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Experimental and numerical investigation of the influence of relative density on the behavior of ring footings on an inclined surface

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HIGHLIGHTS

- Behavior of ring footings with radius ratios of n = 0.25, 0.5, and 0.75 was investigated.
- The bearing capacity of ring foundations decreases as the surface inclination increases from 10° to 20°.
- Numerical simulations of the ring foundations were carried out using the PLAXIS 3D finite element program.
- The bearing capacity of ring footings decreased by 15% when the slope angle increased from 10° to 20°.

Keywords:
Bearing capacity
Centrifuge modeling
Ring footing
Inclined surface
Numerical analysis

ABSTRACT

Ring footings are a crucial foundation type for supporting large and tall structures, as they enhance structural stability, mitigate the risk of overturning, and resist lateral forces. Compared with conventional circular foundations, ring footings also provide savings in construction materials and overall cost. This study examines the behavior of ring footings with radius ratios of n = 0.25, 0.5, and 0.75. The models consist of steel footings with a thickness of 50 mm and an area of 2200 mm², placed on granular sandy soil with a dried unit weight of 16 kN/m³ and a relative density of 50%. The footings were positioned at a distance of b/Do=1 from the slope crest to assess the influence of inclined surfaces. Centrifuge modeling was employed to simulate realistic field stresses, while numerical analyses were performed using PLAXIS 3D to verify and supplement the experimental data. The results show that the bearing capacity of ring foundations decreases as the surface inclination increases from 10° to 20°. On average, this reduction is about 10–15%, indicating the significant effect of slope angle on foundation performance. Furthermore, increasing the radius ratio of the footing leads to an additional decrease in bearing capacity, which aligns with previous studies. The combined experimental and numerical approach highlights the importance of considering slope inclination and geometry in the design of ring footings. These findings offer practical guidance for enhancing foundation stability and cost efficiency in geotechnical engineering applications involving sloping sandy soils.

1. Introduction

Ring foundations are a specialized type of shallow foundation characterized by an annular geometry, defined by an inner and outer radius, making them particularly suitable for structures with circular symmetry and central voids. They are widely applied in practice to support silos, chimneys, cooling towers, storage tanks, and offshore platforms, where the annular configuration provides both structural efficiency and material economy by concentrating the bearing area along the perimeter while eliminating the unused central portion. The performance of ring foundations is strongly influenced by the ratio of inner to outer radius, soil strength parameters, and load distribution, which govern both the bearing capacity and settlement behavior. Compared to conventional circular footings, ring foundations reduce material usage and achieve similar or higher efficiency but exhibit greater sensitivity to soil conditions and geometric parameters. In contrast to strip footings, which are optimized for linear load transfer along walls, ring foundations are superior for cylindrical structures due to their ability to distribute loads more uniformly along the annular path. When compared with raft foundations, ring foundations are more economical and lighter for circular loads. However, rafts remain preferable in very weak or compressible soils where a larger bearing area is required. Overall, ring foundations provide a balance between material efficiency and structural performance, making them an attractive option in geotechnical engineering design when soil conditions and structural geometry allow.

Initial studies on ring footings primarily examined their general performance, with early contributions highlighting their practicality and load distribution behaviour [1]. Subsequent advances included finite element analyses by Bowles and Guo [2], and experimental work by Ohri et al. [1], which suggested an optimal radius ratio of n ≈ 0.38. Later investigations refined this

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ratio to around n = 0.4 [3-9] reported a slightly lower optimum of $n \approx 0.35$. More recent theoretical developments, such as the application of Finite Element Limit Analysis [10]. In recent years, several studies have focused on improving the understanding of soil–foundation interaction and bearing capacity under different soil conditions. Compared theoretical and experimental behaviors of shallow foundations on cohesive soils, showing that advanced constitutive models such as the Hardening Soil model provide more accurate predictions than the classical Mohr–Coulomb model [11]. Mahmood et al. [12], investigated the influence of partial saturation on skirted foundations and found that partially saturated sand significantly enhances the ultimate bearing capacity compared to fully saturated conditions. Recently, Salih et al. [13] examined soil–foundation interaction in fine-grained soils using PLAXIS 3D and demonstrated that variations in soil properties strongly affect stress distribution and settlement behavior and experimental studies on gypseous soils [14], have further broadened the understanding of ring footing behaviour. In parallel, centrifuge modelling has provided valuable physical insights into soil–foundation interaction under controlled conditions [15-17].

Despite extensive research on ring footings, limited attention has been given to their behaviour on inclined surfaces or near natural and man-made slopes. Given the increasing demand for infrastructure development in sloping or undulating terrains, it is essential to evaluate how surface inclination influences the ultimate bearing capacity of such foundations. To address this gap, the present study examines the performance of ring footings with radius ratios n = 0.25, 0.5, and 0.75, placed on sandy soil with a relative density of 50%, at a setback distance of b/Do=1 from the slope crest, and subjected to surface inclinations of 10° and 20°. A centrifuge modelling approach, complemented by numerical analyses using PLAXIS 3D, was employed to investigate load–settlement behaviour and ultimate bearing capacity. The outcomes provide new insights into the combined effects of foundation geometry, soil density, and slope inclination, offering practical guidance for the safe and efficient design of ring footings in sloping ground conditions.

2. Laboratory model tests

The model construction for this investigation utilized a robust container with internal dimensions of 500 mm in length, 500 mm in width, and 500 mm in depth. The box is constructed entirely of steel plates. The container is joined with the arm of the centrifuge system through welding to prevent any distortion during the test, as shown in Figure 1.

The tests used solid steel three-ring model footings with ring radius ratios (n) of 0.25, 0.5, and 0.75. The cross-sectional area of all the foundations is constant and equal to 2200 mm², and the thickness is 50 mm. Table 1 depicts detailed information on the foundations.

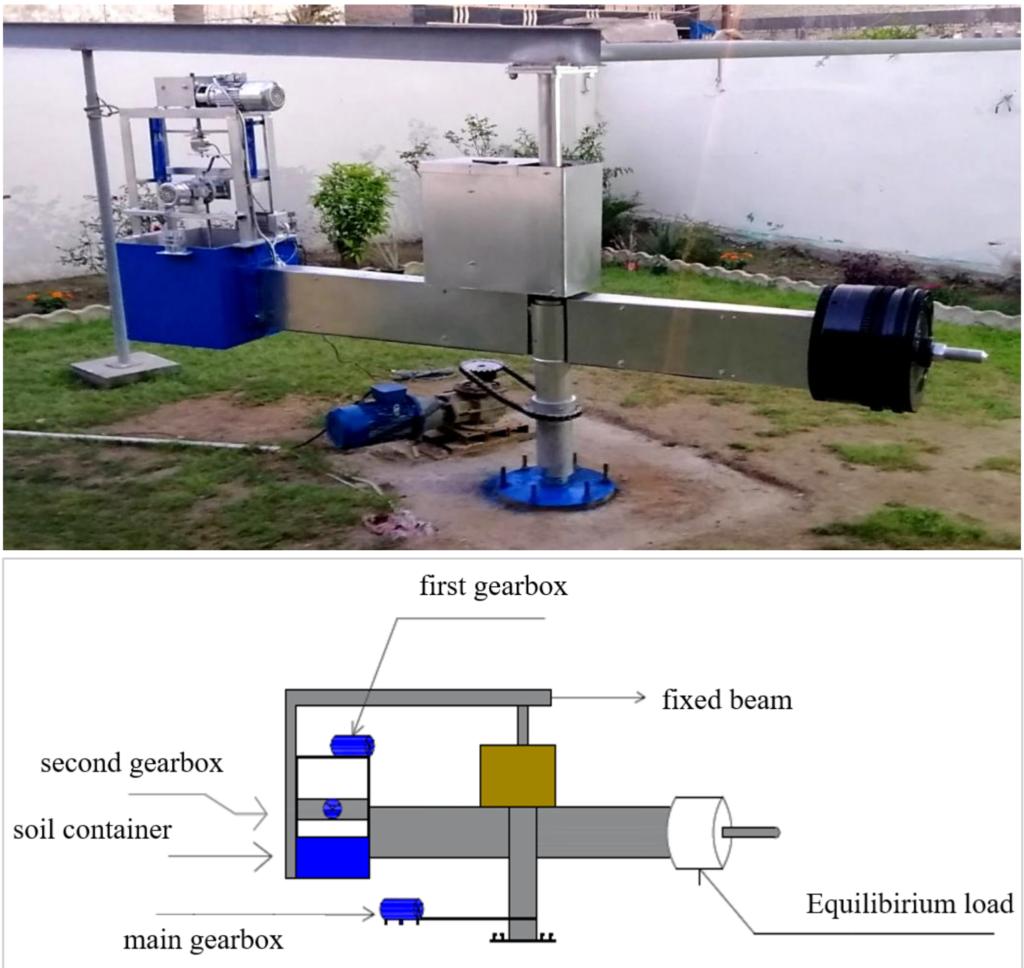

Figure 1: Centrifuge system

Table 1: Diameters of circular and ring foundations

Model No.	Footing type	$n = {Di}/{Do}$	Diameter (mm)	
			Di	Do
1	Circular	0	0	52.9
2	Ring	0.25	13.6	54.6
3	Ring	0.5	30.4	61
4	Ring	0.75	59.9	79.9

3. Limitation and scale effect

Newton's Second Law of Motion, which governs the rotation of mass around a fixed axis with a constant radius along a radial path at a specific angular velocity, is practically implemented through centrifuge modeling. According to the theory of centrifuge modeling, the soil density in the prototype and model is equivalent. The scale factor, denoted as N, is the ratio between the prototype's equivalent and the model's linear measurements. Consequently, the scale factor for displacement is also 1: N. The stress-to-strain ratio is 1:1. The gravitational stress experienced in the prototype is analogous to the inertial stress encountered in centrifuge modeling.

4. Test material

This study utilized medium sand that was dried, poorly graded, and cleanly rounded, as classified by the Unified Soil Classification System (USCS). The dry sieve analysis was used to determine the particle size distribution, as shown in Figure 2, by the standard test method ASTM D422-02. The sand's effective size (D_{10}) was 0.14 mm, its median size (D_{60}) was 0.51 mm, and its cap D_{30} was 0.31. Its uniformity coefficient (Cu) was 3.64, and its curvature (Cc) coefficient was 4.48. Table 2 details additional characteristics of the sand.

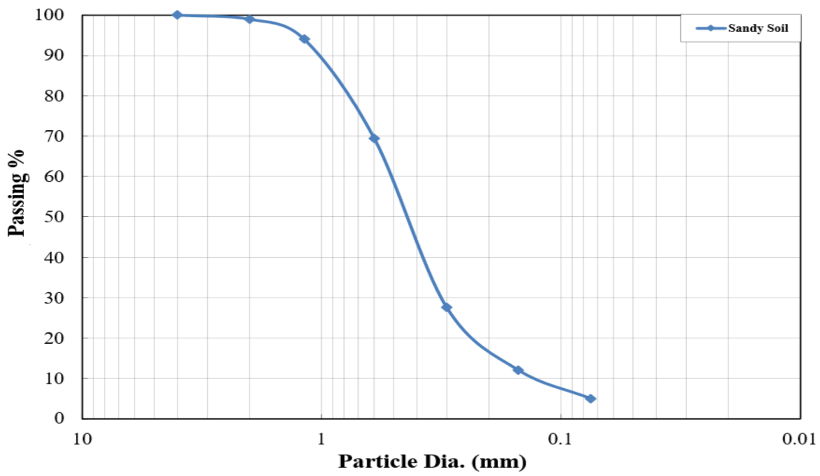

Figure 2: Grain size distribution

Table 2: Mechanical properties of sand

Description	Value	Specification
Maximum dry unit weight	18.1 kN/m^3	ASTMiD4253-00
Minimum dry unit weight	14.25 kN/m^3	ASTM D4254-00
Specific gravity	2.651	ASTM D845-00
Peak angle of friction	41°	ASTM D3080
Res. Angle of friction	27°	ASTM D3080

5. Testing procedure

This study established a consistent relative density of 50% with a dry unit weight of 16 kN/m³. The preset weight approach, as outlined by [18,19], was employed to arrange the sand beds in a 50 mm thick layer. Preparing the soil inside the container follows the described technique. When creating the soil model, the inclined surface's opposite side was positioned to counteract the centrifugal force. Subsequently, two steel plates were employed to stabilize the soil surface. One plate was affixed to the horizontal surface, while the other was adjusted to the required inclination angle for the examination. The plates were secured to the plate edges with two bolts, ensuring that the height of the plate corresponded to the inclined angle of the surface. After that, the plates were coated with silicon to prevent overflow from the container during rotation while the device was in operation.

The footing model was subsequently fastened to the shaft of the secondary transmission. According to the British Standards Institution Code of Practice (BS 5918:1980), the horizontal shaft of the first gearbox descends vertically by a distance, v, that ranges from 0.85 times the pitch to 1.15 times the pitch per revolution until it interacts with the shaft of the secondary gearbox. The horizontal shaft of the initial transmission is subsequently elevated to facilitate the load cell.

The experiment was designed to investigate the effect of a stabilizing medium, such as sand, on the load-settlement curves of ring foundations. The footings were positioned at a distance of (b/Do=1) from the edge of a sand slope with inclination angles of β=10° and β=20°. The sediment substrate has a dried unit weight of 16 kN/m³ and a relative density (RD) of 50%.

6. Results and discussion

Experiments were conducted on foundations with a ring radius ratio of n = 0.25, using sand with a relative density (RD) of 50%. The trials were performed at surface inclination angles of β = 10° and β = 20°. The findings indicated that an increase in the inclination angle corresponded with a reduction in ultimate bearing capacity, underscoring the detrimental effect of slope inclination on foundation stability, as shown in Figure 3.

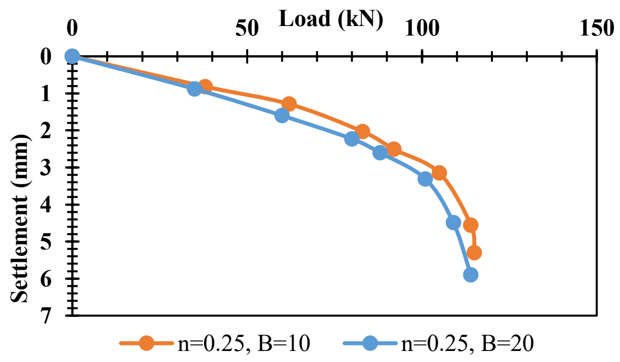

Figure 3: The load-settlement curve for a ring footing with n=0.25 and β=10° and β=20°

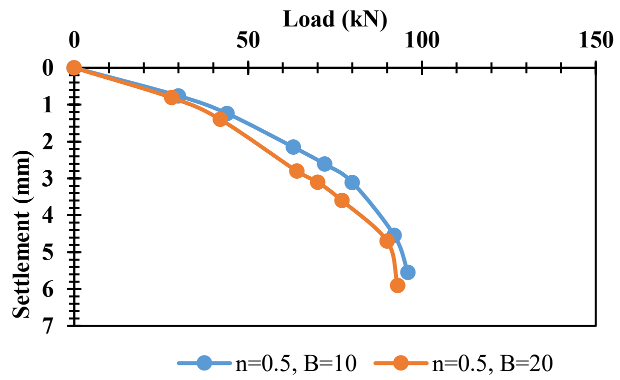

Figure 4: The load-settlement curve for a ring footing with n=0.5 and β=10° and β=20°

Another series of experiments was conducted on foundations with a ring radius ratio of n = 0.5, which were positioned on medium sandy soil with a relative density (RD) of 50%. The objective of these experiments was to examine the influence of surface inclination on the bearing capacity by adjusting the inclination angle (β) to 10° and 20°. The load-settlement curve in Figure 4 illustrates the impact of increasing inclination angles on foundation performance, as evidenced by the results of these experiments. A significant decrease in bearing capacity was observed as the surface inclination increased from β = 10° and β =20°. The soil's capacity to effectively support burdens is diminished as a result of the loss of lateral confinement [20-22].

The final set of experiments was conducted on footings with a ring radius ratio of 0.75, which were placed on medium sandy soil with a relative density of 50%. The purpose of these experiments was to evaluate the effect of surface inclination on bearing capacity by adjusting the inclination angles (β) to 10° and 20°.The goal was to gain a more comprehensive understanding of the impact of increasing the ring radius ratio on the performance of footings in sloped environments. The load-settlement behavior observed in these experiments, as illustrated in Figure 5, exhibits a distinct trend of decreasing bearing capacity with increasing inclination angle. The soil's capacity to withstand loading decreased as the inclination angle increased from β = 10° to β = 20°. This decrease can be attributed to the altered stress distribution and decreased confinement afforded by the surrounding soil, which results in higher settlement rates and earlier failure [23,24].

Additionally, the foundations with a ring radius ratio of 0.75 demonstrated a more significant reduction in bearing capacity compared to previous experiments that utilized lower ring radius ratios (n = 0.25 and n = 0.5). This implies that the foundation becomes more susceptible to fluctuations in surface inclination as the interior diameter of the ring foundation increases, resulting in a reduction in the efficacy of load transfer to the surrounding soil. The results emphasize the importance of carefully selecting the ring radius ratio in foundation design, particularly in sloped terrain where stability concerns are especially critical [25-28].

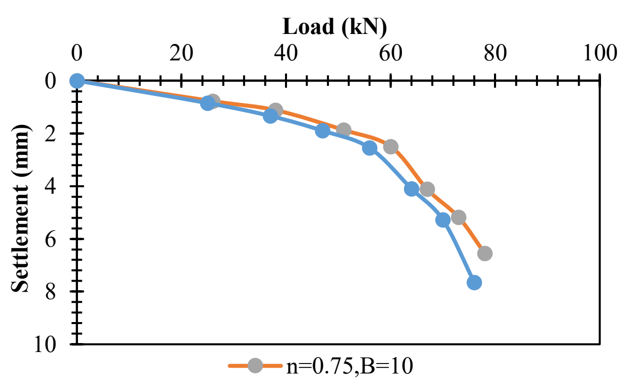

Figure 5: The load-settlement curve for a ring footing with n=0.75 with β=10° and β=20°

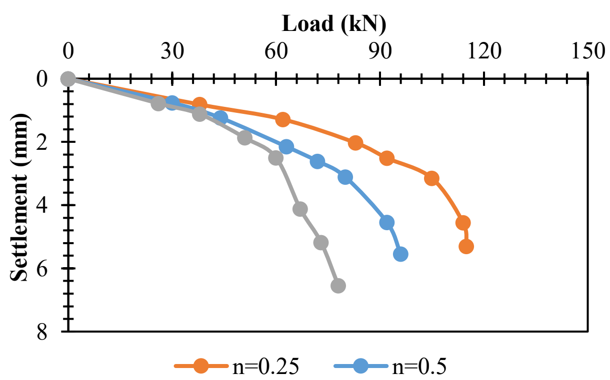

Figure 6: Load-Settlement curve for RD=50% and β=10°

The results indicate that the ultimate bearing capacity of ring foundations decreases by approximately 10–15% as the surface inclination increases from 10° to 20°, which aligns with the general reduction trends for shallow foundations on slopes reported by Bowles [2], and Meyerhof [29]. A comparative evaluation of ring footings with n = 0.25, n = 0.5, and n = 0.75 on sandy soil with a relative density of 50% further highlights the significant effect of slope inclination, consistent with the findings by Zhu [7], and Benmebarek [30], and similar observations regarding the sensitivity of foundations to slope conditions were also reported by Raj and Bharathi [31], reinforcing the importance of incorporating slope inclination effects in the safe design of ring foundations on granular soils.

Figures 6 and 7 demonstrate that the ring foundation with n=0.25 has the highest bearing capacity among the other foundations. This finding is based on previous studies by [3-6,32], and [33]. It is also worth noting that the bearing capacity of all foundations with n=0.25, 0.5, and 0.75 decreases as the inclination angle increases.

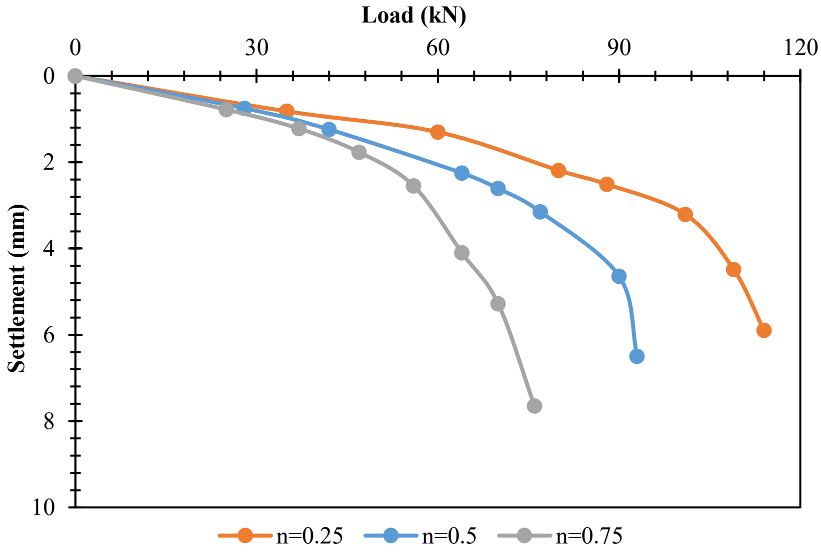

Figure 7: Load-settlement curve for RD=50% and β=20°

7. Numerical analysis

The finite element method (FEM) was employed to simulate the previously mentioned testing of ring footings that are situated on sloping sandy soil using PLAXIS 3D software. PLAXIS is intended to evaluate the stability and deformation of geotechnical engineering projects. The soil was modeled using the Mohr-Coulomb model. PLAXIS utilizes a fully automatic mesh generation process that partitions geometry into elements of the basic element type and compatible structural elements. PLAXIS offers five distinct mesh densities: very coarse, coarse, medium, fine, and very fine. Consequently, the fine mesh was selected.

The model geometry has been subjected to automatic boundary conditions by default. PLAXIS generates automated boundary conditions fixed at the base and seamless at the vertical sides. The input parameters for ring footings, which are made of steel, are listed in Table 3.

Table 3: Parameters of ring footings

Parameter	Value
Modulus of elasticity (E) kN/m^2	21×10^7
Poisson's ratio	0.3
Density of ring footings (**γ**) kN/m^3	78.5

Table 4 presents the mechanical characteristics of sand with a relative density (RD) of 50%, derived from laboratory analyses and direct shear testing. These qualities were then included in the numerical analysis.

Table 4: Soil parameters used in numerical simulations

Parameter	Value
Dry Density of Soil (**γ**) kN/m^3	16
Angle of Friction (ϕ)(degree)	33
Soil Cohesion (c) kN/m^2	2
Modulus of elasticity (E) kN/m^2	15000
Poisson's ratio	0.25

The bearing capacity could not be directly computed using the PLAXIS 3D program. As a result, the foundation underwent a specified settlement sequentially, and its response force was documented at each stage. The load-settlement curve is shown in Figures 8 and 9.

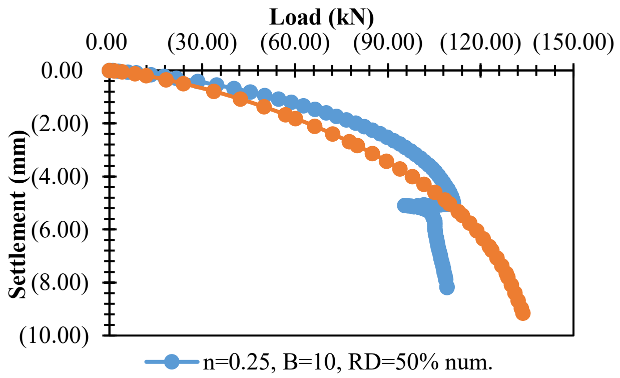

Figure 8: Load-settlement curve for RD=50% and β=10

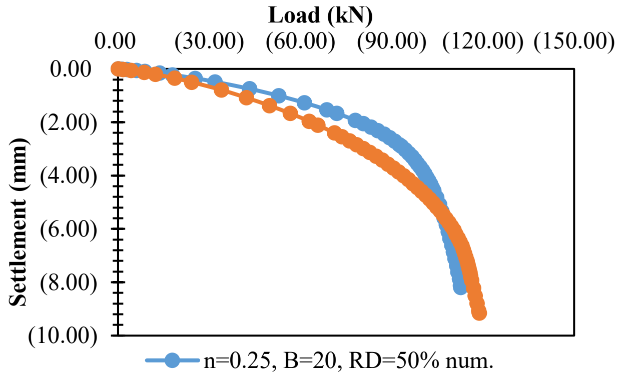

Figure 9: Load-settlement curve for RD=50% and β=20

A comparison between centrifuge test results and PLAXIS 3D simulations for the ring footing with n = 0.25 on sandy soil with a relative density of 50% at slope angles of 10° and 20° shows a similar overall trend. In both methods, increasing the slope angle results in greater settlements and a lower ultimate bearing capacity. The centrifuge tests typically yielded slightly larger settlements, whereas PLAXIS 3D exhibited a stiffer response, unless the soil parameters were carefully calibrated. The difference in ultimate bearing capacity between the two approaches was approximately 10–15%, which is consistent with earlier studies on foundations near slopes [2,7,20]. These results confirm that centrifuge modeling can capture the physical behavior of the soil, while numerical analysis with PLAXIS 3D can provide reliable predictions when calibration is performed [34-36].

8. Conclusion

This research has demonstrated that the ultimate bearing capacity of ring footings is significantly influenced by the inclination angle of the soil surface, resulting in a reduction in the overall load-bearing capacity. Centrifuge testing was employed to analyze the behavior of three steel ring foundations with radius ratios of 0.25, 0.5, and 0.75 in this research. The foundations were located on a powdery soil surface at a distance of b/Do = 1 from the slope's edge. The study compares the performance of different ring configurations and investigates the effect of varying surface slope angles (10° and 20°) on the bearing capacity of the foundations.

The experimental approach is supplemented by the PLAXIS 3D finite element program to validate the results. The findings suggest that the bearing capacity of ring footings on granular slopes decreases by 15% as the surface slope angle increases from 10° to 20°. Experimental and numerical results consistently demonstrate that the foundation with a radius ratio of n = 0.25 has the highest ultimate bearing capacity among the tested configurations. These insights are instrumental in understanding the behavior of ring foundations in sloped terrain and provide valuable recommendations for optimizing foundation design in geotechnical applications.

Author contributions

Conceptualization, **H. Ghanim, S. Al-Wakel** and **Z. Samueel**; data curation, **H. Ghanim**; formal analysis, **H. Ghanim**; investigation, **H. Ghanim**; methodology, **S. Al-Wakel**; project administration, **S. Al-Wakel, H. Ghanim**; resources, **H. Ghanim**; software, **H. Ghanim**; supervision, **S. Al-Wakel** and **Z. Samueel**; validation, **S. Al-Wakel, Z. Samueel** and **H. Ghanim**; visualization, **H. Ghanim**; writing—original draft preparation, **H. Ghanim**; writing—review and editing, **S. Al-Wakel** and **Z. Samueel**. All authors have read and agreed to the published version of the manuscript.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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