3$ with three or fewer layers (N), or when the reinforcement length is insufficient. The tension failure occurs when the ties break, that is, when the spacing (u) is less than $2B/3$, particularly with four or more layers and extensive spans of reinforcement [26].

The optimal reinforcement layer spacing (h) was $0.4D$ in this study, which is consistent with the findings in [5] and within the range found in [44-45, 47]. The results from this study contradict those of other studies, with an h/D equal to 0.4 and slightly higher than 0.3, as indicated in [27, 30] and higher than 0.25 suggested by [28, 31]. The discrepancy in the results could be due to the variations in the foundation, geometric measurements, and material characteristics applied in this work.

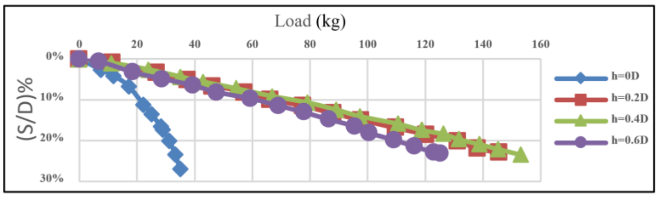

Fig. 20. Load–settlement behavior for reinforced soil at $e = 0$.

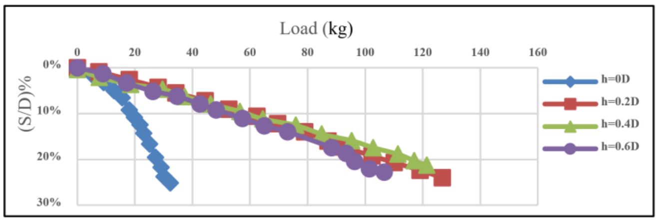

Fig. 21. Load–settlement behavior for reinforced soil at $e = 0.04D$.

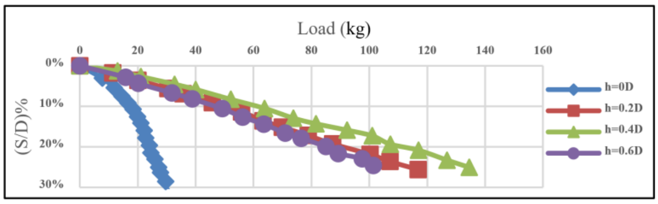

Fig. 22. Load–settlement behavior for reinforced soil at $e = 0.08D$.

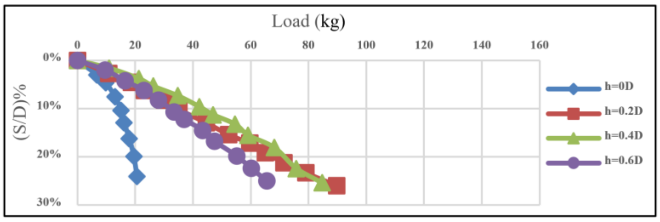

Fig. 23. Load–settlement behavior for reinforced soil at $e = 0.16D$.

C. *Comparison Between Loosely Skirted Foundations and Reinforced Soil*

The comparison between the reinforced soil and loosely skirted foundations considers the improvement rate, cost evaluation based on the quantity of geogrid required, feasibility of implementation methods, and excavation depth requirements. Both methods enhance the soil stability and bearing capacity, but their approaches and specific applications differ.

Based on the results of the present study, the IF for the reinforced soil (3.571) was higher compared to the IF for the skirted foundation (2.714), which can be attributed to differences in the soil behavior, implementation procedures, and materials used. The reinforced soil method is more sensitive to the eccentricity than the loosely skirted foundation method, as seen in Figure 24, also confirmed by a 28% decrease in the IF in reinforced soil. This behavior is due to the skirts confining of soil and mobilizing passive resistance laterally, which counteracts the eccentric moments. This system behaves like a "deep foundation," making it less sensitive to the load eccentricity. The reinforced soil method improves the bearing capacity by tensile resistance. The load redistribution depends on the reinforcement layout, which is less effective under asymmetric loading.

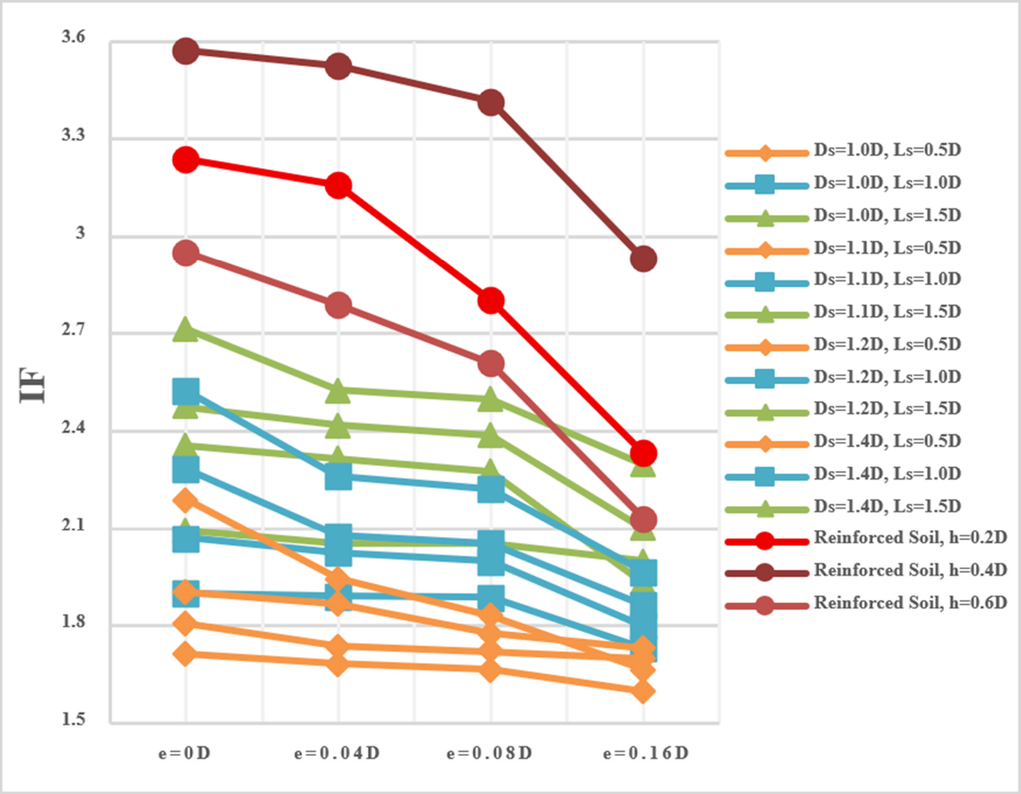

Fig. 24. IF values for skirted foundation and reinforced soil at varying loading eccentricities.

The quantity of the geogrid material required for the soil reinforcement method is significantly greater than that needed for the skirt foundation method, so the reinforcement cost is higher compared to the loosely skirted foundation. Geogrids are environmentally friendly, requiring minimizing excavation and material, thereby presenting a viable alternative to conventional methods. Geogrids are more resilient, cost-effective and sustainable compared to the reinforced soil [7, 48]. The skirted foundations can replace pile driving in challenging soils, lowering the project costs and installation time while providing higher strength [10, 46]. The skirted foundations result in cost savings by minimizing the material usage and the installation time [8].

In the current study, the soil reinforcement method required excavation depths of 6.5 cm, 10.5 cm, and 14.5 cm for reinforcement layer spacings (*h*) of 0.2D, 0.4D, and 0.6D, respectively. As for the skirted foundation, the excavation depths were 5 cm, 10 cm, and 15 cm for skirt lengths of 0.5*D*, 1.0*D*, and 1.5*D*, respectively. With slight variations in depth, the reinforcement method achieved the highest IF values of 3.238, 3.571, and 2.952 for the three depths tested, compared to a maximum IF of 2.714 for the skirted foundation method.

The reinforced soil method is ideal for roads, embankments, and light structures with low budget. Skirted foundations are optimal for bridges, towers, and heavy infrastructure where deep soil stabilization is critical. The choice between the skirted foundations and reinforced soil depends on the project requirements, including soil type, loading conditions, and economic limits, even though both techniques aim to improve the soil stability, increase the bearing capacity, and reduce the settlement. Because each method has distinct advantages and limitations, it can be used in various infrastructure development and construction scenarios.

IV. CONCLUSION

This study presents a comparative investigation between two improvement methods, the soil reinforcement and the use of a loosely skirted foundation, to enhance the bearing capacity and reduce the settlement of circular footings resting on loose sandy soil subjected to eccentric loading conditions. Previous studies have primarily concentrated on either reinforcement techniques or skirted foundations individually, in contrast to the current work. According to the successful laboratory tests conducted for this study, the following conclusions can be drawn:

- A loosely skirted footing improves the load-settlement performance by containing soil and preventing the lateral movement of the sand particles. Increasing the diameter and length of a loosely skirted foundation enhances the bearing capacity of a circular footing. This increases the foundation's Improvement Factor (IF) from 1.6 to 2.714 across all tests.
- The ideal load intensity value was found at $D_S = 1.4D$ and $L_S = 1.5D$ for both concentric and eccentric loads.
- Geogrid-reinforced sand beds enhance the load-settlement behavior for circular footing. The additional adhesive shear resistance activated between the reinforcements increases the reinforced soil's load-bearing capacity. In all tests, the reinforced soil's IF varies from 2.133 to 3.571.
- The ideal spacing (h) between the reinforcing layers was 0.4 times the footing's diameter.
- All experiments demonstrated a significant reduction in the Settlement Reduction Factor (SRF), which ranged from 47% to 70%, when the loosely skirted system was installed beneath the footing. It varied from 58% to 79% with the reinforced soil.
- Smaller skirts provide less improvement but are less sensitive to the eccentric loading effects.
- Unimproved footings lead to punching shear failure in sand. This issue stems from the properties of loose sandy soil, characterized by a Relative Density (RD) of less than 35%.
- In terms of the bearing capacity enhancement, reinforcing the sandy soil with geogrid outperformed the loosely skirted foundation beneath a circular footing. The reinforcement resulted in the most significant increase in the bearing capacity, at 54%. In comparison, the loosely skirted foundation exhibited its peak percentage improvement at 36%. Nonetheless, the method of reinforced soil demonstrated greater sensitivity to eccentricity.

The results from this study align with those of previous research that highlights the performance of geogrid reinforcement, but they surpass it by going further by measuring its significance compared to the loosely skirted foundations under eccentricity loading conditions. Also, this research introduces a novel comparative framework, which represents a qualitative addition in this field. Future studies could investigate experimental tests and numerical models for a different type of soil under varying load conditions and expand on these findings.

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