

Bearing Capacity Enhancement of Hexagonal Skirted Footings: Numerical, Regression, and ANN-Based Prediction

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Abstract

This paper presents a comprehensive numerical analysis of the improvement in bearing capacity and settlement performance of hexagonal shallow footings with inclined skirts. Various numerical analyses were conducted using PLAXIS 3D to investigate the influence of skirt length-to-footing width (L/B) ratios and skirt inclination angles (θ) on hexagonal footings in loose sand. The models showed very good agreement with experimental data reported in previous studies, with an R^2 value of 0.996 and a maximum error of less than 4.31%. It was concluded that the inclusion of inclined skirts has a positive effect on bearing capacity, increasing it by up to approximately 2.97 times compared to non-inclined configurations, while significantly reducing settlement. In addition to numerical simulations, an empirical formula for bearing capacity and settlement was developed using multiple regression based on geometric and inclination parameters. The model demonstrated a good fit ($R^2 = 0.993$). Furthermore, an Artificial Neural Network (ANN) model with a 4-10-10-1 architecture was proposed to predict bearing capacity using normalized input parameters, including skirt depth, inclination angle, stress, and settlement ratio. During training, validation, and testing, R^2 values greater than 0.998 were achieved, indicating a high level of accuracy with low prediction error. These findings highlight the importance of skirt inclination in enhancing foundation design, providing an efficient and cost-effective approach to increase the safety factor of foundations constructed on weak soils without the need for additional structural elements such as panels or strips.

Keywords: Hexagonal Skirted Footings; Inclined Skirts; Bearing Capacity; PLAXIS 3D; Regression Analysis; Artificial Neural Network.

1. Introduction

Foundations are the most important components in construction as they securely transmit a building's load to the ground, preventing settling or sliding and guaranteeing long-term stability. Selection of a proper foundation depends on a number of factors such as the type of soil, load characteristics and distribution, groundwater condition, or propensity to have earthquakes. In regions of loose ground, the conventional shallow footings tend to be limited by bearing capacity failure and high settlement. Instead of relying on deep foundations, which can be expensive and cumbersome, engineers have developed some more down-to-earth ideas. A valid alternative is composed of skirted footings that enhance the performance of shallow foundations by including vertical extensions (skirts) at the base. These skirts increase the effective depth of foundation and mobilize resistance from the surrounding soil; because of this, overall stability is increased, and settlement-related issues are reduced [1, 2].

Skirt footings are an advanced development of the conventional shallow foundations to perform better under unsatisfactory soil conditions. It is possible to enhance the performance of a foundation dramatically by adding vertical or sloping extensions (skirts) around the perimeter of footings. Usually made from concrete or steel, these skirts serve

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to increase the extent of load transfer through mobilization of more resistances from the adjacent soils in the form of side friction and passive earth pressure. Skirted footings are especially efficient in soft clays, silts, or loose sands where conventional foundations experience high settlements or even failure [3-5].

A special design is the hexagonal skirted footing, which combines the advantages of skirted systems with geometric efficiency. The hexagonal shape is beneficial because it provides better load distribution, a larger bearing surface area, and improved resistance to lateral movements. This makes such footings particularly suitable for use in confined or irregular construction areas. Skirted hexagonal foundations are increasingly considered a viable option for supporting infrastructure such as communication towers, offshore platforms, and structures built on challenging soils. Their distinctive form has attracted considerable interest, leading to renewed investigations into key design variables such as skirt depth, number, and geometry [6].

The geometry of shallow footings plays an important role in load distribution and overall foundation performance, as an optimal footing shape can enhance stability, reduce local stress concentrations, and improve constructability. The geometric efficiency of shallow footings, particularly hexagonal footings, has been examined by several researchers. Thakur & Dutta (2020) [7] noted that hexagonal footings represent an intermediate solution between square and circular shapes. Square footings may offer a higher theoretical shape factor but tend to create stress concentrations at the corners, while circular footings provide a more uniform stress distribution but are less suitable for modular layouts. Hexagonal footings, on the other hand, achieve a relatively uniform pressure distribution, reduce corner effects, and typically attain 90–95% of the ultimate bearing capacity of a circular footing with an equivalent area, thereby offering an effective balance between structural performance and ease of construction [8].

A wide range of related studies has enhanced the understanding of skirted footing performance under different configurations and soil conditions. Thakur & Dutta (2020) [6] investigated the behavior of irregular hexagonal footings—unskirted, singly skirted, and doubly skirted—on three types of sand. A combination of small-scale model tests and numerical analysis was used to study the influence of skirt depth on bearing capacity and settlement behavior. The results showed that the use of skirts, particularly double skirts, significantly increased the bearing capacity, with the highest improvement (57.6%) observed for doubly skirted footings at a skirt depth of 1.5.

Building on this, Nazeer & Dutta (2021) [9] conducted a detailed numerical study using ABAQUS to estimate the ultimate bearing capacity of skirted and embedded E-shaped footings on stratified sand. Their findings indicated that the bearing capacity could increase by more than 280%, depending on soil conditions and skirt parameters. Gnananandarao et al. (2023) [10] complemented these findings through laboratory tests on T-shaped footings resting on sandy soil with relative densities ranging from 30% to 60%. The results demonstrated that the use of skirts significantly enhanced bearing capacity, reaching up to 3.86 times that of unskirted footings, while reducing settlement across all density ranges.

Expanding on design parameters, Al-Shyokhi et al. (2023) [11] examined the effect of inclined skirts on the bearing capacity and settlement of square foundations using both numerical modeling and experimental testing. Their results showed that inclined skirts improved bearing capacity by up to 2.72 times compared to vertical skirts and reduced settlement by more than 80%. Similarly, Abd-Alhameed & Albusoda (2023) [12] reported that the use of skirts in gypseous soil under inclined loading increased bearing capacity by 193% and reduced settlement ratios to 0.14. Considering different soil conditions, Alhalbusi & Al-Saidi (2024) [13] studied the effect of skirt inclination under eccentric-inclined loading and found significant reductions in tilting and improved stability, although a slight increase in lateral displacement was observed. Finally, Pradhan & Pradhan (2025) [14] conducted experiments on circular skirted footings in riverbed sand and reported an increase in bearing capacity of up to 2.42 times at all strain levels, with an overall increase of up to sevenfold under both high- and low-strain conditions, regardless of sand compactness.

Overall, these studies consistently demonstrate that skirt geometry, skirt depth, inclination angle, and soil type are key factors influencing the performance of shallow foundations. They highlight the effectiveness of skirted footings as a cost-efficient and flexible solution for improving bearing capacity under a wide range of subsurface conditions.

This novel research utilizes advanced numerical simulation and data-based prediction to supplement the lack of research on hexagonal footing with an inclined skirt. The study involves the numerical modeling of shallow footing bearing capacity and settlement under vertical load using two parameters—skirt inclination angle and embedment ratio in PLAXIS 3D finite element. In addition, the numerical results are verified with experimental values, which means the model is valid. Furthermore, based on some normalized geometric parameters, several regression models and a 4-10-10-1 ANN model are developed. The ANN model is a reliable and rapid design tool for geotechnical applications; it also exhibits excellent predictive capacity. On that account, the proposed method can shed light on inclined skirts and give practical guidance for improving shallow foundations in bad soils.

2. Research Methodology

A systematic flowchart summary of the complete research methodology is illustrated in Figure 1. The steps of the present methodology start with defining the research problem and introducing the important contributing parameters such as skirt length ratio (L/B) and skirt inclination angle (θ), which are anticipated to have a significant effect on the bearing capacity of hexagonal skirted foundations. The next step is the generation and validation of a numerical model that can simulate soil-footing interaction under vertical loading by either comparing it against existing experimental or theoretical results to ensure proper calculation predictions. After validating the model, a parametric study is performed to examine in a systematic manner how the ultimate bearing capacity, footing settlement, and failure mode are affected by various skirt lengths and inclination. The obtained data are further utilized to construct a regression model representing simple empirical relationships between the essential parameters, bearing capacity and settlement of the footing, and an ANN model, which can predict directly the performance of footing for various inclination angles. Finally, comparison of the prediction ability of regression and ANN models is done so that their allowable discrepancy, consistency, and application to negligible estimation in practical design can effectively be used.

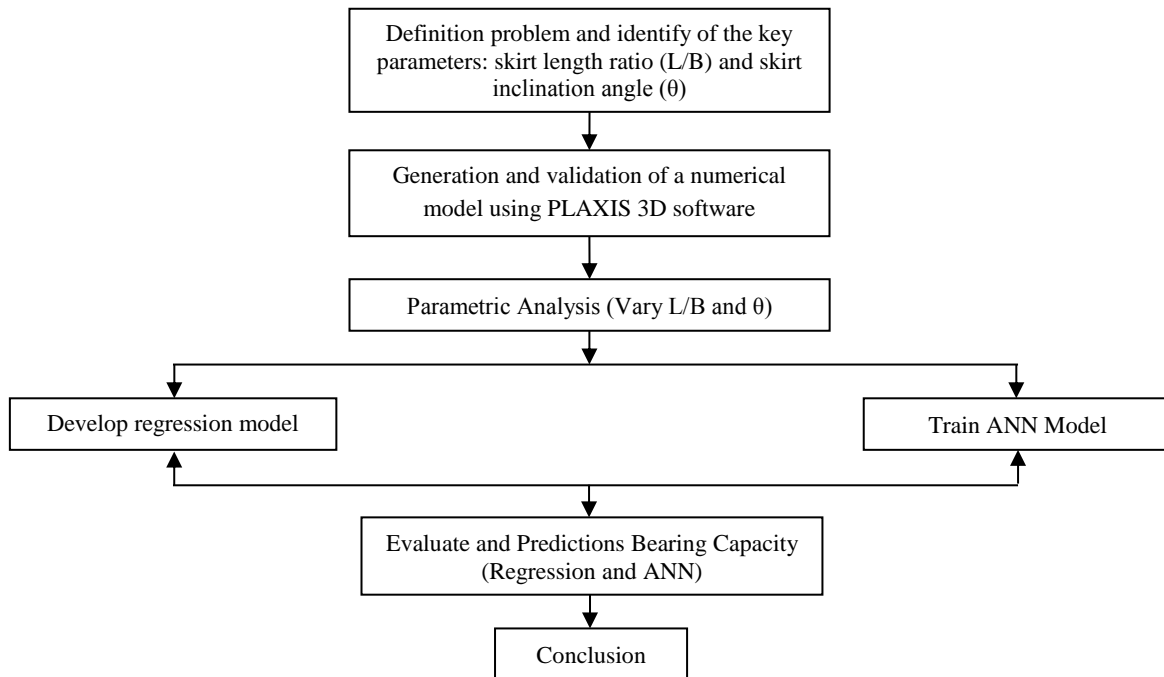


Figure 1. Methodology of study

3. Validation Problem

The accuracy of the program in simulating shallow foundations, specifically hexagonal footings with skirts, was assessed by comparing the numerical results of this study with those reported by Thakur & Dutta (2020) [6], which included both experimental test series and numerical simulations using ABAQUS software. These results served as a benchmark to verify the accuracy and reliability of the PLAXIS 3D simulations conducted in this study. In their work, a series of laboratory investigations was performed using plate load tests to evaluate the behavior of hexagonal footings, both with and without skirts, resting on sand with a relative density of 30%. The tests were conducted in a steel tank with internal dimensions of 700 mm in length, 450 mm in width, and 600 mm in height. The hexagonal footings were fabricated from 10 mm thick iron plates, and the skirts were welded along the perimeter to form skirted footings (Figure 2). The skirt length was varied progressively from $0.0B$ to $1.5B$, where B represents the footing width.

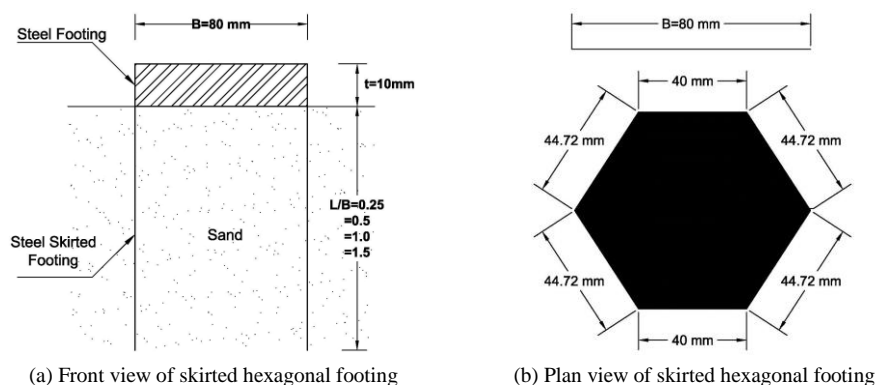


Figure 2. Geometric configuration and dimensions of skirted hexagonal footing

3.1. Numerical Modeling

The numerical simulation was performed using PLAXIS 3D software. The modeling closely replicated the experimental setup to ensure consistency between the two approaches, as illustrated in Figure 3. The boundary conditions of the numerical model were selected to represent the experimental configuration and to minimize size and scale effects. The lateral boundaries and the maximum embedment depth of the skirted footings were set at a distance of approximately $5B$ (where B is the footing width). These dimensions follow commonly accepted guidelines and ensure that boundary effects on the computed stress distribution and settlement are negligible.

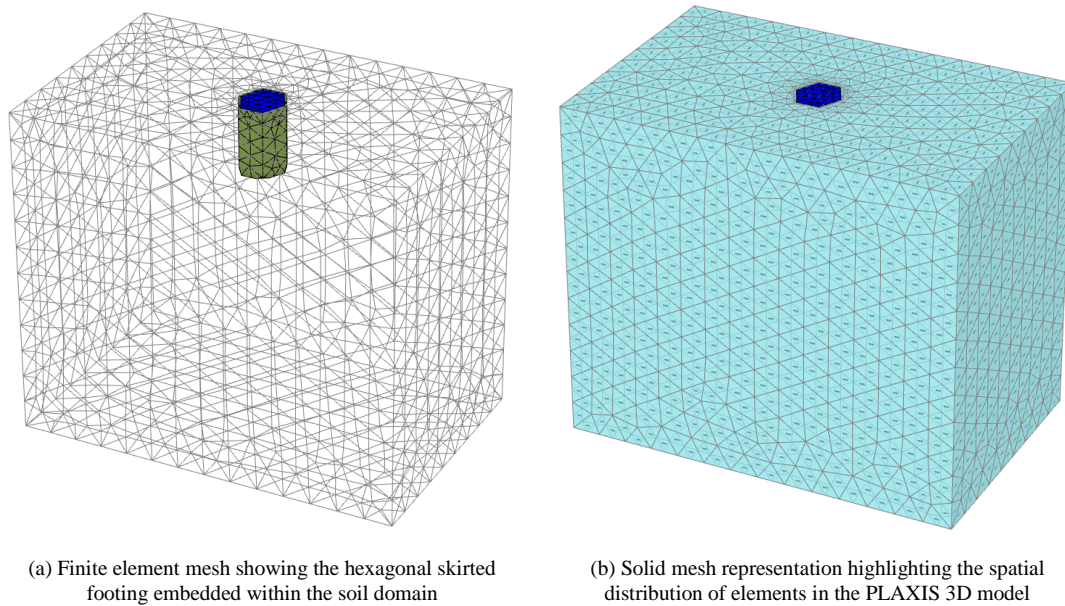


Figure 3. Numerical model configuration in PLAXIS 3D corresponding to the experimental setup

The mesh sensitivity in the numerical estimates of footing load–settlement response presented in Figure 4 to. The corresponding comparisons show increasing predicted values of the ratio $S/B\%$ as refinement in the mesh from coarse to fine, with this evident more once applied stress exceeds 100 kPa. Such response is attributed to the well-known numerically stiffening behavior related to coarse discretization, in which the mesh fails to resolve sharp stress gradients and emergence of strain localization involving localized plastic strains near footing corners. While the fine mesh leads to the result with the best mathematical convergence, frequently being these measurements ultimately in closest agreement with experiments. This is because it provides a pragmatic trade-off between numerical accuracy and the global stiffness usually obtained in laboratory tests.

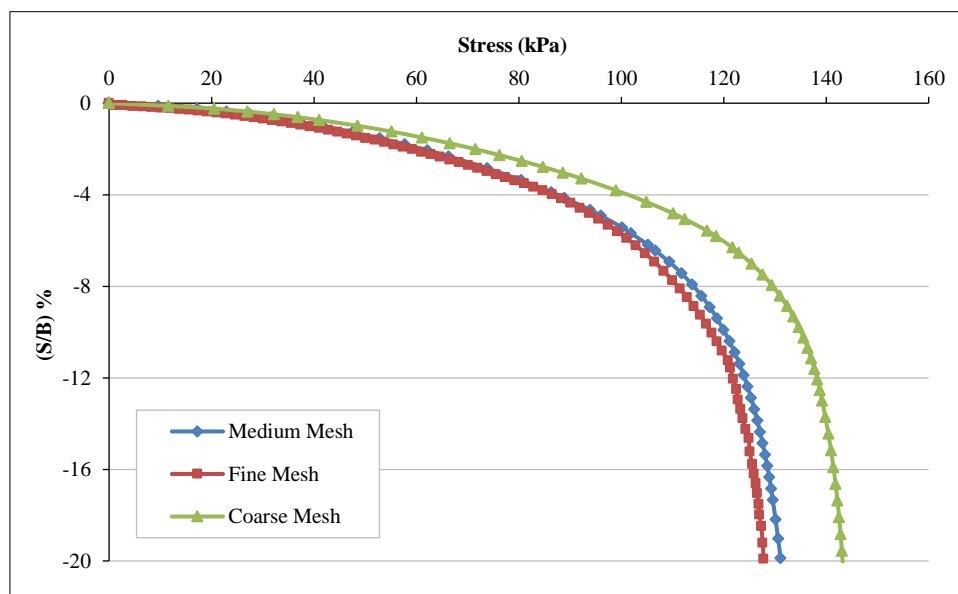


Figure 4. Load-settlement relationship for hexagonal footing using different mesh size

3.2. Soil Modeling

In this study, the Mohr-Coulomb constitutive model was employed to simulate the mechanical behavior of sandy soil with the input parameters adopted from Thakur & Dutta (2020) [6], as presented in Table 1. Meanwhile, both the hexagonal footing and the attached skirt were modeled using a linear elastic material model to represent their structural response under applied loads that were outlined by Thakur & Dutta (2020) [6], as shown in Table 2.

Table 1. Parameter of the sandy soil [6]

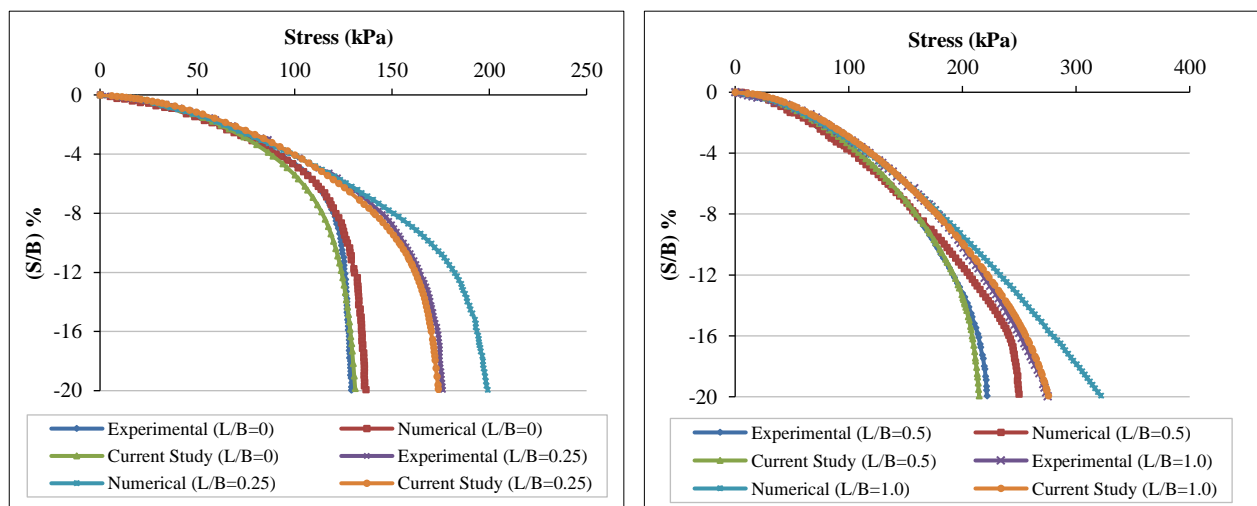
Parameter	Value
Unit weight of (kN/m ³)	14.38
Poisson’s ratio, ν	0.3
Young’s modulus, E (kPa)	4800
The angle of internal friction, ϕ	33.37°
Cohesion, c (kPa)	0.0

Table 2. Parameter of hexagonal skirted footing [6]

Parameter	Hexagonal footing	Skirted footing
Thickness of plate (mm)	10	5
Unit weight of (kN/m ³)	78	78
Poisson’s ratio, ν	0.2	0.2
Young’s Modulus, E (MPa)	210×10 ³	210×10 ³

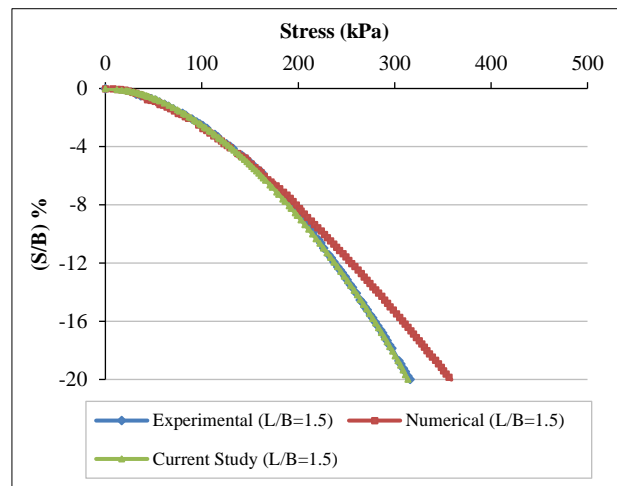
3.3. Comparison between Results

To verify the accuracy and reliability of the present numerical model, a validation study was performed in which the behavior predicted by this study was compared with experimental and numerical results presented in Thakur & Dutta (2020) for hexagonal skirted footings under vertical loading. Comparison is performed for the skirt depth ratios in the range ($L/B = 0, 0.25, 0.5, 1.0, \text{ and } 1.5$), where L is embedded skirted depth and B is width of footing, as shown in Figure 5. For all skirt arrangements, the present study reveals an agreement with experimental data to a high degree, especially regarding the ultimate capacity and settlement performance. The model satisfactorily simulates initial stiffness and onset of plastic behavior for shallow skirts ($L/B = 0.25$ and 0.5). For a higher value of skirt depth ($L/B = 1.0$ and 1.5), the model effectively captures the experimental trend and slightly exceeds the numerical results reported by Thakur & Dutta (2020) for nonlinear settlement response at high stress levels. The consistency indicates that the proposed finite element modeling approach is well-calibrated and capable of simulating stress–strain behavior of skirted footings accurately.



(a) Load–settlement relationship for hexagonal skirted footings with skirt depth ratios $L/B = 0$ and 0.25

(b) Load–settlement relationship for hexagonal skirted footings with skirt depth ratios $L/B = 0.5$ and 1.0



(c) Load–settlement relationship for hexagonal skirted footing with skirt depth ratio $L/B = 1.5$

Figure 5. Load–settlement behaviour of hexagonal skirted footings at various skirt depth ratios (L/B)

4. Parametric Study

To evaluate the performance of shallow footings with improved stability characteristics, the behavior of hexagonal skirted footings placed in sand soil is considered in this work with specific emphasis on the effect of inclination angle of the skirt along with length on bearing capacity. Parametric analysis was performed via numerical modeling of the footings using PLAXIS 3D to assess the ultimate bearing capacity and settlement behavior. In continuation of an experimental program involving hexagonal footings with various skirt depths tested on a 30% relative density sandy soil, the present study incorporates inclined skirts in order to investigate their effect on the foundation behavior. The skirts were modeled at various inclination angles: 10° , 15° , and 20° with respect to the vertical. The inclination angles were chosen to cover a realistic and meaningful interval for skirt footings. Angles greater than 20° are physically feasible, but less common in practice due to difficulties during construction and possible local instability of the soil. So adopt 20° as an upper cutoff value only out of consideration for practical convenience. Subsequent to this modification, the geometries were adopted into the PLAXIS 3D modeling, and load-settlement responses, bearing capacity resistance, and failure modes were assessed. The inclusion of skirt inclinations may change the soil confinement effect and stress level under footing, which may result in enhancing the overall stability and performance. The schematic of this configuration is shown in Figure 6.

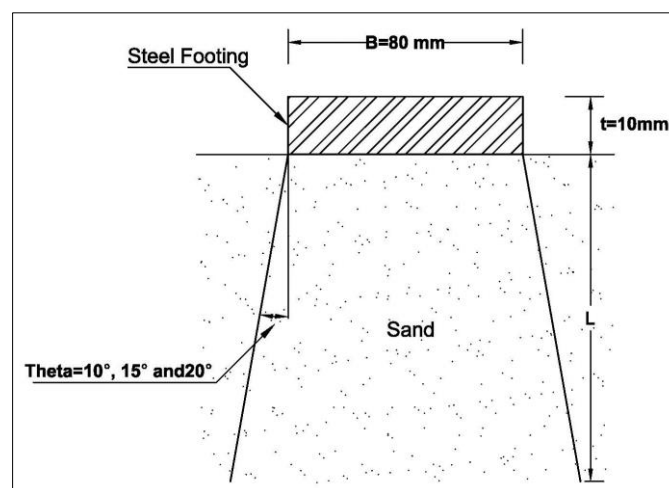


Figure 6. Geometric configuration and dimensions of inclined skirted hexagonal footing

5. Results and Discussion

5.1. Effect of Skirted Depth Bearing Capacity

Pressure-settlement curves obtained from the numerical analyses for skirted and inclined skirted hexagonal footings with three inclination angles of 10° , 15° , and 20° and different skirt embedded depths ($0B$, $0.25B$, $0.5B$, $1.0B$, and $1.5B$) are shown in Figure 7. The corresponding ultimate bearing capacities as derived from these numerical simulations are presented in Table 3. It should be noted that the values of bearing capacity were adopted based on a 10% S/B settlement

ratio for all cases of skirted and inclined skirted foundations (S is settlement of hexagonal footing and B is width of footing). As per Table 3, the bearing capacity of skirted hexagonal footing without inclination ($\theta=0^\circ$) was found to be 153.7 kPa, 176.63 kPa, 199.56 kPa, and 214.61 kPa with skirt depths of 0.25B, 0.5B, 1.0B, and 1.5B, respectively. For skirts inclined at $\theta = 10^\circ$, the bearing capacities of them were up to 191.42 kPa, 223.49 kPa, 314.32 kPa, and 389.06 kPa for these embedment depths, respectively. At $\theta = 15^\circ$, bearing capacities increased further to 197.28 kPa, 255.21 kPa, 386.59 kPa, 495.45 kPa, etc. The largest increments occurred at $\theta = 20^\circ$, the bearing capacities of which reached 209.0 kPa, 284.78 kPa, 448.21 kPa, and 639.38 kPa, respectively.

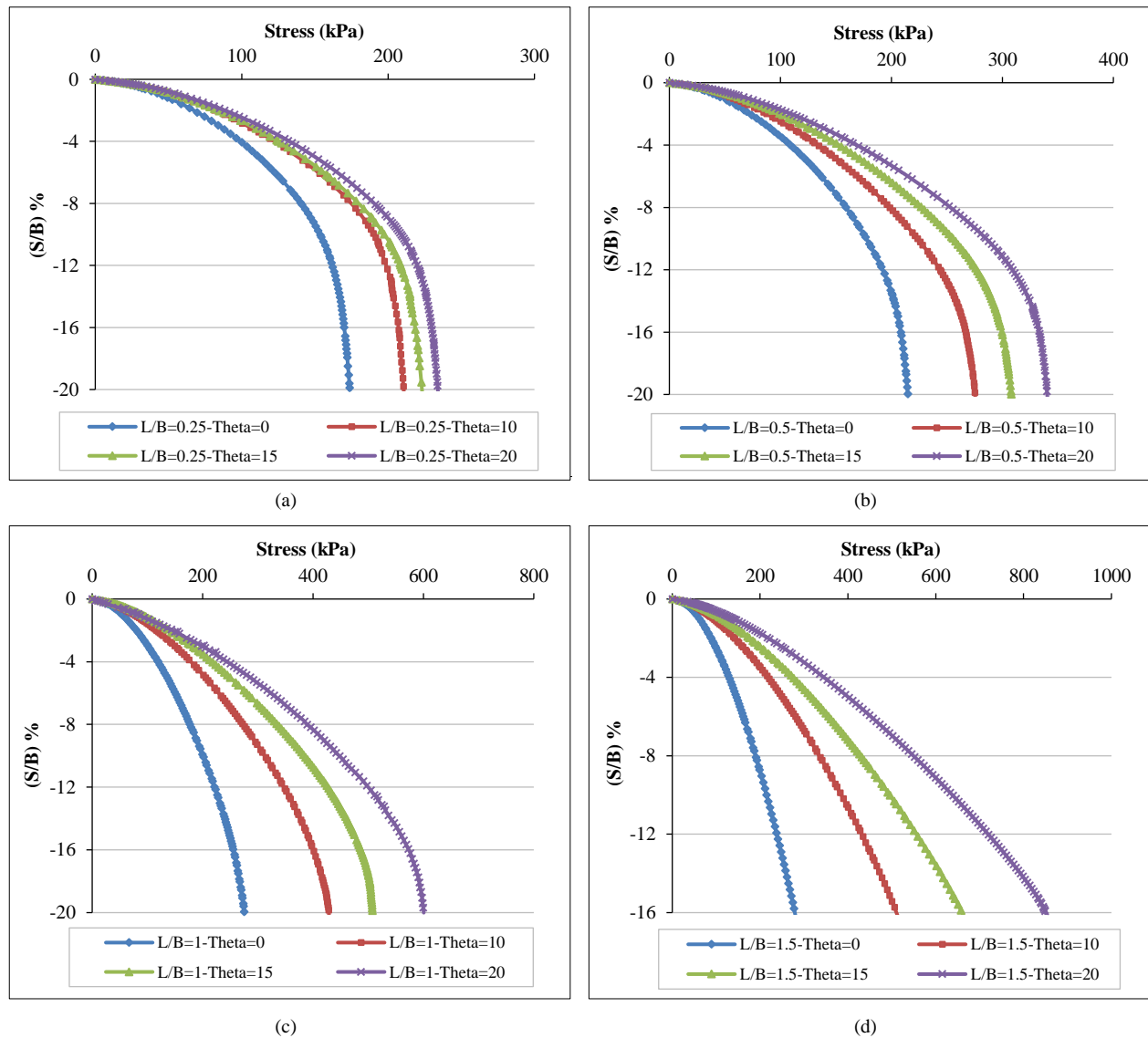


Figure 7. Effect of skirted inclination angle ($\theta = 5^\circ, 10^\circ,$ and 15°) on settlement response of hexagonal-skirted footing at various skirt embedment ratios (L/B): (a) 0.25, (b) 0.5, (c) 1.0 and (d) 1.5

It can be seen from Table 3 and Figure 7 that the bearing capacity of inclined skirted hexagonal footings resting on sand is consistently higher than that of their vertical counterparts, with the greatest increases observed at larger inclination angles. This improvement is attributed to the enhanced passive resistance and soil confinement mobilized at higher inclination angles, which enable more effective redistribution of vertical loads and a reduction in settlement.

This trend is further emphasized by the percentage increases presented in Table 3, where the bearing capacity at $L/B = 1.5$ rises by as much as 81.3%, 130.8%, and 197.9% for inclination angles of $10^\circ, 15^\circ,$ and 20° , respectively. Based on these results, it is evident that combining an appropriate inclination angle with sufficient embedment depth provides a promising design approach for significantly enhancing the bearing capacity of hexagonal skirted footings in a cost-effective manner, without increasing embedment depth or requiring additional construction measures.

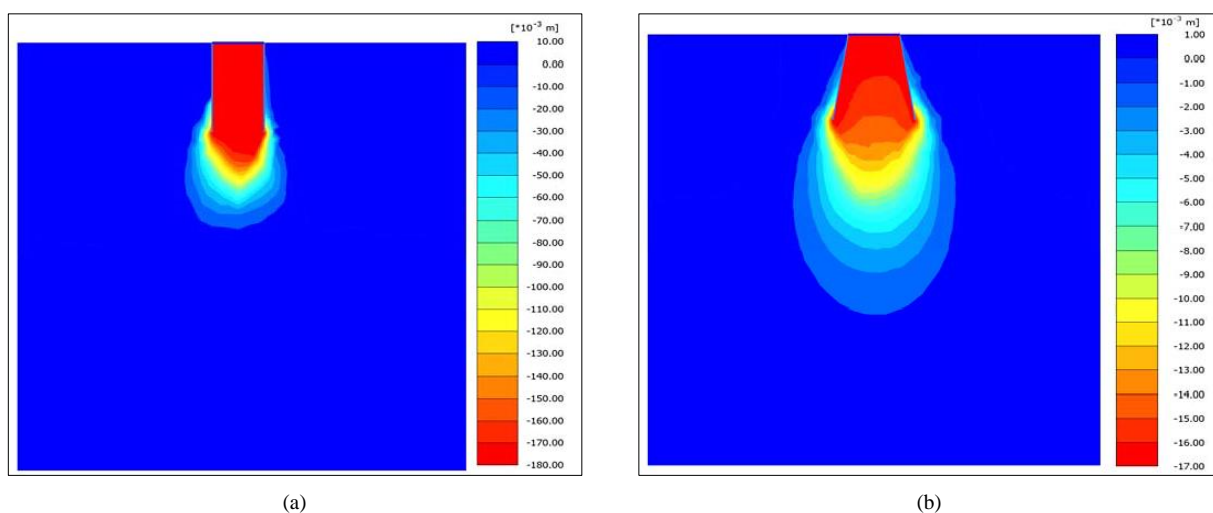
Table 3. Bearing capacity ratios of inclined hexagonal skirted foundations under different skirt length-to-footing width (L/B) ratios and inclination angles (θ)

Skirt inclination	Skirt length/footing width (L/B)	Numerical Bearing Capacity, Q_u for S/B=10% (kPa)	Bearing capacity improves (%) compared to the vertical (θ°)
			Improvement Rate (%) = $\frac{Q_u - Q_{u(\theta=0)}}{Q_{u(\theta=0)}} \times 100$
0°	0.0	119.94	–
	0.25	153.70	–
	0.5	176.63	–
	1.0	199.56	–
	1.5	214.61	–
10°	0.25	191.42	24.5
	0.5	223.49	26.4
	1.0	314.32	57.5
	1.5	389.06	81.3
15°	0.25	197.28	28.3
	0.5	255.21	44.5
	1.0	386.59	93.9
	1.5	495.45	130.8
20°	0.25	209.0	35.9
	0.5	284.78	61.2
	1.0	448.21	124.6
	1.5	639.38	197.9

Figure 8 shows the typical failure patterns developed for skirted hexagonal footings (skirt depth L/B = 1.5) at various inclination angles ($\theta = 5^\circ, 10^\circ,$ and 15°). These failure modes illustrate the overall displacement shape and are important for estimating actual displacement under loading. Such information is necessary to ensure that vertical settlement in footing design remains within acceptable limits. The analysis indicates that the case with $\theta = 20^\circ$ exhibits greater performance than those with $0^\circ, 10^\circ,$ and 15° , implying a higher bearing capacity of the footing.

In addition, the figure shows that the failure patterns remain well within the selected lateral and vertical boundaries for both vertical and inclined skirted hexagonal footings, indicating that the chosen domain size is adequate for the problem. The displacement contours also explain why skirt inclination affects bearing capacity. Although the applied load is vertical, the inclination of the skirts alters the soil–structure interaction mechanism. Inclined skirts trap a larger volume of soil and mobilize greater passive resistance along the inclined boundaries. By restricting lateral soil movement, the load is transferred to deeper soil layers.

The contours further show that as skirt inclination increases, the displacement zone becomes wider and deeper, indicating that a larger mass of surrounding soil participates in resisting the load. This behavior generally results in higher resistance compared to vertical skirts, as the soil becomes more confined before failure occurs.



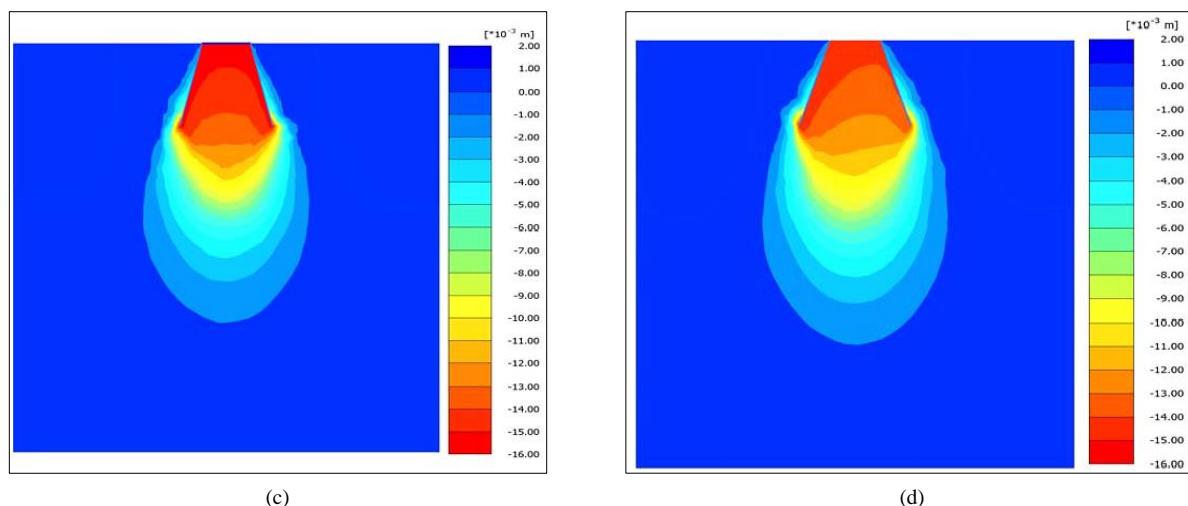


Figure 8. Failure pattern of the hexagonal skirted footing at a skirt depth of $L/B=1.5$ at various inclination angle (θ) (a) 0° , (b) 10° , (c) 15° and (d) 20°

5.2. Regression Analysis for the Prediction of Bearing Capacity Ratio

To better predict the influence of geometric and inclination factors on the bearing capacity of skirted and inclined skirted hexagonal footings, a multiple regression analysis was performed. The main objective was to develop an empirical model to estimate the bearing capacity ratio (i.e., the ratio of inclined bearing capacity to non-inclined bearing capacity) based on the skirt inclination angle (θ) and the L/B ratio. The numerically generated dataset presented in Table 3 was used in this analysis, and the bearing capacities were calculated under different inclination angles (0° , 10° , 15° , and 20°) and embedment ratios ($0B$, $0.25B$, $0.5B$, and B).

The regression analysis showed that the bearing capacity ratio is strongly influenced by both variables (θ and L/B), indicating that inclination angle and embedment depth have a combined effect on the load-carrying behavior of the footing. The results demonstrated that second-order polynomial models adequately describe the data, with a high coefficient of determination ($R^2 = 0.993$), by capturing the nonlinear interaction between the confinement effect induced by inclination and the mobilization depth of passive soil resistance.

The general form of the best-fit regression equation is expressed as:

$$\text{Bearing Capacity Ratio} = 1.0352 - 0.0055 \times \theta - 0.0724 \times (L/B) + 0.0004 \times \theta^2 + 0.0180 \times (L/B)^2 + 0.0623 \times ((\theta \times (L/B))) \quad (1)$$

where, Bearing Capacity Ratio is $(Q_{u(\theta)}/Q_{u(\theta=0)})$ = the ratio of inclined to non inclined bearing capacities, θ is inclination of skirted footing, and L/B is embedment depth to width of skirted footing.

A comparison of the predicted and measured bearing capacities based on skirted and inclined skirted hexagonal foundations using multiple regressions is given in Figure 9. The plotted data points are very close to the 1:1 reference line, illustrating the model predictions agree with the numerically estimated bearing capacity values in the entire range of inclination angles and embedment ratios. The computed coefficient of determination ($R^2 = 0.993$) also validates the model's outstanding prediction accuracy, which implies that 99.3% variability in bearing capacity is effectively represented by the regression equation. Such a high level of fit provides evidence that the chosen predictors, skirt θ and L/B , and their interaction components adequately account for the complex interplay between geometry and load-carrying capability. The small differences found at higher capacities are negligible, and they can be considered within acceptable error margins, which validate the application of the regression model in engineering design. In general the figure and analysis corroborate the validation of the developed empirical relationship, particularly for predicting net bearing capacity improvements of skirted footing systems under various geometric configurations.

The comparison of predicted and experimental bearing capacity ratio is shown in Figure 10. The strength relationship between the predicted and experimental data is high, with $R^2 = 0.996$, which is within a reasonable limit. In this study, a regression model is proposed that predicts the bearing capacity of hexagonal skirted footing, and the maximum deviation between the predicted and experimental value is kept at 3.1%. This finding shows that even in the worst-case scenario, predicted values remain very close, by about 3.1%, compared with the measured data, and it confirms both the predictive strength and the accuracy of this model.

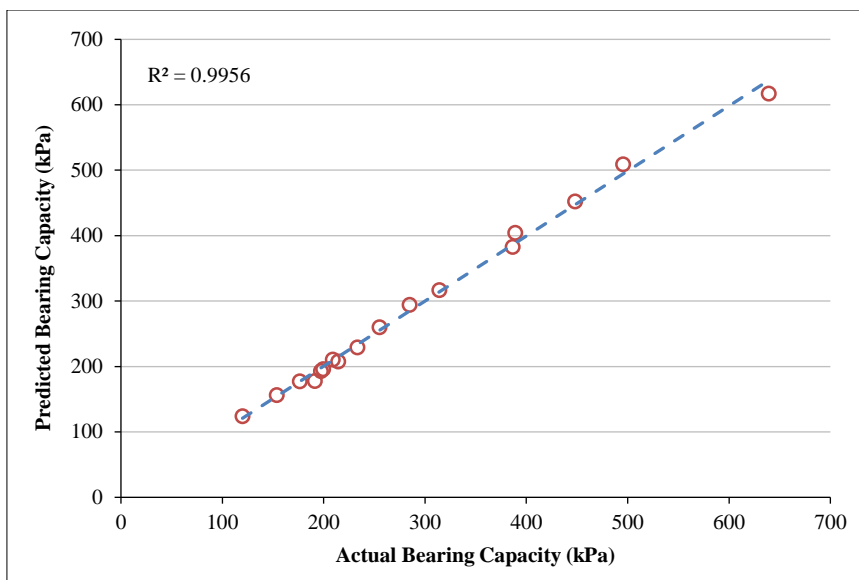


Figure 9. Comparison between actual and predicted bearing capacity for the inclined skirted hexagonal footing

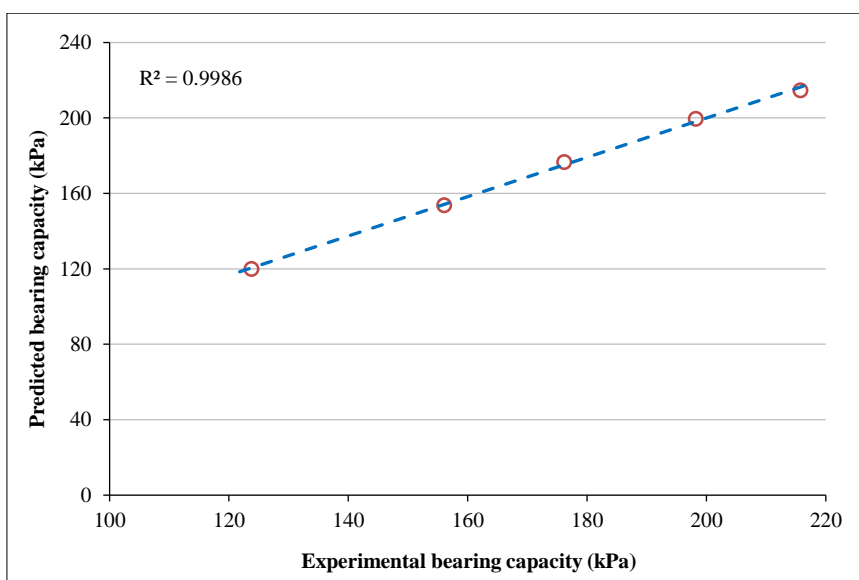


Figure 10. Comparison between experimental and predicted bearing capacity for the skirted hexagonal footing

5.3. Regression Analysis for the Prediction of Settlement Ratio

A study was conducted on the settlement behavior of skirted and inclined skirted hexagonal footings using multiple regression models, from which important implications regarding the effects of inclination angle (θ) and embedment ratio (L/B) on normalized settlements were derived. The settlement ratio, defined as the ratio of inclined to non-inclined settlement, was modeled using an exponential regression equation, which provided a very good fit ($R^2 = 0.993$), indicating that the model explains 99.3% of the observed variance in the ratio. The resulting exponential equation shows that the settlement ratio decreases with increasing inclination angle, reflecting the improved stiffness and load distribution of inclined skirts. The general form of the best-fit regression equation is expressed as follows:

$$\text{Settlement Ratio} = e^{-0.0116-0.0316\theta+0.0783(L/B)+0.0007\theta^2-0.0547\times(L/B)^2-0.0382\times(L/B)\times\theta} \tag{2}$$

where, *Settlement Ratio* is $S_{(\theta)}/S_{(\theta=0)}$ = the ratio of inclined to non inclined settlements, θ is inclination of skirted footing, and L/B embedment depth to width of skirted footing

Figure 11 compares the actual settlement measurements with those predicted by the multiple regression analysis for skirted and inclined skirted hexagonal footings. The plotted data points lie close to the 1:1 reference line, confirming that the model accurately reproduces the settlement response obtained from numerical simulations. This strong agreement is observed across all investigated inclination and embedment ratios, demonstrating the reliability of the proposed prediction model. Furthermore, the high coefficient of determination ($R^2 = 0.993$) indicates that the regression

equation provides an accurate estimation of the key parameters controlling settlement, offering engineers a practical and reliable tool for predicting settlement behavior under various design conditions, including different footing geometries.

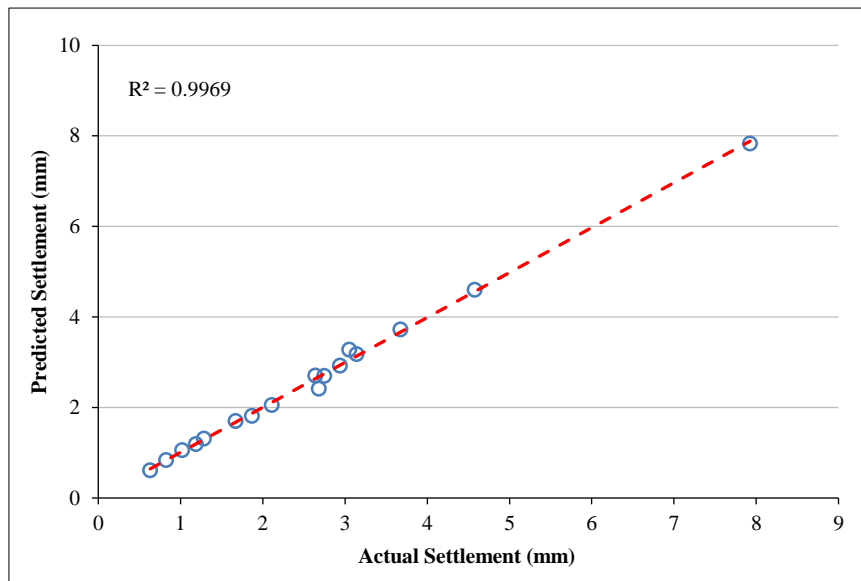


Figure 11. Comparison between actual and predicted settlement for the inclined skirted hexagonal footing

The comparison between predicted and experimental settlements for vertical skirted footings is shown in Figure 12. It can be seen that there is a strong matching with a high R^2 of 0.9964 and a low maximum deviation of 4.31% that confirms the model’s accuracy and reliability for practical design.

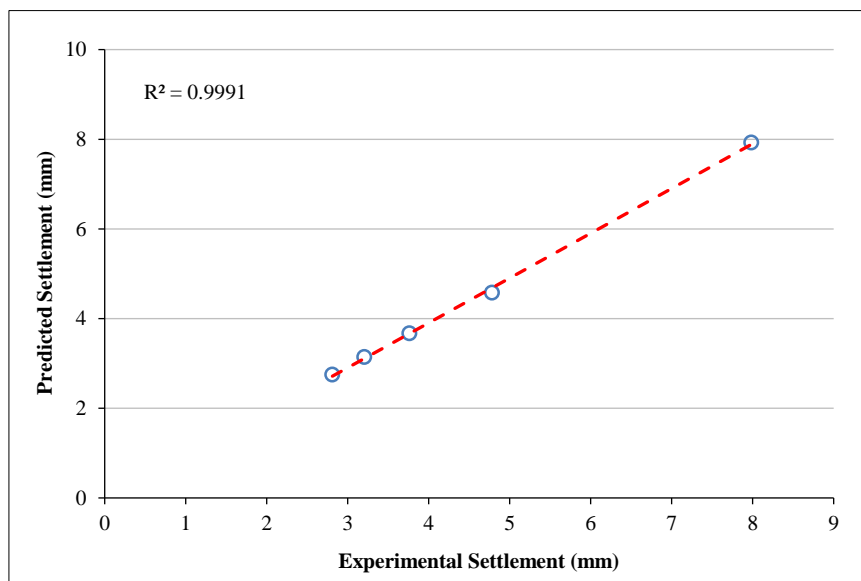


Figure 12. Comparison between experimental and predicted settlement for the skirted hexagonal footing

5.4. ANN Analysis for Stress Prediction

Accurate prediction of stress beneath shallow foundations in geotechnical and structural engineering, especially for complex footing geometries, has been a great challenge. Skirt footings with hexagonal and inclined skirt shapes have been the subject of interest for their likely ability to increase the load-carrying capacity and reduce settlement in weak or layered soils. This type of member is extensively used in difficult soil conditions, where conventional footing designs can be ineffective or unstable [15].

However, to analytically or numerically predict the dynamics of these systems still remains a challenge. It is caused by the nonlinear coupling between the footing geometry, inclination angle, and skirt depth, which standard methods fail to describe accurately. FEM models are useful tools; however, they can be computationally expensive and strongly influenced by initial assumptions [16]. Accordingly, engineers are investigating alternative modeling schemes that can provide reasonably accurate predictions while maintaining computational efficiency.

Artificial Neural Networks (ANNs) have proven to be a useful tool in this field. Due to their ability to learn from data and recognize complex nonlinear relationships, they are highly suitable for applications in civil engineering. Over the past two decades, ANNs have demonstrated effectiveness in various geotechnical problems such as bearing capacity prediction, slope stability analysis, and soil classification [17, 18]. Unlike conventional regression or curve-fitting techniques, ANNs do not require a predefined mathematical model; therefore, they can adapt to data structures more easily and provide strong predictive performance even with limited domain knowledge [19].

The development of the ANN model for predicting the bearing capacity of inclined skirted hexagonal footings on sand was carried out systematically by selecting key input and output variables. The input parameters included the normalized skirt depth (L/B), the normalized settlement (S/B), the stress applied to the non-inclined skirted footing, and the angle of inclination (θ), while the output variable was the ultimate bearing capacity. The performance of ANN models is strongly influenced by the network architecture and parameter tuning; therefore, a trial-and-error approach was used to determine the optimal network structure. According to previous studies [20], the number of neurons in hidden layers should be approximately two-thirds of the input layer size and remain below twice its size, while maintaining a balanced structure between input and output layers to ensure stability and generalization capability. Based on these guidelines, a multilayer feedforward network with a 4-10-10-1 architecture was adopted, as shown in Figure 13. The model was trained and tested using data obtained from numerical simulations, and the input–output parameters are summarized in Table 4. The dataset was randomly divided into 70% for training, 15% for validation, and 15% for testing to ensure a balanced and reliable evaluation of the network’s predictive performance.

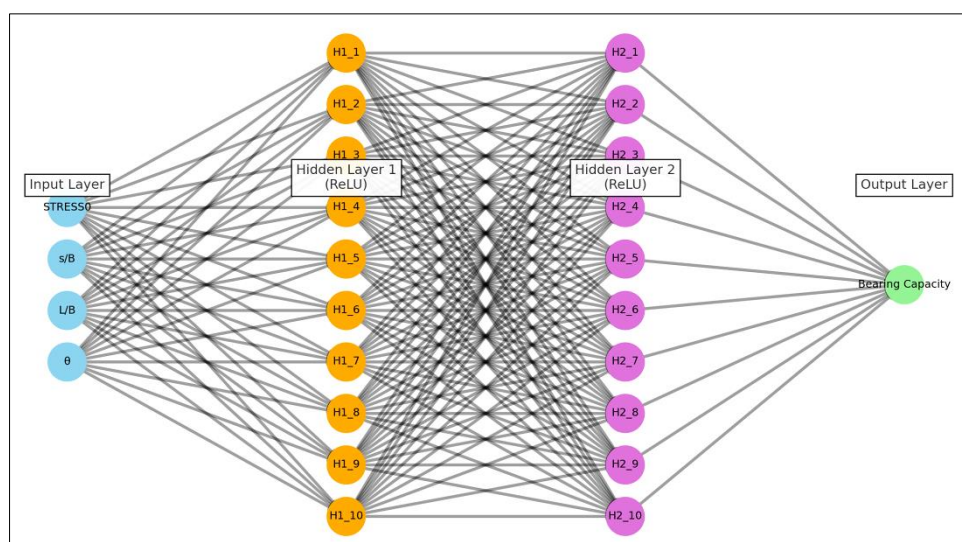


Figure 13. Neural Network Representing 4-10-10-1 Architecture

Table 4. Minimum and maximum data range used for the ANN model.

Parameters	Minimum	Maximum
Normalized skirt depth (L/B)	0	1.5
Normalized settlement (S/B)	0	20
Stress associated with non-inclined skirted footing	14.21	131.14
Inclination angle (θ)	0	20

The performance of the artificial neural network (ANN) model with a 4-10-10-1 architecture was evaluated using standard error metrics (R^2 , MSE, RMSE, and MAE) across the training, validation, and testing datasets. As shown in Figure 14, the model converges rapidly in terms of mean squared error (MSE) during the initial training epochs, and both the training and validation curves stabilize after approximately 100 epochs. This rapid decrease indicates that the input–output relationships are effectively learned, after which convergence continues with only minor improvements. The training and validation MSE curves remain closely aligned throughout the training process, suggesting good generalization and minimal overfitting. Furthermore, the green dashed horizontal line indicates that the test MSE remains low and consistent with the training and validation errors, demonstrating that the model retains its predictive capability on an independent dataset.

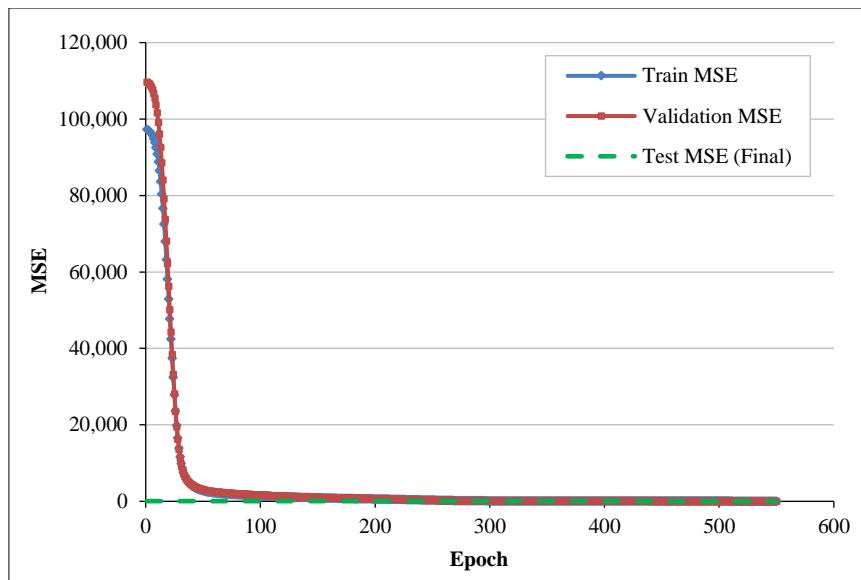


Figure 14. Training, validation, and test MSE vs. epochs for ANN-based prediction of bearing capacity

The reliability of the model is further supported by quantitative evaluation. The coefficient of determination (R^2) values are 0.9986 for training, 0.9986 for validation, and 0.9982 for testing, as presented in Table 5. These high R^2 values indicate an excellent agreement between predicted and actual results. Additionally, all MSE values are low, with the training dataset achieving the lowest value (MSE = 37.9594), while the validation and testing datasets show similarly low values of 39.5939 and 47.7838, respectively. All RMSE values are below 7.0, with the lowest value (approximately 6.16) obtained during training, indicating low prediction variability. The mean absolute error (MAE) values are consistently within the range of 4.8 to 5.4, demonstrating stable and accurate predictions with minimal deviation.

Overall, these results indicate that the proposed ANN model effectively captures the complex nonlinear relationship between the geometry and loading conditions of inclined skirted hexagonal footings and their bearing capacity. The model not only exhibits strong fitting capability but also demonstrates robust generalization when applied to new data. This suggests that it can serve as a reliable and valuable tool for geotechnical design, particularly in cases where analytical models are unavailable or numerical methods are computationally expensive.

Table 5. Performance metrics of the ANN model for training, validation, and testing sets

Metric	Training Set	Validation Set	Testing Set
R^2	0.9986	0.9986	0.9982
MSE	37.9594	39.5939	47.7838
RMSE	6.1611	6.2924	6.9126
MAE	4.8124	4.8451	5.3502

5.5. Model Equation

The final prediction model developed in this study is based on a fully connected feed forward artificial neural network (ANN) architecture with a topology of 4-10-10-1, where the input layer receives four normalized parameters: Stress associated with non-inclined skirted footing, Normalized skirt depth (L/B), Normalized settlement (S/B), and the inclination angle (θ). The input layer is connected to two hidden layers; each comprising ten neurons activated using the Rectified Linear Unit (ReLU) function, followed by a single output neuron that computes the predicted stress value through a linear activation function.

Mathematically, the output bearing capacity (Q) is computed by propagating the input features through a series of weighted sums and non-linear activations. The first hidden layer transforms the input vector $[x_1, x_2, x_3, x_4]$ using learned weights $W^{[1]}$ and biases $b^{[1]}$, applying the ReLU activation to yield the first hidden output $h^{[1]}$. This result is then passed through a second linear transformation defined by $W^{[2]}$ and $b^{[2]}$, again followed by ReLU, producing the second hidden output $h^{[2]}$. Finally, the bearing capacity (Q) is computed using a weighted sum of $h^{[2]}$ with weights $W^{[3]}$ and bias $b^{[3]}$. The general form of the equation is:

$$Q = \sum_{j=1}^{10} w_j^{[3]} \cdot ReLU \left(\sum_{i=1}^{10} w_{ji}^{[2]} \cdot ReLU \left(\sum_{k=1}^4 w_{ik}^{[1]} + b_i^{[1]} \right) + b_j^{[2]} \right) + b^{[3]} \tag{3}$$

The specific weights and biases obtained from training are summarized in the following Tables 6 to 9, which show the optimal weights and bias of the generated feed forward ANN model with a 4-10-10-1 structure. The architecture of the network is four neurons at the input layer, two hidden layers each including ten neurons, and an output neuron. The hidden layers take the Rectified Linear Unit (ReLU) activation function, defined as $f(x) = \max(0, x)$ which helps to model complex nonlinear relationships of the network and avoids vanishing gradients. In each layer, the input is linearly combined with its corresponding weight and then modified by means of a bias before being passed through the activation function. The first hidden layer represents the primary nonlinear interactions between the governing parameters, and the second hidden layer represents a refinement of such interaction, which allows for superior prediction accuracy. The value and the sign of these weights indicate the relative importance of direction for each parameter. The weights and biases displayed are sufficient to fully specify the trained ANN model and reproduce its use for predictions independently.

Table 6. Weights $W^{[1]}$ and Biases $b^{[1]}$ (input layer \rightarrow 1st hidden layer)

Neuron	w_{i1}	w_{i2}	w_{i3}	w_{i4}	b_{i1}
1	1.2574768	-0.01952573	2.4404895	3.0442798	1.0980873
2	-0.99682254	-0.9797452	-1.591831	-1.6961219	-0.5581945
3	1.2700047	1.3138264	1.9097402	2.0209727	0.83726466
4	0.08469682	-1.7303097	-1.9596164	-2.1296487	3.6418874
5	1.8841187	-0.93920815	1.8886179	0.20993707	2.2075808
6	1.4927346	1.1545637	0.8492227	2.6459885	1.1781611
7	2.08799	0.8783346	2.733178	0.47233298	0.76088727
8	0.06220982	-0.258009	2.194843	2.4256725	-0.4995803
9	-1.47635	-0.60264724	0.14672187	1.2634746	1.9533379
10	2.1748428	2.6642687	0.4823518	0.9656723	0.2714637

Table 7. Weights $W^{[2]}$ and Biases $b^{[2]}$ (1st hidden layer \rightarrow 2nd hidden layer)

Neuron	w_{j1}	w_{j2}	w_{j3}	w_{j4}	w_{j5}	w_{j6}	w_{j7}
1	-0.39249077	-0.04891589	-0.16503015	-0.46702397	-0.07885455	-0.25857568	-0.56471056
2	1.0893074	-0.17861429	-0.3054647	-0.23361692	-2.5059302	1.5887741	-2.8025408
3	0.7408484	1.9888321	-0.9251057	0.8133269	1.0814936	-0.26162228	1.0261899
4	1.526304	-2.0843804	1.9717144	3.1499066	1.734738	1.535758	1.8407454
5	1.0056764	1.8346604	-0.8768882	-0.56339985	0.90446246	0.47650063	-0.14593638
6	2.188389	-1.7892978	2.139458	3.1359627	1.763677	1.8049874	1.4986558
7	2.019326	-1.9161062	1.8888797	4.0118546	1.5258782	1.7673291	1.033589
8	0.93338484	1.8091062	-0.25602072	1.3052562	-1.4299707	-0.5618983	0.26119095
9	1.2297907	2.132527	2.008629	3.6723835	1.4986355	1.4001851	1.0833939
10	-0.4076406	-0.63973856	0.06989031	-0.5779126	2.456925	-0.65186423	1.2359834

Table 8. Weights $W^{[2]}$ and Biases $b^{[2]}$ (1st hidden layer \rightarrow 2nd hidden layer)

Neuron	w_{j8}	w_{j9}	w_{j10}	b_{j2}
1	0.15803564	0.29162195	0.22384438	-0.02293664
2	-0.19321418	2.8669126	0.45033398	2.0028017
3	0.5055383	-1.0087788	-1.4216207	0.92520356
4	2.2004058	1.8244857	1.0420331	0.9013498
5	1.4014742	-0.10152331	-2.7232194	0.2876394
6	1.5798838	1.3420316	0.766949	0.72841656
7	1.874205	1.3974957	0.98362046	0.84296453
8	2.261407	-2.0669475	0.1173526	-0.12331505
9	1.8666803	1.4092933	1.6777744	0.7660717
10	0.2175829	-1.824394	-1.0553749	1.0592668

Table 9. Weights $W^{[3]}$ and Bias $b^{[3]}$ (2nd hidden layer \rightarrow output layer)

Neuron	w_j^3
1	-2.1605239e-04
2	-6.6205058
3	-2.7752137
4	2.1848929
5	-4.7663116
6	2.4272666
7	2.2484007
8	-3.4529693
9	2.5278535
10	-5.2631183

Bias (output) b_3 : 0.5105246 (4)

The predictive performance of the artificial neural network model was evaluated by comparing the estimated and actual bearing capacity values for skirted hexagonal footings with varying inclination angles, as shown in Figure 15. The results across training, validation, and testing phases reveal a high level of agreement, as evidenced by the strong alignment of data points near the ideal 1:1 line. With R^2 values of 0.9986 for both the training and validation sets and 0.9982 for the testing set, the model demonstrates excellent fitting accuracy and strong generalization to unseen data. The model's low prediction errors and dispersion show that it can describe nonlinear behavior impacted by inclination, depth to width, and stress response. These results demonstrate that the selected ANN design (4-10-10-1) can accurately and efficiently predict the bearing capacity of inclined skirting footings on sandy soils for complicated geotechnical interactions.

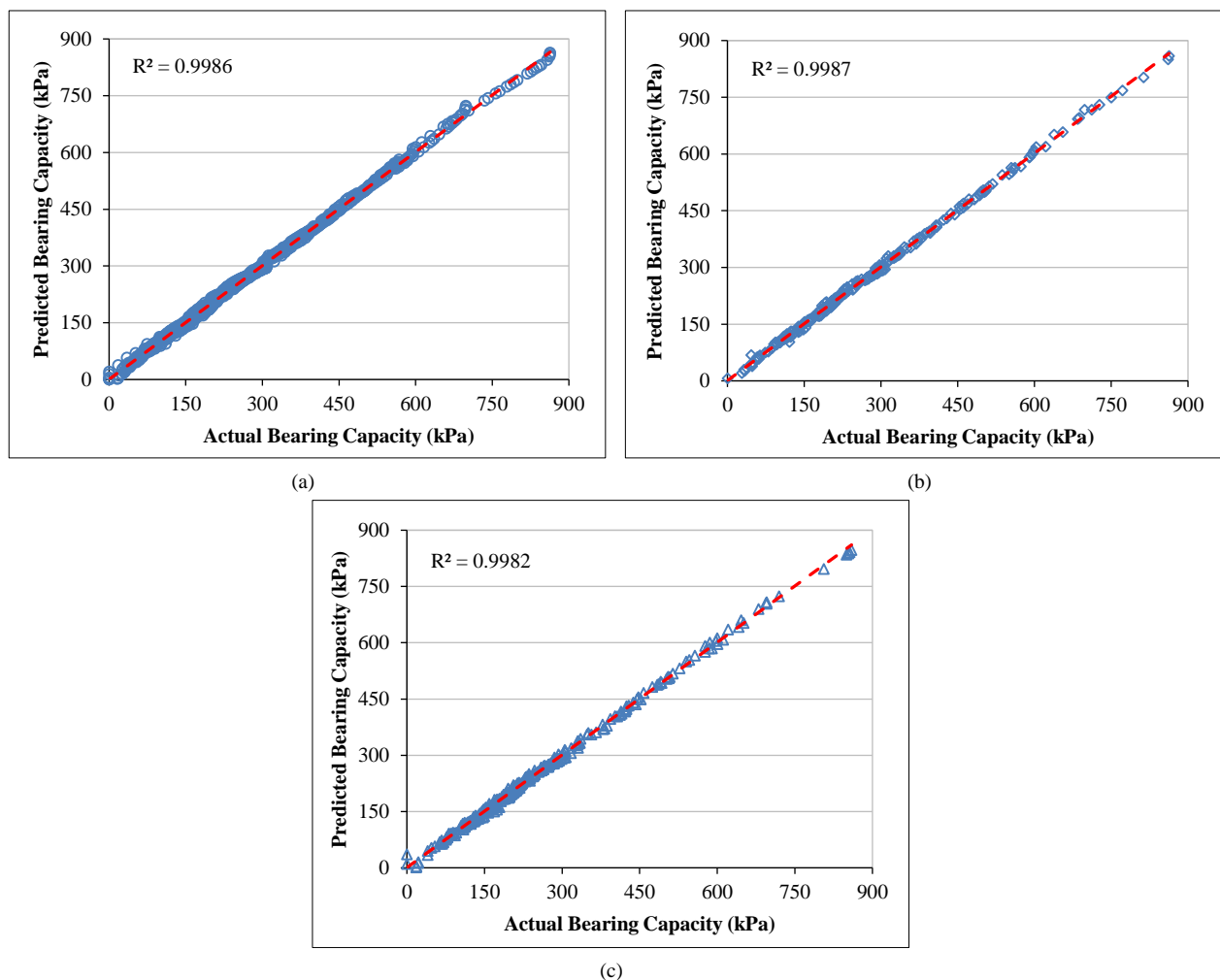


Figure 15. Predicted versus actual bearing capacity (kPa) for inclined skirted hexagonal footings resting on sand using the developed ANN model with 4-10-10-1 architecture: (a) Training dataset, (b) Validation dataset and (c) Testing dataset

6. Conclusions

In the present study, the behavior of hexagonal footings with and without inclined skirts resting on loose sandy soil under vertical loading was investigated. Numerical simulations were conducted to evaluate the system under different conditions, including embedment lengths and skirt inclination angles. The results confirmed improvements in bearing capacity and a significant reduction in settlement due to the installation of inclined skirts. The main findings of this study can be summarized as follows:

- The bearing capacity values obtained from numerical analysis are in good agreement with experimental results for hexagonal footings with different skirt embedment lengths. This strong agreement confirms that the numerical approach accurately represents the essential features of bearing behavior and provides confidence in its application for analyzing various skirt configurations.
- The load-carrying capacity increases significantly with the incorporation of inclined skirts in hexagonal footings. The bearing capacity of inclined skirted footings is approximately 1.25 to 2.97 times higher than that of non-inclined skirted footings. These results demonstrate that skirt depth and inclination angle are key parameters in enhancing ultimate bearing capacity.
- The peak stress in the stress–settlement curve decreases approximately linearly with increasing L/B when the hexagonal footing is equipped with inclined skirts. Additionally, increasing L/B is consistently associated with reduced settlement under a given applied stress, highlighting the beneficial effect of skirt inclination on footing performance.
- A strong correlation was observed between numerical and experimental results, with an R^2 value of 0.996 for both bearing capacity and settlement, confirming the reliability of the model. Furthermore, regression equations used to predict bearing capacity and settlement of hexagonal skirted footings showed maximum deviations of 3.11% and 4.31%, respectively, compared to experimental results.
- Both ANN and regression analyses showed good agreement with experimental and numerical results; however, the ANN model consistently outperformed regression by providing more accurate and reliable predictions, confirming its effectiveness in modeling complex geotechnical behavior.

7. Declarations

7.1. Author Contributions

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

7.2. Data Availability Statement

The data presented in this study are available in the article.

7.3. Funding

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

7.4. Conflicts of Interest

The authors declare no conflict of interest.

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