Research Article

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The optimum reinforcement length for ring footing resting on sandy soils resisting inclined load

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Abstract: The primary components of successful engineering projects are time, cost, and quality. The use of the ring footing ensures the presence of these elements. This investigation aims at finding the effective length of geogrid reinforcement layers under ring footing, which is subjected to inclined loading. For this purpose, experimental models were used. The parameters were studied in order to find the effective reinforcement length, including the ring footing optimum radius ratio, optimum depth ratio of the first reinforcement layer, and optimum reinforcement length. The results of the experimental study showed the optimum radius ratio, optimum reinforcement depth, and optimum reinforcement length to be 0.4, 0.25*B*, and 5*B*, respectively. The tilting improvement ratio due to soil enhancement for the load inclination angles 5, 10, and 15° were 10, 12, and 15%, respectively

Keywords: ring footing, sandy soil, geogrid, carrying capacity, inclined load

1 Introduction

Ring footings are a unique type of shallow foundation in addition to carrying loads of axisymmetric structures such as bridges, piers, jacket structures, silos, wind turbines, and water tower structures. The ring foundation can resist different types of loads such as inclined load [1]. The load inclination significantly reduces the carrying capacity of the supporting soil by tilting or foundation sliding and lifting the supporting soil. This becomes more complicated when the soil is weak and might be avoided by either increasing the carrying capacity of the soil beneath the foundation or constructing the foundation with larger dimensions to minimize the contact load, but this is costly and inefficient. Another solution is using soil reinforcement material and this is the aim of this study.

Generally, the soil has a low tensile strength [2]. Therefore, it is often necessary to use soil reinforcement to improve the soil, increase its carrying capacity, and reduce differential settlement. Many researchers have shown how soil reinforcement can boost bearing capacity at a low cost, such as by using reinforcement materials [3–5].

Thomas and Philip [6] investigated the bearing capacity of ring foundations resting on both unreinforced and reinforced sand by geonet. They found that the bearing capacity depends on the depth and the number of layers of reinforcements. If the number of layers increased, then the bearing capacity also increased. As the depth increased, the bearing capacity decreased.

Al-Khaddar and Al-Kubaisi [7] investigated numerically the behaviors of ring footing located on two layers when an inclined load was applied. The effect of multi-layered soil has been simulated in the model. The results showed that, both vertically and horizontally, stresses are affected when the inclination angle of the load exceeded 45° with a reduction of 40–80% when compared to those with an inclination angle of 0°. Furthermore, the bending moment and shear forces within the footing were affected by the diameter ratio of inner diameter/outer diameter and by the inclination angle of the load.

In this article, a small experimental model was used to evaluate the performance of ring footing resting on reinforced sandy soil resisting inclined loading, which is an unpopular topic; also there is a lack of studies on the ring footing subjected to inclined loads.

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2 Materials and laboratory testing work

2.1 Soil used

The sand used in this study was Al-Ekhaither sand, with a passing sieve no. 10 (B.S.). The grain size distribution curve is shown in Figure 1. The sand properties and their values are listed in Table 1.

Table 1: Properties of the sand used

Property	Value	Specification
Classification	SP	ASTM D 2487 [8]
Coefficient of uniformity (C_u)	4	ASTM D 422 [9]
Coefficient of curvature (C_c)	1	ASTM D 422 [9]
Specific gravity (G_s)	2.67	ASTM D 854 [10]
Optimum water content (%)	12.3	ASTM D698 [11]
The angle of friction (Ø), dr = 30%	32°	ASTM D 3080 [12]
The angle of friction (Ø), dr = 75%	35.6°	ASTM D 3080 [12]
Maximum dry unit weight (γ)	17.40 kN/m^3	ASTM D 4253 [13]
Wet unit weight (γ)	15.55 kN/m^3	ASTM D 4254 [14]
Dry unit weight in test (γ_d), dr = 30%	14.6 kN/m^3	ASTM D 4254 [13]
Minimum dry unit weight	14.6 kN/m^3	ASTM D 4254 [13]

2.2 Geogrid

In this study, geogrid was used as a reinforcement material (Figure 2). The geogrid was of a biaxial type, which could resist the stresses in both directions by the same amount; its physical properties are shown in Table 2.

2.3 Laboratory testing setup

A steel container with a dimension of 700 × 700 mm in length and width and 500 mm in height and a plate with a thickness of 3 mm was used as the container walls, while an angle section of 50 mm × 3 mm was used as the frame. All parts were welded together by electrical welding. The internal walls of the box were covered with a nylon layer to reduce the friction that might be induced between the box walls and the soil.

The footing model is a small-scale physical model of a steel ring footing with a 100 mm outer diameter (*D*), a variable inner diameter (*d*), and a 20 mm thickness (*H*).

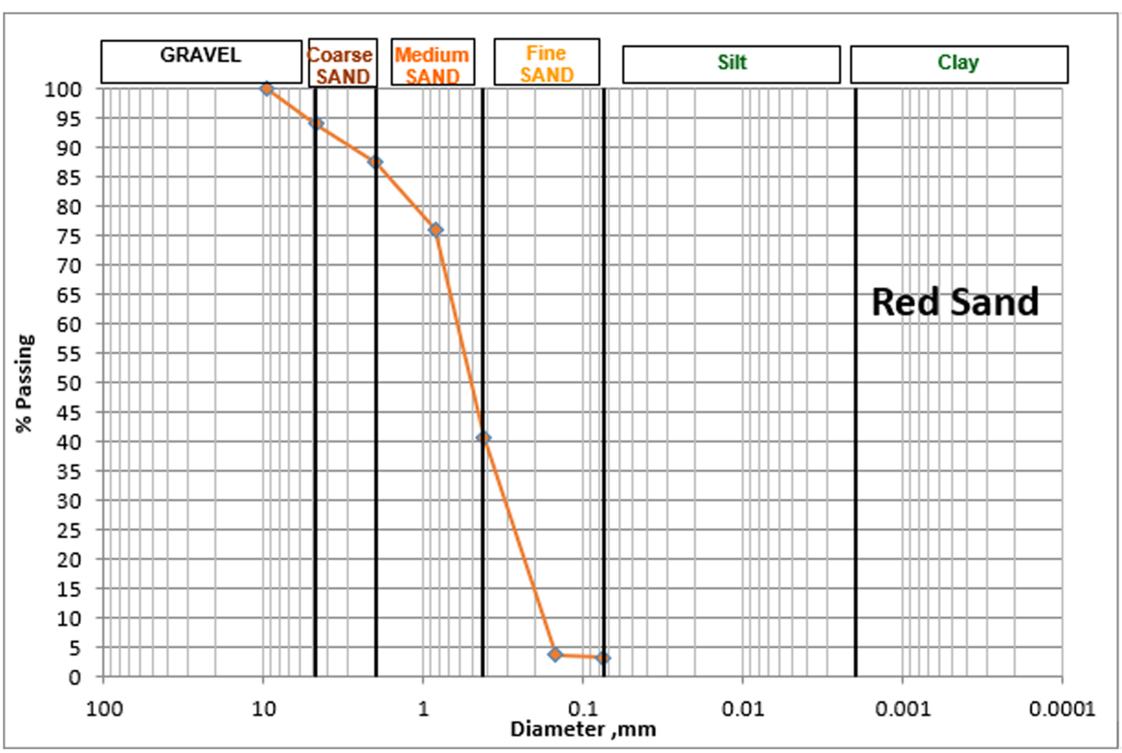

Figure 1: The grain size distribution curve.

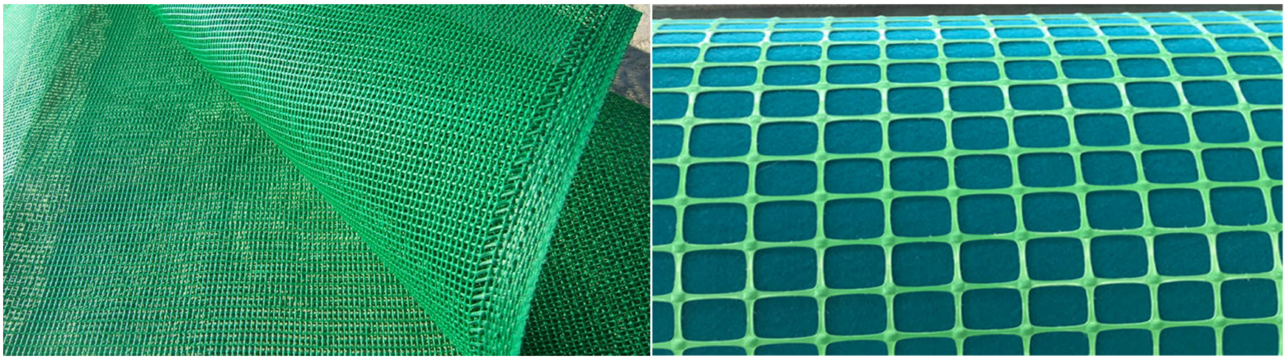

Figure 2: Geogrid used.

Table 2: Physical properties of the geogrid

Property	Data
Mesh type	Rectangle
Rib thickness	1.5 mm
Rib width	1.6 mm
Junction thickness	1.8 mm
Roll width	1.2 m
Roll length	30 m
Elastic modulus	0.26 GPa
Tensile strength	2.25 MPa

Many devices were used to measure the load–settlement of the ring foundation. The load was measured using a load cell (SC516C) of 1 ton capacity (Figure 3a) while the settlement and the displacement were recorded using a three-dial gauge Mitutoyo brand with a capacity of 50 mm (Figure 3b).

The loading system was made using an electrical jack with a capacity of 3 tons working on a battery with 12 V and 15 A, as illustrated in Figure 4. The rate of loading was adjusted to 1 mm/min.

Figure 3: Measuring instruments. (a) load cell; and (b) dial gauge.

3 Boundary conditions and scale effect

1. Container walls may significantly reduce the vertical stress with depth. To avoid wall-side friction, the container's height/diameter ratio must be ≤1 [15].
2. To keep the coefficient of lateral earth pressure at rest (K_o) close to its assumed value with no lateral strain, the effect of horizontal deflection of the container wall should be lesser than H_c/2,000 (container height/2,000).

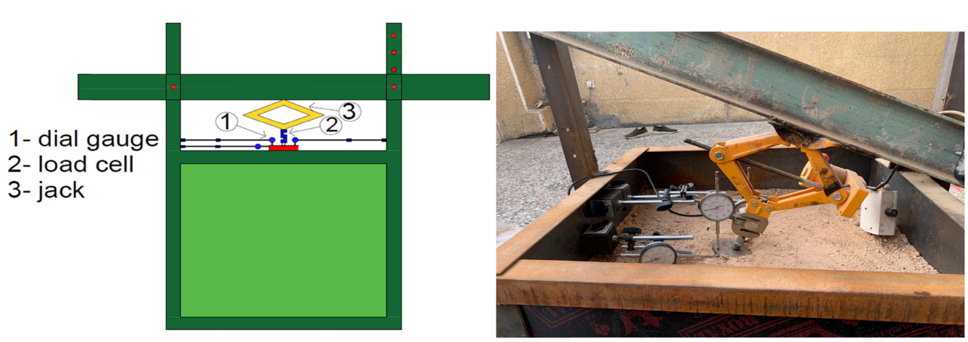

Figure 4: Loading system.

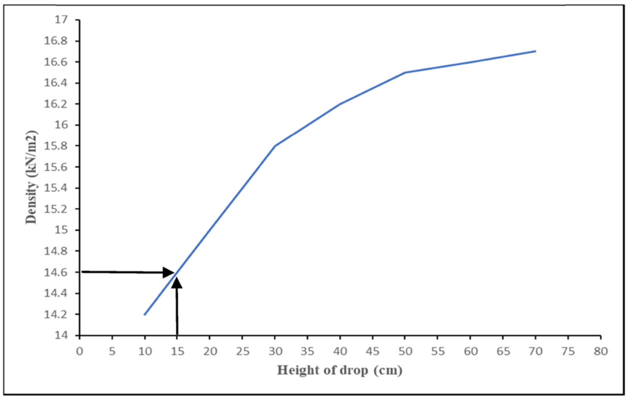

Figure 5: Relationship between the density and height of the sand drop.

3. It has been demonstrated that a sand thickness of >3*B* below the footing is sufficient to eliminate any rigid bottom boundary effect in shallow foundations [16].
4. For the best reinforcement effect, the width of the foundation should be 13–27 times the average particle size.

4 Testing procedure

To achieve the required density of the sandy soil, the rain technique was used. A mechanical system similar to that recommended in the study of Bieganousky and Marcuson [17] was used. Many researchers have used this technique [18–20]. Many tests have been done with various heights to obtain the desired density. A drop with a height of 15 cm was chosen, which gave a placing density of 14.6 kN/m^3 corresponding to a void ratio and a relative density of 0.79 and 30%, respectively, as illustrated in Figure 5. A relative density of 30% was used in this test program to represent the weak soil, and an improvement was noted in the geogrid used.

The sand was poured for each test until the designed level of sand was reached, and the foundation model was placed centrally in the tank. The load was subjected to the footing through an electrical jack. The load was recorded from the load cells that are connected to the digital screen.

The dial gauges were installed on both sides of the foundation for reading the differential settlement and lateral displacement.

5 Studied parameters

Several parameters were studied to evaluate the performance of ring footing. These parameters include the optimum radius ratio R_I/R_O (inner radius/outer radius), optimum embedment ratio U/B of the first geogrid layer (depth of the first reinforcement layer/foundation width), and the optimum geogrid length L/B (reinforcement layer length/foundation width). Different load inclination angles (α = 0, 5, 10, and 15°) were used to perform this study. The testing program is shown in Table 3.

6 Results and discussion

6.1 Optimum radius ratio1

Many tests were performed to investigate the effect of the radius ratio on the behavior of the ring footing. A footing

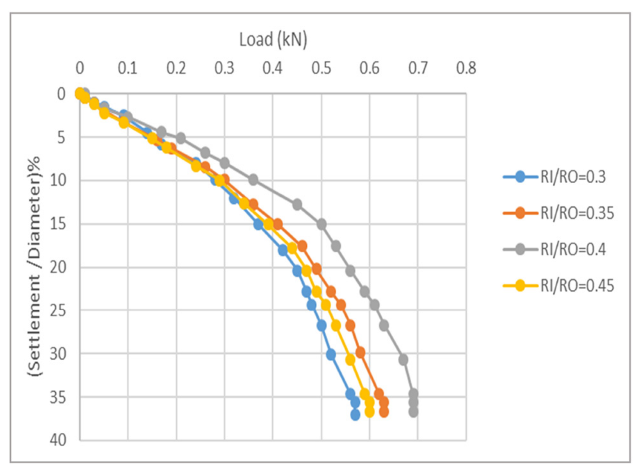

Figure 6: Load–settlement curves (α = 0°).

Table 3: Testing program

Studied parameters	Radius ratio R_I/R_O	Depth ratio U/B	Length ratio L/B	State
Radius ratio R_I/R_O	(0.3) (0.35) (0.4) (0.45)	—	—	Unreinforced
Depth ratio U/B	Optimum	0.25*B*-0.5*B*-0.75*B*-*B*	7*B*	Reinforced
Length ratio L/B	Optimum	Optimum	*B*-2*B*-3*B*-4*B*-5*B*-6*B*-7*B*	Reinforced

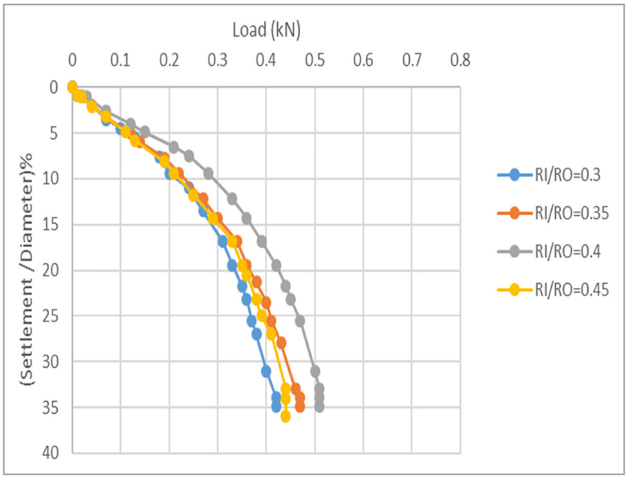

Figure 7: Load–settlement curves(α = 5°).

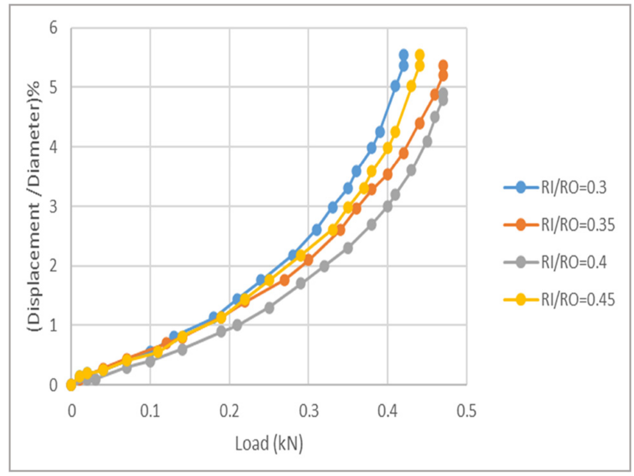

Figure 10: The load–displacement relationship (α = 5°).

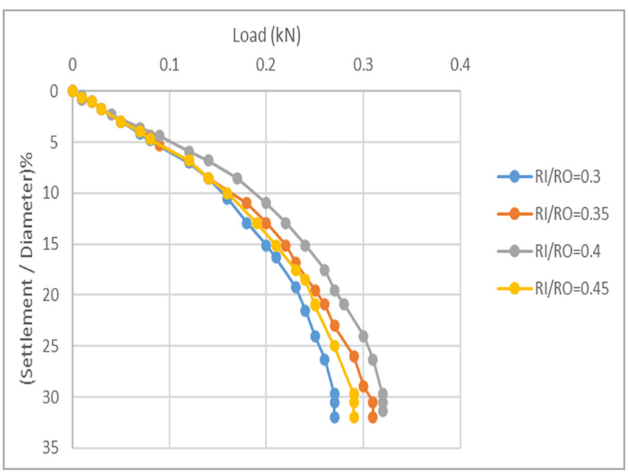

Figure 8: Load–settlement curves (α = 10°).

model with varied radius ratios (R_I/R_O = 0.3, 0.35, 0.4, 0.45) was used. The model was subjected to various load inclination angles (α = 0, 5, 10, and 15°) and rested on unreinforced sand. Figures 6–9 show the load–settlement curves, and Figures 10–12 show the load–horizontal displacement relationship.

From Figures 6–9, the optimum radius ratio value was found to be 0.4. As the load inclination increased, the settlement decreased. In addition, the values of the ultimate carrying capacity decreased. This occurs due to the increasing horizontal load component, which increases the lateral pressure on the surrounding soil, leaving less resistance to support the vertical pressure generated by the vertical load component [21]. Figures 10–12 show that the value of R_I/R_O = 0.4 reduces the lateral displacement as a result of increased friction area.

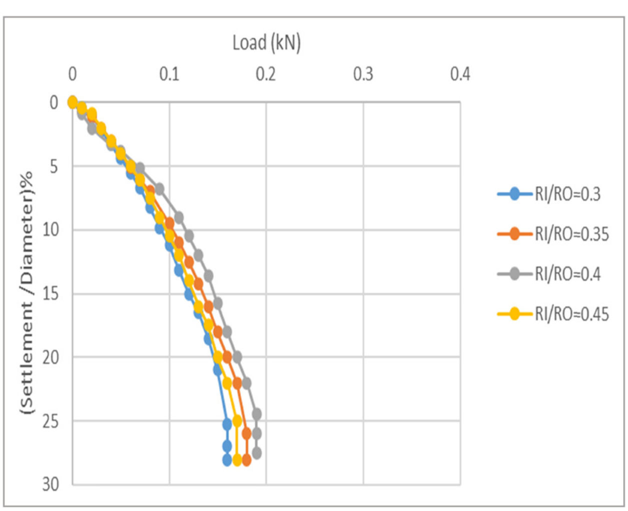

Figure 9: Load–settlement curves (α = 15°).

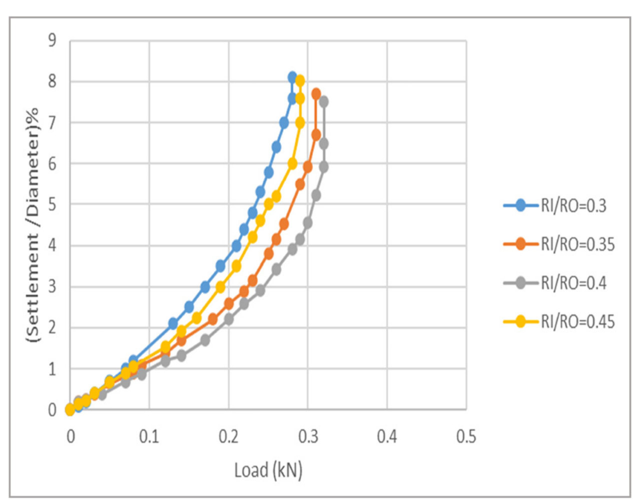

Figure 11: The load–displacement relationship (α = 10°).

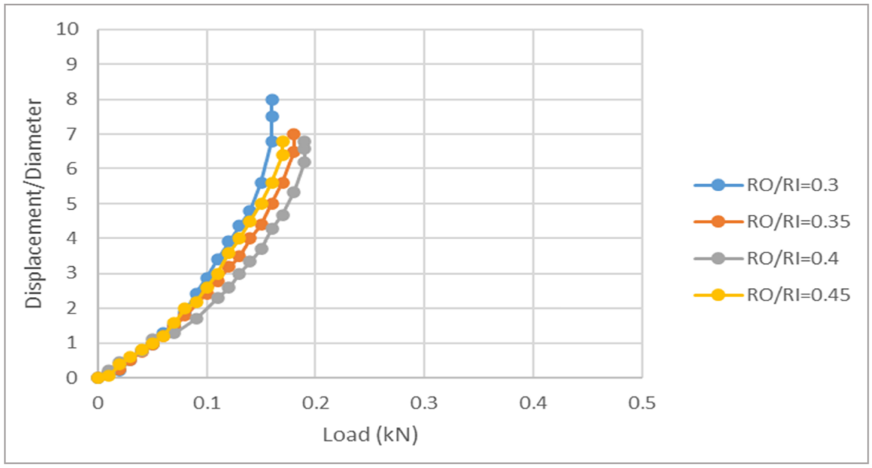

Figure 12: The load–displacement relationship (α = 15°).

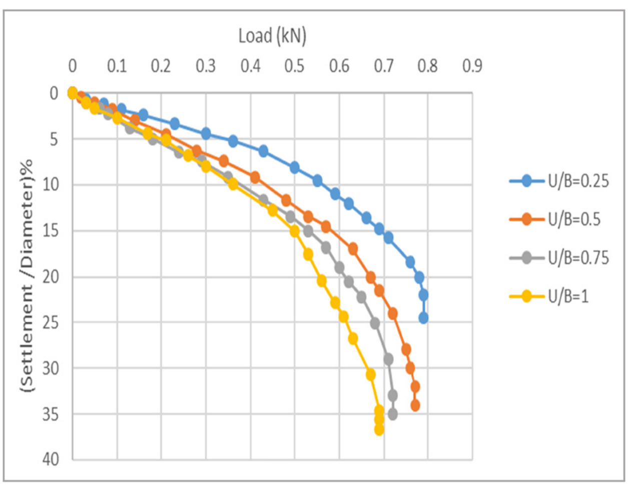

Figure 13: Load–settlement curves (α = 0°).

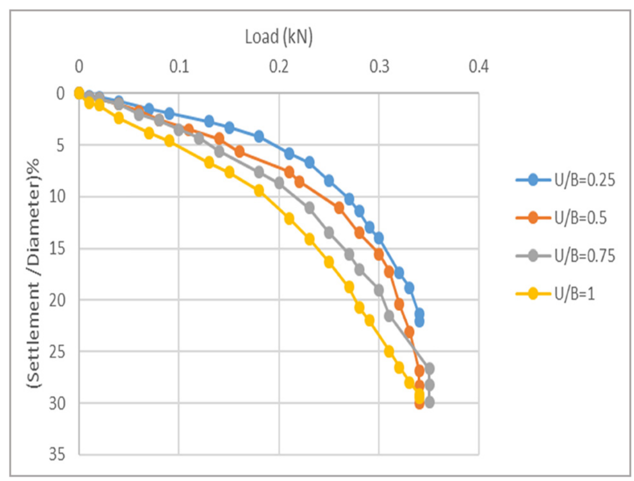

Figure 15: Load–settlement curves (α = 10°).

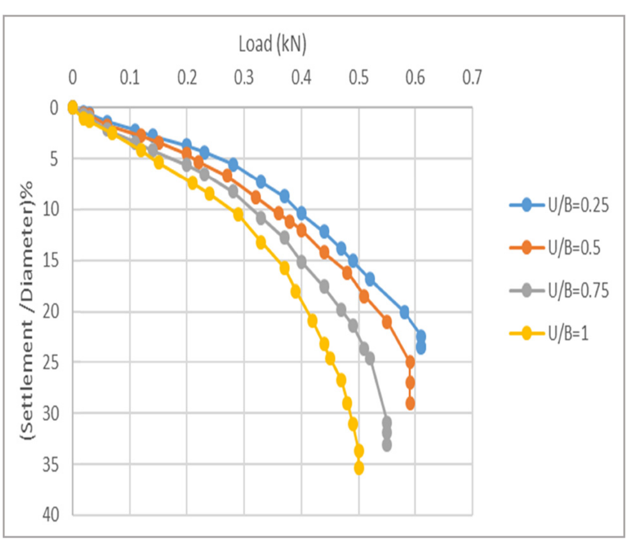

Figure 14: Load–settlement curves (α = 5°).

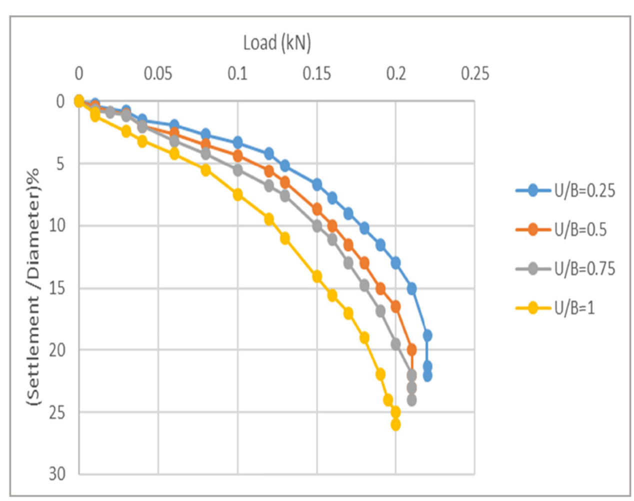

Figure 16: Load–settlement curves (α = 15°).

6.2 Optimum depth ratio

To investigate the effect of the depth ratio U/B, 16 tests have been conducted on a footing model with an optimum radius ratio $R_I/R_O = 0.4$. The suggested depth ratio values were 0.25B, 0.5B, 0.75B, and B subjected to various load inclination angles α (0, 5, 10, and 15°). Figures 13 and 14 show the load–settlement curves, and Figures 17–19 illustrate the load–horizontal displacement relationship.

As can be seen from Figures 13–16, the optimum depth ratio value is 0.25B, and according to load–horizontal displacement curves in Figures 17–19, the depth ratio value of 0.25 has a noticeable effect on reducing the horizontal displacement.

The results indicate that vertical and lateral displacements of the footing increase as the depth of the reinforcement layer increases. The reduction percentage of the lateral displacement for the depth ratios 0.25B, 0.5B, 0.75B, and B are 12, 7, 2, and 0%, respectively.

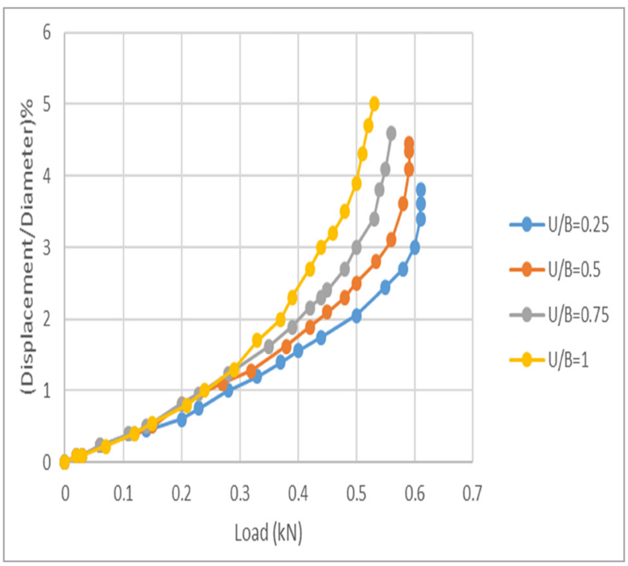

Figure 17: The load–displacement relationship (α = 5°).

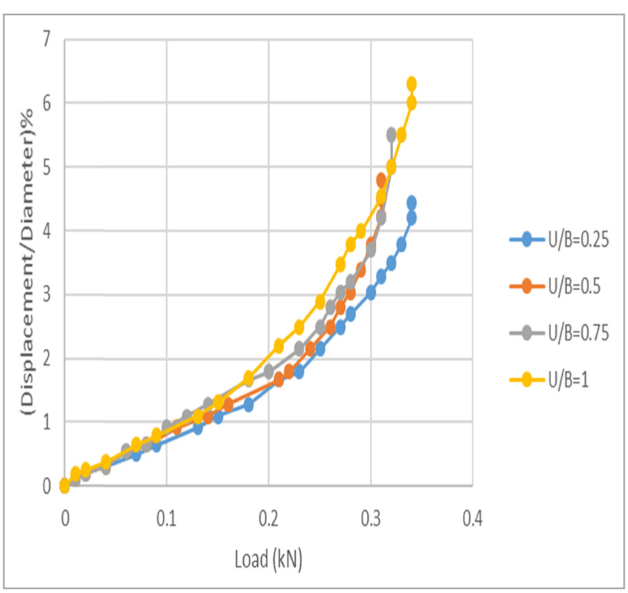

Figure 18: The load–displacement relationship (α = 10°).

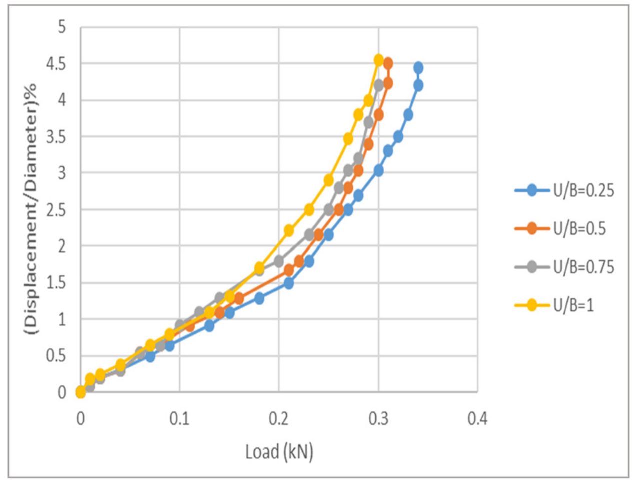

Figure 19: The load–displacement relationship (α = 15°).

6.3 Optimum reinforcement length ratio

The total number of tests to investigate the optimum reinforcement layer length is 28. The suggested length ratios L/B are B, 2B, 3B, 4B, 5B, 6B, and 7B with load inclination

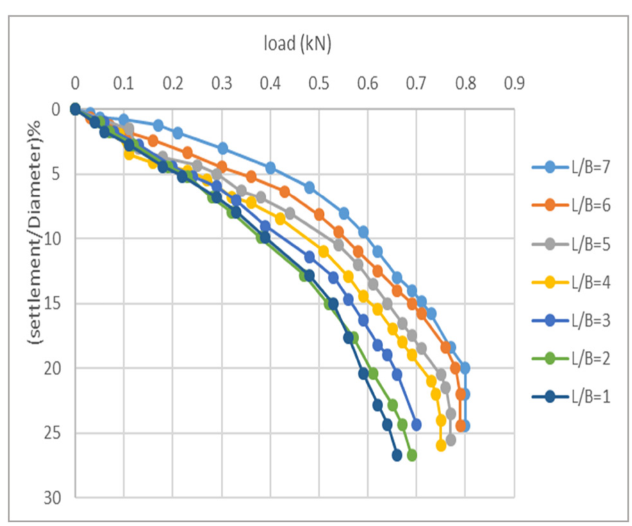

Figure 20: The load–settlement relationship (α = 0°).

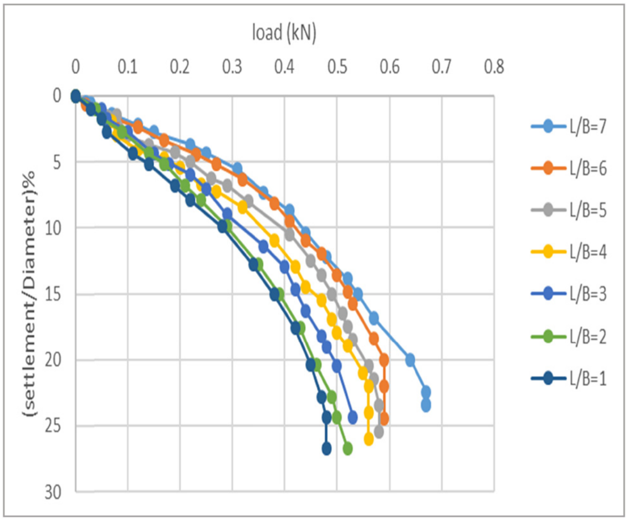

Figure 21: The load–settlement relationship (α = 5°).

angles α equal to 5, 10, and 15°. Figures 20–23 show the load–settlement relationship.

It is clear from Figures 20–23 that when the ratio of reinforcement length is less than 4B, it does not have a noticeable effect on the carrying capacity and the footing settlement; when the value is beyond 5B, it slightly influences the bearing capacity. The most cost-effective length ratio is 5B and is the optimum value. The load carrying improvement $[(P_r/P) \times 100]$ (where P_r and P are the maximum loads for reinforced and unreinforced sand, respectively) for lengths 4B, 5B, 6B, and 7B were 12, 23, 24, and 25%, respectively. If a foundation with a diameter of 10 m was used, the additional cost for

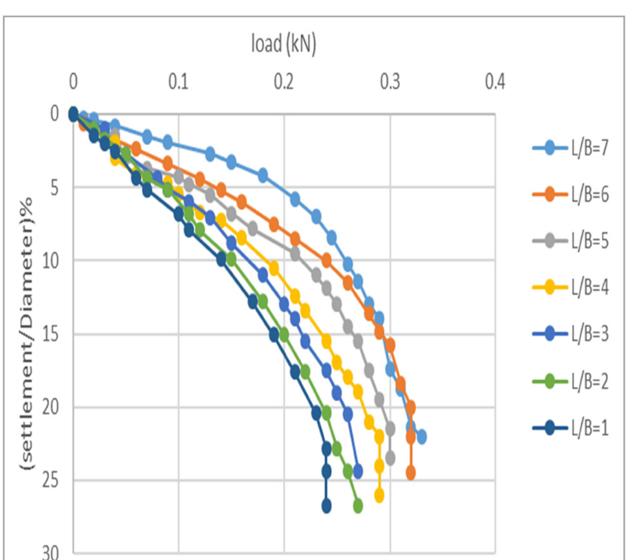

Figure 22: The load–settlement relationship (α = 10°).

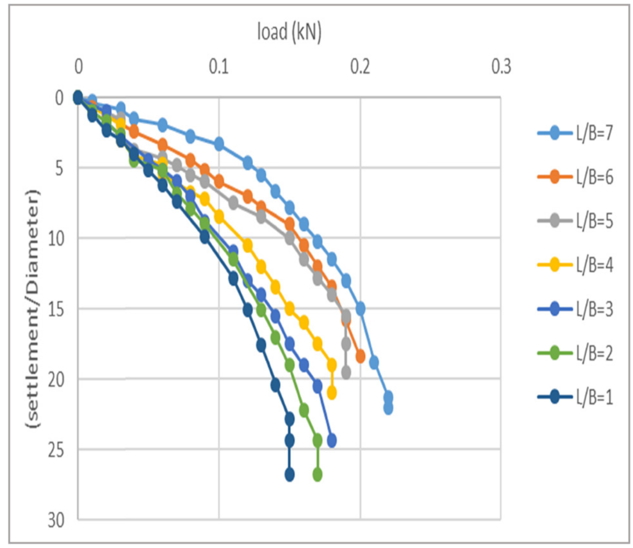

Figure 23: The load–settlement relationship (α = 15°).

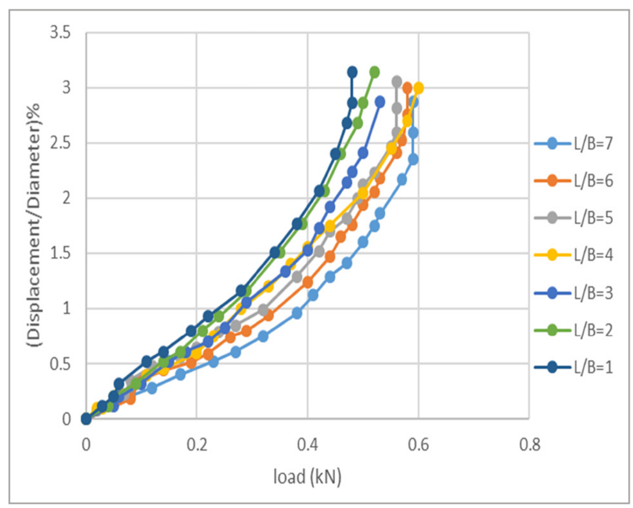

Figure 24: The load–displacement relationship (α = 5°).

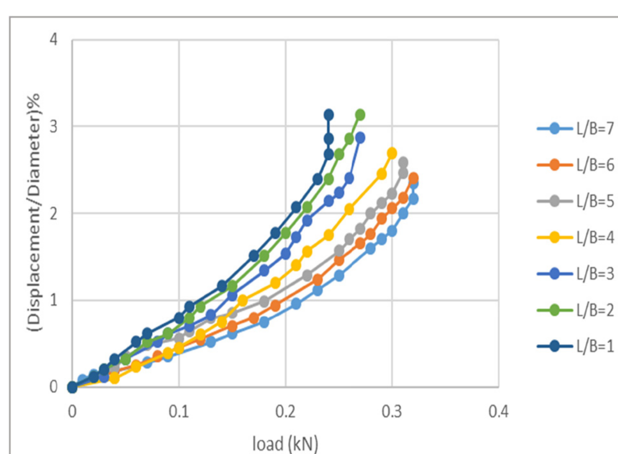

Figure 25: The load–displacement relationship (α = 10°).

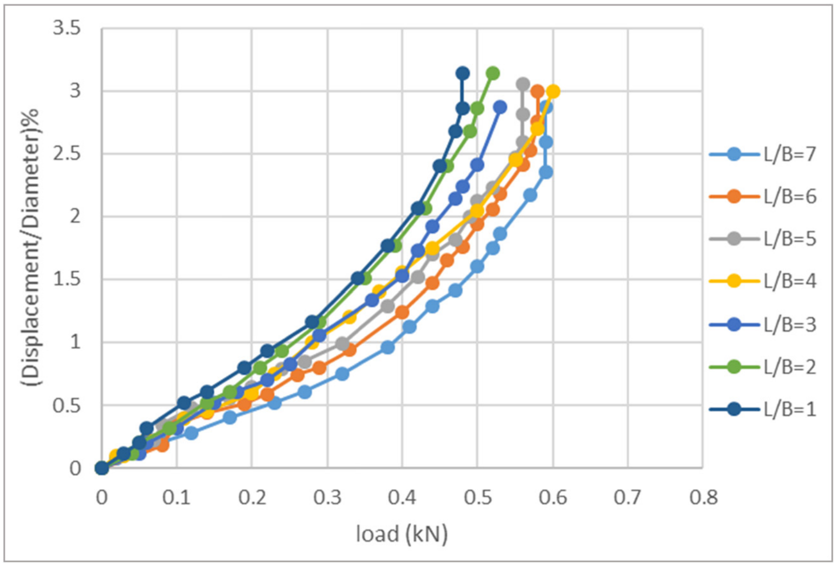

Figure 26: The load–displacement relationship (α = 15°).

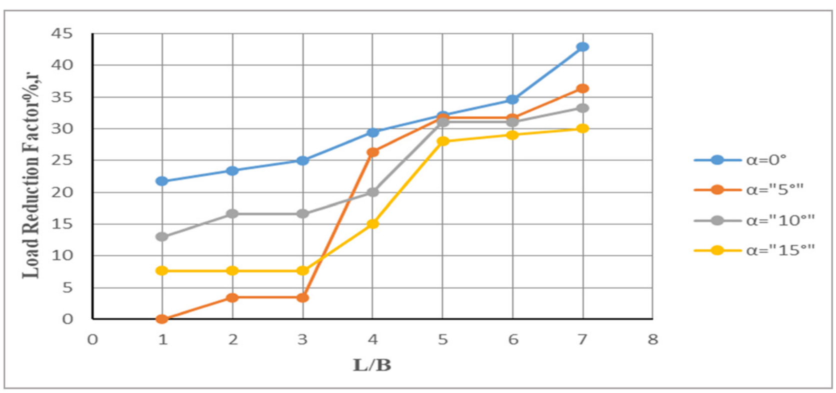

Figure 27: Load reduction factor *vs* reinforcement length (L/B).

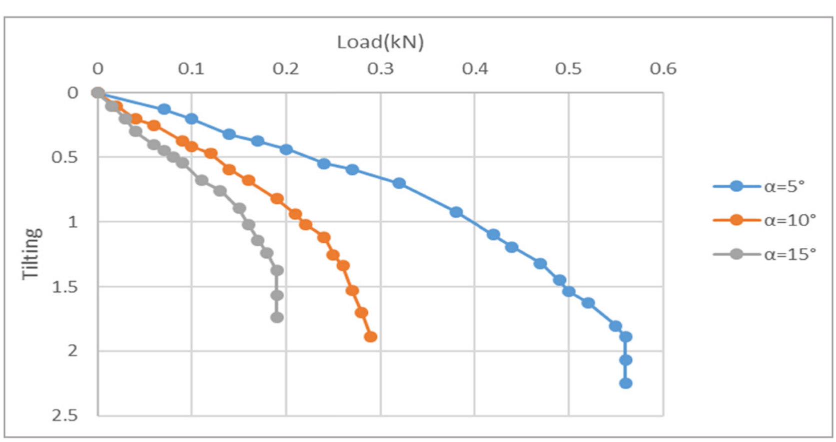

Figure 28: Load–tilting with an optimum reinforcement length ratio (L/B).

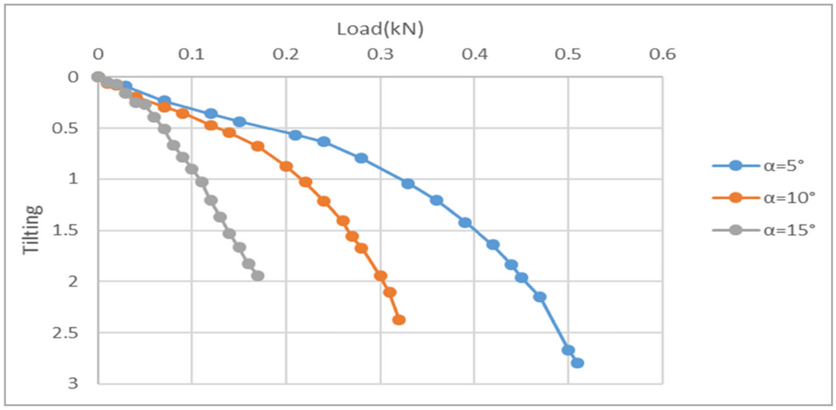

Figure 29: Load–tilting unreinforced case.

each length 6*B* and 7*B* will be 1,100$ and 1,300$, as the square meter price is 1$.

A soil reinforcement redistributes the surface stresses by restraining the granular fill, which reduces the normal stress on the underlying foundation. This is known as the confinement effect.

Figures 24–26 show the load–horizontal displacement relationship. It was observed that increasing the length of the geogrid decreases the horizontal displacement of the footing as the load inclination increases.

Figure 27 shows the load reduction factor, $r = (1 - L_{uu}/L_{ut}) \times 100$, where L_{uu} and L_{ut} are the ultimate loads for unreinforced and reinforced soils, respectively. The figure shows that the load reduction factor increases as the geogrid layer length ratio (L/B) increases. The load reduction factor, r, increases to about 35% as the L/B ratio increases from B to 7B.

The tilt–load relationship (difference between both vertical dial gauge (mm)/footing diameter (mm)) is shown in Figures 28 and 29. The tilt curves for unreinforced sand were similar to those for the reinforced sand. The tilt decreases as the length ratio of reinforcement increases. As the inclination angle increased, the tilt value increased; similar results were observed by Abbas and Hasan [22]. The tilting improvement percentage for the load inclination angles 0, 5, 10, and 15° were 10, 12, and 15%, respectively.

7 Conclusion

1. The optimum radius ratio (R_I/R_O) is 0.4 and it achieves the highest carrying capacity. The reduction in the carrying capacity for the load inclination angles 5, 10, and 15° are 40, 60, and 72%, respectively.
2. The value of the radius ratio slightly affects the horizontal displacement of the ring footing and the reduction percentage of the lateral displacement for the reinforcement layer numbers 1, 2, 3, 4, and 5 are 12, 16, 18, 20, and 21%, respectively.
3. The optimum depth ratio for the first geogrid layer (U/B) is 0.25. The effect of using reinforcement decreased as the depth ratio increased.
4. Increasing the length of the reinforcement layer increases the carrying capacity. The length ratio (L/B) value of 5 is considered to be the optimum value.
5. The optimum reinforcement length under the ring footing resting on sandy soils resisting an inclined load is 5*B*.
6. Increasing the reinforcement length ratio decreases the horizontal displacement of the ring footing. The reduction percentage of the lateral displacement for the reinforcement length ratios *B*, 2*B*, 3*B*, 4*B*, 5*B*, 6*B*, and 7*B* are 0, 0, 2, 7, 10, 10, and 12%, respectively.
7. The tilt decreases as the length ratio of reinforcement increases. The tilting improvement percentages for the load inclination angles 5, 10, and 15° are 10, 12, and 15%, respectively.

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