Loosely Skirted Circular Foundation under Different Loading Conditions: Performance, Mechanism, and Limitations

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ABSTRACT

The term loosely skirted foundation is used to describe the geogrid skirts that are positioned beneath the footing. This technique enhances soil performance and reduces costs when compared to rigid skirted footings. The present study examines the performance of loosely skirted circular footings on poorly graded sand with and without horizontal reinforcement layers inside the skirt rooms. The footings are subjected to loading eccentricities, (*e*) of 0, 0.08 *D* and 0.16 *D*, where *D* is the diameter of the footing. The depth of the skirt (*L*) was adjusted to values of 0.5 *D*, 1 *D*, 1.5 *D*, and 2 *D*. The number of geogrid layers (*N*) was varied based on the skirt depth. The spacing between horizontal reinforcements (*Y*) was evaluated at 0.25 *D*, 0.5 *D*, 0.75 *D*, and 1 *D*. The loosely skirted circular footing without lateral reinforcement within the skirt demonstrated optimal performance at *L*/*D* = 1.5, enhancing bearing capacity by 111.64%, 91.5%, and 76.3% and reducing settlement by 57.1%, 52.7%, and 51%, respectively, for *e*/*D* = 0, 0.08, and 0.16. Concerning the loosely skirted circular footing with lateral reinforcement within the skirt, the optimal performance was observed at *L*/*D* = 2 and the minimum spacing reinforcement was evidenced at *Y* = 0.25 *D*, which enhanced the bearing capacity by 235.6% and 224%, respectively. The results revealed that the best performance was obtained for the loosely skirted circular footing without lateral reinforcement within the skirt, with enhancements of 111.64%, 91.5%, and 76.3% in the bearing capacity and reductions of 57.1%, 52.7%, and 51% in the settlement at *e*/*D* = 0, 0.08, and 0.16, respectively. Conversely, the best performance for the loosely skirted circular footing with lateral reinforcement inside the skirt was observed at *L*/*D* = 2 and the minimum spacing reinforcement *Y* = 0.25 *D*, with enhancements of 235.6%, 224%, and 194% in the bearing capacity and reductions of 72.2%, 67.2%, and 68% was noted at *e*/*D*= 0, 0.08, and 0.16, respectively.

Keywords-loosely skirted circular footing; geogrid; reinforcement; bearing capacity; settlement reduction; improvement

I. INTRODUCTION

Geotechnical engineers around the globe are pursuing novel techniques to augment the bearing capacity and curtail settlement of footings in soil. Even though a number of techniques for soil stabilization are available, they can frequently be expensive and constrained by the specific conditions of the site in question. The application of these techniques to the existing foundations can present certain challenges in specific circumstances [1-4]. Structural skirts demonstrate promise as a viable method for enhancing the load-bearing capacity and minimizing the settlement of footings on the soil. Structural skirts have been employed for an extended time period to augment the depth of foundations in marine and other settings, where water scour represents a considerable challenge. This method of improving the bearing capacity does not entail soil excavation and is not constrained by a high-water table [5-8]. For over four decades, geogrid-reinforced soil has been used in numerous geotechnical engineering applications to evaluate the bearing capacity and mitigate the footing settlement owing to its cost-effectiveness and straightforward implementation [9-12]. Skirts may be constructed from either rigid or loose materials. The concept of a loosely skirted foundation entails the placement of geogrid skirts beneath the footing with the objective of enhancing soil performance. Numerical and physical modeling methods have been employed by several researchers to demonstrate the beneficial effects of skirted foundations in multiple soil types.

A. Skirted Foundations under Static Loading

A number of authors have carried out extensive studies into the response of skirted foundations under static loading, employing both numerical and physical modeling techniques. Authors in [13-21] determined that the skirted foundation exhibits enhanced efficacy in comparison to the conventional foundation. Authors in [22] demonstrated that a skirt length-to-footing width ratio of 2 yields the optimal results in terms of the enhanced bearing capacity and reduced settlement. As indicated by authors in [23], the use of a skirted foundation serves to enhance the resistance against uplift and compression loads. Authors in [24-25] found that the ultimate bearing capacity of square, H-shaped, T-shaped, plus, and circular skirted foundations with equivalent contact areas on the ground is comparable in both horizontal and vertical directions. The behavior of skirted strip footing in proximity to a sand slope was investigated through the implementation of mathematical and experimental tests, as the ones conducted by [26]. It has been demonstrated that the bearing capacity is influenced by a number of factors, including the depth of the skirt, the distance between the footing and the crest of the slope, and the slope inclination. Authors in [27,28] showed that the capacity to resist lateral stresses increases with the length of the skirt. Authors in [29] determined that the ultimate bearing capacity can be influenced by a number of factors, including the size of the footing, the length of the skirts, and the relative density of the sand. Furthermore, the rough-skirted foundation is more efficacious in reducing the settlement and increasing the bearing capacity in comparison to the smooth-skirted foundation. In a separate study [30], it was reported that the bearing capacity of a skirted foundation was 262% higher than that of an unskirted foundation. Authors in [31, 32] studied the behavior of inclined skirted foundations. The performance of loosely skirted square footings was evaluated on sandy soil reinforced with geogrid layers [33]. The study examined various parameters, including skirting depth, number and spacing of geogrid layers, and vertical loads with different eccentricities. The addition of horizontal geogrid reinforcement resulted in a reduction in the settlement and an improvement in the bearing capacity.

B. Skirted Foundations Under Dynamic Loading

The analysis of skirted foundations under dynamic loading demands the application of numerical methods, given the intricate mechanical and geometrical nature of the majority of problems encountered. Authors in [34-37] have found that the use of skirted foundations may successfully mitigate the effects of seismic activity by restricting the soil within a confined space. It is noteworthy that a considerable number of studies have concentrated on the enhancement of soil properties through the use of diverse materials attached monolithically to the foundation. The present study, however, examines the impact of geo-grid skirts placed beneath the footing in isolation. The objective of this study is to provide an understanding of the behavior of a loosely skirted circular foundation with different reinforcement configurations within the skirt, when subjected to vertical loads that are both concentric and eccentric, on poorly graded sand.

II. EXPERIMENTAL WORK

A. Physical Model

The foundation, which is constructed with a loosely skirted base, has been subjected to rigorous examination in the context of experimental research. A physical model with a loosely skirted configuration and a geogrid horizontal reinforcement layer were used in the experimental setup, as shown in Figure 1. The experimental setup, as originally manufactured, is presented in Figure 2. The experimental setup comprises a glass container box with dimensions of 0.6 m × 0.6 m × 0.6 m (length × breadth × height). In order to address the issue of boundary effects, this study has used a previous methodology, [38]. The glass has a thickness of 10 mm and is reinforced with 3 mm-thick iron plates on the exterior to prevent any lateral deformation. The glass container allows for a more comprehensive observation of soil behavior. The loading system comprises a steel arch frame equipped with a mechanical jack of 2 tons, capable of applying a concentrated, eccentric, and inclined load. The jack is connected to a load cell (SS300-1T) in order to accurately measure the applied load on the footing. The cell was constructed using stainless steel and has a maximum capacity of 1 ton. The load was applied in incremental steps in accordance with the methodology outlined in the plate load test standard (ASTM D1194). The load increments were maintained at a constant level until the settlement reached a stable point. The settlement was measured on either side of the foundation using two Linear Variable Displacement Transducers (LVDTs) with a capacity of 100 mm. The data logger was successfully connected to the load cell and the LVDTs. A footing of circular cross-section with a diameter of 10 cm was employed.

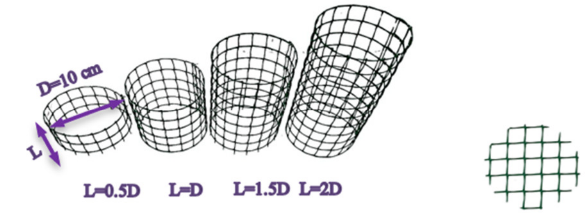

Fig. 1. Loosely skirts and horizontal reinforcement layer made from geogrid material.

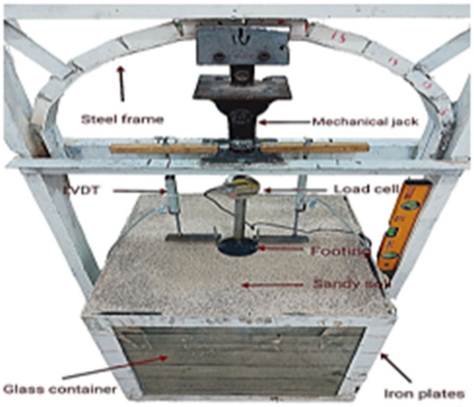

Fig. 2. Experimental setup.

B. Materials

a) Soil

The soil utilized in this study was obtained from the Al-Basrah government in southern Iraq, and it was then washed and dried. The soil was classified according to the Unified Soil Classification System (USCS) and ASTM D-2487 [39,] as poorly graded sand (SP) with a specific gravity of 2.66, based on ASTM D-854 [40]. The maximum and minimum dry unit weights of 17.73 kN/m^3 and 16.08 kN/m^3, respectively, were obtained according to ASTM D-4253 and ASTM D-4254 [41, 42]. The angle of internal friction (∅) was measured by performing a direct shear test on the basis of ASTM D-3080 [43] on sand prepared at a relative density of 30%. The angle of internal friction was found to be 39.2°.

b) Geogrid

Geo-grids are composed of polymer materials used as skirting and horizontal reinforcements. The properties of geo-grids are portrayed in Table I.

TABLE I. REINFORCEMENT PROPERTIES (PRODUCT SPECIFICATION)

Property	Data	Property	Data
Mesh type	Square	Color	Green
Tensile strength	2.25 MPa	Packing	Rolls
Roll width	1.2 m	Roll length	30 m
Rib thickness	1.5 mm	Rib width	1.6 mm
Junction thickness	1.8 mm	Elastic modulus	0.25 GPa

C. Testing Program

An intensive testing program was performed to investigate the influence of diverse skirt types on the footing behavior. The experiments were conducted in three distinct series. In Series A, only the footing was employed. In Series B, only the skirts without lateral reinforcement were tested. In Series C, a footing with skirt and horizontal reinforcements placed inside the skirt underwent testing. The footing was subjected to both vertical concentric (e=0 *D*) and eccentric loading (*e*/*D*=0.08 and 0.16), where *D* is the diameter of the footing. The distance between the horizontal reinforcement layers (*Y*) was altered at intervals of 0.25 *D*, 0.5 *D*, 0.75 *D*, and 1.0 *D*. The length of the skirt (*L*) was maintained at 2 *D*, 1.5 *D*, 1 *D*, and 0.5 *D*, respectively.

D. First Layer Reinforcement

A substantial amount of research has been performed by numerous scholars examining the depth impact on the initial reinforcement layer situated beneath a circular footing. In the present study, the initial reinforcement layer was maintained at a depth of 0.1 *D* below the base of the footing for all tests, in accordance with the findings of [44-46].

E. Preparation Of Sand Bed

In this study, the sand-soil raining method was followed to fill the box with a uniform sand layer at the desired density. The density of the sand in the raining technique is dependent upon the flow rate of the sand and the height of the pour [47, 48]. The optimal drop height for each sand density was determined and is illustrated in Figure 3. A discernible correlation exists between the height of the pour and the resulting increase in sand density. The dropping height can be calculated for any specified relative density. The requisite dropping height to attain the desired density of 30% was 22.5 cm in all tests. The sand bed was formed with six layers, each measuring 10 cm in height, and levelled by a sharp plate to ensure uniformity and prevent disturbance.

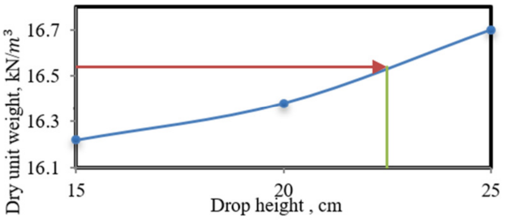

Fig. 3. Relationship between drop height and dry unit weight.

F. Placement of Skirt and Horizontal Reinforcement.

The skirts were positioned with precision on the leveled sand bed, taking into account the desired depth of each skirt. Once the skirt was carefully positioned, horizontal geogrid reinforcements were placed inside the skirts, ensuring that the required spacing between horizontal reinforcement layers was met. Once the skirt and reinforcement layers were appropriately positioned, the remaining portion of the sand layer was filled in accordance with the standardized sand raining procedure.

G. Test Procedure

The circular foundation was situated at the center of the level surface of the prepared sandy soil with great precision. Subsequently, the load was applied via a hand-operated hydraulic jack, which was supported against a reaction frame until failure occurred. The skirted foundation was installed with precision during the pouring process, certifying that it was placed at the appropriate depth. Subsequently, the container was filled, and the foundation was meticulously positioned on top of the skirt. Special attention was given to ensure that the placement of the foundation and skirts does not affect the relative density, as this is a crucial factor regarding the overall stability of the structure. The settlement of the footing was determined by calculating the mean value of the two LVDTS measurements taken on each corner of the footing model. Furthermore, the applied load was quantified using a load cell.

III. RESULTS AND DISCUSSION

A total of 51 model footing tests were performed to examine the stress-settlement relationships for surface footings lacking skirts, footings only having skirts but no horizontal reinforcement layers, and footings with skirts and horizontal reinforcement layers. The enhancement in the bearing capacity resulting from the incorporation of skirts and reinforcement layers can be quantified through the use of two non-dimensional terms: the Bearing Capacity Ratio (BCR) and the Settlement Reduction Factor (SRF). The term "bearing capacity ratio" is frequently used to express and compare the test data of reinforced and unreinforced soils, as:

$$BCR = \frac{q_R}{q_{UR}} \tag{1}$$

where q_R and q_{UR} represent the bearing capacity for reinforced and unreinforced soils, respectively. In addition, the BCR has been calculated by authors in [49, 50] using the same formula. The bearing capacity for the footing-soil system was obtained from stresses-settlement curves at a settlement equal to 10% of the foundation width [51]. The SRF can be calculated in accordance with [49, 52]:

$$SRF = \frac{S_{UR} - S_R}{S_{UR}} \quad (2)$$

where S_{UR} is the settlement of unreinforced sandy soil at failure footing stress and S_R is the settlement of reinforced soil at the same footing stress.

A. *Effect of Skirt without Reinforcements*

Twelve model footing tests were conducted to examine the stress-settlement behavior of loosely skirted circular foundations lacking lateral reinforcement under diverse loading eccentricities. The bearing capacity ratios and settlement reduction factors for varying skirt depths are presented in Table II. An increase in the *L*/*D* ratio results in an enhancement of the bearing capacity ratio. The bearing capacity ratios are 1.49, 1.73, 2.12, and 1.815 for skirted foundation with *L*/*D* ratios of 0.5, 1, 1.5, and 2, respectively. The results indicate that the bearing capacity is lower when the *L*/*D* ratio 2 is compared to 1.5. This can be attributed to the increase in soil confinement within the skirts, which is significantly enhanced at *L*/*D* = 2. This results in soil dilation, reduced shear strength, and a subsequent decrease in the bearing capacity. A similar trend is observed for footings with a skirt subjected to eccentric loading. The substantial enhancement in the bearing capacity can be ascribed to the following factors. When a skirt is placed alone under the footing, the interaction between the geogrid skirt and soil leads to a (pseudo-homogenized) structure that acts as a monolithic block, thus confining the soil beneath the footing and increasing the stiffness of the sand. This also results in a modification of the failure mode, despite the tendency of sand particles to spill out laterally due to the larger aperture size of the skirt relative to the sand particle size, as concluded by [53]. Nevertheless, this does lead to a notable bearing capacity improvement for both concentric and eccentric loading. An increase in the *L*/*D* ratio corresponds to an increase in the confining pressure, which in turn results in a significant improvement in the load-carrying capacity and a notable reduction in settlement. The SRF value increases as the depth of the skirts increases, reaching a maximum value of 0.571 at *L*/*D* = 1.5 for footings with only a skirt arrangement under concentric loading.

B. *Effect of Skirt with Reinforcements*

Thirty-six model footing tests were performed to examine the stress-settlement behavior of loosely skirted foundations with unskirted and skirted lateral reinforcement under diverse loading eccentricities. Figures 4-15 depict the impact of a skirt with and without reinforcement on the footing under both concentric and eccentric loading. The symbols (Un), (SW), and (SR) refer to unskirted, skirted without reinforcement, and skirted with reinforcement foundations, respectively. The vertical spacing between the horizontal geogrid layers is a substantial factor in determining the optimal number of horizontal reinforcements. An increase in the skirt depth allows for the maximum number of horizontal reinforcements to be placed inside, enabling the transfer of superimposed loads to a deeper depth with higher confining and overburden pressure. The results demonstrate a remarkable enhancement in the bearing capacity and a reduction in settlement. It is worth mentioning that the maximum bearing capacity ratio was observed for a spacing of 0.25 *D*, irrespective of the skirt depths (*L*/*D* = 0.5, 1, 1.5, and 2.0). The bearing capacity ratios were found to be 2.07 at *L*/*D* = 0.5, 2.64 at *L*/*D* = 1, 2.98 at *L*/*D* = 1.5, and 3.36 at *L*/*D* = 2. The present findings appear to be in alignment with the conclusions of other studies [33]. Furthermore, it was determined that the most effective method to enhance the bearing capacity and minimize settlement for the skirts is the incorporation of horizontal reinforcement within the structure, specifically at (*L*/*D* = 2, *Y* = 0.25 *D*). The interlocking between the soil and geogrid can be enhanced through the strategic placement of horizontal reinforcement layers. The deployment of reinforced soil effectively prevents lateral deformation or potential tensile strain. The vertical deformation of the soil is reduced, while the lateral confinement is improved, leading to an enhanced bearing capacity of the reinforced soil [54]. Authors in [55] discovered that this mechanism was effective when using short reinforcement with a length equal to the footing width, which was also efficient for reinforcing sand in the current study. As the spacing increased to 0.5 D, 0.75 *D*, and 1.0 *D* for each skirt depth, the bearing capacity decreased in conjunction with the corresponding BCRs due to increased settlement. As showcased in Table II, the optimal SRF value for footings with skirts and lateral reinforcement is evidenced when the spacing ratio (*Y*/*D*) is at its minimum value of 0.25, for both concentric and eccentric loading. As the spacing ratio increases to 0.5, 0.75, and 1.0, the SRF value demonstrates a gradual decline. The vertical spacing of reinforcements placed within the skirts has a considerable influence on the SRF value. The BCRs reported in this study range from 1.19 to 3.36, while the SRFs range from 0.2 to 0.722. The results of this study are in accordance with those of other studies [33], which documented BCRs ranging from 1.19 to 3.03 and SRFs varying between 0.17 and 0.86.

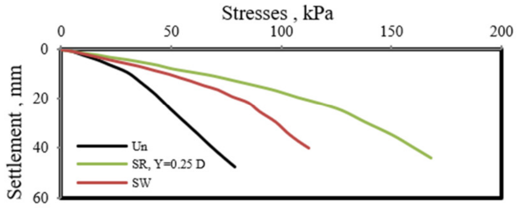

Fig. 4. Stress –settlement behavior at *L* = 0.5 *D*, *e* = 0 *D*.

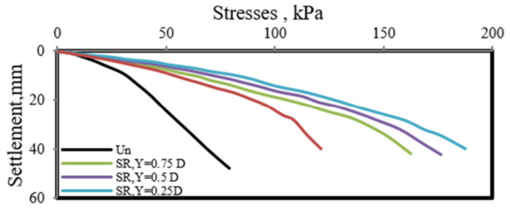

Fig. 5. Stress –settlement behavior at *L* = *D*, *e* = 0 *D*.

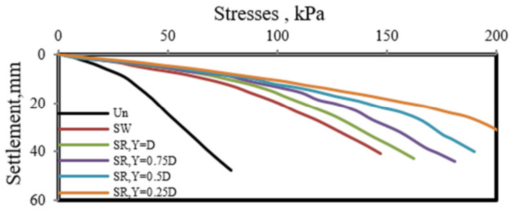

Fig. 6. Stress –settlement behavior at *L* = 1.5 *D*, *e* = 0 *D*.

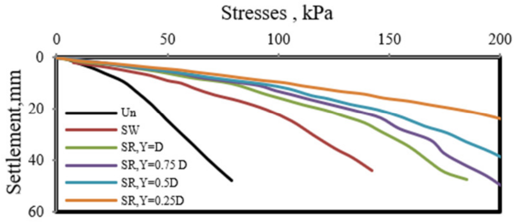

Fig. 7. Stress –settlement behavior at *L* = 2 *D*, *e* = 0 *D*.

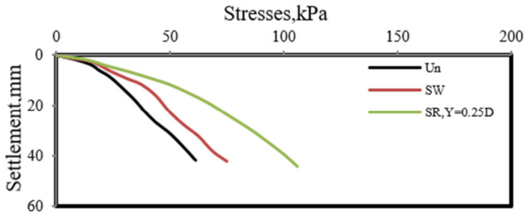

Fig. 8. Stress –settlement behavior at *L* = 0.5 *D*, *e* = 0.08 *D*.

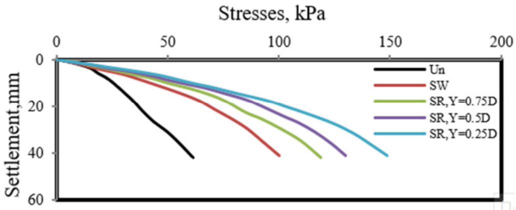

Fig. 9. Stress –settlement behavior at *L* = *D*, *e* = 0.08 *D*.

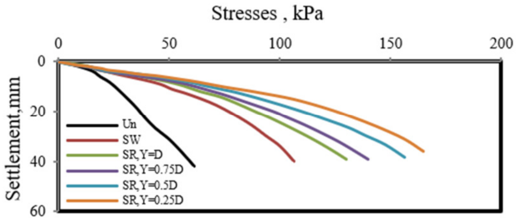

Fig. 10. Stress –settlement behavior at *L* = 1.5 *D*, *e* = 0.08 *D*.

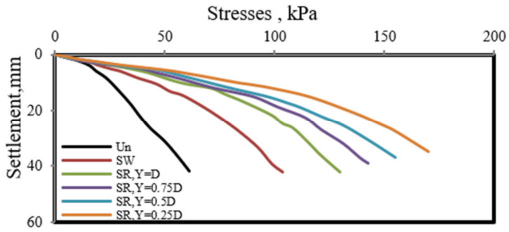

Fig. 11. Stress –settlement behavior at *L* = 2 *D*, *e* = 0.08 *D*.

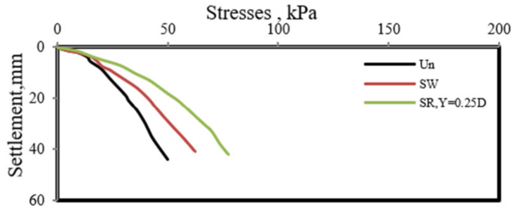

Fig. 12. Stress –settlement behavior at *L* = 0.5 *D*, *e* = 0.16 *D*.

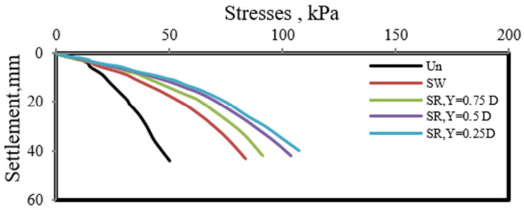

Fig. 13. Stress –settlement behavior at *L* = *D*, *e* = 0.16 *D*.

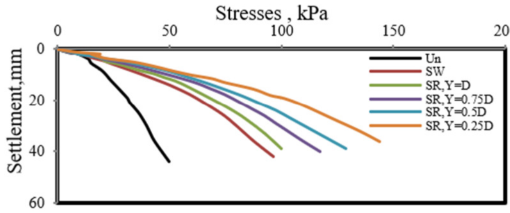

Fig. 14. Stress –settlement behavior at *L* = 1.5 *D*, *e* = 0.16 *D*.

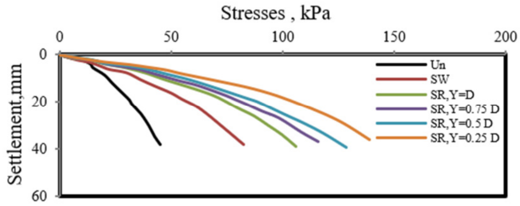

Fig. 15. Stress –settlement behavior at *L* = 2 *D*, *e* = 0.16 *D*.

TABLE II. BCRS AND SRFS FOR CONCENTRIC AND ECCENTRIC LOADING

L/D	***Y/D***	***N***	**BCR**			**SRF**		
			(*e*=0 *D*)	(*e*=0.08 *D*)	(*e*=0.16 *D*)	(*e*=0 *D*)	(*e*=0.08 *D*)	(*e*=0.16 *D*)
0.5			1.49	1.31	1.19	0.4	0.298	0.2
0.5	0.25	2	2.07	1.76	1.617	0.574	0.513	0.477
1			1.73	1.65	1.57	0.5	0.417	0.4
1	0.75	2	2.03	1.96	1.85	0.577	0.542	0.52
1	0.5	2	2.31	2.2	2.05	0.619	0.589	0.533
1	0.25	4	2.64	2.39	2.216	0.681	0.63	0.567
1.5			2.12	1.91	1.76	0.571	0.559	0.51
1.5	1	2	2.422	2.27	2.04	0.627	0.601	0.529
1.5	0.75	2	2.632	2.45	2.28	0.642	0.622	0.595
1.5	0.5	3	2.83	2.68	2.53	0.675	0.653	0.625
1.5	0.25	6	2.98	2.93	2.747	0.704	0.683	0.644
2			1.815	1.74	1.63	0.5	0.44	0.41
2	1	2	2.52	2.26	2.12	0.64	0.616	0.592
2	0.75	3	2.718	2.49	2.31	0.662	0.63	0.6
2	0.5	4	2.9	2.75	2.58	0.687	0.655	0.63
2	0.25	8	3.36	3.24	2.94	0.722	0.672	0.68

IV. CONCLUSIONS

The behavior of loosely skirted square footing resting on reinforced sand under vertical concentric and eccentric loading was evaluated through a series of laboratory model tests on different foundation configurations. In consideration of the results and the discussion presented above, the following conclusions may be drawn.

- The inclusion of geogrid skirts beneath the footing has a considerable influence on its overall behavior. They enhance the bearing capacity and mitigate settlement by confining the soil beneath the footing. The findings indicated that the loosely skirted circular footing without lateral reinforcement inside the skirt achieved the optimum bearing capacity value at L/D=1.5 for both concentric and eccentric loading. The optimal bearing capacity value for a loosely skirted circular footing with lateral reinforcement within the skirt was determined to be L/D=2 and a minimum spacing reinforcement of Y=0.25 D, for both concentric and eccentric loading, was identified.
- For a given skirt length, loose skirts with lateral reinforcement inside, even at higher spacing between the horizontal layers, have proved to be more effective than skirts without reinforcement.
- The bearing capacity of surface foundations was enhanced by the loosely skirted circular system under the footing, with a factor of improvement ranging from 1.19 to 3.36. This variability is attributed to the influence of various factors, including the skirt depth, number of horizontal layers, spacing between reinforcement layers, and eccentricity.
- The loosely skirted circular system positioned beneath the footing serves to enhance the stress-settlement behavior. The Settlement Reduction Factor (SRF) exhibited a notable decline, with values ranging from 20% to 72.2% across all tests. The extent of this reduction is contingent upon a number of factors, including the depth of the skirt, the number of horizontal layers, the spacing between reinforcement layers, and the eccentricity.
- The experimental results demonstrate an essential increase in BCRs and SRFs when a minimum spacing (Y=0.25 D) of reinforcement is employed for all skirt depths. Furthermore, an increased number of reinforcements has a substantial influence on the footing behavior.
- The spacing between horizontal reinforcements is of great importance in enhancing the bearing capacity and minimizing the settlement of the footing, when situated within the skirt. An increase in the vertical spacing between horizontal reinforcements, from a value of Y=0.25 D to Y=D, has been observed to lead to a reduction in the ultimate bearing capacity and an increase in the footing settlement.
- As the eccentricity increases, the bearing capacity declines gradually. This decline is most evident at e=0.16 D, due to the asymmetrical failure of an eccentrically loaded footing.

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