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Improving the Performance of Shallow Footing Subjected to Uplift Loading Using Structural Skirt

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Abstract

The increasing demand for internet and phone services had required the construction of transmission towers in various terrains, including loose sand, which was often found in desert areas and exposed to wind loads that can pull out these towers. This study aims to improve the uplift resistance of shallow footings subjected to pure uplift forces. In this research, a loading system with a data logger, a shallow footing model, and skirts with different shapes, lengths, and inclination angles was used. The performance and behavior of unskirted footing resting on loose sand with 30% relative density were analyzed and compared with skirted footing under uplift loads. The results showed that increasing the L/B (where L is the footing length and B is the footing width) up to 2 and the inclination angles up to 45° of the skirt gave a significant increase in uplift resistance for skirts with straight corners by 26 times and 19 times for chamfered corners, compared with unskirted footing. It is noted that increasing L/B has less effect than increasing inclination angles by recording 6 times with L=2B and 0°. Skirt footing with straight corners demonstrates better performance than chamfered corners.

Keywords: Skirted Footings; Straight Corners; Chamfered Corners; Loose Sand; Uplift Capacity.

1. Introduction

The basic principles of designing structures in civil engineering are safety factors and economic cost. Therefore, the search for new ways to reduce costs and achieve the required safety is still ongoing, according to researchers. This applies to the design of foundations in the field of geotechnical engineering, as researchers have developed many methods for designing foundations to be constructed on weak soils. Al-Mosawe et al. [1, 2] investigated the overall behavior of utilizing geogrid reinforcement to improve the soil. The results indicated that when single-layer reinforcement was utilized, there was an ideal depth of reinforcement embedment at which the load-carrying capacity was its highest. Al-Mosawe et al. [3] presented the results of a comparison between the laboratory model tests utilized to investigate the load-carrying capacity of footing that has a square shape on geogrid-reinforced loose sand and the theoretical equation proposed by Huang and Menq. The overall behavior of employing the geogrid to improve the soil was investigated by examining the influence of various parameters. Results demonstrate that the bearing capacity of loose sand can be estimated using the theoretical equation.

Liquid asphalt stabilization of gypseous soil was investigated by Sarsam et al. [4]. According to the test results, stabilizing gypseous soil enhanced its C.B.R. value, permeability, rebound consolidation, shear strength, compressibility, cohesion, and unconfined compressive strength. The behavior of the reinforced gypseous soil

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embankment model under cyclic loading was examined by Sarsam et al. [5]. Ameer & Al-Saidi [6] investigate the ideal number of geogrids reinforcing layers. The optimum geogrid layer number was found to be 4. Studies by Al-Saidi et al. [7] investigated how injection affected the consolidation settlement of soft clay. Ali & Al-Saidi [8] examine the influence of eccentric-inclined forces on the performance of ring footings situated on both treated and untreated loose sand. Test results indicated that the bearing capacity of the footing diminishes with an increase in the ratio of eccentric-inclined loading force to the footing radius.

A skirt is a structural element that was attached to shallow foundations to be a successful alternative to deep foundations. These skirts were designed to confine the soil beneath and to improve the bearing capacity and resist the uplift forces so they will improve the footing performance. Much experimental and theoretical research had been conducted to study the behavior and performance of shallow skirt foundations subjected to uplift forces.

Investigating and studying the behavior of a shallow footing resting on loose sand under uplift loading and how it can affect the enhanced uplift capacity it has has become a necessity because the big lack in the research and studies deals with shallow skirted footing exposed to the uplift forces, and this is the main purpose of the research. This study included conducting 29 laboratory tests on a shallow skirt footing resting on loose sand exposed to pure uplift forces. The aim of this study is to improve the uplift capacity of the soil using a structural skirt attached to a shallow footing and studying the effect of various parameters, such as the length, inclination angle, and shape of the skirt, on the uplift capacity, and which parameter achieves the best value according to the results obtained.

The paper contains 7 sections. The first section presents the introduction, which presents the aim of the study and approach to fill the gap in the literature. In the second section, which reviews the published literature. In the third section, the research methodology is presented through a graph. In the fourth section, it presents the experimental facilities. The results and discussion are given in the fifth section. In the sixth section shown, the symbols used in the article and the conclusions of the paper are summarized in the seventh section.

2. Literature Review

Abd-Alhameed & Albusoda [9] conducted a study to examine the impact of employing a skirt with a square foundation, measuring 100 mm in width, on dry gypseous soil. The findings indicate that the implementation of a skirt enhances the load-carrying capacity and diminishes the settlement of foundations situated on loose gypseous soil, with the degree of improvement escalating as the skirt depth relative to the foundation width (Ds/B) increases. Alhalbusi & Al-Saidi [10] analyzed sandy soil with a relative density of 30% to explore the behavior of shallow and inclined skirted foundations resting on it. The results indicated that the utilization of skirts significantly enhances load-bearing capability and reduces tilting. Under comparable loads, tilting diminished with an increasing inclination angle of the skirt. Additionally, tilting decreased under both positive and negative eccentric-inclined loading with a 30° skirt inclination, 15° load inclination, and e=0.15, exhibiting a reduction from 10% to 2% for positive loading and from 2.3% to 0.66% for negative loading at specified parameters. Unskirted foundations demonstrate increased settlement and minimal horizontal displacement. Horizontal displacement is greatly affected by an increase in the load inclination angle, but for negative eccentric-inclined loads, horizontal displacement can be diminished with greater eccentricity while maintaining a fixed load angle.

Neely et al. [11] conducted an experimental analysis of a vertical strip anchor in a cohesionless material, employing the method of characteristics alongside a trial failure surface method. Skirted foundations made of concrete are employed as anchorages for tension leg platforms [12]. Steel-skirted foundations have successfully replaced piles in jacket constructions [13]. Kelly et al. [14] studied the effectiveness of multiple footing structures utilizing suction caisson foundations and found that it would be enhanced if the upwind leg(s) were capable of withstanding substantial tensile loads. Skirted foundations have demonstrated effectiveness as an alternative to surface, pier, and pile foundations in multiple offshore applications, including wind turbines, oil platforms, offshore industrial facilities, and jacket structures [15]. Merifield & Sloan [16] conducted a numerical investigation to quantify the ultimate uplift capacity for vertical and horizontal plate anchoring in friction soils, utilizing the limit analysis theorem. The analysis revealed that the roughness of the anchor interface had a substantial effect on the capacity of vertical anchors.

Two types of investigations were conducted by Senders [17] to analyze the behavior of suction caissons under a tripod. Initially, an existing computer program was enhanced to forecast the standard loading conditions for a tripod foundation. Centrifuge tests on small-scale suction caissons were conducted to examine their behavior during installation and loading phases. Zhou et al. [18] developed a numerical analysis model to replicate the breakout process of a disk initially resting on the surface of a porous, elastic, saturated seabed. A numerical analysis was performed by Ahmadi & Ghazavi [19] to investigate the pullout response of skirted foundations with angled surfaces. The findings reveal numerous overarching conclusions. The skirted foundation's pullout capability with angled sides is achieved at greater displacements compared to vertical-sided foundations. As the undrained shear strength of the soil increases, the pullout capacity correspondingly elevates, especially for foundations with an inclined skirt surface. According to Singh et al. [20], the implementation of a skirted footing enhances the load-carrying capacity, minimizes displacement, and alters the load-displacement behavior of the footing. The load-carrying capacity of a circular-shaped footing increases by 11.2% to 30%, affected by the geometry shape and attributes of the skirt surface and the qualities of the sand bed.

The undrained behavior of skirted footings to uplift and compression has been modeled through large deformation finite element analysis, as demonstrated by Chatterjee et al. [21]. A study was conducted that revealed the subsequent uplift capacity of shallow skirted foundations built on lightly over-consolidated kaolin clay is influenced by consolidation and compressive preloading. The findings indicate that uplift executed immediately following preloading yields a diminished uplift capacity caused by the remolding of the clayey soil and the decrease in soil strengths caused by the preloading process. The consolidation process can restore and enhance soil strength [22]. The pullout capacity of a skirt foundation was influenced by several elements, including the submerged weight of the skirt, skin friction along the skirt side, the soil confined within the skirt, the soil tension strength at the base of the skirt, and the pressure of suction generated from tension loads within the skirt foundation [23]. Wang et al. [24] and Xie et al. [25] conducted a study examining how the geometry of a skirt influences the uplift capacity of skirt foundations. The geometry, undrained shear strength, and length-to-diameter ratio significantly affect the uplift capacity of the skirt foundation. Kulczykowski [26] presented findings from 1g model tests conducted under single gravity on a skirted foundation placed in sand and exposed to a rapid uplift load. Test results demonstrate that the rate of displacement substantially influenced the quantity of uplift resistance and the suction under the foundation cover while exerting minimal impact on the correlation between stresses and foundation displacement.

Ahmed et al. [27] examined techniques to improve structural stability during initial construction phases utilizing a skirt-raft foundation system. PLAXIS 3D was utilized to model and assess raft foundations on clay soil. The findings indicated that incorporating a skirt foundation enhances stability, markedly diminishing excavation-related damage, settlement, rotation, and lateral displacement.

Ahmed et al. [28] investigate the performance of ring foundations subjected to lateral loads, with the objective of improving their resistance by the integration of skirt foundations. Research indicated that augmenting the skirt foundation depth improves lateral resistance by 50-100%, while a skirt inclination ratio of 45° increases resistance by as much as 650%. Al Dabi & Albusoda [29] conducted experimental research to examine the performance of loosely skirted circular footings on poorly graded sand, comparing designs with and without horizontal reinforcing layers within the skirts. The results indicate that lateral reinforcement yielded optimal performance at L/D = 2 and Y = 0.25D, enhancing bearing capacity by as much as 235.6% and decreasing settling by up to 72.2%. Salah Alhalbusi and Al-Saidi [30] conducted laboratory tests to investigate the performance of shallow and inclined skirted foundations on 30% sandy soil, concentrating on the impacts of positive and negative eccentric-inclined loading.

Research demonstrated that skirted foundations substantially enhance load-bearing capability and diminish tilting. Inclined skirts reduce tilt by 2.3% to 0.66% under negative load conditions and by 10% to 2% under positive load conditions. Afaj et al. [31] performed a numerical study to investigate the carrying capacity of footings with and without skirts by finite element analysis in the Geo-slope program, taking into account different skirt depths and slope crest positions. The findings indicated that bearing capacity enhancements varied from 16.7% to 52.7% across diverse skirt depths and slope distances, indicating considerable efficacy.

3. Research Methodology

Figure 1 illustrates the flowchart delineating the research approach designed to fulfill the objectives of this research.

The principal objective of this research is to assess the performance of skirted footings situated on loose sand subjected to uplift loads.

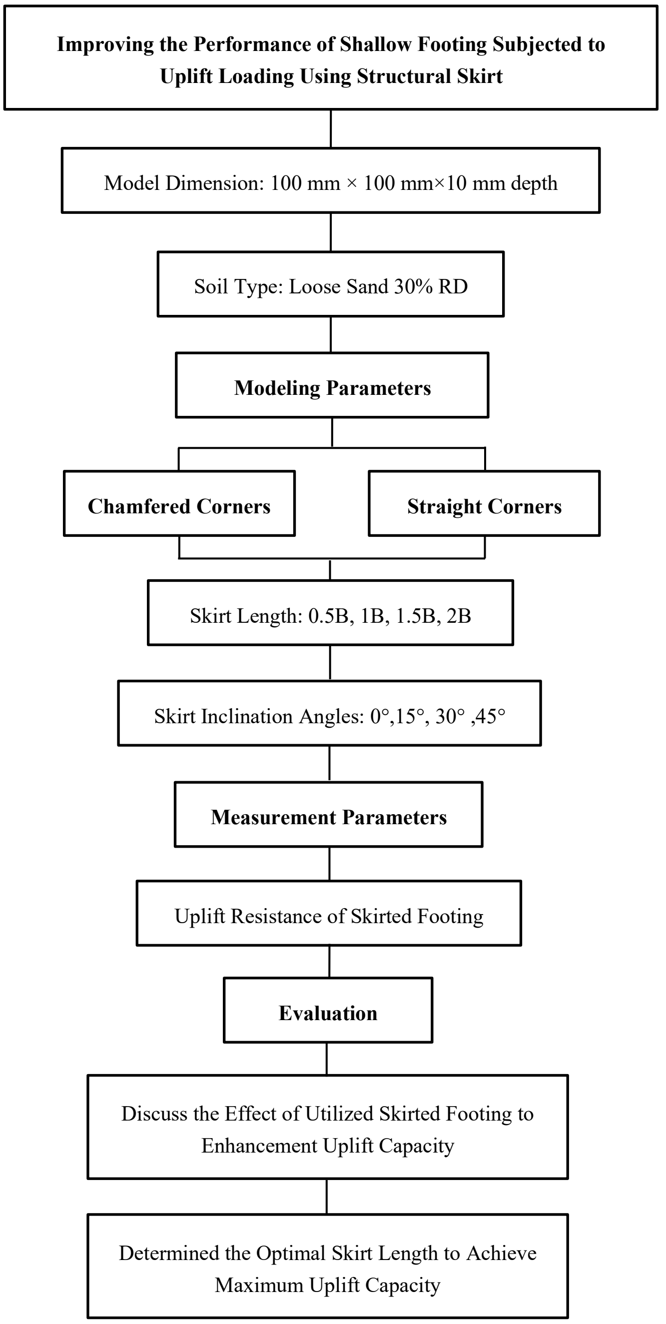

Figure 1. Research Methodology

4. Experimental Facilities

4.1. Model Box Test

The device that we use for testing, as shown in Figure 2, consists of a square steel soil container, square footing model, sand raining device, and uplifting system. The soil container was 600×600×600 mm in dimension, the outside frame consisted of 3 mm thick angle steel, the sides and base were constructed from 2 mm thick steel plates, and a 6 mm thick glass plate was utilized for the front face for enhanced monitoring of soil behavior, and reference marks were utilized on the front side of the container to assist in the creation of the requisite sand model. The container's dimensions adequately met the boundary conditions regarding the footings' response. The loading system consists of a steel loading frame manufactured to support the base of an electrical jack that was installed upside down and attached with a compression tension load cell (SC516C-1 ton is a S-type) at the other end and provided with a converter to regulate the speed of loading. The load cell is linked to the data logger to precisely measure the applied uplift load measurements. The sand- raining technique is used in experimental work. The uplift displacement of the foundation was measured using two linear variable differential transducers (LVDTs) having a capacity of 50 mm. The two LVDTs were connected to a data logger, and the test data was retrieved using the "Lab-VIEW" program.

Figure 2. Testing device

4.2. Model Soil Test

This experimental study was conducted utilizing the sands of Karbala. The sand was cleaned, dried, and subsequently sieved through a 4.75 mm sieve before the test. Figure 3 displays the particle size distribution of the used sand. The particle size distribution of the sand utilized was analyzed in accordance with ASTM (D422-63) standard, as depicted in Table 1.

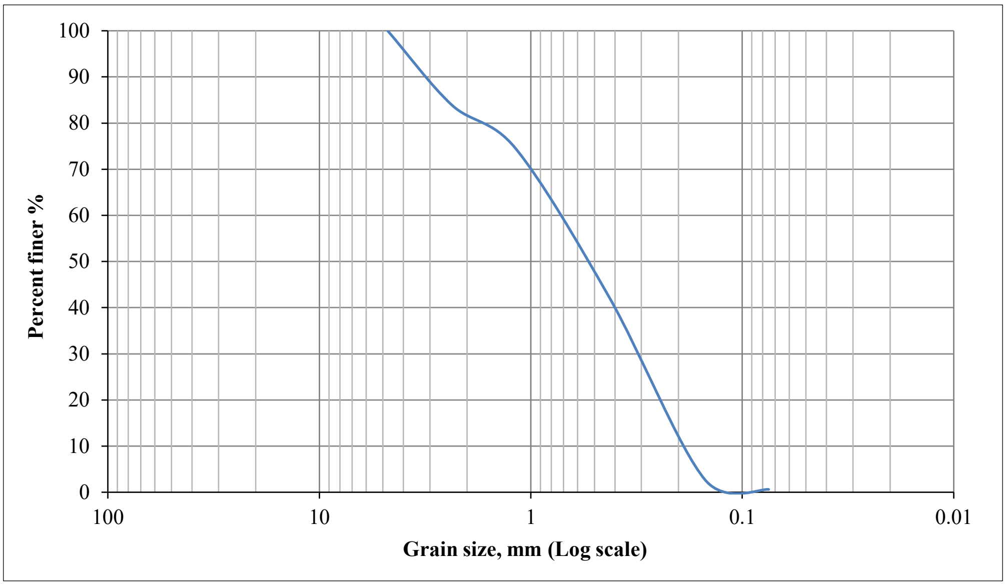

Figure 3. Grain size distribution of the sand

4.3. Preparation of Sand Bed

The rainy method was employed to fill the container with sand to the specified level. A raining system was constructed to achieve a consistent sand layer with a certain density. The apparatus was a plastic cone with a hole diameter of 25mm connected to a steel rope functioning as a hand lever to facilitate the upward movement of the cone, while lateral movement was executed manually. A ball valve (opening diameter of 25 mm) positioned at the cone's exit to regulate the sand flow rate, achieving the height necessary for the desired relative density. The flow rate of sand and the height of the pour influence the sand density in the raining technique [39]. The relative density was maintained at 30% across all experiments to investigate this effect in loose sand. The necessary level to attain the desired density of 30% is 224 mm.

Table 1. Physical properties of used sand

Property Index	Value	Specifications
Specific gravity (Gs)	2.65	ASTM D-854-92 [32]
D10 (mm)	0.2	
D30 (mm)	0.34	
D60 (mm)	0.84	ASTM D-422 [33]
Coefficient of uniformity (Cu)	4.188	
Coefficient of curvature (Cc)	0.684	
Maximum dry unit weight (KN/m^3)	18.56	
Minimum dry unit weight (KN/m^3)	16.09	(ASTM D 4253) & (ASTM D 4254) [34, 35]
Dry unit weight in test (KN/m^3) at R.D=30%	16.76	
Relative density (R.D)%	30	(ASTM D2049-64) [36]
The angle of interior friction Ø at R.D=30%	33.7°	(ASTM D3080) [37]
Soil classification (USCS)	(SP)	Unified soil Classification System [38]

4.4. Model Skirted Footings

A square footing with dimensions of (100 mm × 100 mm) and a thickness of 10mm has a nut with a size of 27 mm welded into the surface that used to fix the footing with the loading arm with a size of (15.65) mm. Four disks with a size of 13 mm are welded on each side of the footing and skirt; four screws 10mm in size) and disks are welded on each side of the skirt with four nuts to connect the skirt with the footing, and tiny holes are drilled into the surface of the footing to prevent the LVDT from shifting position, as shown in Figure 4. A skirt with four sides and dimensions of 100 mm x 100 mm, (0.5, 1, 1.5, and 2) B (where B = width of footing) in depth and 2 mm thick was employed. Skirt inclination angle (0°, 15°, 30°, and 45°) with chamfer corner as illustrated in Figure 5 and straight corner in Figure 6.

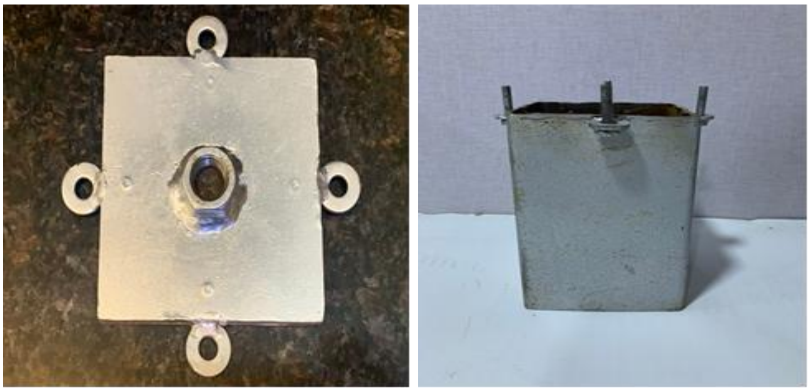

Figure 4. Model Skirted Footings

Figure 5. Chamfer Corners Skirted Footing Model

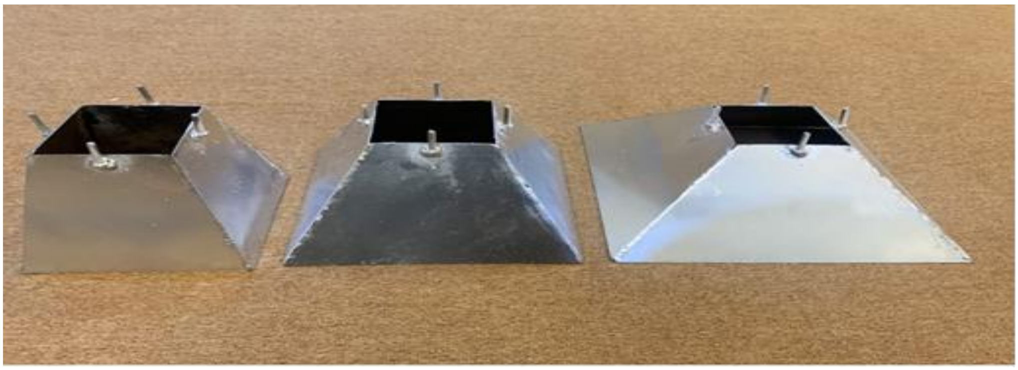

Figure 6. Straight corners skirted footing model

5. Test Results and Discussion

In this study, the primary parameters examined in the testing methodology were the effects of shape with chamfer and straight corner, embedding ratio (L/B), where L represents the length side of the skirt, and skirt inclination angles on the lifting capacity by conducting 29 laboratory tests. One test for footing without modification, 4 tests for 0° inclination angle, 12 tests for chamfer corner skirted footing, and 12 tests for straight corner skirted footing. As for the embedding ratio(L/B), the ratios were taken (0.5, 1, 1.5, and 2), and the skirt inclination angles were taken (0°,15°, 30°, and 45°).

5.1. The Effects of Embedment Ratio of Model Skirt

The uplift force of the foundation was calculated without modification to be a datum for comparison with the uplift force obtained by making improvements by adding the skirt to the foundation, where the value of the uplift force was 13.88 N. The initial tests examined the influence of the embedding ratio (L/B) on the uplift capacity. The uplift capacity of the shallow skirted foundation is proportional to the embedding ratio. By increasing L/B, uplift capacity increased. Figure 7 illustrates the load-displacement relationships for skirt footings. The load reaches its maximum value at a minimal displacement as the model skirt footing provides resistance to the pullout load. Following the attainment of the ultimate load, the load supported by the model skirts progressively diminishes as the friction between the sand and the skirt sides decreases linearly. The ultimate uplift observed was 80.76 N for L/B of 2, which is about 5.81 times greater than the skirt footing without modification and 3.27 times greater than the skirt footing with L/B of 0.5, having a peak resistance of 24.64 N. The optimal depth plays a crucial role in maximizing uplift resistance. The ultimate load comprises the self-weight of the usual skirt, the weight of the soil confined within the skirt, the friction between the soil and the skirt's external surface. These variables jointly improve anchoring and assist in alleviating the impact of uplift forces on the foundation, especially in wind-prone or seismic regions. The results above comply with the result obtained by Landlin & Chezhiyan [23] that showed the uplift capacity rises with the L/D ratio of the skirt footing in dry conditions (where D is the skirt diameter). The maximum uplift capacity recorded was 57.8 N for the model skirt with an L/D ratio of 2.5, approximately five times more than the 11.76 N peak resistance obtained for the L/D ratio of 0.5. The curve exhibits a zigzag pattern due to the application of a small vertical displacement rate of 0.5 mm/min. The displacement rate is influenced by the resistance of big sand grains (<4.75 mm) when uplift forces are applied. Table 2 shows percent improvement for different L/B ratios and 0°inclination angles of skirts as compared to L/B=0.

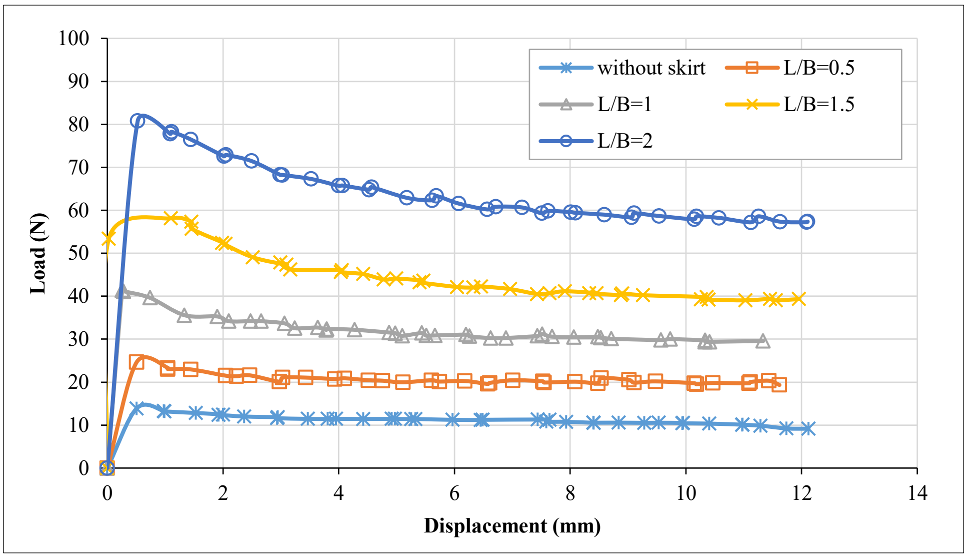

Figure 7. Load-Displacement Relationships of Model Skirts at α =0°

Table 2. Percent improvement for different L/B ratios and 0°inclination angles

L/D ratio	Uplift resistance	Improvement %
0.5	24.64	177.49
1	41.39	298.14
1.5	58.14	418.75
2	80.76	581.71

5.2. The Effects of Inclination Angle of Model Skirt

The behavior of resistance to the uplift force in a skirt with an angle of inclination has the same behavior as that of the skirt when the embedment ratio is increased. Specifically, the maximum force the skirt can achieve occurs within a minimal displacement, after which it gradually diminishes until the residual load is attained. This behavior includes 0° inclination angles too; also, for all L/B of 0.5 and α. In the scenario of a skirt with an increased angle of inclination from 15°, 30°, and 45°, the peak resistance to uplift forces was achieved at minimal displacement, subsequently diminishing with slight displacement. Thereafter, uplift resistance increases again until it attains a maximum at varying displacement values, followed by another decline in uplift resistance. This behavior can be elucidated by recognizing that the skirt's inclination at a specific angle results in an augmented surface area, thereby enhancing the frictional force with the soil. The foundation subjected to vertical uplift loads compels the skirt sides to compress the soil particles above, resulting in their rearrangement and intermingling, similar to the consolidation process associated with compression. This ultimately leads to soil densification and an enhancement of its resistance to uplift forces. As the angle of inclination increases, so does the resistance to uplift. As shown in Figures 8 to 13, The ultimate uplift observed was 33.66 N and 34.14 N for the chamfer and straight corner, respectively, at L/B of 0.5 and inclination angle α = 45°, which is about 2.42 & 2.45 times greater than the skirt footing without modification. In addition, it is 1.36 & 1.38 times greater than the skirt footing with an L/B of 0.5, an inclination angle α = 0°, and a peak resistance of 24.64 N.

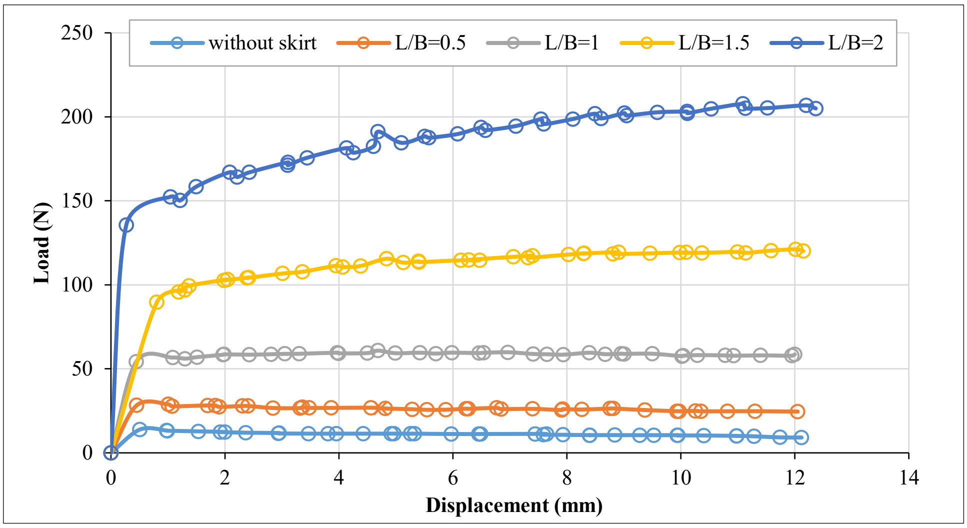

Figure 8. Load-Displacement Relationships of Model Skirts (Chamfered corners) at α =15°

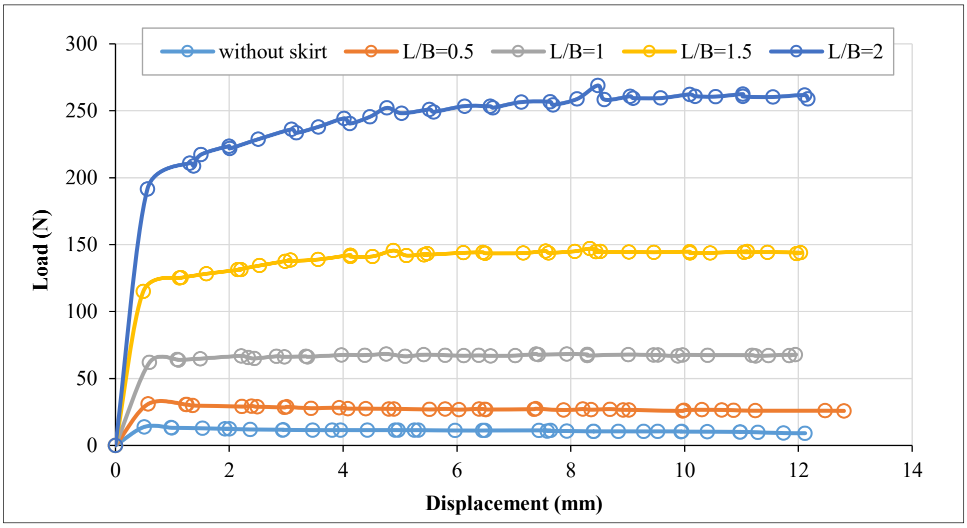

Figure 9. Load-Displacement Relationships of Model Skirts (Chamfered corners) at α =30°

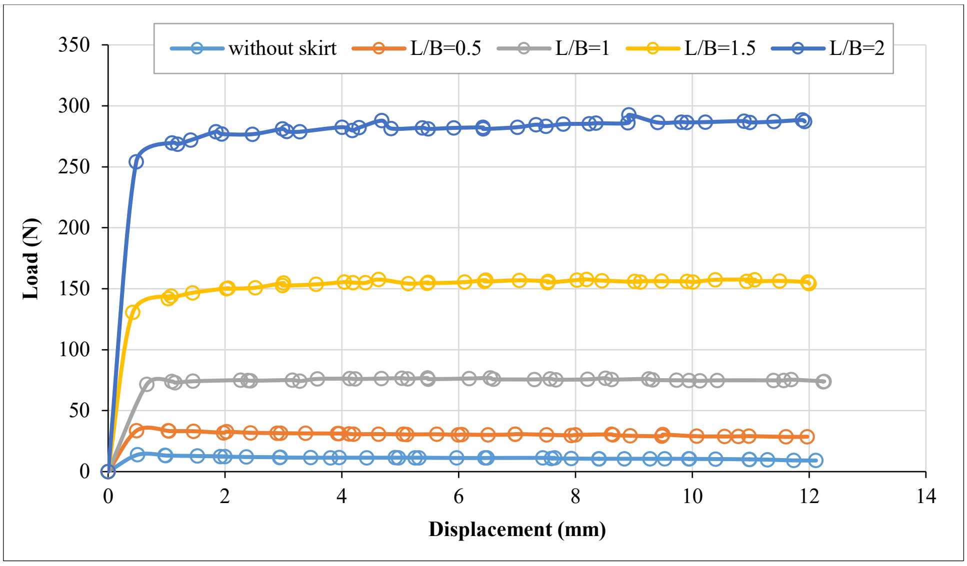

Figure 10. Load-Displacement Relationships of Model Skirts (Chamfered corners) at α =45°

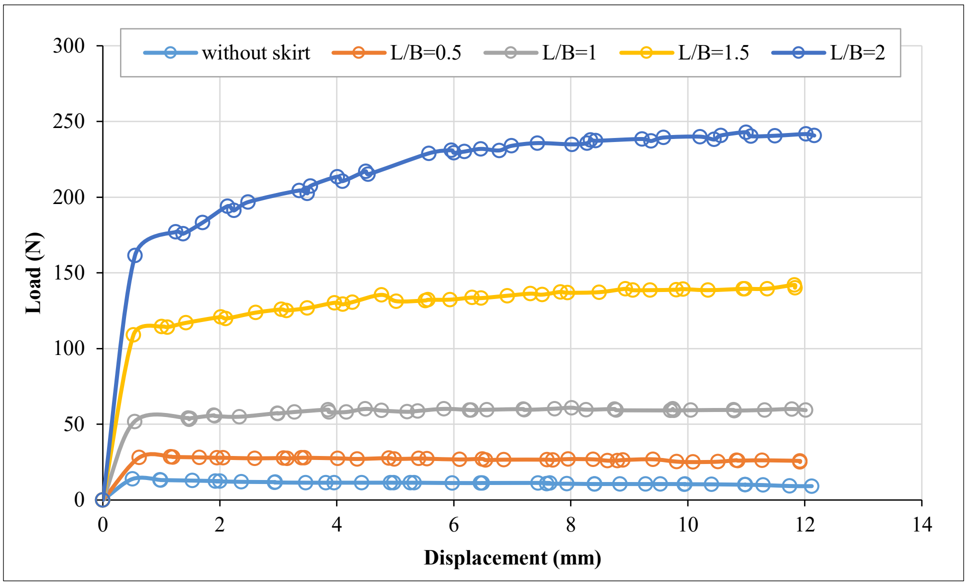

Figure 11. Load-Displacement Relationships of Model Skirts (Straight corners) at α =15°

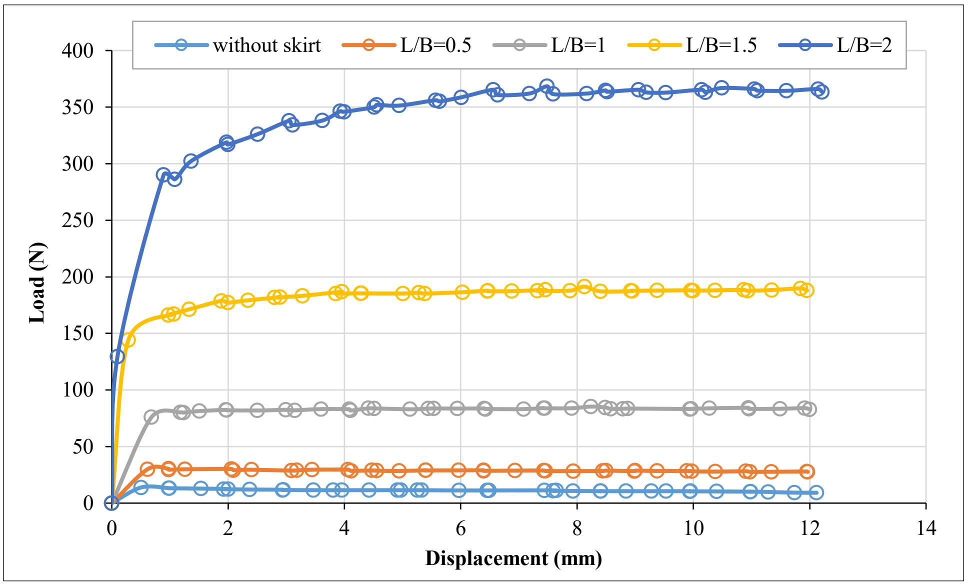

Figure 12. Load-Displacement Relationships of Model Skirts (Straight corners) at α =30°

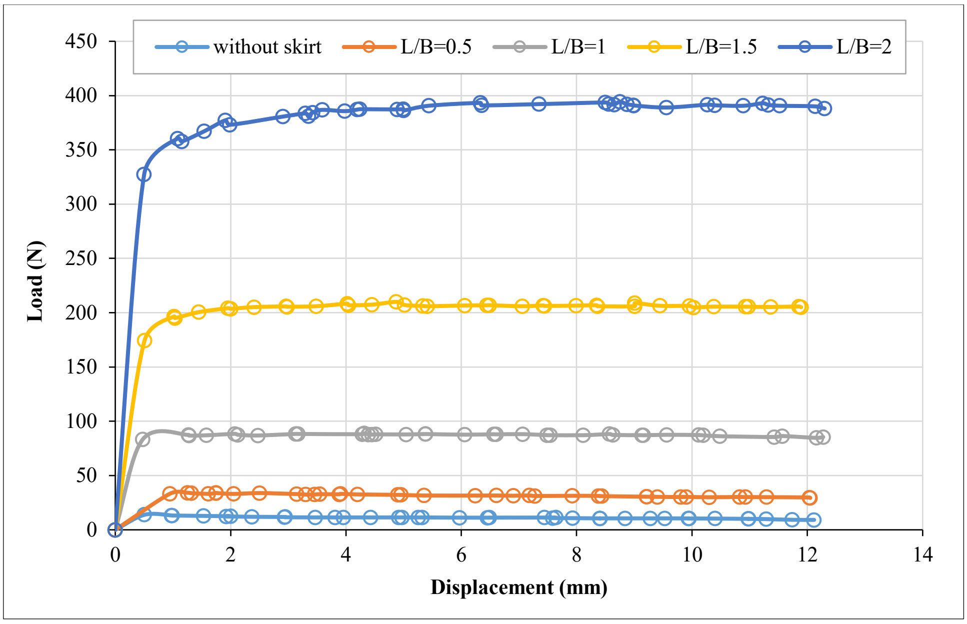

Figure 13. Load-Displacement Relationships of Model Skirts (Straight corners) at α =45°

The ultimate uplift observed was 269.68 N and 360.47 N for chamfer and straight corner, respectively, at L/B of 2 and inclination angle α= 45°, which is about 19.42 and 25.97 times greater than the skirt footing without modification. Moreover, 3.34 & 4.4 times greater than the skirt footing with L/B of 2, inclination angle α= 0° having a peak resistance of 80.76 N.

The belled inclination angle has little influence on uplift bearing capacity and load-displacement curves of belled piles with belled angles (18°̊ to 45°). This is in contrast to the performance of the inclined skirt foundation, which provides optimal uplift capacity at an inclination angle between (15° to 45°) [40-42].

Table 3 presents the uplift resistance values acquired from the experiments of the chamfered skirt, along with the percentage improvement for each L/B ratio and all inclination angles. Table 4 presents the uplift resistance values acquired from the experiments for the straight skirt, along with the percentage improvement for each L/B ratio and all inclination angles. The results indicate that uplift resistance does not rise linearly with rising angles of inclination and embedment ratios; instead, the increase is non-linear. The irregular grain distribution of the soil sample, which varies with each experiment, explains this phenomenon. As seen in Figure 3, the percentage of fine material passing through the large-sized sieves (less than 4.75) is less than the usual percentages for well-graded soil, which indicates the presence of high percentages of coarse grains in the soil sample. As known from table 1, the soil sample is poorly graded, so the grain size is concentrated in disparate regions of the soil container during preparation for testing.

Table 3. Percent improvement for different L/B ratios of chamfered corners skirt

α	L/D ratio	Uplift resistance	Improvement %
15°	0.5	28.89	208.08
	1	56.72	408.60
	1.5	96.94	698.25
	2	152.45	1098.03
30°	0.5	30.98	223.14
	1	64.21	462.54
	1.5	125.48	90.3.81
	2	210.94	1519.33
45°	0.5	33.66	242.46
	1	73.99	532.90
	1.5	143.96	1036.91
	2	269.68	1942.40

Table 4. Percent improvement for different L/B ratios of straight corners skirt

α	L/D ratio	Uplift resistance	Improvement %
15°	0.5	28.62	206.16
	1	54.13	389.91
	1.5	114.50	824.67
	2	177.05	1275.19
30°	0.5	30.31	218.31
	1	80.22	577.75
	1.5	167.16	1204.01
	2	289.99	2088.68
45°	0.5	34.14	245.90
	1	87.47	629.27
	1.5	196.51	1415.38
	2	380.02	2737.13

5.3. The Effects of Shape of Model Skirt

Figures 8 to 13 and Tables 3 and 4, as mentioned previously, showed that the influence of skirt shape on uplift capacity is minimal for skirts with chamfered and straight corners at an embedment ratio of 0.5 and an inclination angle of 15°, which is about 28.89 and 28.62 N. However, significant differences in uplift capacity emerge as the embedment ratio and inclination angle increase, with skirts featuring straight corners demonstrating a marked enhancement in resistance to uplift forces, which is about 360.47 N compared to those with chamfer corners, which is about 269.68 N.

This behaviour can be clarified by recognizing that the straight-cornered skirt possesses a greater surface area than the chamfered-cornered skirt, hence increasing the area of the skirt subjected to friction with soil particles. Moreover, augmenting the surface area of the skirt increases the quantity of soil confined inside it, raising the overall weight of the foundation subjected to uplift forces. Moreover, augmenting the surface area of the skirt applies pressure to the overlying soil, resulting in the rearrangement and densification of soil, elevating the overall weight of the foundation. The straight-cornered skirt shape demonstrated superior uplift resistance compared to the chamfered-cornered skirt.

There is a great deal of similarity between the shape of the inclination skirted shallow foundations and the belled pile in shape for deep foundations, and it had been observed that their behaviour is largely identical. The use of a bell (which is an enlargement of the base of the pile) acts as an anchor to resist the pullout forces [42-46].

The failure surface shown in the Figures 14 to 17 exhibits similarity across all tests, as the tests were performed with a maximum horizontal displacement of 12 mm. The variations in the dimensions of the failure surface area are dependent upon variations in the skirt inclination angle.

Figure 14. Failure Surface of Skirted footing at α = 0°

Figure 15. Failure Surface of Skirted footing at α = 15°

Figure 16. Failure Surface of Skirted footing at α = 30°

Figure 17. Failure Surface of Skirted footing at α = 45°

6. Conclusions

Based on the results obtained from laboratory tests conducted on the shallow foundation under the influence of uplift forces, the following conclusion was reached:

- The uplift capacity of skirted footing increased with an increased L/B ratio of 2 at maximum value, which is about 6 times.
- The uplift capacity of skirted footing increased with increased inclination angles at α= 45°and L/B ratio of (2) at maximum value, which is about 26 times.
- The geometric shape of the skirt has a significant effect on the uplift force, as the maximum uplift force was obtained at the L/B ratio of 2 and α= 45° was 26 times for straight angle corners compared with 19 times for the chamfered corners.
- The load-displacement behaviour of the skirt foundation on loose sand is nearly similar in all conditions in general trend but different values and curves shapes. The ultimate pullout resistance of the skirt was attained for small values of L/B and α, but with high values of L/B and α, it reached the peak value.

- The skirt length has less effect than the angle of skirt inclination.
- By studying the performance of the skirted footing, its behaviour is largely consistent with the behaviour of belled piles; the skirt footings can be considered a successful alternative to the use of belled piles in terms of safety and cost.
- The best location of a bell is at the base of the pile, but for the skirted footing, the skirt connects to the footing at a shallow depth and extends to the specification depth.

7. Symbols

L	Skirt length	B	Footing width
α	Alpha the angle of inclination	Ds	Depth of skirt
D	Diameter of skirt	e	Eccentric distance load
RD	Relative density		

8. Declarations

8.1. Author Contributions

Conceptualization, A.J.A. and A.A.A.; methodology, A.J.A. and A.A.A.; validation, A.A.A.; formal analysis, A.J.A. and A.A.A.; investigation, A.J.A.; writing—original draft preparation, A.J.A.; writing—review and editing, A.A.A.; visualization, A.J.A. and A.A.A.; supervision, A.A.A.; project administration, A.J.A. All authors have read and agreed to the published version of the manuscript.

8.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

8.3. Funding

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8.4. Conflicts of Interest

The authors declare no conflict of interest.

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