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NUMERICAL STUDY OF RING FOUNDATIONS NEAR SLOPES USING PLAXIS 3D

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Abstract

The problem caused by ring foundations adjacent to sloped grounds is the interaction between the soil and the structure, considering the loads imposed, which is a complex geotechnical issue. This research focuses on ring foundations used in axisymmetric structures, such as chimneys, water and oil tanks, silos, and wind turbines. This paper aims to numerically investigate the effect of a ground slope on the behavior of a ring foundation resting on sandy soil and subjected to axial loads. PLAXIS 3D software was used for numerical analysis. Some of the most critical parameters studied are the slope angle (β), the distance between the foundation and the top edge of the slope (b), the inner-to-outer radius ratio (ri/ro), and the foundation thickness (t). The results demonstrate significant reductions in bearing capacity and increased settlement with ring foundations close to steep slopes, especially with $b/B < 1$. The study confirms that a setback distance of $b/B \geq 1$ results in performance that is essentially equivalent to that on flat ground. Furthermore, greater slope angles reduce bearing capacity, while greater foundation thickness enhances performance. These results are key to the safe and economical design of foundations on sloped terrain.

Keywords - Ring foundations, Bearing capacity, Settlement, Slope, PLAXIS 3D, Geotechnical engineering

1. Introduction

The problem of constructing the foundations of a structure near a slope has historically posed a challenge for geotechnical engineers. A special type of ring foundation is a reinforced concrete foundation used to support special types of structures (axi-symmetric structures), such as chimneys, water tanks, and silos. A ring foundation may be built near the upper border of a slope, thereby impacting the bearing capacity and resulting in differential settlement of the foundation. Such a condition complicates matters concerning reduced soil stability and the increased likelihood of uneven stress distribution, as well as various problems associated with

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differential settlement. Even though there is much information on the behavior of strip and circular foundations close to slopes, there has been very little focus on the behavior of ring foundations under these conditions. This research is conducted using advanced finite element simulation with PLAXIS 3D.

The study of shallow foundations near slopes has been explored in several contexts, yet the application to ring foundations remains relatively underdeveloped. Early contributions, such as Kusakabe et al. (1981), provided pioneering analytical solutions for slope foundations using upper-bound plasticity methods. These studies, while simplified, established the foundation for subsequent advancements. By the early 2000s, researchers such as Laman and Yildiz (2003) and Boushehrian and Hataf (2003) had introduced experimental and numerical investigations into geogrid-reinforced sands, highlighting the significant potential of reinforcement to enhance the ultimate bearing capacity of ring foundations. Kumar and Ghosh (2005) further advanced understanding by employing the stress characteristics approach, showing that footing roughness and soil friction angle substantially influence bearing performance. The 2010s marked a period of refinement and expansion, with studies such as those by Benmebarek et al. (2012) and Kumar and Chakraborty (2015) utilizing finite element and limit analysis to establish detailed correlations between soil properties, radius ratios (ri/ro), and bearing capacity factors. Azzam and Elwakil (2016) and Remadna et al. (2017) extended the scope to slope conditions and cohesive-frictional soils, while Keshavarz and Kumar (2017) and Gholami and Hosseininia (2017) delivered validated equations and reliable design tools through advanced numerical methods.

Recent years have witnessed an emphasis on modern applications and performance optimization. Loading conditions were emphasized by Vali et al. (2019) and Al-Azzawi and Daud (2019), who showed that eccentric and point loads reduce capacity compared to uniformly distributed vertical loads. Kumar et al. Hussein (2021) utilized PLAXIS 2D and 3D to investigate reinforced footings near slopes, although their scope was limited to circular and strip foundations. (2022) expanded on this by modeling eccentric-inclined loads, while Ahmed et al. (2024) demonstrated that skirt foundations significantly increase lateral resistance. Wang et al. (2022) highlighted the importance of slope angle and roughness in undrained clay, and Fartosy et al. (2023) confirmed this in laboratory tests, finding that a ri/ro ratio of 0.25 yields optimal performance.

Recent works have extended applications to modern infrastructure. Zhang et al. (2024) communicated that ring foundations in wind turbines derive up to 50% of overturning resistance from the base flange, while Goel and Chatterjee (2024) showed through seismic simulations that concentrated inner loading reduces settlement compared to uniform loading. To fill a knowledge gap, Ghanim et al. (2025) researched ring foundations on sloped ground. They found that both the angle of the slope and the distance of the grade from the structure significantly impact the bearing capacity and the distribution of stress. This raises questions about how designs for such uneven terrain are constructed and suggests that these designs may need to be fundamentally reevaluated.

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Collectively, the researchers have indicated that while ring foundations on flat ground are well-studied, a significant research gap remains regarding their performance near slopes and under complex or dynamic loads. The consensus across decades of research underscores the importance of geometry, reinforcement, footing roughness, and loading type in foundation design. Closing this gap will enable the development of more robust, safe, and economical foundation systems, particularly for structures subjected to challenging soil and slope conditions.

2. Numerical Modeling

2.1 Geometric Modeling

The numerical investigation employs PLAXIS 3D, a powerful software for three-dimensional finite element analysis, to model the response of ring foundations located near slopes.

Efforts were made to define the geometry of the foundation and the adjacent soil mass as accurately as possible under field conditions, while minimizing the effects of the boundaries. The standard model of the ring foundation consisted of an outer radius of 5 m and an inner radius of 3 m, resulting in an inner-to-outer radius ratio (ri/ro) of 0.6. This configuration was chosen as a representative case for engineering applications. Based on previous studies[15][27], it was determined that the soil mass would extend horizontally three times the width of the foundation in both directions (xmin, xmax, ymin, and ymax = 3B), and vertically four times the width of the foundation (Z = 4B). The ring foundation was modeled as an elastic plate, which provided a realistic simulation of its deformation characteristics while interacting with the soil. The primary foundational parameters were: The soil profile was used with slopes set at an inclination of 25° to 45° to assess how greater steepness affects foundation performance.

In numerical modeling, generating a finite element mesh is crucial because it significantly impacts the accuracy of the computed stresses and deformations. By operating in PLAXIS 3D, select the element distribution of the (Fine) mesh. A fine mesh was created in this study with over 30,000 nodes and 19,409 elements.

The Mohr-Coulomb constitutive model was utilized to represent the soil as a single homogeneous layer of sand. The soil properties are used in the standard case described in Table 1. Figure 1 illustrates the ring foundations adjacent to the sand soil slope, which were defined in the software. The bearing capacity and displacement response were measured and recorded while applying a theoretical axial load of 5000 kN/m².

Table 1. Soil material properties (sandy soil)

Soil properties parameter	**Soil standard type**
Dry Unit weight, γ_{unsat} (kN/m^3)	17
Saturated Unit weight, γ_{sat} (kN/m^3)	17

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Effective Young's modulus, E	$50*10^3$
Effective Poisson's ratio, ν	0.3
Effective cohesion (kN/m^2)	1
Effective friction angle, ø'(°)	35
Dilatancy angle, ψ (°)	5

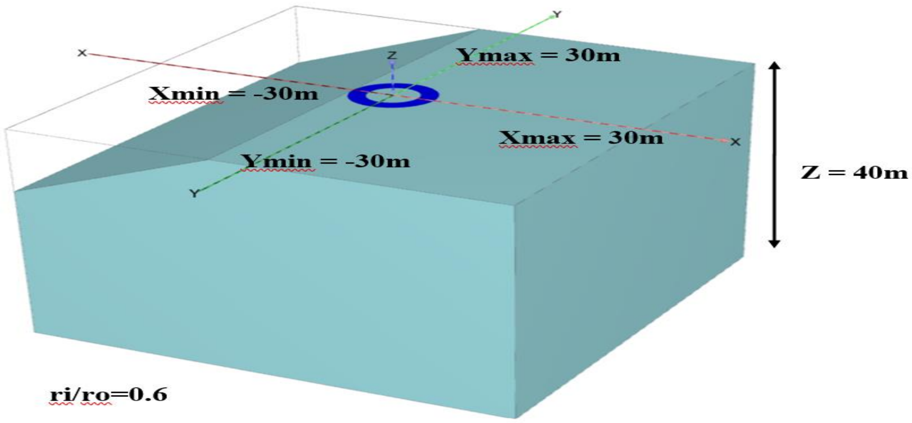

Figure 1. The geometry of the problem.

2.2 Numerical Model Validation

Verifying the accuracy of the numerical model concerning ring foundations on flat ground was crucial to preserving the integrity and credibility of the research findings. The model's accuracy was validated by benchmarking the numerical results against established theories, which in turn confirmed the model's dependability and its potential application in scenarios with limited research, such as ring foundations on sloping ground. Figure 2 illustrates the geometry of the model used for numerical validation. The ring footing was set on flat ground, as theoretical calculations are available for this case. The procedure described by Keshavarz and Kumar (2017) was utilized to predict bearing capacity.

ri/ro=0.6

A primary result from this validation was the notable consistency between the bearing capacity obtained using PLAXIS 3D and the theoretical bearing capacity. It was noted that the simulation yielded a bearing capacity of 1000 kPa, whereas the theoretical method by Keshavarz and Kumar (2017) calculated it to be 918 kPa. A less than 10% difference is acceptable within engineering tolerances and showcases the precision with which the numerical model can simulate the interaction between soil and structures.

Moreover, the model's accuracy was also corroborated by the settlement results. According to the current modelling, a displacement curve indicates a uniform settlement of 50 mm.

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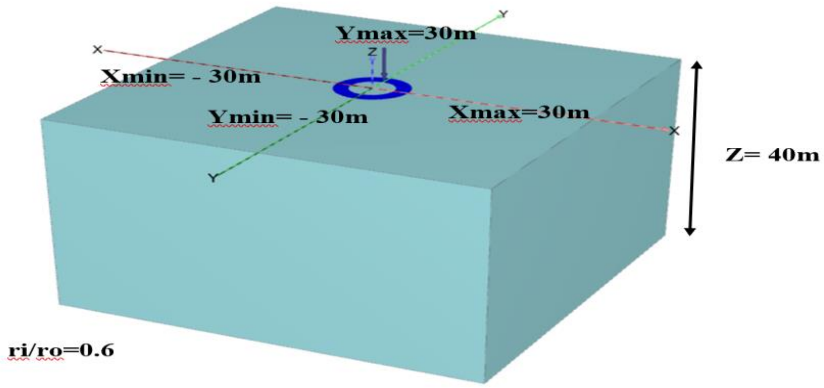

Figure 2. Ring foundation on flat ground in PLAXIS 3D

3. Results and Discussion

In the current study, the impact of several geotechnical parameters on the bearing capacity and settlement was investigated. The most critical parameters are distance from the slope edge (b), slope angle (β), angle of soil friction (ϕ), foundation thickness (t), and the ratio of inner to outer radius of the foundation (ri/ro), as illustrated in Figure 3.

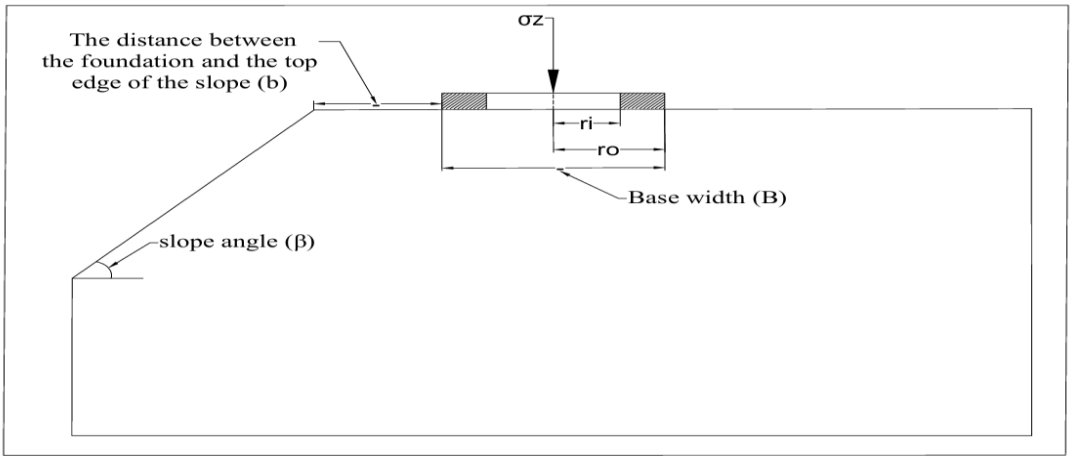

Figure 3. Parameters studied

3.1 Effect of the distance between the foundation and the top edge of the slope

The research investigates the impact of the distance of ring foundations to the edge of the slope on bearing capacity and settlement of the foundation. This is achieved by simulating multiple geometries with a distance from the slope crest ranging from 0 to 4 m. Three different radii aspect ratios (ri/ro = 0.4, 0.6, and 0.8) were considered, with 0.6 being the standard geometrical model. Each configuration was examined with a set of foundation slope angles, ranging from 25° to 45°, to replicate realistic site conditions. Figure 4 illustrates the configuration where the foundation is set at b = 1 m with respect to the upper edge of the slope.

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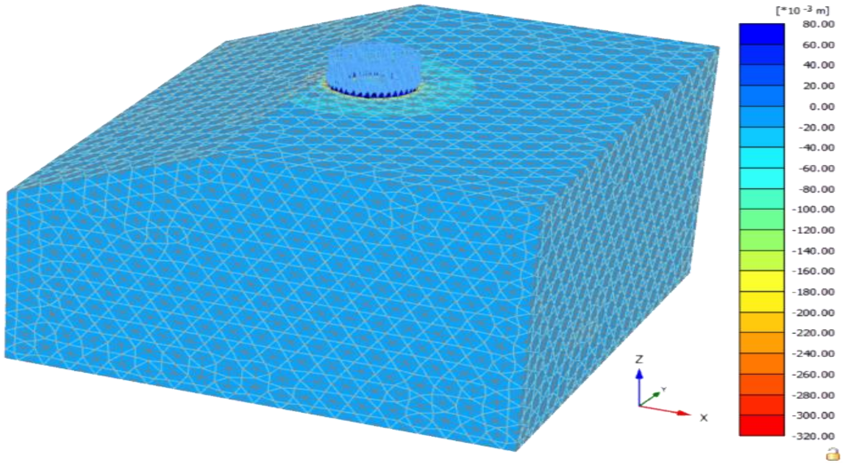
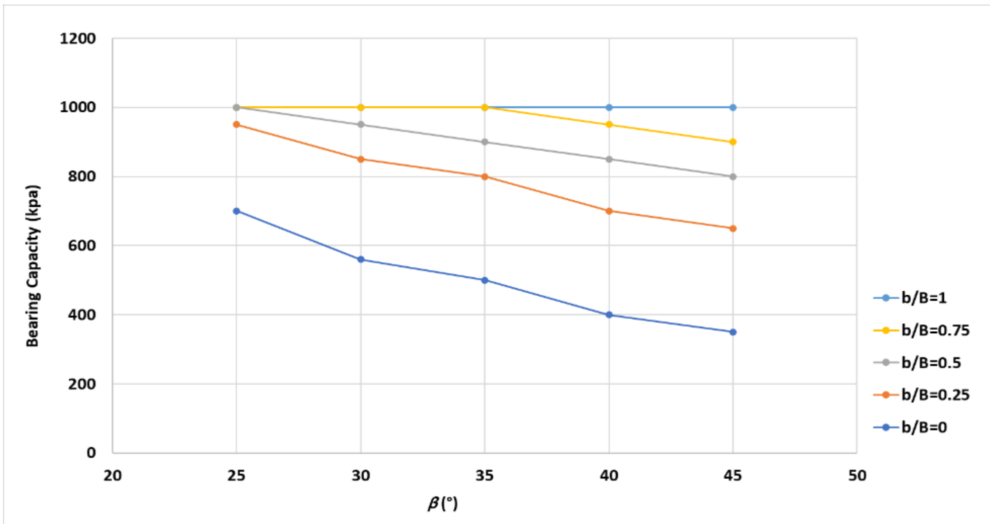


Figure 4 The distance between the foundation and the top edge of the slope (b=1) in the PLAXIS 3D

The effect of the distance between the foundation and the top edge of the slope in Figure 5-a, which plots bearing capacity versus slope angle for different values of the b/B ratio. This ratio is the horizontal distance from the slope edge (b) to the foundation's outer width (B). The figure indicates that bearing capacity generally improves with the increase of the distance b, especially when the b/B ratio is equal to or greater than 1.0. For foundations at b/B = 1.0 or greater, the bearing capacity remains constant at approximately 1000 kPa, regardless of the slope angle. On the other hand, for b/B = 0, the slope proximity significantly increases the slope angle, in which the bearing capacity drops sharply. This observation is consistent with other foundation shape configurations. As shown in Figures 5-b and 5-c, the ri/ro = 0.4 and 0.8 models both demonstrate that although the exact bearing capacity values differ in relation to the ring thickness, the corresponding trend is preserved. This confirms the notion that greater setback distance improves the foundation's bearing capacity, which is beneficial for structural stability, irrespective of the foundation's width.



(a)

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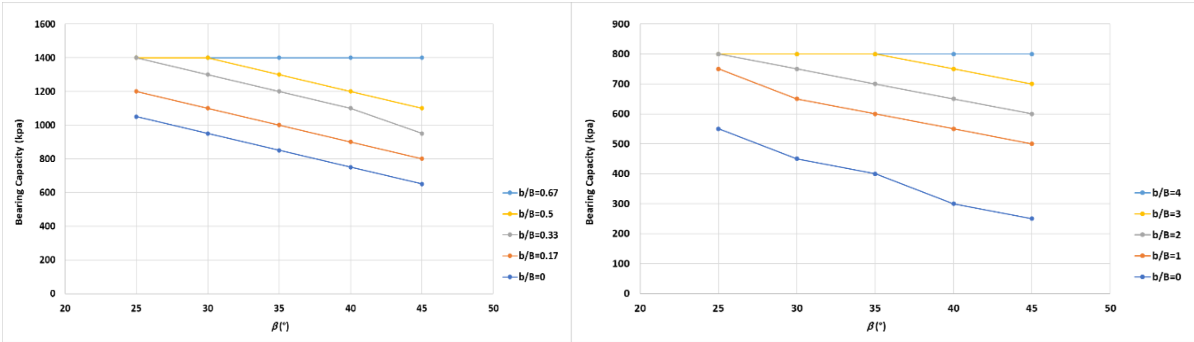

(b) (c)

Figure 5. The influence of b/B on bearing capacity.

a) standard model (ri/ro=0.6), b) model (ri/ro=0.4), c) model (ri/ro=0.8)

The results of ring footing settlement are illustrated in Figure 6, which graphs vertical settlement as a function of b/B ratios for all slope angles in the standard case. Across all angles of slope, all curves approach a settlement value of approximately 54 - 55 mm as b/B equals 1.0 or greater. This result suggests that increasing distance diminishes the impact that slope geometry has on vertical displacement. The consistent convergence at b/B ≥ 1.0 reinforces this value as a practical design limit for minimizing settlement. Like with bearing capacity, the settlement results were evaluated with different foundation geometries. The records for ri/ro = 0.4 and 0.8. Even with the slight variation in settlement amounts due to geometry, the overall trend is the same: benthic settlement is most significant when b/B = 0 and diminishes gradually as spacing increases, before stabilizing at b/B ≥ 1.0.

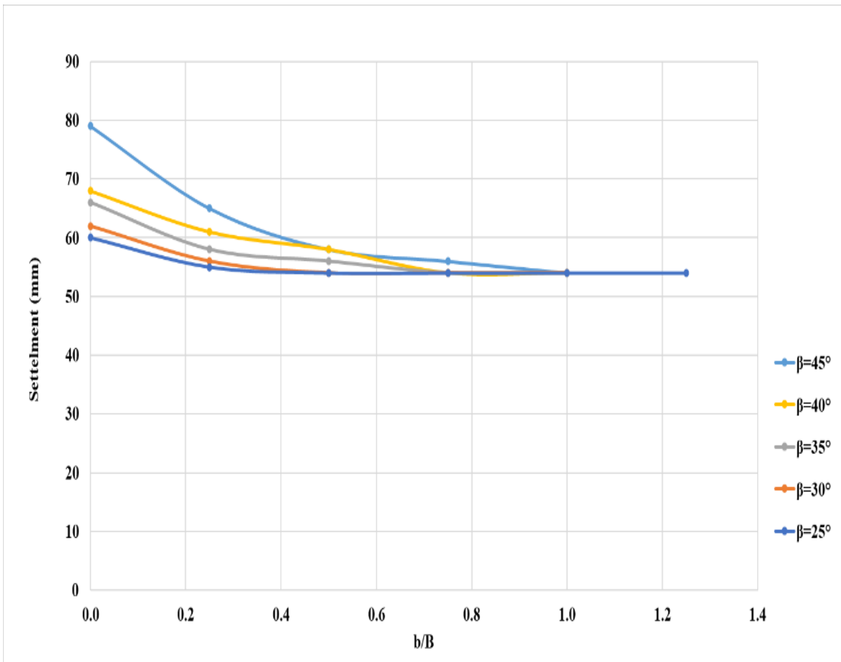

Figure 6. Results of vertical settlement for the standard foundation model (ri/ro = 0.6).

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3.2 Effect of the slope's angle

The angle of slope (β) is vital to the structural performance of ring foundations situated on the edge of silted terrain. Steeper slopes decrease the soil's ability to resist lateral deformation as well as bearing failure. Therefore, the soil's supporting ability becomes weaker and foundations become more unstable. To analyze how the foundation behaves at different angles, the analysis was run to find the bearing capacity and settlement of ring foundations at 25° to 45° slope angles maintained at a 1-meter horizontal distance from the slope. The ring foundations were tested at three ratios of inner to outer radii: 0.4, 0.6, and 0.8. Figure 7 illustrates the zones of settlement and the region surrounding as well as the area beneath the ring foundation for the ultimate bearing capacity at slope angles (β=45°).

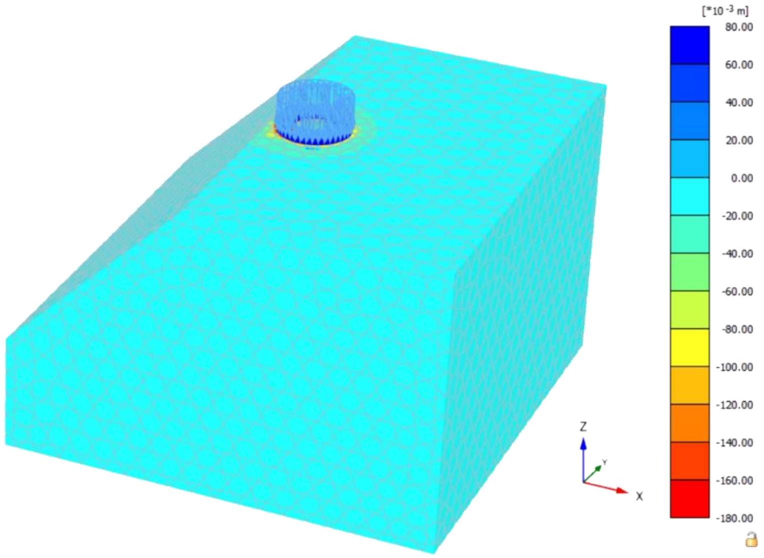

Figure 7. The slope angles (β=45°) within PLAXIS 3D software.

The results presented in Figure 8 illustrate that as the slope angle increases, the bearing capacity decreases in an adjacent linear manner. Moreover, it has been observed that the thicker rings (ri/ro = 0.4) have a higher bearing capacity in comparison to the slender rings (ri/ro = 0.8). Results shown in Figure 8 can be combined and approximated with a single linear equation (Equation 1), which calculates the bearing capacity in terms of the slope angle and the ring ratio.

BC=(20R-28) β+(-1675R+2370) ……. Equation 1

Where: -

BC = bearing capacity of ring foundation (kN/m²).

β = slope angle.

R= (ri/ro).

ri = inner radius of ring foundations (m).

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ro = outer radius of ring foundations (m).

Moreover, Figure 9 shows that all ring geometries show increased displacement when the slope angle increases. The increase is gradual to a slope of β = 40°, beyond which there is a marked increase, especially in the thick ring configuration. This shows how the wider foundations are more sensitive to instability due to the slope. In the case of the slender ring (ri/ro = 0.8), there is a more linear, less severe settlement pattern, meaning there is less active disturbance to the soil bordering the instability zone.

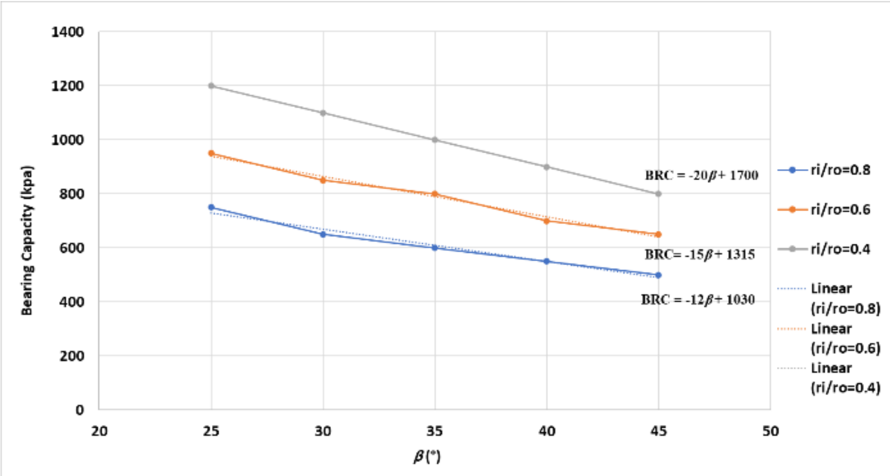

Figure 8. Analysis results of slope angles concerning bearing capacity

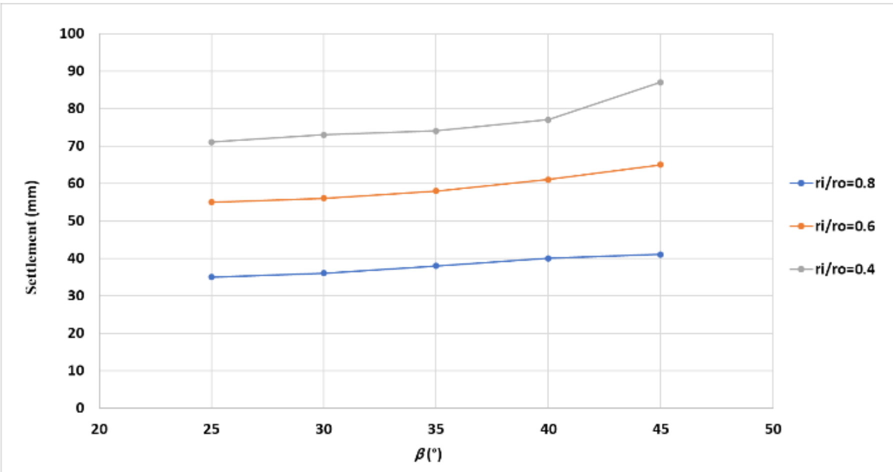

Figure 9. Analysis results of the angle slope regarding the settlement.

3.3 The Effect of the Inner-to-Outer Radius Ratio (ri/ro)

This section presents an analysis of how the ratio of the inner and outer radii of the ring (ri/ro) affects the geotechnical behavior of ring foundations placed on a slope. The analysis focuses on the behavior of the foundation with widths of 0.4, 0.6, and 0.8 in terms of the bearing

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capacity and settlement, with the foundation located at a horizontal distance of b = 1 m from the edge of the slope.

Based on the results included in Figure 10, increasing the ri/ro ratio values leads to a decline in bearing capacity at all slope angles. The bulkiest rings (ri/ro = 0.4), at a slope angle of 25°, deliver maximum capacity in an amount of 1200 kPa, while, on the contrary, the thinnest rings (ri/ro = 0.8) show drastically lower capacity values. The almost parallel character of the curve demonstrates that the rate of capacity loss with slope angle for all geometries is approximately the same.

Using analytical results shown in Figure 8, bearing capacity can be calculated in terms of slope angle and ri/ro ratio in one single linear equation as:

$BC \approx 1967-1010R-15.93\beta$ ……. Equation 4-2

<u>Where: -</u>

BC = bearing capacity of ring foundations (kN/m2).

β = slope angle (°).

R= (ri/ro).

ri = inner radius of ring foundations (m).

ro = outer radius of ring foundations(m).

Furthermore, the results of Figure 11 reveal that settlement behavior improves with the increase in the value of ri/ro. Less vertical displacements characterize foundations with thin rings and are therefore inclined to settle more readily along the steeper angles of a slope. For example, at β = 45°, the displacement of a thick ring (ri/ro = 0.4) is 87 mm. In contrast, the ring classified as thin (ri/ro = 0.8) shows a settlement that is markedly smaller than the previous value.

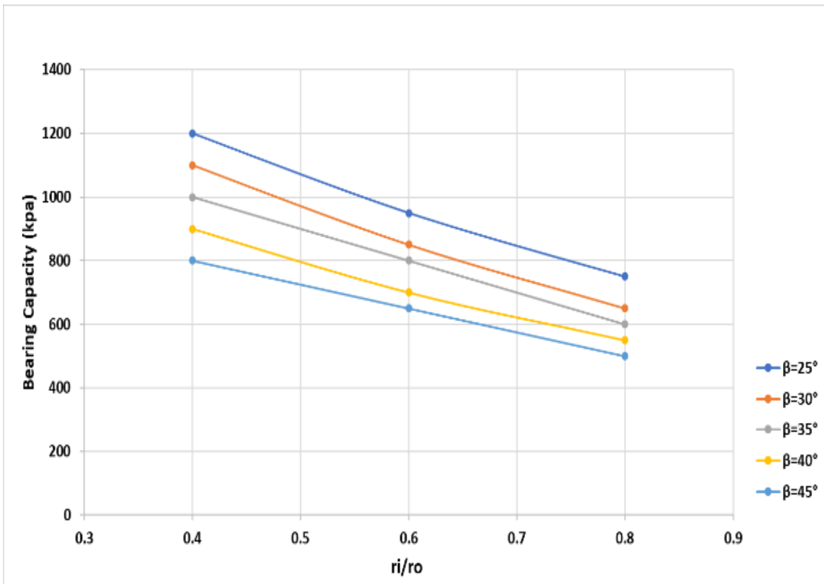

Figure 10. Results of inner-to-outer radius ratio (ri/ro) bearing capacity effect analysis.

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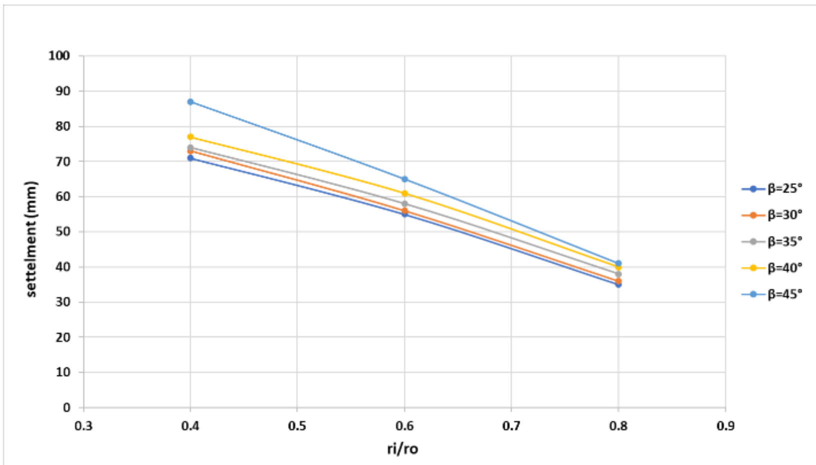

Figure 11. Results of the analysis of the effect of the inner-to-outer radius ratio (ri/ro) on the settlement

3.4 Effect of Thickness (t)

The ring foundation's thickness (t) is an essential factor when analyzing performance in terms of bearing capacity and settlement. For this, PLAXIS 3D was used to simulate the thicknesses of 1 m, 2 m, and 3m at constant slope angles (β = 35°) as well as through a fixed ring ratio (ri/ro = 0.6).

The results presented in Figure 12 show that as the thickness increases, the bearing capacity also increases linearly from 800 kPa to 1000 kPa, suggesting that thicker foundations can mobilize more soil resistance and support greater axial loads near slopes. This improved load-bearing behavior is advantageous within regions having lesser stability due to slope geometry. On the other hand, the Settlement only reduces from 58 mm to 57 mm, indicating that the increase in thickness beyond 1 m contributes very little to improving the settlement.

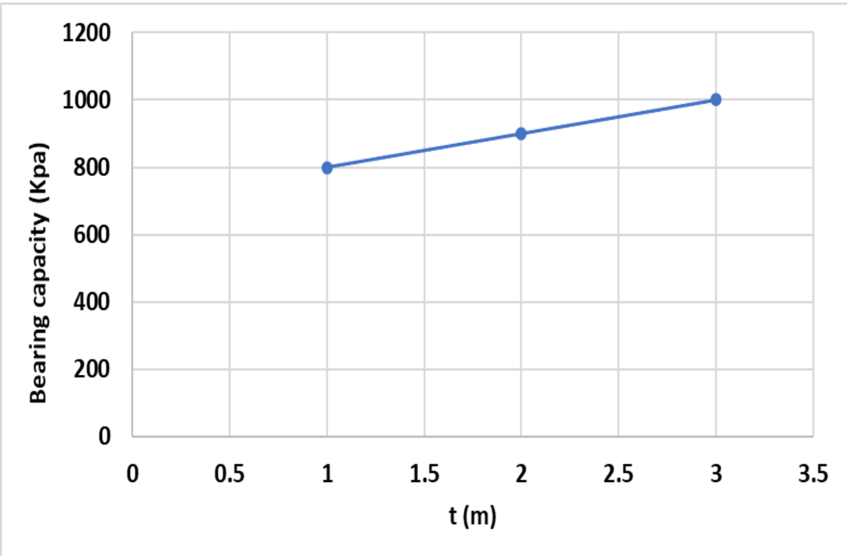

Figure 12. Results of the analysis of the effect of thickness (t) on the bearing capacity

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4. Conclusions

This study numerically examined the behavior of ring foundations adjacent to sloped surfaces using PLAXIS 3D finite element modeling. The study examined the effects of slope angle (β), distance from the slope crest (b), inner to outer radius (ri/ro), and foundation thickness (t) on bearing capacity and settlement. The results suggest that slope geometry affects the performance of the foundation. Foundations located within the edge of the slope ($b/B < 1$) have lower bearing capacity with larger settlement. On the other hand, Foundations that have a setback distance that is equal to or greater than the outer radius ($b/B \geq 1$) have almost the same performance as foundations on flat ground. The study further showed that steeper slopes reduce bearing capacity and increase settlement. At the same time, thicker foundations enhance bearing capacity resistance but offer limited benefit in controlling settlement beyond a specific thickness. Additionally, a smaller ri/ro ratio improves bearing capacity and settlement. The results highlight the need for precise geometry and site aspects when designing ring foundations adjacent to slopes. This study provides essential principles for the economical and safe design of foundations in sloped ground.

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