Increasing the Performance of Ring Foundation to Lateral Loads by using a Skirt Foundation

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ABSTRACT

In numerous engineering foundation designs, the influence of lateral loads is frequently underestimated in calculations. Consequently, recent studies have increasingly concentrated on comprehending the behavior of soil and foundations when subjected to lateral load influences. The present study aims to examine the performance of ring foundations, a common engineering solution employed in the construction of tall and slender structures that are vulnerable to lateral loads, such as those exerted by wind forces. The objective of this study is to enhance the lateral resistance of ring foundations by incorporating skirt foundations. The efficacy of skirt foundations was evaluated through a series of tests conducted on sandy soils of varying densities, ranging from dense to medium loose sand. Subsequently, lateral loads were applied to the ring foundations, both with and without skirt foundations. The results demonstrated that the lateral resistance increased in proportion to the ratio between the inner and outer diameters. Furthermore, the improvement rate was enhanced by the addition of the skirt foundation. Additionally, the lateral resistance increased with increasing the skirt foundation depth, reaching a maximum of approximately 50-100%. Similarly, an increase in the skirt inclination ratio to 45^0 resulted in a lateral resistance increase of up to 650%.

Keywords-lateral loads; ring foundation; skirt foundation; sandy soil; PLAXIS 3D

I. INTRODUCTION

Ring foundations are particularly effective and cost-efficient for high-rise buildings, providing robust support against substantial vertical loads as well as lateral forces. Such foundations are well-suited for structures including chimneys, television antennas, liquid storage tanks, silos, cooling towers, and various offshore installations. The present study examines the potential for enhancing the bearing capacity of ring footings in sandy soil. A variety of approaches were analyzed, including soil reinforcement techniques and structural design methods [1-17]. Among these, the use of skirt elements emerged as one of the most effective methods. Accordingly, the present study analyzes the impact of using skirts with varying inclinations to augment the bearing capacity of the ring footing. The term "skirt" is defined as a wall or series of walls surrounding the soil that augment the foundation and function as a unified entity with the foundation, regardless of whether the foundation is rectangular, square, or circular. The skirt's base is constructed from steel or concrete and may comprise a single element or multiple components. The skirt is thin and can be either vertical or inclined.

The usage of ring foundations was primarily based on their cost-effectiveness. The current study explores the potential for enhancing the performance of ring foundations through the integration of skirt foundations with varying inclinations in sandy soils of differing densities. Consequently, a finite element analysis was conducted using PLAXIS 3D to evaluate the performance of the ring foundation with attached skirts at the outer edge. A number of researchers have examined the impact of the inclination of the skirt foundation, undertaking both experimental and numerical studies to enhance the performance of the shallow square foundation resting on loose sand by using the skirt beneath the base, with varying inclinations of the skirt (10°, 15°, and 20°) [1-2]. The findings indicated that as the slope and depth of the skirt increased, the bearing capacity improved and the settlement decreased. Authors in [3] performed a numerical analysis deploying the PLAXIS-3D program to investigate the impact of the skirt foundation inclination on a strip foundation subjected to an eccentric inclined load in sandy soil. Skirt foundation angles of 0°, 20°, 30°, and 45° were analyzed and a notable improvement in the bearing capacity with an increasing angle of inclination was observed. Similar outcomes were noted in an experimental investigation conducted by authors in [4], who examined the influence of skirt foundation slopes at 5, 10, 15, and 30 degrees on square footing in a loose sandy soil under eccentric inclined load. Authors in [5], carried out an experimental study to demonstrate the significance of utilizing a skirt foundation, defined as a wall situated beneath the edge of a circular footing, in sandy soil with varying densities (loose, medium, dense) under lateral load conditions. The findings revealed that as soil density increased from loose to medium to dense, both the bearing capacity and the lateral movement exhibited a corresponding improvement. Furthermore, an increase in the foundation depth led to an enhancement in bearing capacity and a reduction in lateral movement. In order to investigate the effect of lateral load on a rectangular skirt foundation, authors in [6] performed an experiment, which also included an analysis of the impact of foundation depth and the number of skirt foundation pieces. The study concluded that an increase in the foundation depth resulted in an enhanced bearing capacity. Authors in [7, 8] conducted a finite element study to compare the bearing capacities of footings subjected to concentric vertical loads. The footings had constant dimensions but different shapes. The findings indicated that circular footings exhibited the highest bearing capacity, followed by ring footings with skirts. Authors in [9-12] explored the impact of the skirt foundation on gypsum soils and discovered that the bearing capacity of the soil increases in proportion to the ratio of the skirt depth to the footing diameter (d/D). A number of experimental studies were conducted with the objective of enhancing the stability of the ring foundation [13-19], exploring the potential of reinforcing the soil or adding a skirt foundation as a means of achieving this goal.

The preceding analysis demonstrates that certain structural types are more conducive to using ring footings, yet the incorporation of a skirt foundation enhances the stability of the ring footing. A review of recent studies reveals a paucity of research on the subject of skirt foundations and their associated details. This occurs despite the growing recognition of the importance of skirt foundations as an improvement to the existing foundations. This research considered a number of variables, including the density of the sandy soil and the change in the depth of the skirt foundation with the ratio of the change in/moving/ranging from the inner diameter to the outer diameter. Of particular importance was the change in the slope of the skirt foundation and its effect on increasing the stability of the structure. The objective of this paper is to examine the efficacy of inclined skirt foundations in enhancing the performance of ring foundations against lateral loads, with particular attention to the influence of soil density.

II. NUMERICAL MODELING

The finite element method is a valuable tool in geotechnical engineering, as it enables comprehensive analysis through the use of models, simulations, and calculations to assess the impact of diverse loads [20]. This study was performed implementing the three-dimensional PLAXIS program, which is designed to address a range of geotechnical issues and to consider the interaction between soil and structure. This paper focuses on the representation of soil behavior using the Mohr-Coulomb model, which is regarded as a fundamental approach in soil modeling, as it is based on a linear relationship between shear strength in a plane and the applied stresses [21].

A. Footing Material Modeling

The study employed a model with dimensions of 100 m×100 m and a depth of 20 m. A ring footing with a depth of 0.5 m was constructed using a volume element in PLAXIS 3D with a non-linear elastic model. Three distinct cases were examined for the ring footing diameters, with inner-to-outer diameter ratios (R_1/R_2) of 0.3, 0.4, and 0.5 meters. The footing was encircled by a skirt foundation of varying depths, with a thickness of 20 cm, which was modeled utilizing a plate element that surrounded the outer part of the ring footing. The external ring footing was integrated with the skirt foundation, thus functioning as a unified system. An interface element was incorporated into the model to simulate the interaction between the skirt foundation and the surrounding soil, as well as between the foundation and the internal soil. The value of R, as specified by authors in [22], was employed in this simulation. The model was subjected to analysis using three distinct types of sandy soil: dense, medium, and loose. The model's right and left boundaries were fixed in place, with the exception of the vertical movement, while the bottom was fixed on all sides. These boundary conditions were consistent with those used in several previous studies [23, 24]. This paper considers a lateral movement of 10 cm to be a failure criterion. This signifies that a lateral load is applied to the foundation, and the loading process is concluded once a lateral movement of 10 cm is attained. In order to ascertain the loads corresponding to the pre-lateral movement (10 cm), the surface prescribed displacement method was employed in PLAXIS 3D [25].

B. Model of the Ring Footing with Skirt

The ring footing, with a thickness of 0.5 m and a skirt model, were constructed from concrete with dimensions as the ones shown in Tables I and II. The geometric configuration of the ring footing with a skirt is presented in Figure 1, while the model of the same footing is depicted in Figure 2.

C. Modeling of Soil

This study deployed the engineering properties of sandy soil as determined by the laboratory tests conducted by authors in [26]. The properties of sandy soil with three different densities (dense, medium, and loose) are portrayed in Table III. The soil was modeled as an elastic-perfectly plastic material, and the Mohr-Coulomb failure criterion was employed.

TABLE I. PHYSICAL PROPERTIES OF CONCRETE

Physical properties	Values
Unit weight , γ_c (kN/m³)	24
Modulus of elasticity , E_c (GPa)	26
Poisson's ratio υ	0.25

TABLE II. DIMENSIONS OF THE RING FOOTING WITH THICKNESS 0.5 M WITH SKIRT

Inner diameter R_1 (cm)	Outer diameter R_2 (cm)	R (R_1/R_2)	Skirt length (L, cm)
45	150	0.3	100
80	200	0.4	150
150	300	0.5	200

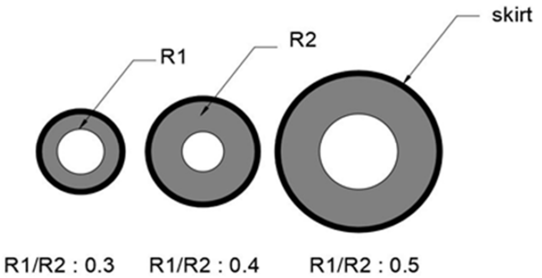
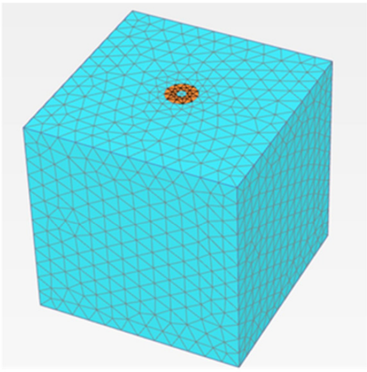


Fig. 1. Geometric configuration (top view) for the ring footing with skirt.

(a)



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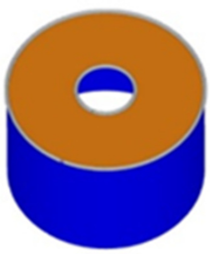

Fig. 2. (a) The model of soil with foundation (b) Model of the ring footing with skirt.

TABLE III. SOIL PROPERTIES

Soil properties	Loose sand	Medium sand	Dense sand
Dry unit weight , γ (kN/m³)	15.66	16.37	17.2
Angle of internal friction, φ (°)	28	32	38
Relative densite	30	55	82
Dilatancy angle, D_ψ (°)	-	2	8

III. VERIFICATION

In order to verify the numerical model, experimental data were utilized [5]. The experimental study involved the use of a steel-plated square footing with dimensions of 50 mm× 50 mm× 10 mm, situated on a layer of poorly graded sand within a box measuring 400 mm× 400 mm× 600 mm. The soil used was classified as (SP), with detailed properties displayed in Table IV, and the relative density of the sand was 30%. The numerical results were validated by being compared with the experimental results, as shown in Figure 3.

TABLE IV. THE PROPERTIES OF SANDY SOIL USED [5]

Property	Value
specific gravity, *Gs*	2.66
unified soil classification system (USCS)	SP
minimum dry unit weight, (kN/m³)	14.1
maximum dry unit weight, (kN/m³)	17.2

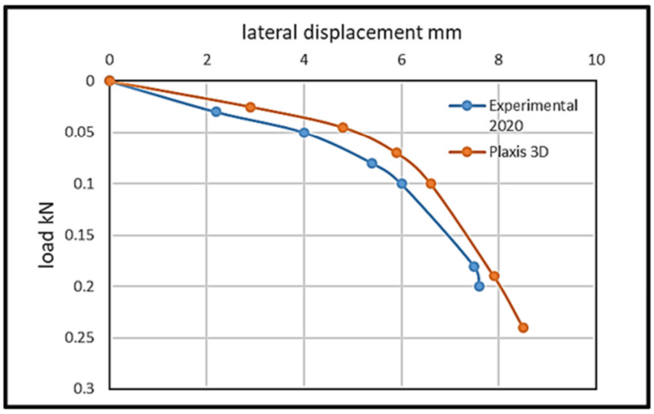

Fig. 3. Comparison of load-lateral movement responses between the model footing test data and the finite element results [5].

IV. RESULTS AND DISCUSSION

A. Diameter Ratio R_1/R_2 of 0.3

This section examines the influence of the diameter ratio (R_1/R_2) on the maximum lateral resistance of the ring foundation. The influence of skirt depth on the lateral resistance of the ring foundation was evaluated for a range of depths, including 0, 1 m, 1.5 m, and 2 m. As showcased in Figures 4 and 5, the maximum lateral resistance of the ring footing without a skirt was approximately 109 kN. The addition of a skirt with a depth of 1 m resulted in a slight increase in the maximum lateral resistance, reaching 119 kN, marking a 9.17% rise. With a skirt depth of 1.5 m, the maximum lateral resistance of the ring foundation increased to 178 kN, exhibiting a 63% rise. The maximum lateral resistance reached 246 kN for a skirt depth of 2 m, corresponding to a substantial increase of approximately 125%. These results indicate that an increase in the skirt depth significantly enhances the lateral resistance of the ring foundation. This is due to the stabilizing effect of the skirt on the soil beneath the foundation, which improves its capacity to resist lateral loads.

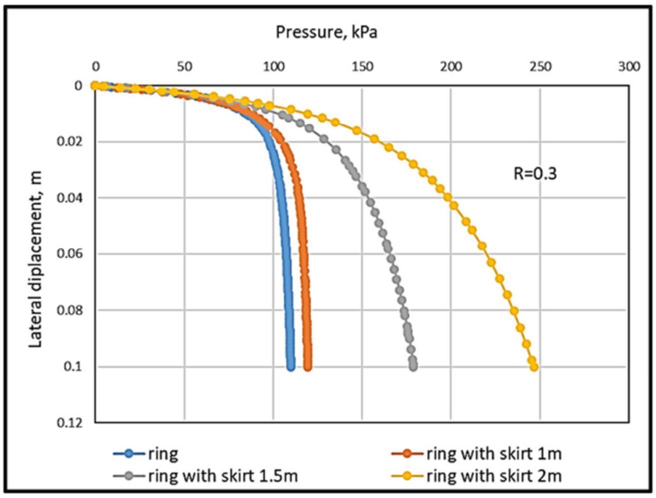

Fig. 4. Load-settlement curve of the ring footing with skirt in sandy soil, with a diameter ratio (R_1/R_2) of 0.3, at various vertical skirt depths.

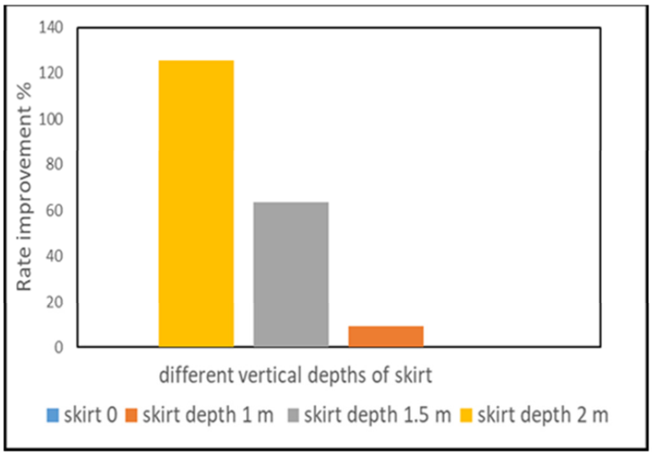

Fig. 5. Maximum lateral resistance rate of the ring foundation with skirt in sandy soil, with a R_1/R_2 of 0.3, at various vertical skirt depths.

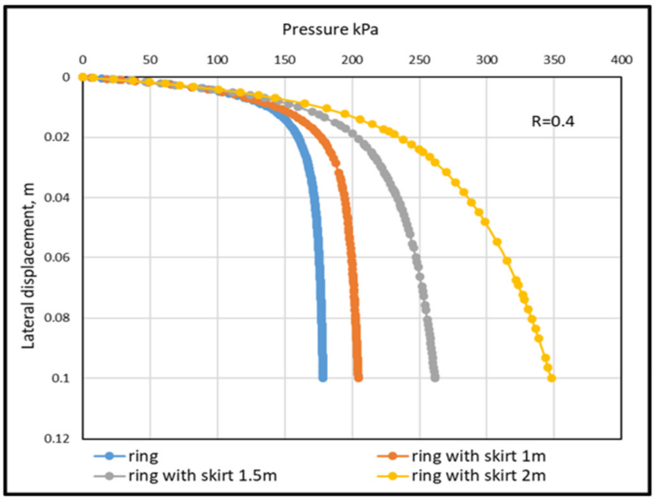

Fig. 6. Load-settlement curve of the ring footing with skirt in sandy soil, with a diameter ratio (R_1/R_2) of 0.4, at various vertical skirt depths.

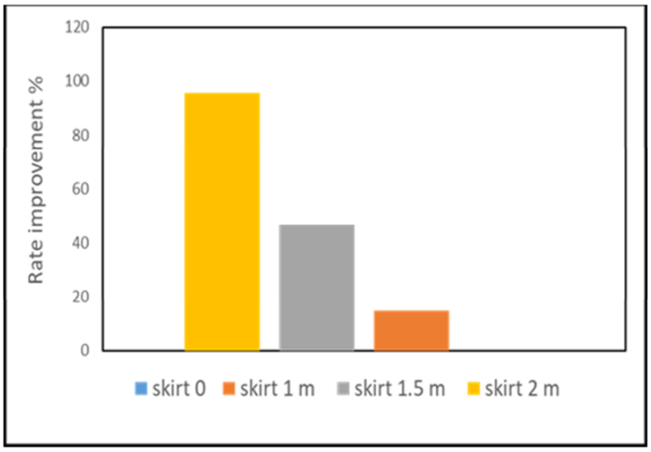

Fig. 7. Maximum lateral resistance rate of the ring foundation with skirt in sandy soil, with a (R_1/R_2) of 0.4, at various vertical skirt depths.

B. Diameter Ratio R_1/R_2 of 0.4

In the second case presented in Figures 6 and 7, a diameter ratio for the ring foundation (R_1/R_2) of 0.4 was used, with a skirt foundation at the same depths. The results indicated a lower rate of maximum lateral resistance values compared to the 0.3 ratio, thereby underscoring the significant role of the diameter ratio in enhancing lateral resistance. In particular, the maximum lateral resistance of the ring foundation in isolation was nearly 178 kN. The addition of the skirt resulted in an estimated 14.6% increase in resistance, reaching a value of approximately 204 kN. At a foundation depth of 1.5 m, the maximum lateral resistance increased to 261 kN, indicating a 46.62% rise. With a depth of 2 m, the lateral bearing resistance reached 348 kN, exhibiting a 95% increase.

C. DiameterRatio R_1/R_2 of 0.5

Figures 8 and 9 demonstrate the final case in which a diameter ratio of 0.5 was employed for the ring foundation. The results manifested a notable decline in the lateral resistance values, which suggests that the diameter ratio played a significant role. As the ratio increased, the effectiveness of the ring foundation diminished. The internal-to-external diameter ratio had a notable impact on the rate of increase in lateral resistance. In particular, the lateral resistance of the ring foundation without a skirt was determined to be 442 kN. The addition of a skirt with a depth of 1 m resulted in an increase in lateral resistance, reaching approximately 483 kN, which indicates a slight increase of 9.27%. As shown in Figure 10, the lateral bearing resistance of the ring foundation surrounded by a skirt at a depth of 1 m exhibited an approximate increase of 9.27%. Upon increasing the depth to 1.5 m, the lateral bearing resistance exhibited a 26.92 % increase. Ultimately, at a depth of 2 m, the improvement percentage reached 40%.

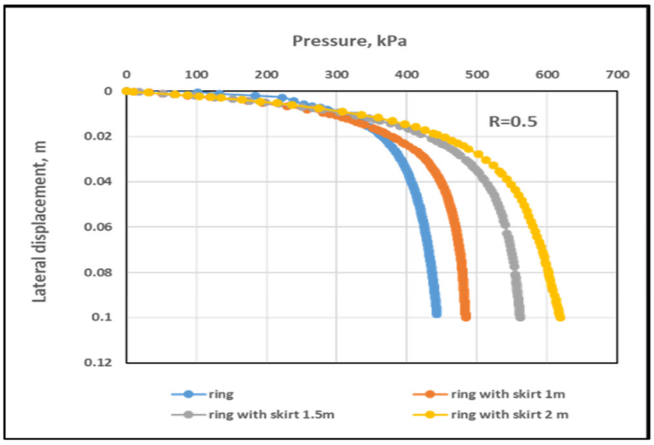

Fig. 8. Load-settlement curve of the ring footing with skirt in sandy soil, with a diameter ratio (R_1/R_2) of 0.5, at various vertical skirt depths.

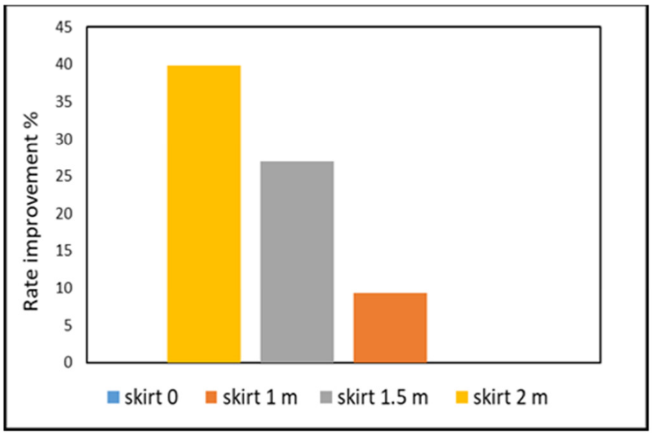

Fig. 9. Maximum lateral resistance rate of the ring foundation with skirt in sandy soil, with a (R_1/R_2) of 0.5, at various vertical skirt depths.

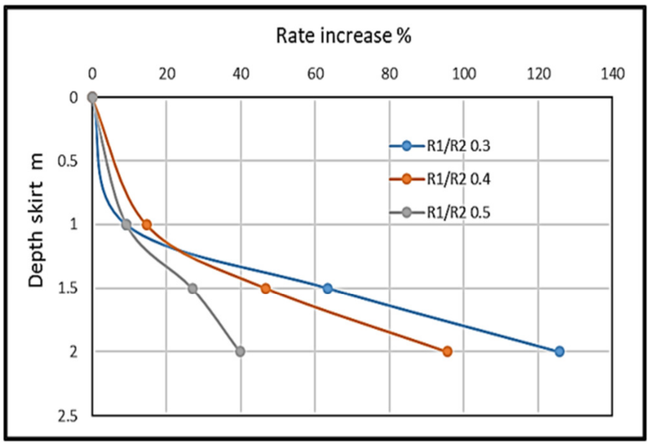

Fig. 10. Maximum rate of lateral resistance for the ring foundation with skirt at varying diameter ratio (R_1/R_2) and different vertical skirt depths.

D. *Different Types of Sandy Soil*

The influence of the relative density on the performance of the ring foundation in the presence of the skirt is examined. Three distinct soil types were put into service in this study: medium, dense, and the previously used loose soil. The results revealed that the maximum lateral resistance exhibited an increase in accordance with the rise in the relative density, as illustrated in Figure 11. At a depth of 1 m, the percentage increase in maximum lateral resistance was 9%, 12%, and 39% for loose, medium, and dense soils, respectively. Upon increasing the depth to 1.5 m, the percentage increase in maximum lateral resistance reached 63%, 82%, and 137% for loose, medium, and dense soils, respectively. Ultimately, at a depth of 2 m, the greatest ratio value for enhanced lateral bearing was observed, reaching approximately 125%, 165%, and 259% for loose, medium, and dense soils, respectively.

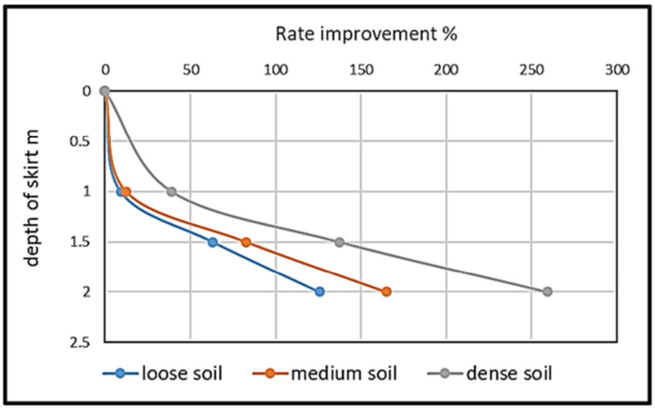

Fig. 11. Improvement rate in maximum lateral resistance of the ring foundation with skirt across three types of sandy soil (loose, medium and dense).

E. *Effect Angle of Skirt on Ring Footing*

Figures 12-15 show the impact of the skirt inclination angle on the performance of the ring foundation. The impact of three inclination angles (10°, 30°, and 45°) on the performance of the ring foundation in loose soil was investigated at varying depths (1 m, 1.5 m, and 2 m) and diameters (0.3). In the initial scenario, at an angle of 0° and a depth of 1 m (Figure 12), the lateral bearing resistance was observed to be nearly 119 kPa. When the skirt foundation was positioned at an angle of 100°, the lateral bearing resistance increased to approximately 230 kPa, representing an increase of about 93%. Upon further increasing the inclination angle of the skirt to 30°, the lateral resistance rose to approximately 439 kPa, representing an increase of about 230%. Ultimately, at an inclination angle of 45^0, the lateral resistance increased to approximately 650 kPa, thereby substantiating the assertion that the inclination angle of the skirt foundation exerts a pivotal influence on the enhancement of the lateral resistance of the ring foundation. The second scenario, presented in Figure 13, involved a foundation depth of 1.5 m and an inclination angle of zero, resulting in a lateral bearing resistance of around 258 kPa. When the skirt foundation was inclined at 10°, the lateral bearing resistance increased to approximately 354 kPa, representing a 37% rise. At an inclination angle of 30°, the lateral resistance exhibited a further increase, reaching nearly 702 kPa, which represents a 268% rise. Ultimately, with an inclination angle of 45^0, the lateral resistance reached approximately 1,566 kPa.

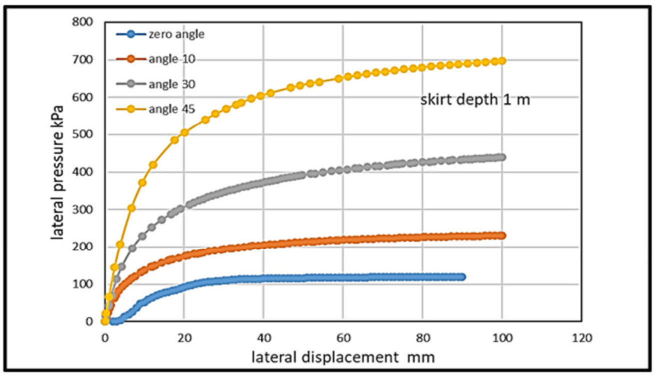

Fig. 12. The relationship between the skirt inclination angle of the ring foundation and lateral resistance for three different angles at a foundation depth of 1m, with a diameter ratio of 0.3.

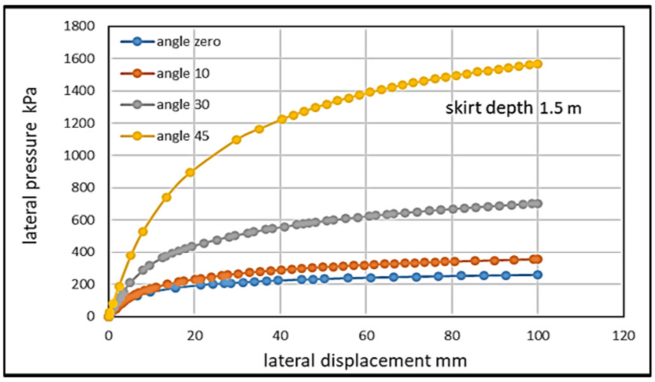

Fig. 13. The relationship between the skirt inclination angle of the ring foundation and lateral resistance for three different angles at foundation depth of 1.5 m, with a diameter ratio of 0.3.

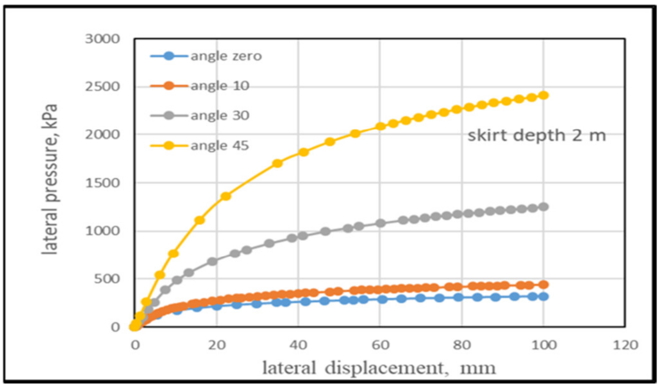

Fig. 14. The relationship between the skirt inclination angle of the ring foundation and lateral resistance for three different angles at foundation depth of 2m, with a diameter ratio of 0.3.

The third scenario examined the impact of a foundation depth of 2 m (Figure 14). When the inclination angle was set to zero, the lateral bearing resistance was found to be approximately 321 kPa. With the skirt foundation inclined at 100°, the lateral bearing resistance increased to approximately 440 kPa, representing a 30% increase. At an inclination of 30°, the resistance increased further, reaching 1,250 kPa, which represents a 289% increase. Ultimately, at an inclination angle of 45°, the lateral resistance reached approximately 2,409 kPa.

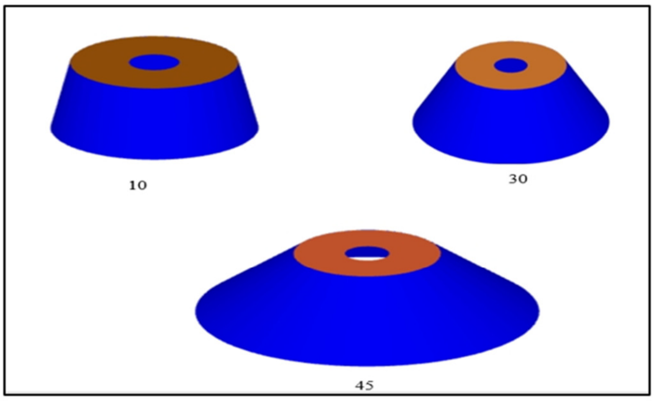

Fig. 15. Skirt with different angles.

V. CONCLUSIONS

After the study was concluded and the results were obtained through numerical analysis, the most significant conclusions are:

- The skirt foundation demonstrated a marked enhancement in lateral resistance relative to the ring foundation, particularly when the diameter ratio was 0.3.
- An increase in the length of the skirt resulted in a notable enhancement in the lateral resistance of the ring foundation. It is noteworthy that at a depth of 2 m, the lateral resistance ratio increased by 125% when the diameter ratio (R1/R2) was 0.3.
- The effect of the relative density plays a role in enhancing the improvement of the lateral resistance of the skirt foundation. It was observed that the lateral resistance increased in dense soils more than in medium and loose soils.
- The skirt inclination angle had an impact on the functionality of the ring foundation. Three cases of angles, including 0°, 10°, 30°, and 45°, with different depths (1 m, 1.5 m, and 2 m) were examined. The diameter ratio of 0.3 was selected for the ring foundation in loose soil. It was observed that when the inclination angle was 45° and the depth of the foundation was 2 m, the amount of lateral resistance reached its optimal value with an increase rate of 650%.

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