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A Review Study to Assess Skirted Foundation's Performance

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ABSTRACT

Innovative structural supports, known as skirted foundations, are primarily employed in offshore engineering. Skirted foundations extend below the footing like conventional shallow foundations and carry loads to deeper soil layers. A "skirt" is a wall that surrounds the foundation from one side or more, is connected to the foundation, and functions as a single unit. These skirts are essential for improving overall stability and transferring loads to more stable subsurface layers, which improves the foundation's performance. Significant features of skirted foundations make them promising for economics and appropriate for use in constructions with large loads and poor soil conditions. It has been demonstrated that skirted foundations are a more effective alternative to conventional foundations like piles, piers, etc. It is regarded as economical because of the reduction of employing building materials, less machinery, and a smaller workforce, as well as the saving of time necessary for installation. This review paper summarizes previous experimental and numerical investigations on skirted foundations and surveys their characteristics; the important conclusions can be summarized: The ratio of skirt length to foundation width (2) gave the best results in improving bearing capacity and minimizing settlement. The ultimate load increased when the skirt inclination increased from 10° to 30° because an attachment area was established between the inclined angle and the soil. Circular skirts can result in higher bearing capacity and lower settlement than square skirts when both are placed under comparable conditions. Also, skirted foundations are suitable for supporting shallow foundations in seismic zones.

Keywords: Skirted foundation, Bearing capacity, Settlement, Bucket foundation.

1. INTRODUCTION

Skirt suction foundations, also known as skirted foundations or bucket foundations, have been used in offshore construction since 1970. To transfer loads to stronger and deeper strata, steel walls, hollow cylindrical concrete, or skirts are inserted into the seabed soil

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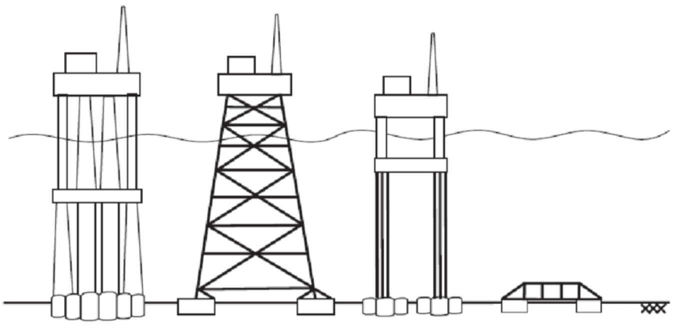
(Saito et al., 2006). Shallowly embedded skirted foundations are a preferred pile replacement for jacket structures and buoyant facilities because they are easier to install and can withstand uplift **(Acosta-Martinez et al., 2008).** Geotechnical engineers continue investigating an alternative method to increase the footing's bearing capacity and minimize its settlement when resting on weak soil. The bearing capacity of foundations is determined by the skin friction between the soil and the skirt, as well as by the end bearing in the skirt's tip **(Lepcha et al., 2022**). Because skirted foundations are less costly than other technologies and have the potential to be implemented, they represent a viable solution for improvement. When skirts are installed with foundations, the soil is tightly trapped within the enclosure. It can absorb the structure's load through the soil plug, as skirted foundations are more straightforward to install than deep foundations and are frequently utilized for offshore structures like wind turbines. Structures for the oil and gas sector have been constructed using shallow skirting foundations. Researchers have attempted to ascertain the parameters influencing the bearing capacity of skirted footings as well as their bearing capacity by numerical evaluation, theoretical configuration, model examination, and experimental field testing **(Tripathy and Singh, 2013).**

Skirted foundations are frequently used in offshore and coastal applications **(Magdy et al., 2022)**. The skirted foundation is mainly used in the following applications **(Tripathy and Singh, 2013)**:

- Jack up unit structures
- Wind turbine foundations
- Oil and gas plants
- Tension leg platforms
- Bridge foundations

Choices for skirted foundation applications are shown in **Fig. 1.**



Jacket **Jack-up** **Wind turbine** **Subsea system**

a. Troll platform installed **b.** Skirted foundation with Jacket, Jacket-Up, Wind Turbine and Subsea System

c. Skirted foundation with bridge sub-structure

Figure 1. Skirted foundation applications (**Tripathy and Singh, 2013)**.

This study aims to identify the characteristics of skirted foundations and the findings of previous studies on their use in enhancing load-bearing capacity, reducing settlement, and resisting lateral displacement. Ongoing research examines how well they perform on a skirted footing in various circumstances. **Tables 1 and 2** provide a summary of some of these research results.

Table 1. Summary of previous experimental studies on skirted foundation.

Study	Focus	Key Findings Continuous
(Al-Aghbari and Mohamedzein, 2004)	Examine the factors that impact strip foundations with structural skirts' bearing capacity.	Based on the geometric and load conditions, structural skirts enhance the bearing capacity by 1.5 to 3.9.
(Al-Aghbari and Dutta, 2008)	Square footing efficiency with structural skirt	Compared to non-skirted foundations, square-skirted foundations have a greater load-bearing capacity.
(Eid et al., 2009)	Square foundation behavior in confined sand	Confined sand increases bearing capacity and minimizes settlement
(Nazir and Azzam, 2010)	This study investigates how sand piles can enhance bearing capacity and regulate settlement. In addition to examining subgrade modulus variation, it aims to comprehend the failure mechanisms of shallow circular footing on replacing soil, whether skirts are present or not.	When skirts are used in place of piles as confined, and when not, capacity increases dramatically. In soft clay layers, the technique utilized could significantly impact the displacement curve of the footing.
(AL-Qaissy and Muwafak, 2013)	An analysis of how a skirted strip model footing with soft clay beds behaves and considers ways to increase bearing capacity.	It increased the extent of bearing capacity with an increased (d/b) ratio (embedded depth to footing width) about the soft clay state without lateral confining, depending on the lateral confining pressure (d/b = 0).
(Tripathy and Singh, 2013)	Establish the skirted foundations' capacity to support vertical and horizontal loads at various relative densities and skirt length-to-diameter ratios.	Improvements in skirt length and the relative density of sand enhanced the skirted foundations' bearing capability. The failure strain decreases with increasing sand bed relative density but rises with footing size and skirt length.
(Fattah et al., 2014)	This paper examines how model footings behave when located on sandy soil and surrounded by a wall that changes in depth and distance from the footing.	For square footing on sand with different densities, the wall's bearing capacity increases with wall depth; the wall's bearing capacity is most affected when its depth (d/B) value is between 1.5 and 2.0.
(Prasanth and Kumar, 2015)	An investigation of the skirted foundation's ability to support loads in sand	A structural skirt improves the footing's load settlement behavior, minimizes settlement, and enhances bearing Capacity. The ultimate bearing capacity increased as the footing's size, skirt length, and relative sand density increased.

Study	Focus	Key Findings Continuous
(Khatri et al., 2017)	The pressurized behaviour of square and rectangular skirting footings on the sand exposed to a vertical force.	The application of a structural skirt significantly improves the footing's carrying capacity. The bearing capacity enhancement was approximately linearly associated with the skirt depth.
(Abd Ali, 2018)	Examine the impact of placing a skirted foundation on dry sand and monitoring its reaction.	The findings demonstrate how the skirt improves the behaviour of the load-settlement, enhancing the load-carrying capability and reducing foundation settlement. With longer skirts and larger foundations, skirted foundations can support higher loads. A closed-end skirt has a substantially higher load-carrying capability than an open-end skirt.
(Zografou et al., 2018)	To examine the effects of applied stress, tension or compression average stress, and low-amplitude cyclic loading after consolidation on the footing reaction, several rounds of centrifuge tests have been conducted on a shallow skirted footing on normally consolidated kaolin clay within different vertical cyclic load sequences.	Lower limit stress results in a steady state existence even at higher cycle matters; lower-level cyclic loading followed by consolidation increases geotechnical resistance, and the average vertical stress determines the footing's vertical displacement reaction and failure mode.
(Gnananandaaro et al., 2018)	The analysis of the pressure-settlement ratio of plus-shaped foundations sitting on sand, whether skirts are present or not.	The carrying capacity of the plus-shaped skirted footing varied from 1.26 to 3.90 times that of the surface plus-shaped footing while considering the same range of other features. In partially difficult and severe conditions, where skirts are not present, the plus-shaped foundation exhibited a settlement ratio of about 8% at Failure. The bearing capacity of the plus-shaped skirted foundation was lower than that of the H-shaped skirted foundation. The BCR of the plus-shaped foundation was higher than that of the H-shaped skirted foundation.
(Thakur and Dutta, 2020)	Experimental and numerical studies of skirted hexagonal footings	Hexagonal skirted footings show encouraging results in load-bearing Capacity
(Gnananandarao et al., 2020)	This paper examines the double box and the unskirted/skirted footings of the model in sand. The variable characteristics are the sand's relative density and the foundation's interaction state, skirt depth, and skirted foundation type.	The skirt enhanced overall behaviour and increased the bearing capacity.

Study	Focus	Key Findings Continuous
(Kumar et al., 2021)	A combined skirted soil reinforcing system was developed to limit ground vibrations directed toward the foundation and lessen the formation of pore water pressure in liquefied soils.	Compared to unreinforced ground, the created skirted ground reinforcing system efficiently decreases how incoming ground movement impacts the foundation and increases the soil's resistance to liquefaction.
(Parmar and Patel, 2021)	The load-bearing capacity of an Isolated square-skirted footing on sandy soil	The effect of increased bearing capacity for 45º skirt angled footing increases with skirt length. Compared to 30º and 60º skirt angled footing, there is a greater increase in bearing capacity between 45º and 60º skirt angled footing. A 60º skirt angle increases carrying capacity when the skirt lengthens.
(Mohammed et al., 2021)	Used experimental models to investigate how skirted foundations behave regarding carrying Capacity. Varying ratios of the footing base's length to length at various relative densities and various saturation levels for soils that are dry, saturated, and partially saturated are taken into	In partially saturated conditions, load-carrying capacity in its medium-dense form is noticeably more significant than that of the loose state in any circumstance involving the loose, medium, and dense states of sand. Therefore, the dense state's increase in ultimate bearing capacity is more significant than that of the medium and loose states. Increasing the skirt's L/B ratio results in a deeper foundation and an increase in depth, lengthening the soil's Failure plain and increasing soil resistance. This ultimately increases ultimate loading-bearing capacity and decreases settlement.
(Thakur and Dutta, 2021)	The study concludes that singly and doubly skirted irregular pentagonal footings improve load-bearing capacity, especially when loose sand exists.	Skirted footings greatly increase bearing capacity compared to unskirted systems. The double-skirted footings showed the most gains, with increases reaching up to 95.13% under specific circumstances. The footings' settlement reaction was consistent, and once a particular number of mesh elements were included in the numerical models, no discernible changes were seen. With an average variance of roughly 8%, the numerical calculations often revealed slightly higher carrying capabilities than the experimental data.
(Örnek et al., 2021)	This study used experiments to examine the skirted footings' ultimate loads in dense and loose sand soil conditions.	After comparing the test findings with several bearing capacity equations, it was found that they were generally consistent. According to 96 test findings, the additional skirted footing sections enhance the ultimate loads.

Study	Focus	Key Findings Continuous
(Magdy et al., 2022)	Examine how skirts impact shallow footing and settle loads by contrasting how square and circular footings behave.	When each foundation had the same dimension and skirt length, the circular footing's load-settlement behavior improved more than the square footing's.
(Mahmood et al., 2022)	We measured the matric suction value of unsaturated soil by examining and analyzing the extent of soil bearing of skirted foundations on sandy soils and studying the influence of soil saturation instances and three cases of water content reduction.	When matric suction is at a depth of 450 mm, the unsaturated case has the maximum soil load-carrying Capacity. The dry and saturated cases, which represent the weakest states of the soil, follow.
(Abd-Alhameed and Albusoda, 2022)	This research examines using square-skirted footings on gypseous soil tested for concentric and eccentric vertical stress for 4,8, and 17mm eccentricity values in 16 experimental model tests.	The outcome shows that a concentric load applied to a square foundation with the highest bearing capacity and Ds/B = 1.5 yields an improvement percentage of 190%. The improvement in bearing capability at (e=0.008m) is almost 120% when comparing a foundation without a skirt to the eccentric load for Ds/B equal to 1.5.
(Abd-Alhameed and Albusoda, 2023)	Examine the effects of applying an inclined load to a 10 cm long skirt with a square base resting on dry, 33% relative density gypseous soil.	When a square foundation is used with a skirt, the load-carrying ability is enhanced, and the rate of settlement reduction for the footing sitting on gypseous soil decreases. The improvement increases as the skirt depth rises relative to the foundation width Ds/B.
(Al-Shyoukhi et al., 2023)	The sloped skirting foundations' carrying capacity on the sandy soil	The inclined skirting foundation's bearing capacity significantly increased because of relative density. Similarly, an increase in the internal friction angle affects bearing capacity, increasing the bearing capacity value. It is observed that the impact of additional skirts on bearing capacity is disregarded.
(Alhalbusi and Al Saidi, 2024)	This study investigated the effect of positive and negative loading with an eccentric inclination on inclined skirt foundations.	The skirted footing has a more significant horizontal displacement than the unskirted footing when compared to the failure load of the unskirted footing with the equivalent load for the skirted footing. Significant settlement and minimum horizontal displacement occur when a foundation is loaded without a skirt.

Table 2. Summary of previous theoretical studies on skirted foundation.

Study	Focus	Key Findings Continuous
(Mana et al., 2013)	Find the critical internal skirt spacing using the criterion that the restricted soil plugging should move as a rigid block to provide the best bearing capacity possible for the undrained failure of shallow skirted footings under circumstances of plane strain.	Fewer internal skirts are needed as the normalized foundation embedment improves; however, more are needed if the soil strength increases with depth. According to the results, there could be a significant decrease in capacity if not enough skirting is provided because this could result in plastic deformation within the soil plug.
(Azzam, 2015)	This work examines the behavior of structural skirting foundations under seismic loading close to a sand slope and how the skirts keep the slope and foundation from collapsing.	This is a great way to increase the stability of the foundation and slope. The limited soil footing system created by these skirts behaved as a dampening element, lowering the expressed disturbance to the adjacent slope by lowering the foundation acceleration. This technique can be considered an efficient means of controlling the slope's deformation and reducing the slope's acceleration during earthquakes.
(Vulpe and Gourvenec, 2014)	The effect of preloading amount and duration on a skirted foundation's undrained vertical bearing capacity in normally consolidated clay	When preload and consolidation are reasonable, substantial improvements in bearing capacity are possible. By improving relative capacity, one-dimensional consolidation in the soil surrounding the skirt may be beneficial. The skirt's existence increases the consolidation period and the drainage path compared to a surface foundation. The bearing capacity increase and settling of a foundation depend on the applied load delivered to the soil and the relative roughness of the soil-skirt contact.
(Sarma and Chetia, 2016)	Determine the surface raft's behavior under two different soil models—the hardening soil model and that without skirts.	For both models, we are increasing the skirt depth. Outcomes include a decrease in settlement and an increase in bearing capacity.
(Vulpe et al., 2016)	The impact on the consolidated undrained roughness of the soil-skirt contacts and the foundation embedment ratio capacity of typically consolidated clay-skirted circular foundations under planar loads	Although the interface roughness and incorporation ratio impact the load distribution through the soil mass, the consolidated undrained capacity under planar loading scales proportionately with the foundation (unconsolidated) undrained capacity.
(Alzabeebee, 2020)	Study the effectiveness of using skirts to minimize the settlement of a strip	When skirts are used, the settlement caused by machine vibration is decreased. Using a new method, innovative, dynamic impedance design equations that implicitly account for

Study	Focus	Key Findings Continuous
	foundation subjected to machine vibration.	the influence of the skirts have been constructed and validated.
(Gautama et al., 2020)	The impact of road settling skirt footings on peat soil	According to the test results comparing skirt and mini piles, circular footings reduce the impact of differential settlement on the soil. Based on the study's findings, skirt footings can improve road stability and tolerate variations in settlement patterns.
(Bashir et al., 2021)	Use parametric research to demonstrate the performance of strip footing with skirts attached to its sides under axial loads when resting on sand and the impact of skirt depth and shearing resistance angle on load capacity.	As the skirt depth increases, the skirted foundation's enhanced capacity correspondingly increases. When the skirt length is 2B, the skirt depth effect is substantial for the 300 internal friction angles. When skirts are added, the bearing capacity is improved six times above traditional strip footing.
(Bashir et al., 2022)	Examine how a square foundation with its component skirts sitting on sand responds to a strain on the side.	The investigation's results show that the lateral capacity ratings for skirted foundations are similar to block foundations due to the same width and length despite their differences. An increased skirt length and resistance to sand shearing increase a skirted foundation's lateral capacity.
(Abd-Alhameed and Albusoda, 2023)	The performance evaluation of the skirted foundation.	Civil engineers have developed the skirted foundation to enhance the bearing capacity and lessen settling on the soil. Because of its lower cost, a skirted foundation can be more durable than other foundation types when the soil has a low bearing capacity.
(Aljuari et al., 2023)	They examined how circular skirted foundations sitting on gypseous soil that have experienced loading, phases of infiltration, and collapse settle.	The skirt encasement and the soil phase ratio significantly impact the ultimate capacity for bearing and settling poor soil; the higher latter parameter results in better skirted stability performance. The collapsing soil stage exhibits the most settling improvement, whereas the loading stage exhibits the least.
(Al Dabi and Albusoda, 2024)	A Review Study on skirted foundation, effectiveness, mechanism, and constraints	Applying geogrid skirts seems feasible for improving the performance of footings under eccentric and inclined loading circumstances.

2. DESIGN AND STRUCTURE OF THE CHARACTERISTICS OF SKIRTED FOUNDATION

Skirted foundations consist of a footing (which can be square, circular, or rectangular) equipped with skirts that extend vertically into the soil. The skirts can vary in length, thickness, angle, and geometry to suit specific site conditions and loading requirements. Skirts are typically made from concrete or steel, providing the necessary strength and durability to withstand applied loads and environmental conditions.

2.1 Length of Skirts

The optimal skirt length may vary depending on specific conditions such as soil density, moisture content, and loading conditions. For instance, longer skirts could be required in weak soil situations.

The soil wedge formed beneath the footing is then used to calculate the static equilibrium and footing bearing capacity. Therefore, the length of the slip lines directly affects the bearing capacity; longer slip lines result in higher bearing capacity. Increasing the footing width or embedment depth can increase the length of slip lines **(Das, 2007).** Another reasonable method to increase the length of slip lines is to use structural skirts that cover the soil beneath the footing **(Ebrahimi and Rowshanzamir, 2013).** Bearing capacity increases as the length of the skirt increases, and the settlement of a two-sided vertical skirt raft foundation decreases as the skirt depth increases **(Pusadkar and Bhatkar, 2013).** With increasing wall length, the load-bearing capacity rises. For square footing on sand with varying densities, the wall has the greatest effect on bearing capacity when the depth of the wall (D/B) value is in the range of 1.5-2.0 **(Fattah et al., 2014)**. The skirt foundation's lateral load-carrying capability improves as the L/D ratio increases (6.6 times higher when L/D = 2.5 than when L/D = 1.0) **(Kannan et al., 2016).** A variety of factors, including the depth of the foundation, the length of the skirt, and the coarseness of the skirt's surface, the skirt can enhance the bearing of a circular foundation sitting on dune sand by about (12 - 470) %. The structural skirt for a given applied load can reduce up to 70% of the initial footing settlement **(Al-Aghbari et al., 2018).** Due to its ability to lengthen, skirts are an invaluable instrument for enhancing ultimate bearing capability, which is 4.70 times further expandable **(Renaningsih et al., 2017).** The foundation's load capacity increases with skirt length. This improvement results from the skirt's capacity to engage more soil, which aids in more efficiently distributing the applied load. The safe load value rises with increasing skirt lengths for footing **(Singh et al., 2021).** Expanding skirt length increases the bearing capacity **(Bashir et al., 2021).** Longer skirts contribute to minimizing settlement when loads are applied vertically. According to research, increasing the skirt can significantly reduce settlement **(Abdulhasan et al., 2020).** The loosely skirted circular arrangement beneath the footing increased the bearing capacity of surface foundations by a factor of 1.19 to 3.36 and enhanced the behaviors of stress settlement **(Al Dabi and Albusoda, 2024).**

Increasing skirt length modifies the foundation's mechanism of Failure. Longer skirts tend to encourage rotational failure modes and are generally more stable under eccentric loading circumstances, while shorter skirts are more likely to experience slide failure. The skirts caused a rotational failure instead of the sliding failure of the circular shallow foundations **(El-Wakil, 2010; Abdulhasan et al., 2020).** The region where the soil is present grows as the skirt's depth increases **(Joybari et al., 2023)**. The lines of Failure beneath the footing will cross over with skirting, and their impact will not reach the soil's surface **(Mahmood et al., 2018).** The skirts improved the lateral capacity of the skirted footing to approximately three and four times the raft footing in size. Additionally, it was proposed that the foundation failure mechanism shifted from a sliding process to a rotational one **(Yun and Bransby, 2003).** It can be assumed that a skirted footing is stiff and that the embedment length equals the skirt length when the foundation is subjected to a vertical load **(Yun and Bransby, 2007).** The effect of sliding and overturning is reduced when skirts with a square foundation are used, and Failure transitions from sliding to rotating **(Abd-Alhameed and Albusoda, 2023).**

Iraq is one of the many places globally with gypseous soils, constituting more than 31% of the nation's surface area **(Al-Busoda and Al-Rubaye, 2015).** These soils, which occasionally had significant gypsum contents, created challenging issues for critical projects and buildings since water passage through the mass dissolved and leached gypsum **(Albusoda and Hussein, 2013).** The properties of collapsible soil provide a variety of challenges for the infrastructure built upon it, including excessive settlement and cracks in roads, bridges, railroad tracks, and buildings **(Mohsen and Albusoda, 2022).** Gypsum has a critical level of (10–20) %, adversely impacting soil shear strength **(Al-Yasir and Al-Taie, 2022).** We have already conducted several previous studies to find ways to minimize the collapse of gypsum soil, including (adding cement, nanomaterials, Cement dust, dihydrate calcium chloride, granular activated carbon, powdered sodium meta-silicate, powdered activated carbon, and sodium silicate solution) **(Al-Busoda, 2008; Al-Busoda and Khdeir, 2016; Al-Taie et al., 2019; Hassan and Al-Busoda, 2022).** Skirts improve the bearing capacity of the surface foundation on gypseous soil. The enhancement increases as skirted footing depth on gypseous soil and relative density increases **(Mahmood et al., 2018).** The load-carrying capacity and settlement caused by soil confinement between the skirt wall and the number of skirts, the ratio of the skirt depth to the foundation width (ds/b), and the soil condition are all improved when skirts with a square foundation resting on gypseous soil are used **(Abd-Alhameed and Albusoda, 2023).**

Researchers used different skirt depth to footing (width or diameter) ratios in their studies, L/B or L/D. **Table 2** summarizes some of these studies.

Table 2. Summary the skirt length to foundation width ratio L/B used in some previous studies.

Study	Skirt depth to footing width ratio (L/B)
(Eid et al., 2009)	ranging between 0 and 1.0
(El Wakil, 2013)	0.0, 0.5, 1, and 1.5
(Tripathy and Singh, 2013)	0.4, 0.6, 1.2, 1.5, and 2
(Kannan et al., 2016)	1.0, 1.5, 2.0 and 2.5
(Abd Ali, 2018)	0.5 to 1.5
(Mahmood et al., 2018)	0, 0.25, 0.5, 0.7, 1, 1.5, 2, and 3
(Gnananandarao et al., 2020)	0.25 to 1.5
(Mohammed et al., 2021)	0, 0.5, 1.0, 1.5, 2.0, and 3.0
(Thakur and Dutta, 2021)	varied from 0.0 to 1.5
(Parmar and Patel, 2021)	0.4 and 0.6
(Singh et al., 2021)	0.0, 0.25, 0.50, 1
(Kirtimayee and Samadhiya, 2022)	1.0, 1.5, 2.0
(Mahmood et al., 2022)	0, 0.5, 1.0, 1.5, 2.0, and 3.0
(Abd-Alhameed and Albusoda, 2022)	0.5, 1, and 1.5

From **Table 2**, the ratio of skirt depth to footing width between 1.5 and 2 is more efficient. The ratio of 3 needs more studies to confirm its effectiveness, as was mentioned in the research **(Mahmood et al., 2018)** (in gypseous soil with a medium relative density, the bearing capacity decreases with L/D = 3 compared to L/D = 2). The skirt depth to footing width ratio is not less than 0.5 and not more than 2.0.

2.2 The Angle of Skirts

A positive skirt angle (inclined away from the foundation) is more effective in minimising settlement than a negative angle (tilted towards the foundation). The stability of the foundation is increased by positive inclination, which produces more lateral resistance. A positive skirt angle is applied to decrease the most crucial component determining the footing's ability to slide. The foundation becomes more stable under vertical loads because of this change in failure mode from sliding to rotating failure.

Previously, several methods have been tried to improve the properties of problematic soils under the influence of eccentric and inclined loads, including using geogrid as reinforcement to the soil **(Al Mosawe et al., 2008; Al Mosawe et al., 2010).** Using ring footing subjected to inclined loading with geogrid reinforcing layers beneath it, 0.5B is the optimum spacing value between geogrid layers, while 4 is the ideal number of geogrid layers **(Bachay and Al-Saidi, 2022).** Inclined skirts enhance the bearing capacity and settlement of the foundation under eccentric and inclined loads. The ultimate bearing capacity and the corresponding settlement are reduced when the skirt inclination angle increases **(Saleh et al., 2008).**

A higher angle of the skirt will result in a higher improvement factor (IR). As the angle of the skirt increased from 10° towards 30° for an enhanced footing with load angles of 5°, 10°, and 15°, the enhanced factor increased from (2.53, 2.51, 2.4) to (3.45, 3.65, 3.97) and from (2.43, 2.58, 2.54) to (4, 4.63, 5.3) for the positive and negative eccentric-inclined load, respectively. For positive and negative eccentrically inclined loads, the settling decrease rate was 34% and 27%, respectively, for a load inclination of 15° and a skirt angle ranging from 10° to 30° **(Alhalbusi and Al-Saidi, 2023).** When a skirt is used, tilting is reduced, the angle of the skirt increases for the same load, and the horizontal displacement decreases for both positive and negative eccentrically sloped loading. An increased improvement factor (IR) results from an increased skirt angle. The ultimate load increased when the skirt inclination increased from 10° to 30° because an attachment area was established between the inclined angle and the soil **(Alhalbusi and Al-Saidi, 2024).**

The skirt inclination more positively impacts a footing's capacity for carrying loads because the increased resistance to footing sliding caused by the lateral soil reaction on the skirt face expands the skirt's influence zone **(Singh et al., 2021).** The improvement in bearing capacity of the 10-degree negative inclined skirt is not as great as that of the 10-degree buoyant inclined skirt **(Singh et al., 2022)**. Compared to the skirted footing at the identical L/b, the inclined skirted foundation has a greater skirt cell size. Because of this, in the case of inclined skirts as opposed to vertical skirts, the sand between skirts is more restricted, and there is a greater confinement zone beneath the surface foundation **(Al-Shyoukhi et al., 2023).** Researchers used skirts from different angles in their studies. **Table 3** summarises some of these studies.

Table 3. Summary of the skirt angle used in some previous studies.

Study	Angle of skirt
(Singh et al., 2021)	0^0, 20^0, 30^0, 45^0
(Lepcha et al., 2022)	15^0, 20^0, and 25^0
(Al-Shyoukhi et al., 2023)	10^0, 15^0, and 20^0
(Alhalbusi and Al Saidi, 2024)	10°, 20°, and 30°

The skirt angle is not less than (10^0) and not more than (30°)

2.3 The Shape of Skirted Foundations

Researchers used different shapes of skirts in their studies. **Table 4** summarises some of these studies.

Table 4. Summary of the shape of the skirt used in some previous studies.

study	Shape of skirt	Result
(Tripathy and Singh, 2013)	Circular	The improved bearing capacity of a circular footing can range from 11.2 to 30%, depending on the sand bed's characteristics and the skirt's surface and geometrical features.
(El-Wakil, 2013)	Circular	Skirts improve the ultimate load of shallow foundations by up to 6.2 times, depending on the circumstances and factors of the study, significantly enhancing the footing's Capacity to sustain the applied load.
(Fattah et al., 2014)	Wall	When walls surround a square foundation, the load capability increases achieves 43% at (H/b = 0.5) (which is the distance between the wall to foundation edge to the width of the foundation ratio) and (D/b = 2) (the depth of the wall to the width of the foundation ratio). The load-bearing capacity in medium sand increases most at (H/b = 0.5) with (D/b = 2). This is for a square foundation encircled by walls. For square foundations on the sand with different densities, the wall's load-bearing capacity improves with wall height; the wall's carrying capability is most affected when its depth (d/B) ranges from 1.5 to 2 load-bearing.
(Prasanth and Kumar, 2015)	Circular	The bearing capability ratio (BCR) has a proportionality at L/d and a disproportionality with the relative density (RD). Sand with a relative density of 30%, BCR is 2.0 and 7.3, for L/d of 0.4 and 2.0. Less relative density and improved L/D ratio are necessary for improved skirted footing performance.
(Thakare and Shukla, 2016)	Rectangular	Increases in the D/B ratio and number of skirts greatly enhanced the footings' ultimate Capacity to support lateral loads. The final lateral load-carrying capacity for shallow footings is significantly impacted by the locations of the skirts, considering the direction of loading. As the inclination of the load in the plan increases, so does the footing's load-carrying Capacity.
(Khatri et al., 2017)	Square and rectangular	The bearing capacity of skirted foundations is 0.25 b, 0.5 b, and 1 b, respectively, for a skirt length was found to be improved over foundations without a skirt in the range of

study	Shape of skirt	Result
		33.3% to 68.5%, 68.9% to 127%, and 146.7% to 262%.
(Gnananandarao et al., 2018)	Plus, shaped	The bearing capacity of the H-plan-shaped foundation was marginally greater than that of the square foundation at a given relative density.
(Sajjad and Masoud, 2018)	Circular	Shallow foundation settling can be decreased to 8% of that of foundations without skirts, and their ultimate bearing capacity can increase up to 5 times.
(Thakur and Dutta, 2020)	Hexagonal skirts, both single and double	With the single-skirted hexagon foundations using 3 grains of sand, the largest enhancement in bearing capacity is 57.67%, or Ds/b = 1.5, while the smallest enhancement is 9.1% at a Ds/b = 0.25. The double-skirted hexagon foundations indicated the greatest enhancement of 56.9% at a Ds/b = 1.5, while the smallest enhancement was 11.73% at a Ds/b = 0.25. The carrying capacity of doubly skirted footings is slightly higher than that of skirted hexagonal footings.
(Gnananandarao et al., 2020)	Plus, and the double box	At a relative density of 30%, the double-sided box-shaped foundation with Ds/b = 1.5 exhibited the highest percentage enhancement, 364.12%. In contrast, the square in shape foundation with Ds/b = 0.25 had the most minor percentage enhancement, 26.08%, at a relative density of 60%. This experiment showed that skirts could reduce settlement by 0.16 to 1 according to the skirt's length ratio and pressure.
(Parmar and Patel, 2021)	Isolated Square Skirted	Factors such as skirt length and placement depth mostly determine the impact of skirt angle on improving bearing capacity. For every embedding depth, the 60º —45º skirt-angled footings exhibit the most increase in bearing Capacity.
(Magdy et al., 2022)	Circular and square	Regarding load-settlement behaviour, a comparative analysis of skirted foundations with two different shapes, circular and square, has revealed that the circular skirted foundations perform better overall. More specifically, when both are placed under similar circumstances, circular skirts can result in higher acquires in bearing capacity and reduced settling compared with square skirts. For example, when compared to typical foundations, circular skirted footings can enhance the maximum load ability by 8.97 times, while square foundations can only

study	Shape of skirt	Result
		increase the ultimate load capacity by a maximum of 5.67 times when the skirt depth ratios are the same.
(Abd-Alhameed and Albusoda, 2023)	Square	The square footing sitting on gypseous soil without a skirt saw a reduction in the settlement ratio (S_r) from (1) % to (0.14) at ds/b, equivalent to 1.5 at θ =0° with the Y-axis (Where θ is the supplied load's inclined angle); additionally, the square skirted footing for ds/b, comparable to 1.5 with θ =15° with the Y-axis, saw an increase in bearing capacity of approximately (193) %.

Previous studies indicate that the best way to choose a skirting foundation design is to comprehend how various shapes affect bearing Capacity, settlement behaviour, and load distribution. In general, circular skirting foundations perform better in terms of load-settlement behavior. Further, when both are placed under comparable conditions, circular skirts can result in higher bearing capacity and lower settlement than square skirts. In comparison to the square foundation, the H-plan-shaped foundation had a substantially larger carrying capacity at a given relative density.

3. FAILURE MODES

- **Shear failure** is the most frequent mode of Failure for skirted foundations, especially shallow foundations. When too much load is placed on the soil surrounding the skirt, shear failure occurs. The failure mechanism is the creation of a slip surface surrounding the skirt, which results in a loss of soil strength and stability. Depending on the loading conditions and the geometry of the skirt, the slip line's shape may change **(Hussein et al., 2021)**.
- **Compression failure** Skirted foundations may fail under compressive loads because of high vertical tension, which causes soil consolidation and potential settlement. The undrained shear strength of the soil, especially for cohesive soils, affects this failure mode. The stiffness ratio of the skirt and the surrounding soil can impact the amount of the failure mechanism that occurs **(Mana et al., 2012).**
- **Uplift failure** Uplift forces can also cause skirting foundations to fail when applied to vertical loads. This collapse mechanism is significant in offshore applications where the foundation may be subjected to floating forces. The skirt's kinematic soil failure mechanisms may cause the soil to be pulled upward, which would cause the foundation to lose its ground anchorage **(Mana et al., 2012).**

(Schneider and Senders, 2010) Three potential reasons skirted foundations can fail were identified (as indicated in **Fig. 2**). Installing skirts transfers the process responsible for shallow footing failure to lower soil layers, possibly leading to harder soils (i). In the case of deep skirts (ii), a flow-round mechanism could occur at the skirted foundation's base. Resistance would be mobilized both there (Qb=qb·Ab) as well as along the sides of the skirted foundation (Qs=τfπDL, where τf is the friction caused by the unit shaft running beside the skirting footing). If the interior soil and the skirting foundation's top plate are separated enough for plug movement to happen, and if the plug resistance (internal shaft friction, Qs, in) is less than the end bearing resistance (Qb), the failure mechanism shown in (iii) may occur. In this instance, end bearing resistance (qb) is limited to the skirting foundation's annulus, and frictional internal and exterior shafts influence the final vertical resistance.

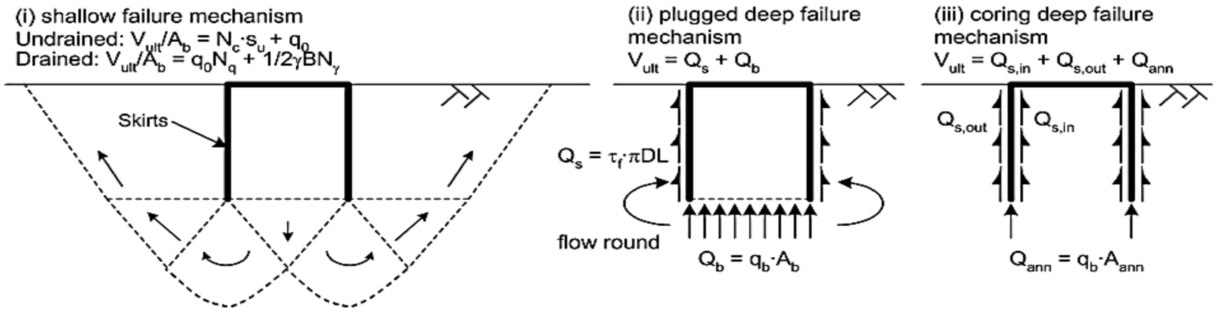


Figure 2. Failure mechanisms for vertical compression loading of skirted foundations/suction caissons **(Schneider and Senders, 2010).**

4. USING A SKIRTED FOUNDATION FOR SUPPORTING FOUNDATIONS UNDER SEISMIC LOAD

Several studies were carried out to assess the performance of skirt foundations in seismic zones. **(Azzam, 2015)** Finding the confined soil footing system by such skirts decreased the acceleration of the foundation, enabling it to be utilised as a damping element and reducing the disturbance expressed to the slope adjacent to it. This approach is a successful method to reduce the acceleration of the slope during earthquakes and control the deformation of the slope. The slope foundation soil structure with skirts' lateral movement time history (**Fig. 3**) demonstrated that the top point had a small amount of slope deformation and that toe point #3 had the largest horizontal deformation. As observed in recorded point #4, which had the least amount of horizontal deformation during an earthquake, the skirts also impacted and reduced the horizontal movement of soil between the skirts.

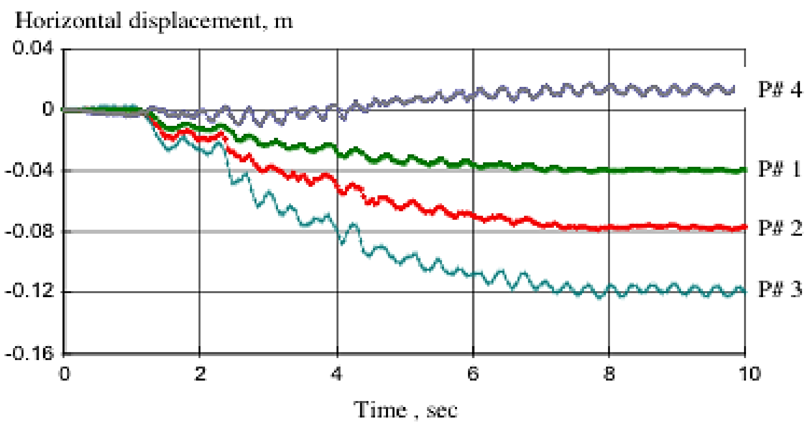


Figure 3. Horizontal displacement time history for slope during the earthquake **(Azzam, 2015).**

(Kumar et al., 2021) A composite skirted ground reinforcing system was designed to reduce the production pressure from water in liquefiable soils and minimize the foundation's exposure to entering earth vibrations. The composite approach uses polyurethane foam to reduce vibration and stone columns as an isolating wall to increase soil densification and permeability. To determine the effectiveness of this method, its performance was assessed according to conditions of recurrent quickening loading. A saturated ground model with a relative density of 40% and 60% was generated for testing, and it was studied using and without composite reinforcing. The tests' findings demonstrated that, compared to unreinforced earth, the designed skirted ground reinforcement system enhances the soil's resistance to liquefaction and efficiently reduces the conflict between the impending ground vibrations in conjunction with the foundation. **Fig. 4** shows the time needed to reach the maximum pore pressure value in skirting ground reinforced [PUFSC-R] and unreinforced [UR] soil deposits under repeated loading scenarios when they were ready for a 40% density condition.

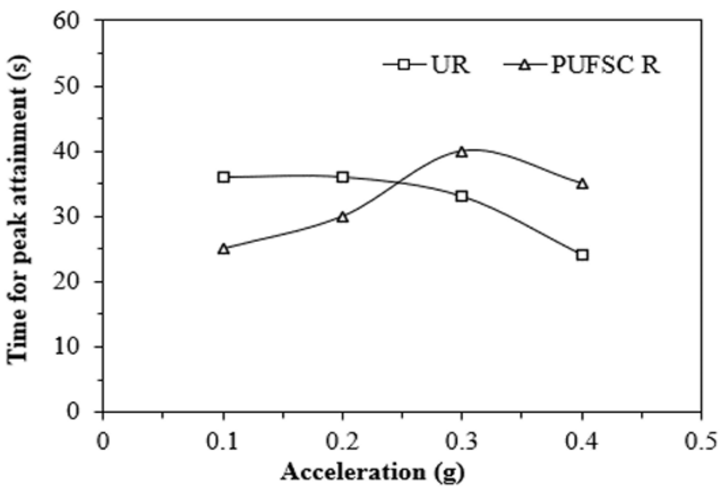


Figure 4. The relationship between peak attainment and acceleration **(Kumar et al., 2021).**

(Moghadam, 2023) The behaviour of square-skirted footings beneath compressive loads, both static and earthquake, is the main subject of this study, which employs physical and numerical modeling methods. Taking into account vertical load circumstances with a 40% soil density, it particularly evaluates the impact of the depth of the skirt on the foundation's bearing capacity and settlement. Various skirt depth-to-width ratios (d/b) of 0, 0.5, 1, and 1.5 are considered in the analysis. The findings show that adding skirts enhances surface footings on sand's bearing capability and settling characteristics, and these benefits increase with the depth of the skirt. These results imply that skirt installation is useful for lowering vertical displacements and accelerations, strengthening footing resistance, and enhancing the structure's capacity to withstand seismic stress.

In summary, skirted foundations are suitable for supporting foundations in seismic zones since they function better under earthquake stresses and have improved stability and liquefaction risk mitigation. The skirt's length and angle should be carefully selected to enhance its efficiency in earthquake-prone areas.

5. CONCLUSIONS

After presenting the previous studies on skirt foundation, the following conclusions can be obtained:

1. Skirted foundations enhance bearing capacity compared to non-skirted foundations by a factor of 1.5 to 3.9, depending on the specific geometric and load conditions. Longer and deeper skirts improve load-bearing capacity and minimize settling. The effects of using skirts to reduce settlement varied from 0.16 to 1.0, based on the length ratio of the skirt and the pressure used. For sand with relative densities of 30% and 50%, the skirted footings proved more efficient than those of 70% and 87%. Their enhanced load-bearing capacity makes skirted foundations suitable for supporting bridges and other large structures, particularly in challenging soil conditions. Skirted foundations can be utilized in urban construction to provide better stability and less settlement in soft soil environments.
2. Using skirts can improve the footing when sitting on gypseous soil. Bearing capacity was enhanced by about 190%, and the settling was reduced by about 186% when using a skirt for a length equivalent to 1.5 from the width of the square footing and applying a vertical load.
3. The skirt angle affects stability; the improvement factor (IR) will increase with a greater skirt angle as the angle increases from 10° to 30°. The value of the inclined skirts' significant reduction in skirted foundation settlement exceeds 80%.
4. According to a comparative study of skirted foundations with different shapes (square vs. circular), circular skirted foundations perform better overall in load-settlement behaviour. An insignificant difference was observed between the bearing capacities of square footing and H-plan-shaped footing. The double-skirted design significantly increases bearing capacity compared to hexagonal footings with single skirts.
5. The loosely skirted circular system placed underneath the footing improves the stress-settlement behaviour and bearing capacity of surface foundations by a ratio of 1.19 to 3.36.
6. Implementing skirts effectively decreases vertical displacements and acceleration, strengthens the foundation, and dramatically increases the structure's ability to withstand seismic loads. Skirted foundations will likely become increasingly prevalent in modern engineering practices, particularly in earthquake-prone areas.

NOMENCLATURE

Symbol	Description	Symbol	Description
B	Foundation width, m.	L	Skirt length, m.
BCR	Bearing capacity ratio	D	Footing diameter, m.
D_s	Skirt depth, m.	D_f	Foundation depth
	Depth of wall, m.	H	Distance between footing and wall
E	Load eccentricity, m.	IR	Improvement ratio
Sr	settlement ratio	RD	Relative density
θ	Load's inclined angle		

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Credit Authorship Contribution Statement

The authors have read and approved the manuscript. Rawaa Rafea wrote the original draft of the manuscript. Bushra Suhale, reviewed and edited the manuscript.

Declaration of Competing Interest

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

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دراسة مراجعة لتقييم أداء الاساس ذو الحواف

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الخلاصة

تُستخدم الدعامات الهيكلية المبتكرة، والمعروفة باسم الأساسات ذات الحواف في المقام الأول في الهندسة البحرية. تمتد الأساسات ذات الحواف أسفل الأساسات مثل الأساسات الضحلة التقليدية وتحمل الأحمال إلى طبقات التربة العميقة. "الحواف" عبارة عن جدار يحيط بالأساس من جانب واحد أو أكثر، وهو متصل بالأساسات ويعمل كوحدة واحدة. تتميز الحواف بحوائط عمودية أو مائلة لتحسين القدرة على تحمل الأحمال وتقليل الهبوط وتقليل الفشل الانزلاقي. تعتبر هذه الحواف ضرورية لتحسين الثبات الكلي ونقل الأحمال إلى طبقات تحت سطحية أكثر استقراراً، مما يحسن أداء الأساس. إن الميزات الهامة للأساسات ذات الحواف تجعلها واعدة من الناحية الاقتصادية ومناسبة للاستخدام في الإنشاءات ذات الأحمال الكبيرة وظروف التربة السيئة. وقد ثبت أن الأساسات ذات الحواف هي بديل أكثر فعالية للأساسات التقليدية مثل الركائز وركائز الجسور وغيرها. كما أنها تعتبر اقتصادية بسبب تقليل استخدام مواد البناء، وتقليل استخدام الآلات، وتقليل عدد القوى العاملة، فضلاً عن توفير الوقت اللازم للتركيب. تلخص هذه الورقة البحثية الدراسات العملية والنظرية السابقة على الأساسات ذات الحواف وتستعرض خصائصها؛ ويمكن تلخيص اهم الاستنتاجات: أعطت نسبة طول الحواف إلى عرض الأساس (2) أفضل النتائج في تحسين قدرة التحمل وتقليل الهطول. زاد الحمل النهائي عندما زاد ميل الحواف من 10 درجات إلى 30 درجة لأنه تم إنشاء منطقة ارتباط بين الزاوية المائلة والتربة. يمكن أن تؤدي الحواف الدائرية إلى قدرة تحمل أعلى وهطول أقل من الحواف المربعة عندما يتم وضع كلاهما في ظروف مماثلة. كما أن الأساسات ذات الحواف مناسبة لدعم الأساسات الضحلة في المناطق الزلزالية.

الكلمات المفتاحية: الأساس ذو الحواف، قدرة التحمّل، الهبوط، أساس الدلو.