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Experimental and Numerical Parametric Studies on Inclined Skirted Foundation Resting on Sand

Tamer Al-Shyoukhi [1*], Mahmoud Elmeligy [1], Ayman I. Altahrany [1]

[1] *Structural Engineering Department, Faculty of Engineering, Mansoura University, Mansoura, Egypt.*

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Abstract

Skirted foundation behavior is enhanced due to the increase in skirt angle. The bearing capacity of the inclined skirted foundations resting on sandy soil is influenced by the soil parameters and skirting systems. Finite element analyses were carried out using Plaxis-3D software to find out the influence of the relative density, the internal friction angle of the supported soil, and the additional skirts on the bearing capacity of the inclined skirted foundations. The experimental work on a small physical scale was also carried out to support the numerical findings, which give an acceptable agreement. The findings revealed that the increase in relative density resulted in a significant increase in the bearing capacity of the inclined skirted foundation. In the same way, as the internal friction angle increases, the bearing capacity is affected by this increase, which improves the bearing capacity value. The effect of the additional skirts on the bearing capacity is observed to be neglected, and, in some cases, it causes a negative effect. The findings of this study contribute to a greater comprehension of the behavior of inclined skirted foundations and can assist in the future design of more efficient and effective foundation systems.

Keywords: Inclined-Skirted Foundation; Bearing Capacity; Sand; Internal Friction Angle; Relative Density; Additional Skirt.

1. Introduction

The purpose of the foundation is to transfer the building's loads to the supporting soil. Based on load quantity, soil capacity, and structural requirements, there are primarily two types of foundations: shallow and deep. In most cases, the load is light enough to be supported by the existing soil; however, when the soil is relatively soft and the water table is high, deep foundations are an excellent alternative. In certain geotechnical cases where shallow foundations are inadequate and deep foundations are too conservative, semi-deep foundations, such as skirted foundations, can be used.

A skirted foundation is a shallow foundation attached with thin plates (skirts) at the foundation’s perimeter. These skirts may be reinforced concrete or mainly steel, which is preferable due to ease of installation. These plates are installed at different depths according to the degree of improvement required. The added skirts restrict the soil, restrict the lateral movement of the soil below the foundation during shear deformation, and transfer the load to a deeper level. Generally, skirts are installed vertically to create a soil block under the foundation, which enhances the bearing capacity and settlement performance. Various experimental and numerical investigations and studies were carried out to assess the behavior of vertically skirted foundations in terms of bearing capacity and settlement [1–6]. The findings of these studies consistently indicate that the presence of skirts results in a notable improvement in the performance of foundations, with increased load-bearing capacity and reduced settlement. The integration of skirts has been observed to have a substantial impact on the behavior of foundations, leading researchers to concentrate on examining the effects of various parameters on the efficacy of skirted foundations.

* Corresponding author: tamershyoukhi@std.mans.edu.eg; shtamer@outlook.com

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ShabanaSalih & Joseph (2017) conducted experimental studies on skirted foundations resting on non-uniform sand to find out the effect of the sand conditions. They found that the skirts control the tilt of the footing at the weaker portion [7]. The effect of the skirt angle on the skirted foundation's behavior was also investigated. Vijay et al. (2020) studied the effect of the internal inclined skirts along with the outer vertical skirt on the skirted foundation behavior [8]. They proved that the internal inclined skirts have a significant effect on the bearing capacity of the skirted foundations. Based on Lepcha et al. (2021), numerical studies on skirted foundations were performed to find out the effect of skirt angle, and it was found that the bearing capacity improved as the skirt angle increased [9]. The inclined skirted foundation revealed reliable improvements in terms of bearing capacity and settlement reduction. Al-Shyoukhi (2023) compared vertically skirted foundations to 10^0 inclined skirted foundations with the same embedded skirt length, revealing that the inclined skirted foundation provides two and a half times the bearing capacity as the vertically skirted foundation [10]. However, despite the extensive research on skirted foundations, there remains a notable research gap concerning the investigation of the specific effects of parameters such as soil relative density, internal friction angle, and the presence of internal vertical skirts on the behavior of inclined skirted foundations.

The relative density of the sand, the internal friction angle, and the presence of additional vertical skirts may increase the bearing capacity of the inclined skirted foundation. In this study, 10^0 inclined-skirted foundations were selected as the reference case. This foundation rested on loose sand with a relative density of 35%, as reported by Al-Shyoukhi (2023) [10]. Finite Element Analyses were carried out using Plaxis-3D software and supported by experimental tests to find out the effect of the chosen parameters in this paper. Increasing the relative density of the sand and the internal friction angle increased the bearing capacity compared to the reference case. However, the addition of vertical skirts slightly reduced the bearing capacity of inclined skirted foundations compared to those with only external skirts. This study aims to provide valuable insights into optimizing inclined skirted foundations resting on sand.

2. Finite Element Analysis

Detailed three-dimensional modeling with the use of finite element software Plaxis-3D [11] of a vertically loaded square inclined-skirted foundation resting on sand was done to determine the influence of the relative density of the sand, the internal friction angle, and the additional skirts on bearing capacity.

2.1. Modelling and Material

Based on Magdy et al. (2022) and Magdy (2022), the data for this study were gathered and adopted due to their availability in the laboratory [12, 13]. According to Eid (2013) and Schanz et al. (2019), the appropriate constitutive model for describing soil behavior is the Hardening Soil Model (HS) [14, 15]. The HS model is a constitutive model used to describe the mechanical behavior of soil. The HS model considers the effects of soil compression, dilation, and hardening (increased stiffness) due to applied loads, in addition to the effects of different factors, such as initial void ratio and plastic strains, to capture the complex behavior of soil. According to the HS model, soil stiffness is represented as secant stiffness, E_{50}^{ref}, tangent stiffness, E_{oed}^{ref}, and unloading/reloading stiffness, E_{ur}^{ref}. While sand is purely frictional soil, the software provides a tiny measure of cohesiveness by default without significantly influencing the findings. As numerical parametric investigations are backed by experimental ones, a 60×60×20 mm, Physical Square footing model will be employed in this research. The skirt angle is 10, and the skirts will be placed at various depths ranging from 0.25 to 1.00 in terms of skirt-length/footing-width ratio. The additional skirts will have the same properties as the inclined skirts but will be installed vertically. Linear Elastic Model is used to represent the footing and skirts. Table 1 summarizes the used material properties. The dimensions and properties of the inclined skirted foundation are shown in Figure 1.

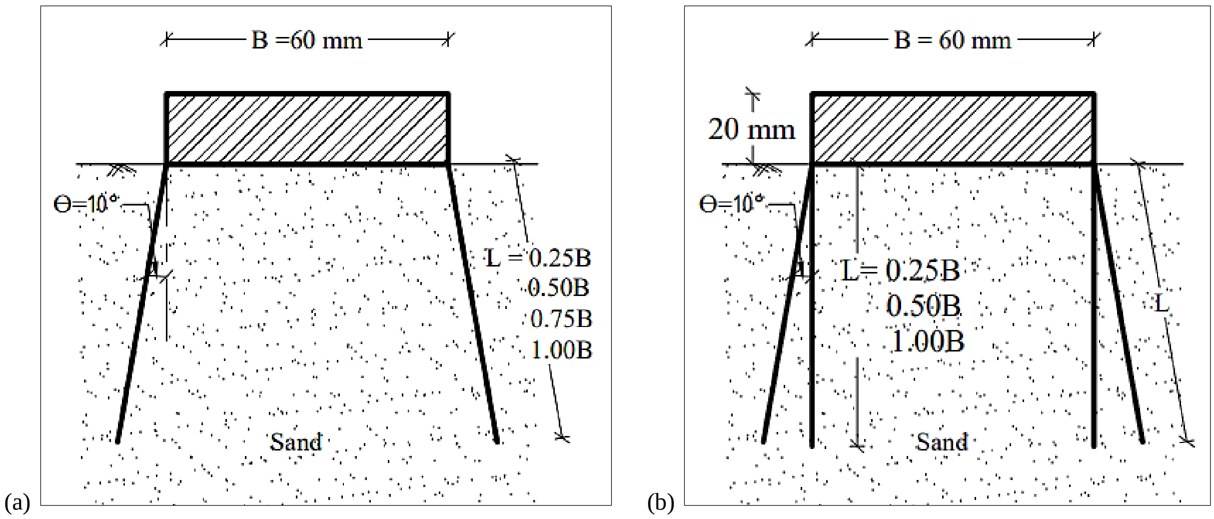


Figure 1. Schematic diagram of (left) inclined-skirted foundation, (right) additional vertical skirts

Table 1. Material properties used

Parameter	Soil	Footing &Skirts (steel)
Material Model	Hardening soil	Linear elastic
Unit Weight (kN/m^3)	15.60[a], and 16.05[b]	78
Poisson's Ratio	0.2[c]	0.2
Void Ratio	0.7188[a], and 0.657[b]	N/A
Young's Modulus (kN/m^2)	N/A	2×10^8
E_{50}^{ref} (kN/m^2)	2×10^4[d]	N/A
E_{oed}^{ref} (kN/m^2)	2×10^4[e]	N/A
E_{ur}^{ref} (kN/m^2)	6×10^4[f]	N/A
Peak Friction Angle (degrees)	34.5[a], and 32.5[b]	N/A
Cohesion (kN/m^2)	1[a,b]	N/A
Dilatancy Angle (degrees)[g]	4.5[a] and 2.5[b]	N/A
Interface Strength Factor	0.70 [h]	N/A

[a] Soil No. 1, used in the analysis of effect of relative density; [b] Soil No. 2, used in the analysis of effect of internal friction angle; [c] Soil Poisson's ratio as assumed by Obrzud & Truty (2020) [16]; [d] Soil secant stiffness as concluded by Lengkeek (2003) [17]; [e] Soil tangent stiffness as estimated by Schanz et al. (2019) [15]; [f] Soil unloading/reloading stiffness as estimated by Schanz et al. (2019) [18]; [g] Soil dilatancy angle as suggested by Hong et al. (2019) [19]; and [h] Interface strength factor as reported by Magdy (2022) [13].

To reduce boundary impacts, the soil geometry was taken based on the experimental set-up: 2.5B wide from the footing edge and 5.5B deep from the skirt tip. According to Maleki et al. and Maleki & Imani, adequate consideration should be given to the lateral boundary distance and the distance between the lower bound of the model and the top to minimize the impact of boundaries in the numerical model on the results [20, 21]. The displacement and stress contours shown in the numerical software suggest that the stated distance is adequate. The interface, skirt, footing, and sand were each represented by triangular elements with six, six, 10, and 12 nodes, respectively. The chosen element configurations were determined based on their suitability for capturing the desired behavior and interactions within the system.

2.2. Meshing

The generation of a suitable mesh is a crucial aspect of achieving precise and reliable outcomes from computational simulations. This is due to the fact that it guarantees the representation of fundamental features and the behavior of the system being analyzed. Moreover, the computational efficiency of the simulation can be significantly impacted by the quality of the mesh, as more efficient and well-structured meshes tend to yield faster and more precise outcomes. According to Maleki et al. (2022) and Maleki & Nabizadeh (2021), to generate meshing in numerical models, multiple numerical simulations were conducted utilizing varying mesh dimensions. The mesh dimensions were gradually reduced until the changes in displacement became negligible [22, 23]. Furthermore, to enhance the precision of computations, the concentration of elements is increased in the surrounding area of the foundation. Numerical simulations were conducted on a surface footing measuring 60 mm, which was supported by sand. The simulations utilized three distinct mesh sizes: coarse, medium, and fine. The selection of a medium-mesh size with a finer local mesh around the footing is indicated by the data presented in Figure 2. According to Das (2011), since the foundation is supported by loose sand, the load-settlement curve does not have a precise value indicating the ultimate bearing capacity [24]. Thus, the ultimate bearing capacity was selected to correspond to a 20% settlement (S) of the footing width (B) [12]. The mesh approach utilized in numerical modeling is seen in Figure 3.

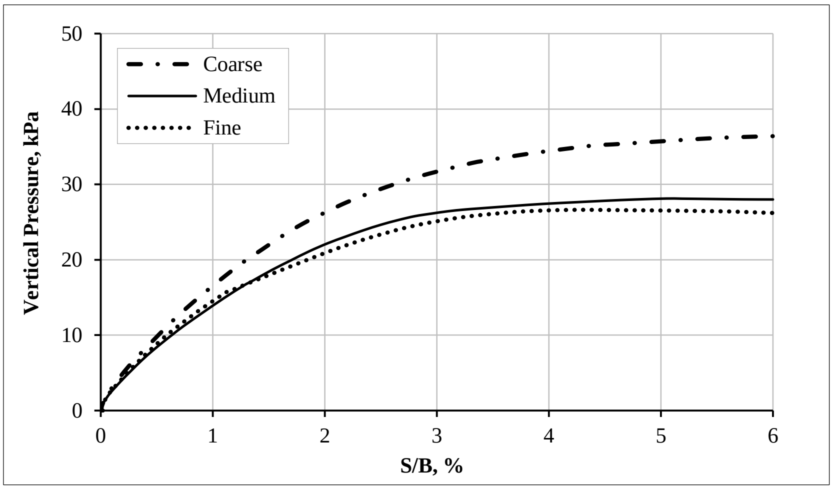
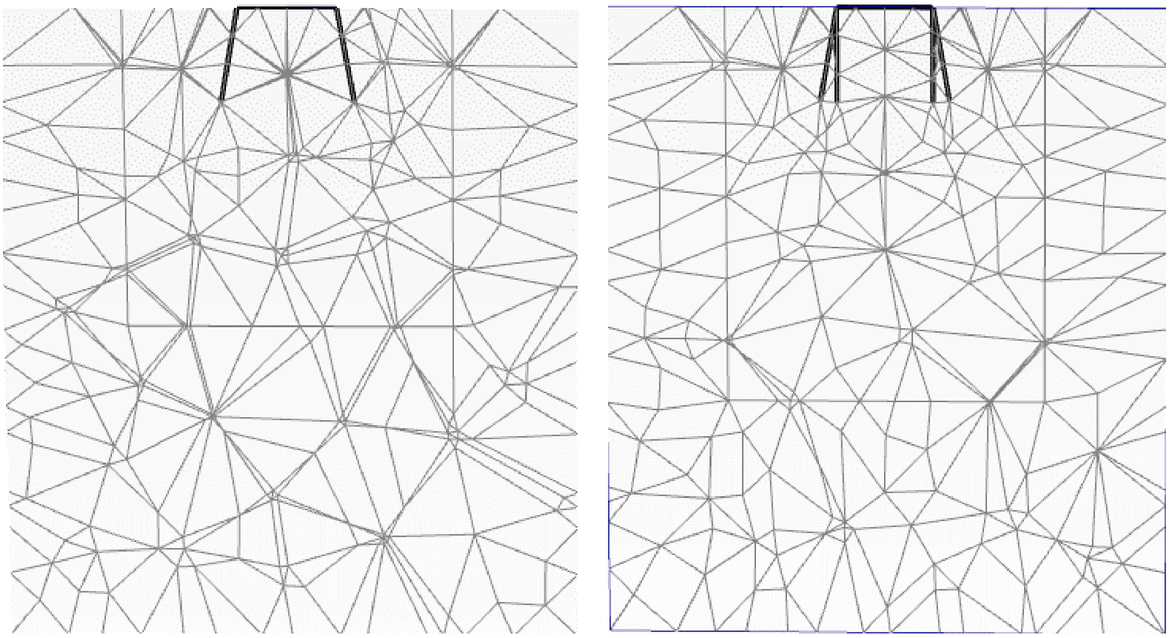


Figure 2. Surface footing behavior using different mesh sizes



(a) (b)

Figure 3. Meshing for (a) inclined-skirted, (b) additional skirt

2.3. Calculation Process

The calculation process comprises four distinct phases. During the initial stage, the assignment of initial stresses was conducted utilizing the K_o Procedure. During the second phase, known as the "skirt" phase, and the subsequent third phase, referred to as the "footing" phase, the interfaces, skirts, and footing were activated. During the final phase of the process, known as "prescribed displacement", the assigned displacement was activated, and a plastic analysis was carried out. Significantly, the resetting of displacement to zero was implemented during the fourth phase, thereby limiting the analysis to the loading phase exclusively. Through the division of the calculation process into discrete phases, the simulation can be executed in a systematic and organized way, thereby guaranteeing the precision, reliability, and uniformity of the outcomes. The flowchart of the numerical simulation is shown in Figure 4.

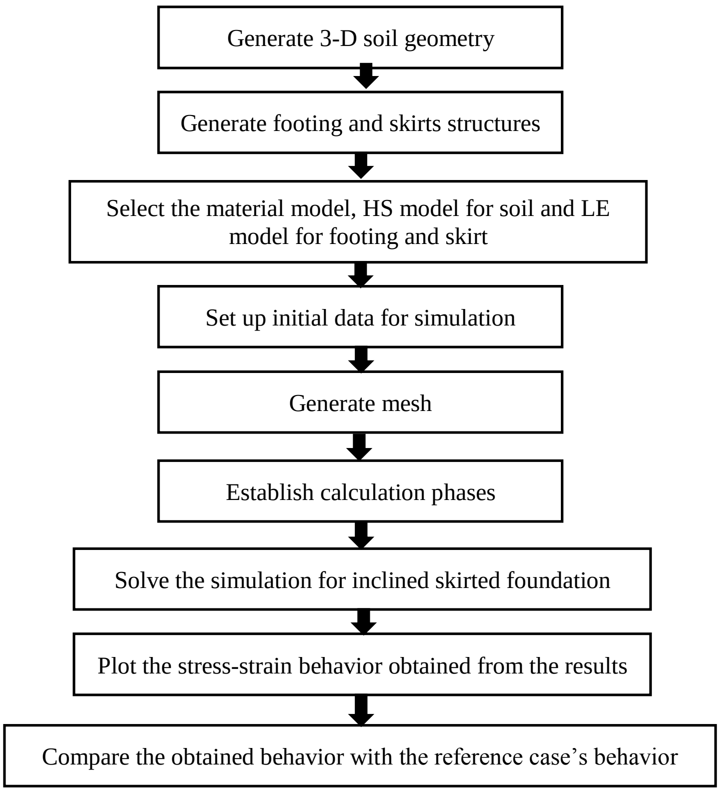


Figure 4. Flowchart of the numerical methodology

3. Experimental Program

3.1. Testing Setup

Extensive experimental testing was conducted to validate the numerical results. The foundation is represented by a small steel model measuring 60 mm in width and having a thickness of 20 mm. While the skirts were built of 2-mm-thick welded plates. The length of the inclined skirt varies between 0.25, 0.50, 0.75, and 1.0 of the foundation size B at an angle of 10^0. The lengths of the additional vertical skirt were 0.25, 0.50, and 1.0B. Sand Nos. 1 and 2 were borrowed from Gammasa City, Egypt. Sand No. 1 was utilized in the reference case with a relative density of 35%, the case in which the relative density was changed to 60%, and in the case of additional vertical skirts. However, Sand No. 2 was used to determine the effect of altering the internal friction angle. As reported by Magdy (2022), the test tank was placed on top of a movable cap with a strain rate of 1 mm/min [13]. See Figure 5 for the dimensions of the test tank: 360 mm outer diameter, 550 mm height, and 3 mm rigid steel thickness. The Proving Ring and Electronic Dial Gauge were employed to determine the applied load and footing displacement, respectively. The precision of both gauges is 0.001 mm. The proving ring has a maximum capacity of 4.5 kN, and the electronic gauge is 25 mm. The gauges used were meticulously calibrated by the National Institute of Standards (NIS) (2022), ensuring their accuracy and traceability [25].

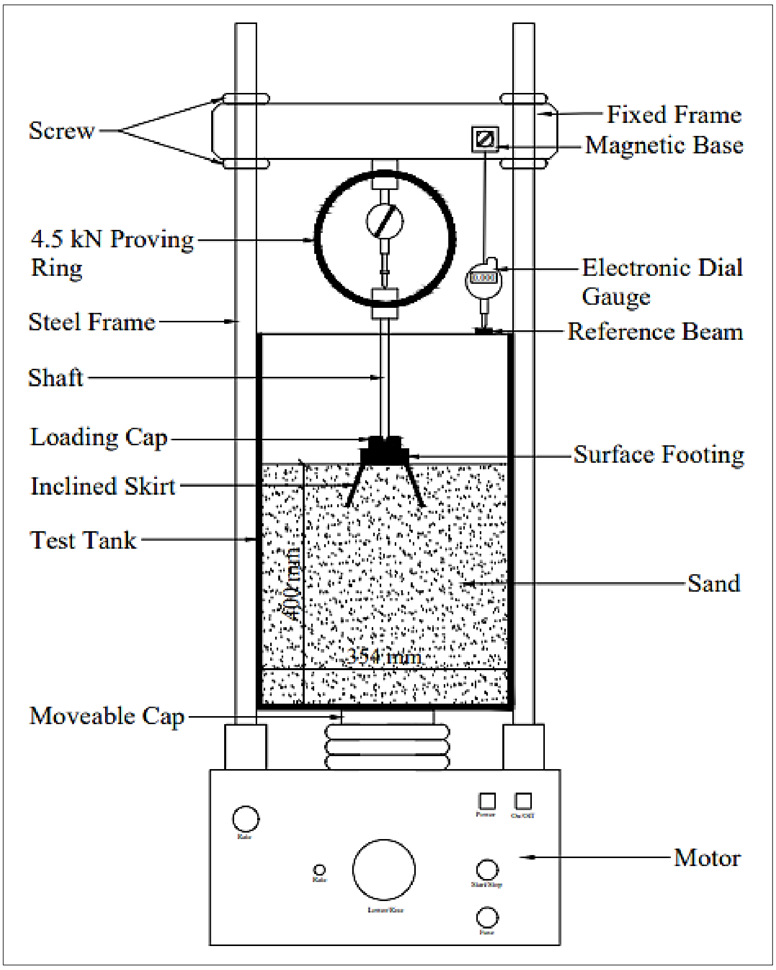


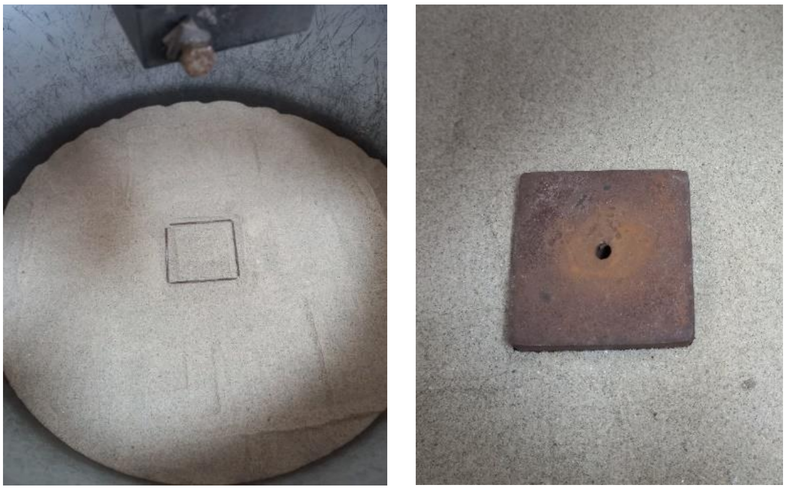
Figure 5. Schematic diagram of the apparatus used

3.2. Testing Procedure

The test tank or soil bin was filled with 400 mm of sand in five layers of 80 mm each and compacted to achieve the desired relative density. To assure layer-to-layer compatibility, the placed layer's upper surface was scraped before adding the next one. The sand was added until the skirted foundation had been positioned at the correct height. See Figure 6. After that, the sand was dropped and compacted carefully. The installation process involved a significant focus on implementing measures aimed at reducing fluctuations in relative density. Refer to Figure 7 for an illustration of the process of leveling the final surface and placing the footing with the skirt model. Refer to Figure 8 for an image of the calibration process of load and settlement measurement gauges, which involves resetting them to zero before the beginning of the test. The movable cap was gradually displaced at a rate of 1 *mm/min*. The displacing was stopped at the required settlement of 20% of the footing's width, B. Each test was repeated at least twice to ensure the reliability and consistency of the results, with the criterion that the variation between the repeated tests' results was less than 5%. At the end of each test, the sand was completely replaced with a fresh one. The experimental results were compared with numerical outcomes to validate the latter's findings.

(a) (b)

Figure 6. The surface of sand (a) the proper height before installing the skirt model, (b) after installing the skirt model



(a) (b)

Figure 7. The final surface of sand (a) before installing the footing model, (b) after installing the footing model

Figure 8. Measurement gauges set to zero

4. Result and Discussion

4.1. Validation

To establish the credibility of the proposed models, a comprehensive verification process was undertaken, incorporating both experimental and numerical approaches. The verification primarily focused on a representative case involving a 60-mm-square surface footing resting on sand. In the experimental test, the footing underwent vertical loading conditions, and precise measurements of vertical pressure and settlement were recorded. These experimental results were subsequently compared with relative findings from the existing literature [13]. Notably, the comparison exhibited a remarkable level of concurrence between the experimental data and the reported results, thus demonstrating strong consistency and reliability. Additionally, numerical simulations were conducted employing the representative case, and the resulting outputs were compared with the corresponding experimental data. Once again, close behavior was observed, further substantiating the validity and accuracy of the utilized models (see Figure 9). In each case of investigation, the experimental results are in reasonable agreement with the numerical ones. The numerical and experimental approaches' findings will be illustrated in terms of stress-settlement relationship curves. The discussed studies are presented in the following subsections.

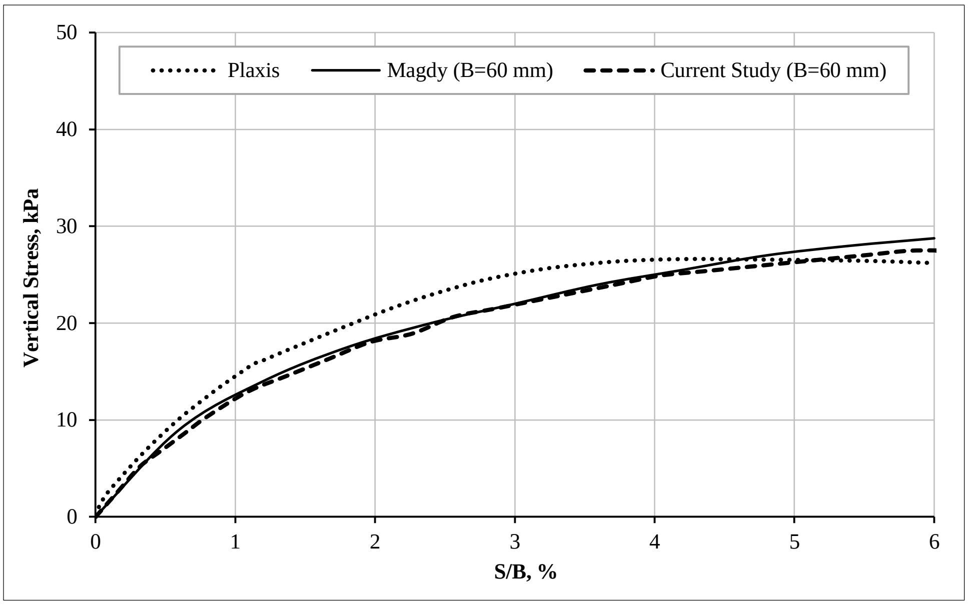


Figure 9. Comparison of the experimental and numerical results obtained from the verification study

4.2. Effect of the Relative Density

The relative density of Sand No. 1 for the reference case was 35%, and the relative density of 60% was used to determine the effect of relative density on the bearing capacity of the inclined-skirted foundation. Figure 10 illustrates the experimental and numerical results of the bearing capacity behavior of a 10^0 inclined-skirted foundation. It is obvious that relative density has a substantial effect on bearing capacity. As the relative density rises, the soil particles become closer and more interlocked. As the relative density of the soil increases, so does its stiffness and resistance to deformation. Because of the improved stiffness and resistance to deformation, the inclined-skirted foundation can support a greater load without excessive settlement or bearing failure. As concluded by Tripathy (2013), it is also observed that the increase in bearing capacity approaches an exponential relationship with the increase in relative density [26]. In the case of L/B = 1, the increase in bearing capacity is significantly greater than in the case of L/B = 0.25. Due to the increased interlocking of the sub-footing soil. When the skirt cell size increases, the bearing capacity enhancement increases. The experimental and numerical approaches allowed for comprehensive analysis and validation of the results. Figure 11 shows the failure patterns of the inclined skirted foundations at different relative densities generated from numerical analysis. The failure pattern shown in the figure represents the contours of displacement at the given ultimate settlement. The data generated by these types of contours is useful for evaluating the failure pattern and the allowable settlement of the footing [27].

The provided contours are represented at the foundation's ultimate bearing capacity, corresponding to the ultimate settlement. The analysis of these figures reveals that the dimension of the isobar is higher in the case of a relative density of 60% than in the case of a relative density of 35%, indicating that the sand with a relative density of 60% has a greater bearing capacity. The relationship between the relative density and bearing capacity that has been observed provides important implications for the optimization and design of inclined-skirted foundations. This knowledge can be employed by engineers and practitioners to choose suitable relative density values for particular soil conditions, thereby guaranteeing sufficient bearing capacity and reducing the potential for settlement risks. However, this study is subject to certain limitations, such as the focus on a specific range of relative density values.

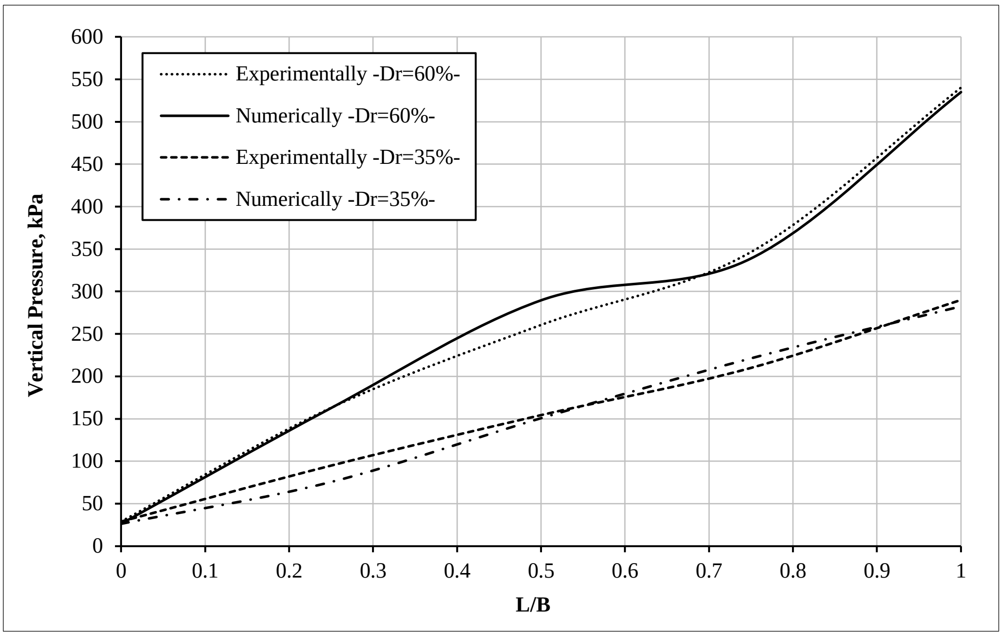
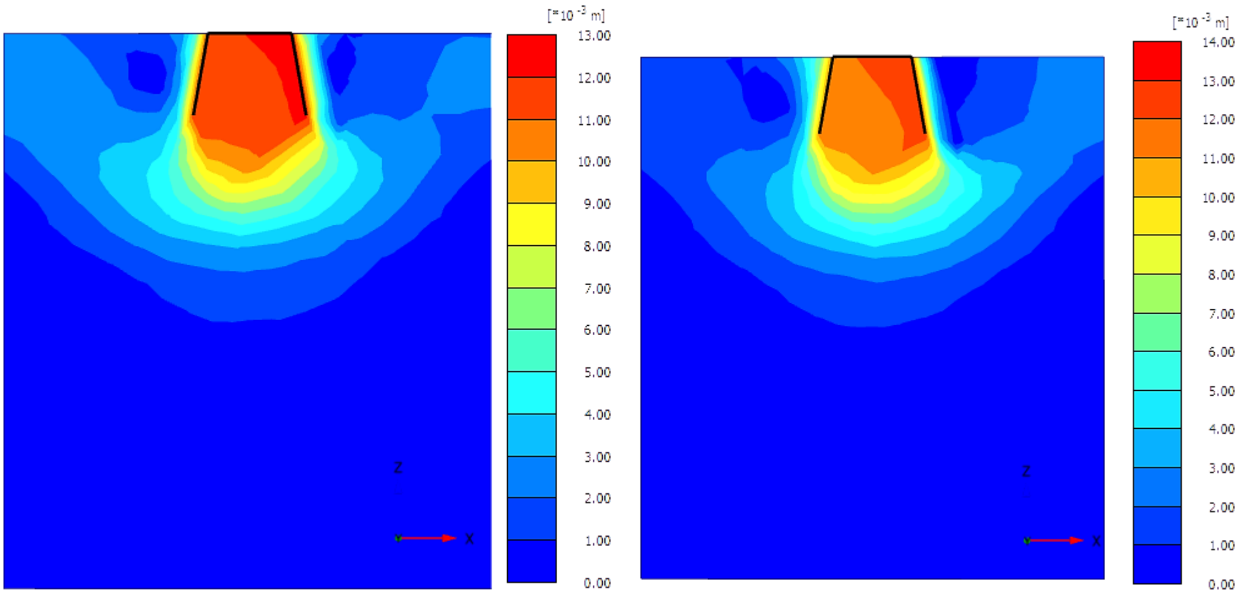


Figure 10. Effect of changing relative density of sand



(a) (b)

Figure 11. Failure pattern of inclined skirted foundations at different soil relative densities, (a) 35% and (b) 60%.

4.3. Effect of Internal Friction Angle

The effect of the internal friction angle on the bearing capacity of the inclined skirted foundation was investigated using Sand No. 2 with a 32.5^0 internal friction angle and compared to the reference case with an internal friction angle of 34.5^0. Figure 12 shows the relationship between bearing capacity and internal friction angle. It has been observed that a greater angle of internal friction results in a greater bearing capacity at the same L/B ratio. Consistent with the established geotechnical engineering knowledge, it can be concluded that an increase in the internal friction angle of the supported soil leads to an increase in the bearing capacity of the skirted foundation. According to Terzaghi (1996), this is because the internal friction angle of the soil is a measure of the soil's shear strength, which is a critical factor in determining the bearing capacity of the foundation [28]. An increase in the soil's internal friction angle increases its resistance to sliding and shear failure. This enhanced resistance to failure enables the foundation to support a larger load without excessive deformation or settlement. Consequently, the bearing capacity of the foundation increases as the internal friction angle of the soil increases. The effect of the internal friction angle on the bearing capacity of the skirted foundations is in similar line with the findings of Tripathy (2013) [26]. Figure 13 shows the failure patterns of the inclined skirted foundations at different internal friction angles of sand. Contour lines show that when the sand has an internal friction angle of 34.5^0 gives a higher value of bearing capacity compared to the internal friction angle of 32.5^0 . The increase in the bearing capacity of the foundation due to an increase in the internal friction angle of the soil has design effects on the foundation. Engineers can specifically select a foundation type and size based on the internal friction angle of the soil to ensure that the foundation can support the required load safely.

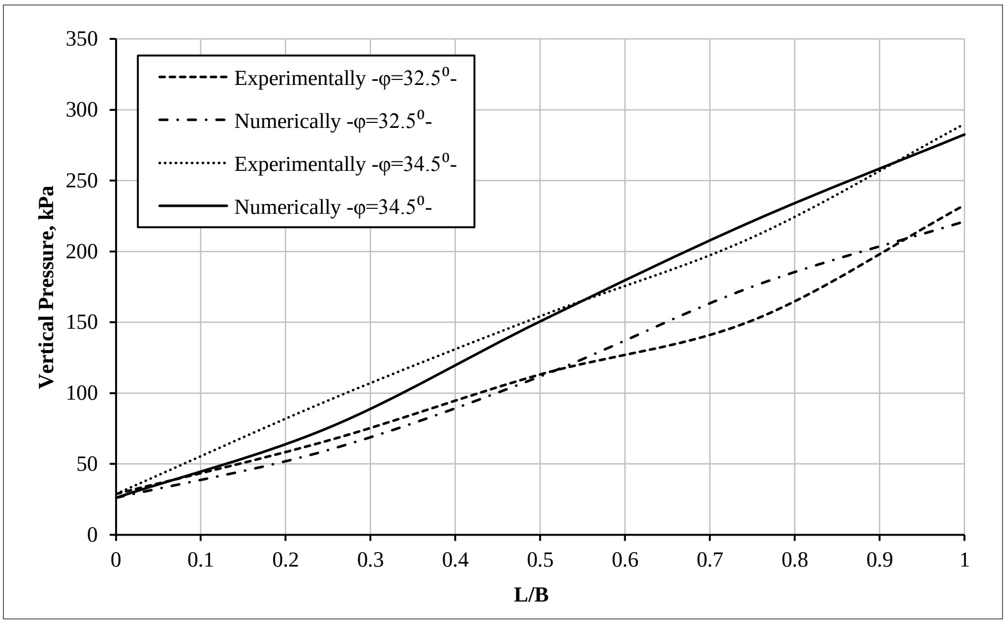


Figure 12. Effect of internal friction angle on bearing capacity of inclined-skirted foundation

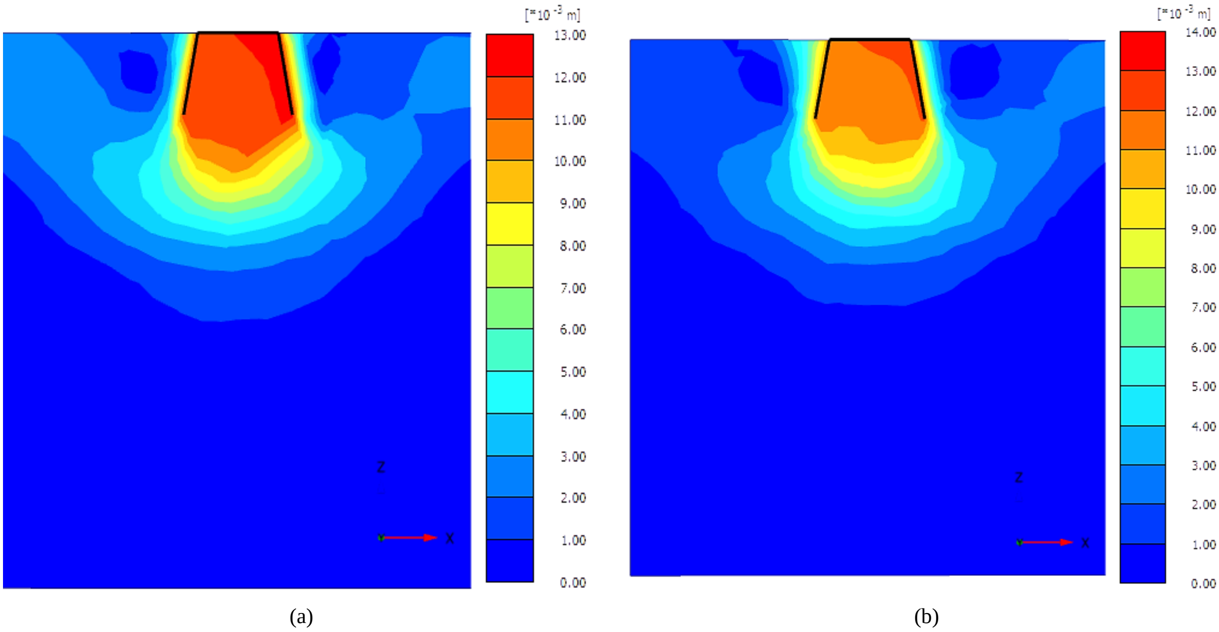


Figure 13. Failure pattern of inclined skirted foundations at different internal friction angles, (a) 34.5^0 and (b) 32.5^0

4.4. Effect of Additional Skirts

The 10^0 inclined skirted foundation with L = 1.0B was utilized to determine the influence of additional skirts on the bearing capacity. The added skirts were installed vertically and measured 0.25, 0.50, and 1.0B in length. The stress-settlement behavior of the inclined skirted foundation with additional skirts is seen in Figures 14 and 15. The experimental results provide a reasonable agreement with the numerical ones. It was observed that the additional skirts have a slight influence on the bearing capacity (the bearing capacity is approximately 280 kPa), but in some instances, they have no impact, such as when the vertical skirt length is 0.5B. The vertical skirt lies within the cell formed by the inclined skirts. Since the additional skirts do not alter the size, shape, or depth of the skirt cells, their effect on the bearing capacity will be minimal. When an additional skirt L = 1.0B is present, a negative effect on the bearing capacity can be observed. These observations are consistent with the findings of Yun et al. (2007) that the addition of vertical skirts slightly reduced the bearing capacity of skirted foundations compared to those with only external skirts [29]. According to Vesic (1973), as soil particles move during loading, they produce a zone of influence around the foundation that can increase its bearing capacity [30]. The additional skirts may prevent the soil particles confined between the inclined and vertical skirts from moving in the same manner as the soil particles beneath the footing, reducing the zone of influence. The bearing capacity decreases as the size of the zone of influence decreases. See Figure 16 of the contour lines in the case of the addition of the vertical skirts (L = 1.0B). It can be seen that the additional skirts have a negligible effect on the bearing capacity.

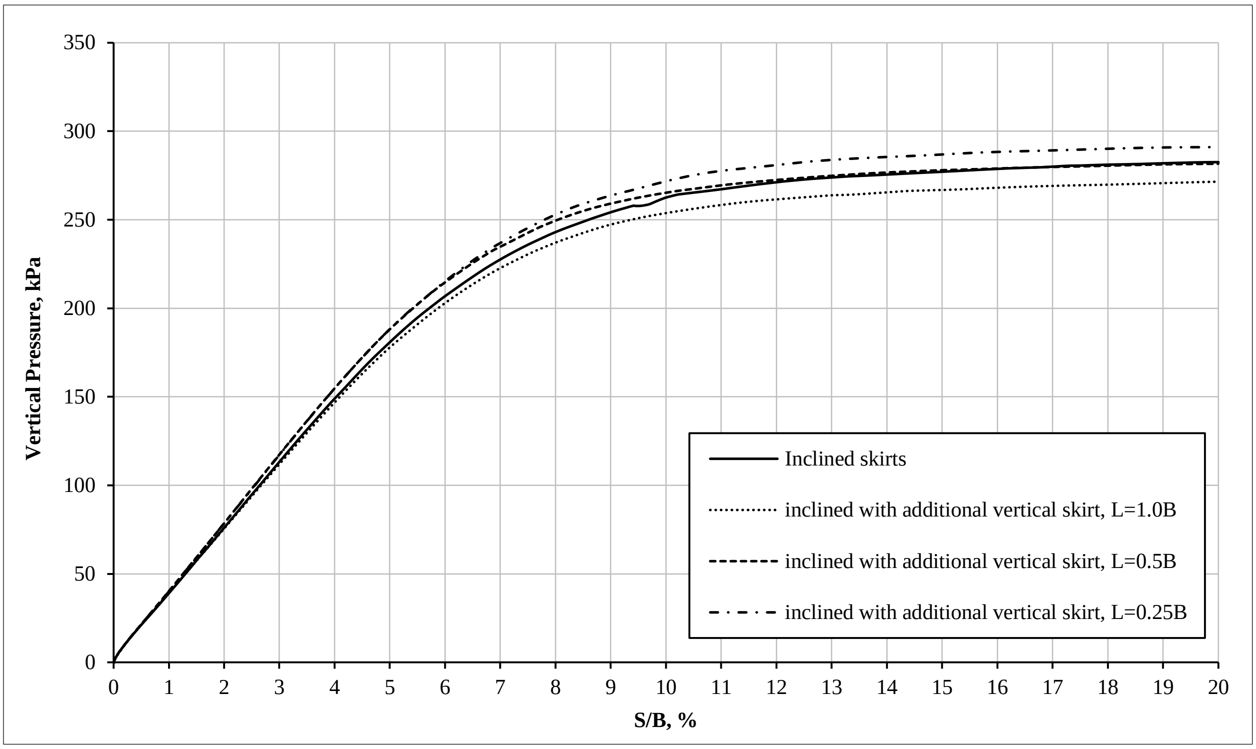


Figure 14. Numerical results of the effect the additional skirts on bearing capacity of inclined skirted foundation

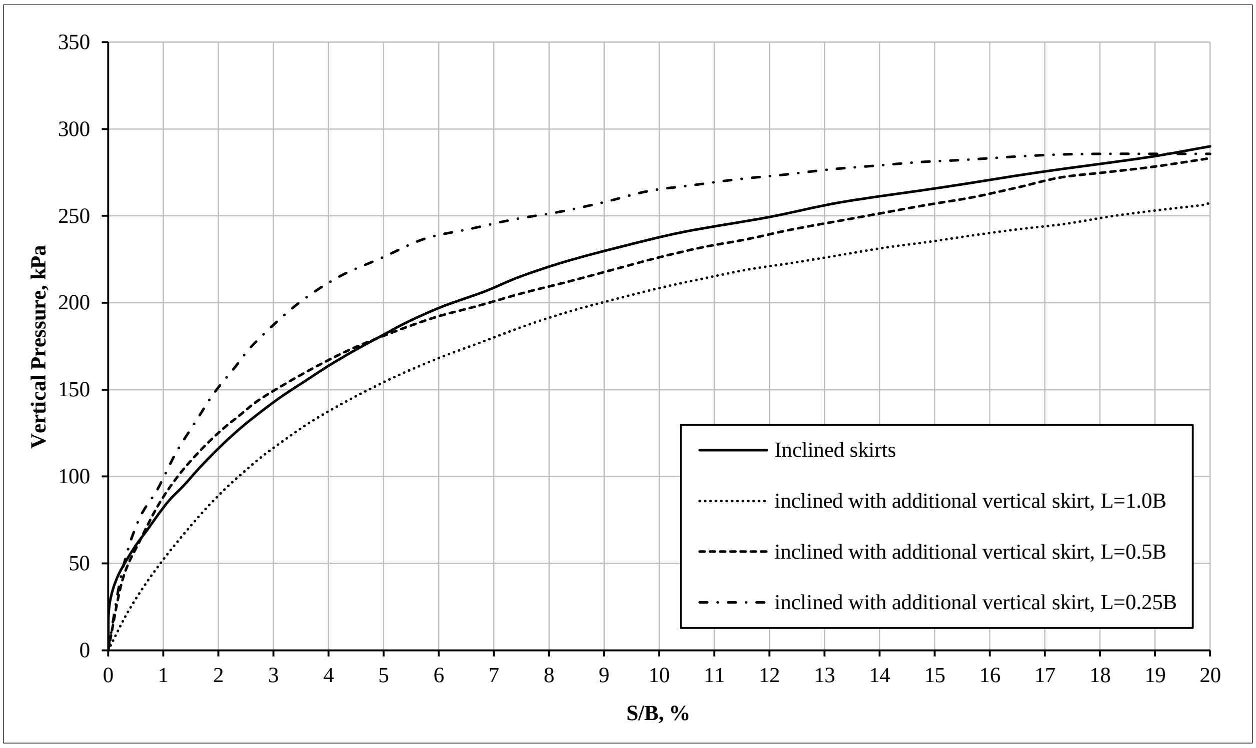


Figure 15. Experimental results of the effect the additional skirts on bearing capacity of inclined skirted foundation

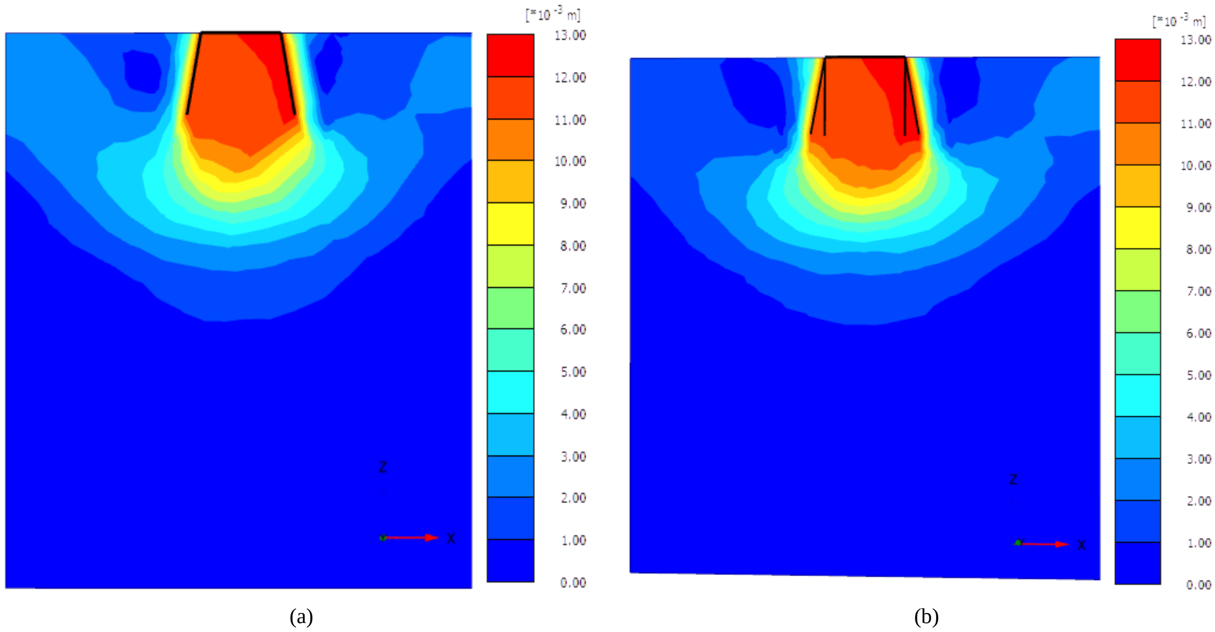


Figure 16. Failure pattern of inclined skirted foundations, (a) without additional vertical skirts and (b) with additional vertical skirts

5. Conclusion

The present study has made theoretical contributions to the understanding of inclined skirted foundations. The investigation has focused on the effects of various parameters on the bearing capacity of the inclined skirted foundations. The influence of relative density, internal friction angle, and the presence of additional vertical skirts on the inclined skirted foundation's performance has been thoroughly examined. Parametric Studies have been performed numerically and supported by experimental work. The study has revealed that increasing relative density generally leads to an increase in bearing capacity. The bearing capacity almost doubled when the relative density of sand was 60% in the case of L = 1.0B. The internal friction angle has a critical influence on the bearing capacity of the inclined skirt foundation. Increasing the internal friction angle increased the bearing capacity. The bearing capacity may not always be affected by the addition of the vertical skirt. Moreover, the additional skirts may cause a negative effect on the bearing capacity.

The study’s results reveal important insights into the behavior of inclined skirted foundations. However, it is important to acknowledge the limitations of this study. The findings are specific to the investigated configurations and may not be directly applicable to all scenarios. Additionally, the study is limited to laboratory-scale experiments and numerical simulations, which may not fully capture all the complexities of field conditions. The limitations of the study pave the way for further investigations to explore additional factors and improve the accuracy of predictive models. Despite these limitations, the findings of this study have significant implications for geotechnical engineering practices. The observed relationships between parameters such as relative density and internal friction angle with the bearing capacity provide valuable guidance for foundation design and optimization. The presence of additional vertical skirts has been found to have a limited impact on bearing capacity, highlighting the importance of considering the specific configuration and properties of skirted foundations.

6. Declarations

6.1. Author Contributions

Conceptualization, T.Sh. and A.T.; methodology, T.Sh., M.M., and A.T.; software, T.Sh.; validation, T.Sh., M.M., and A.T.; formal analysis, T.Sh.; investigation, A.T.; resources, T.Sh.; data curation, T.Sh.; writing—original draft preparation, T.Sh.; writing—review and editing, T.Sh., M.M., and A.T.; supervision, M.M. and A.T.; project administration, M.M. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

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

6.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6.4. Acknowledgements

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6.5. Conflicts of Interest

The authors declare no conflict of interest.

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