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Experimental Study of a Strip Footing under Inclined and Eccentric Load on Geogrid Reinforced Sandy Soil

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Abstract

This study investigates the bearing capacity of a strip footing subjected to inclined and eccentric load on geogrid reinforced sandy soil by using physical modeling. The effect of each of the depth ratio of the first sheet of reinforcement, the vertical space ratio between consecutive sheets, number of reinforcement sheets, and the effective depth ratio of reinforcement on the bearing capacity were investigated. Also, the combined effect of load inclination angle, eccentricity ratio of the load and the relative density on the ultimate bearing capacity were studied. The results illustrated that by increasing the number of reinforcement sheets, the bearing capacity increased, but there is an optimum value (4-5). The optimum depth ratio of the first sheet of reinforcement was 0.35B. The optimum vertical space ratio between consecutive sheets was 0.25B. Using a test results with helping a statically analysis software program, a new easy and reliable empirical equation for computing the ultimate bearing capacity of the strip footing subject to inclined and eccentric load supported on geogrid reinforced sandy soil was developed.

Keywords: Bearing capacity, eccentric load, inclined load, geogrid, reinforced sand, strip footing.

دراســـة تجريبية لأساس شريطي تحت حمل مائل ولا مركزي على تربة رملية مسلحة بالمشبكات الأرضية

الخلاصة

تستكشف هذه الدراسة قابلية تحمل أساس شريطي معرض لحمل مائل ولا مركزي على تربة رملية مسلحة بالمشبكات الأرضية باستعمال نمذجة فيزيائية. تم استكشاف تأثير نسبة عمق الدفن لأول طبقة من التسليح ونسبة المسافة العمودية بين طبقات التسليح المتعاقبة وعدد طبقات التسليح ونسبة العمق الفعال لطبقات التسليح على قابلية التحمل. كذلك تم تفحص التأثير المشترك لميلان الحمل ونسبة اللامركزية في الحمل والكثافة النسبية للتربة على قابلية التحمل القصوى. أظهرت النتائج أنه عند زيادة عدد طبقات التسليح فان قابلية التحمل تزداد لكن إلى قيمة مثلى (4-5) طبقات. إن نسبة العمق الأمثل لأول طبقة من التسليح كانت 0.35 من عرض الأساس. وأن نسبة المسافة العمودية المثلى ما بين طبقات التسليح المتعاقبة كانت 0.25 من عرض الأساس. و باستخدام نتائج الفحوصات وبمساعدة برنامج تحليل إحصائي تم وضع معادلة وضعية جديدة وبسيطة لحساب قابلية التحمل القصوى للأساس الشريطي معرض للأحمال المائلة واللامركزية والمسند على تربة رملية مسلحه بالمشبكات الأرضية.

الكلمات الدالة: قابلية التحمل، حمل لا مركزي، حمل مائل، رمل مسلح، أساس شريطي.

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Notations

B : width of the footing.
B.C.R: bearing capacity ratio.
c : soil cohesion.
d : effective depth of reinforcement.
D_f : Depth of footing
α : load inclination .
e : load eccentricity.
h :vertical space between constitutive gogrid sheets.
N: number of reinforcement sheets.
q_{ur}: Ultimate bearing capacity of strip footing subjected to inclined and eccentrically load on reinforced sand.
q_u: Ultimate bearing capacity of concentrically loaded strip footing on unreinforced sand.
U: depth of first sheet of reinforcement below the footing base.
R_D: Relative density
ϕ: Angle of internal friction of sand.
γ: Unit weight of the soil.

Introduction

Footing is used to transmit the load from a structure to the supporting soil on a larger area to reduce the pressure. Different types of footings are used for different applications. The footing type used in this study is a strip footing which is largely used to support bearing a and retaining walls. The strip footing is rectangular in shape but its length is much greater than its width. Analyzing a strip footing is a simple case as it can be analyses in two dimensions.(plane strain conditions).

When a building is construct, their foundations are often under inclined and eccentric loading such as: vertical load, horizontal load and bending moment from wind loads, structure's nature or earthquake[1].

The load inclination and eccentricity significantly reduce the bearing capacity of the supporting soil by tilting or sliding the footing and heaving the supporting soil. This can be avoided either by increasing the footing dimensions to minimize the contact pressure and this may be lead to uneconomical design or by improving the bearing capacity of the supporting soil.

Several researches have been reported on the useful use of soil reinforcement as a cost-effective way to enhancement the ultimate bearing capacity under shallow foundations. This was occurred by removing the weak soil up to a certain depth and then exchanging the soil or fills the same soil back with the implying of horizontal sheets of geosynthetics at different depths under the footing. Therefore, with the advantages of using soil reinforcement both the type and the size of foundation may be changed causative an economic design [2-9].

There are many types of geosynthetics according to function and application, (geotextiles, geogrids, geonets, geomembranes, geopipes, geofoam, geocomposite, etc.). Geogrids are plastic formed into very open, grid like configuration with large apertures between individual ribs in the machine and cross machine directions. The opening are usually (12-100)mm in length and/or depth; geogrids are transported to the site in (1-4)m width of rolls. Geogrids are formed in various ways[10].

The use of geogrid sheets could be particularly convenient when the mechanical properties of the soil under a foundation would suggest the designer in using alternative solutions. Recently, the use of geogrids as a soil reinforcement has become widely used, because geogrids are dimensionally stable and combine features such as high tensile modulus, open grid structure which provides enhanced soil reinforcement interaction, shear connection properties, light weight, and long service life[11].

In this study the bearing capacity of a strip footing subjected to inclined and eccentric loading on geogrid reinforced sand using physical modeling was investigated. Then by using the results of the experimental tests a new empirical equation to estimate ultimate "bearing capacity" of strip footing subjected to inclined and eccentric load on geogrid reinforced sand was developed.

Laboratory Model Tests

The testing equipments consist of four main parts, test tank, model footing, loading system, and vibratory system[12].

Test Tank

The test tank is about a steel box with inside dimensions 900mm × 900mm and 550mm in height. The sides and the bottom were made of 6 mm thickness plate; the plate was supported by four steel channels, with 150 mm high from the base of the steel box. The internal faces of the box were painted (in order to reduce the slide friction which may develop during the process). A mark lines were drawn to give the required thickness of the layers and the location of geogrid, Figure (1) shows the test tank[12].

Fig. 1. Test box

Model Footing

The test footing was a strip steel channel 80mm × 800mm. The load applied to the footing by proving ring of 5 kN capacity, while the vertical deflection and horizontal displacement of the footing was measured using three dial gauges (0.01 mm/ division) as shown in Figure (2)[12].

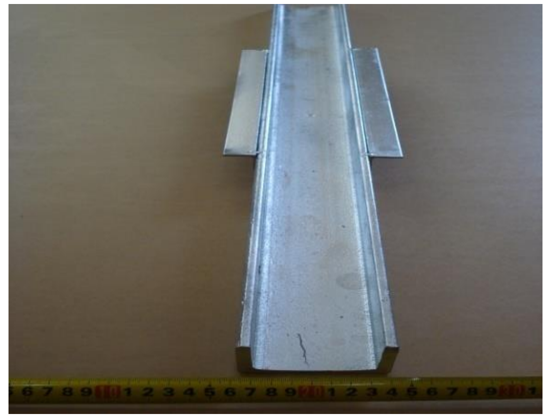

Fig. 2. Strip footings model

The loading frame

The test box was placed over 1100×1100mm strong steel base of 80mm thick. The base was connected to a stiff loading frame, which was locally manufactured. As shown in Figure (3). The frame consists of two columns of steel channels 1520mm height, which intern bolted to a loading platform. The platform was designed to slide along the columns and can be fixed at any desired height by means of slotted spindles and holes provided at different intervals along the two columns. The two steel columns were fixed by four short steel angle pieces connected to the lower plate in the frame[12].

Fig. 3. Loading system

The loading system

The load was applied by means of mechanical arrangement technique that was employed for the test. The proving ring was attached to a cylindrical steel toothed shaft device of 550mm long and 40mm diameter, which transfers the load to the footing and help to be adjusting the height of ring to any position required before or after test. A steel plate was made for each one of the footings, as shown in Figure (4) which attached at the end of the proving ring and work to transfer loading as equally distributed line load. Three dial gauges were attached to the footing and fixed to measure the footing vertical and horizontal displacement.

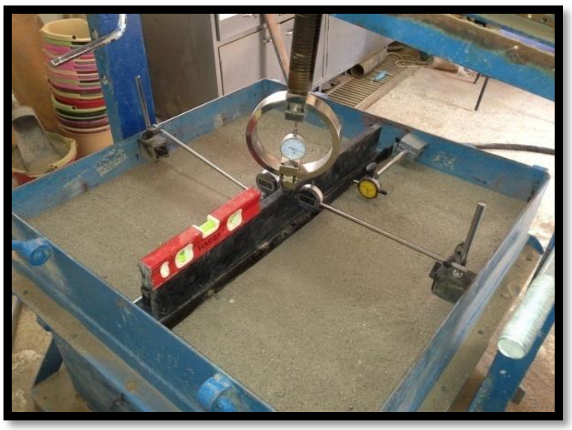

Fig. 4. A steel plate model which transfer distributed line load on the strip footing

Vibration System

To achieve the required relative densities, it is easier to use an electrical vibrator. This method based on placing the soil in the box in layers each layer of thickness 50mm then placing a plate 700×700mm, then moving the vibrator over the whole area of the plate in a specified time

The time needed to reach the desired relative density was founded by performing a series of attempts with different measured time. In each attempt, the densities were determined by collecting samples in small aluminum cans of known volume putted at different locations in the test tank[12].

Experimental Setup

The footing was putted in position and the load was applied to it through the proving ring. The load was gradually increasing until failure happened.

Materials Properties

Sand Properties

In this study a poorly graded sand passing sieve No.4 is used. In order to remove as much dust as possible the sand was washed with running water.

The test was performed with medium dense and dense sand corresponding to a dry unit weight of approximately 16.943kN/m^3 and 17.455kN/m^3 for relative density 60% and 80%, respectively. The maximum and minimum dry unit weights of the sand were founded according to the ASTM (D4253-00) and ASTM (D4254-00), respectively. The results of maximum and minimum dry unit weight of sand are 18kN/m^3 and 15.573kN/m^3 respectively. The specific gravity was determined according to the ASTM D-854. The specific gravity of used sand is 2.585. The grain size was analyzed according to the ASTM D-421. The grain size distribution curve was shown in Figure (5). The sand has a coefficient of uniformity (C_u) equal to 3.0 and coefficient of curvature (C_C) is 1.0.[13]

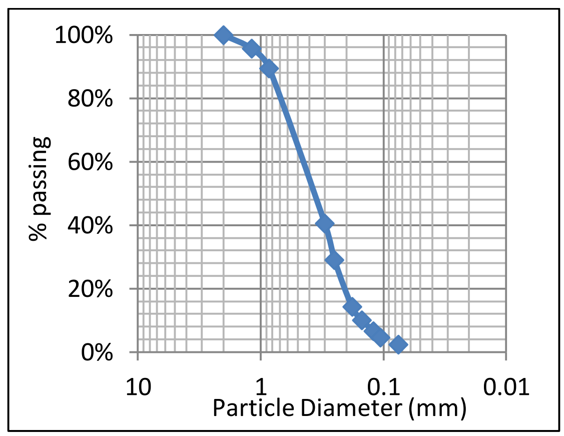

Fig. 5. Particle Size Distribution of the sand

Geogrid

One type of geogrid was used TriAx® TX140 Geogrid produced from a punched polypropylene sheet, which is then oriented in three substantially equilateral directions so that the consequent ribs have a high degree of molecular orientation, which continues at least in part through the mass of the integral node. The characteristics contributing to the performance of a mechanically stabilized layer are illustrated in Table (1).

Table 1. Engineering characteristics of Tenax TT Samp geogrid

Index Properties	Longitudinal	Diagonal	Transverse	General
• Rib pitch(2), mm (in)	40 (1.60)	40 (1.60)	-	
• Mid-rib depth(2), mm (in)	-	1.2 (0.05)	1.2 (0.05)	
• Mid-rib width(2), mm (in)	-	1.1 (0.04)	1.1 (0.04)	
• Rib shape				rectangular
• Aperture shape				triangular
Structural Integrity				
• Junction efficiency(3), %				93
• Aperture stability(4), kg-cm/deg @ 5.0kg-cm (2)				3.0
• Radial stiffness at low strain(5), kN/m @ 0.5% strain				225
(lb/ft @ 0.5% strain)				(15,430)
Durability				
• Resistance to chemical degradation(6)				100%
• Resistance to ultra-violet light and weathering(7)				100%

Test Program

A number of 280 tests were conducted to reach the aim of the study. Fourteen tests were conducted on unreinforced soil. These tests are used as a reference to compare the improvement of using a geogrid as a reinforcement. Also, they are used to find the effect of changing the load inclination angle (α) and eccentricity on the bearing capacity on unreinforced sand for the two relative densities.

161 tests for a single layer of reinforcement were conducted to located the optimum depth of the first sheet of geogrid (U /B). The remaining (105) tests which were representing the main part of this research, show the effect of the multi-reinforcement layers on the bearing capacity and the effect of the other parameters on the optimum number of the reinforcement layers.

There are several parameters, which affect the bearing capacity of a strip footing under inclined and eccentric loading on geogrid-reinforced sandy soil. In this study, most of these parameters were varied within their reasonable ranges in order to explre their effects on the bearing capacity and on each other.

The effects of the following parameters: load inclination angle (α) (0°, 5°, 10°, and 15°), load eccentricity ratio (e/B)(0, 0.05, 0.1 and 0.15), number of geogrid layers (N) from (1 to 5 layer), depth of topmost layer of geogrid (U/B) varied (0.25, 0.5, 0.75, 1.0, 1.25 and 1.5), and distance between consecutive layers (h/B) varied (0.25, 0.35, 0.45, 0.65 and 0.95). All the above parameters are studies for two relative densities (60% and 80%) to represent medium dense and dense sand. After that, the optimum values are obtained.

The expression of bearing capacity ratio (BCR) is presented to illustrate the combined effect of soil reinforcement with load inclined and eccentricity on the bearing capacity and it can be written as:

$$\mathrm{BCR} = \frac{q_{ur}}{q_u} \quad \text{……………………………….. (1)}$$

Where:

q_{ur}: Ultimate bearing capacity of strip footing subjected to inclined and eccentrically loaded on reinforced sand.

q_u: Ultimate bearing capacity of strip footing on unreinforced sand under vertical and concentric load. Figure (6) shows the major reinforcement parameters of strip footing under inclined and eccentric load on geogrid reinforced sand.

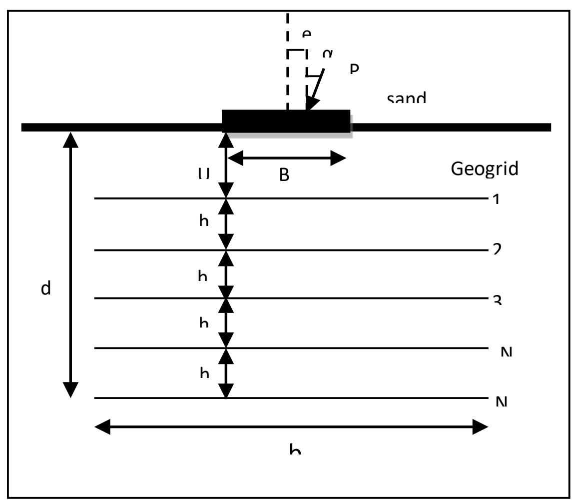

Fig. 6. Major reinforcement parameters of inclined and eccentric loaded strip footing

Results and Discussion

Optimum Number of Geogrid sheets

Figures (7) and (8) show the relationship between the number of geogrid sheets (N) and the bearing capacity ratio (BCR) for different values of load inclinations (α) for relative densities 60% and 80%, respectively. It is noticed that, the (BCR) significantly increased with the increase of the number of geogrid layers. In addition, it is noticed that there is an optimum value of (N) after which little increase in the value of (BCR) is observed.

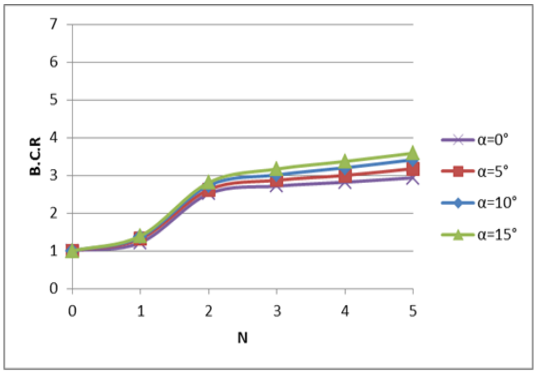

Fig. 7. "Bearing capacity" ratio versus Number of reinforcement layer for (α = 0°, 5°, 10° and 15°) and (RD=60%)

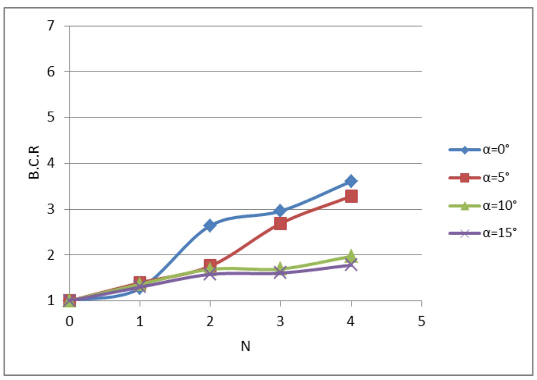

Fig. 8. Bearing capacity ratio versus Number of reinforcement layer for (α = 0°, 5°, 10° and 15°) and (RD= 80%)

Figures (9) and (10) show the relationship between the number of geogrid sheets (N) and the bearing capacity ratio (BCR) for different values of eccentricity ratio (e/B) for relative densities 60% and 80%, respectively. It is noticed that, the (BCR) significantly increased with the increase of the number of geogrid layers. In addition, it is noticed that there is an optimum value of (N) after which little increase in the value of (BCR) is observed.

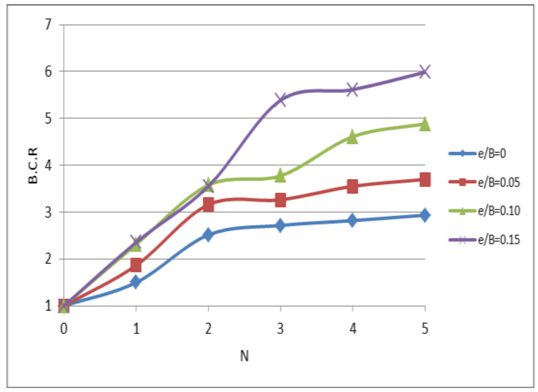

Fig. 9. Bearing capacity ratio versus number of reinforcement layer for (e/B = 0, 0.05, 0.10 and 0.15) and (RD=60%)

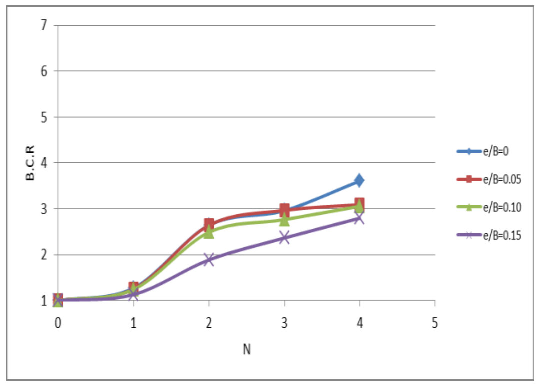

Fig. 10. Bearing capacity ratio versus number of reinforcement layer for (e/B = 0, 0.05, 0.10 and 0.15) and (RD=80%)

Figures (11) and (12) illustrate the effect of number of geogrid sheets (N) on the horizontal displacement of the footing which is due to load inclinations (α). It can be seen that the increasing of the reinforcement (N) decreases the horizontal displacements for different values of load inclination (α) for relative densities 60% and 80%, respectively.

Figures (13) and (14) illustrate the effect of number of geogrid sheets (N) on the tilt of the footing which is the ratio of the difference between the settlements of the two edges of the footing to the footing width. It can be seen that the increasing of the reinforcement (N) increases the footing tilt for different values of eccentricity ratio (e/B) for relative densities 60% and 80%, respectively.

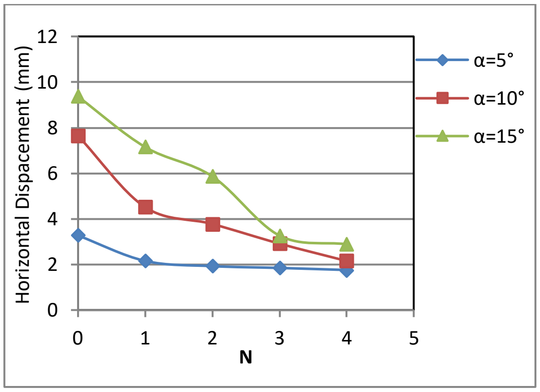

Fig. 11. Horizontal displacement (mm) versus number of reinforcement layer for different values of (α) (RD= 60%)

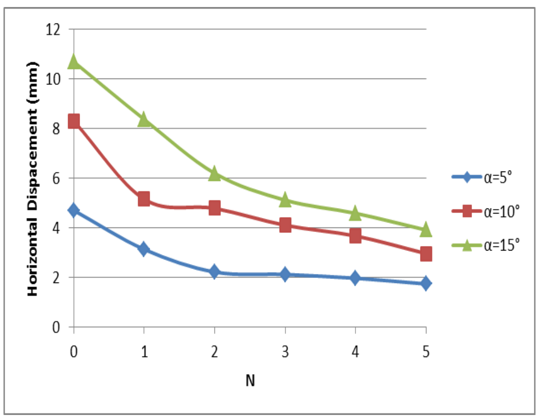

Fig. 12. Horizontal displacement (mm) versus Number of reinforcement layer (N) for different values of (α) and (RD= 80%)

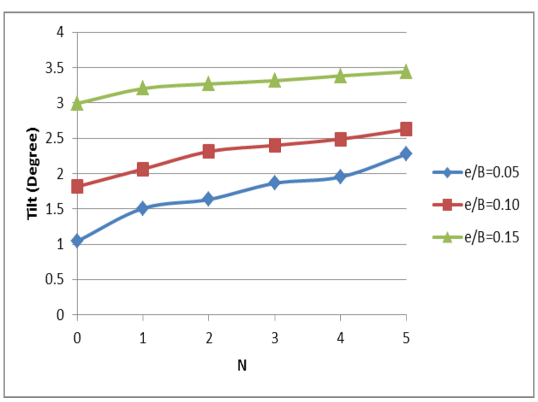

Fig. 13. Tilt (Degree) versus Number of reinforcement layer (N) for (e/B = 0, 0.05, 0.10 and 0.15) and (RD= 60%)

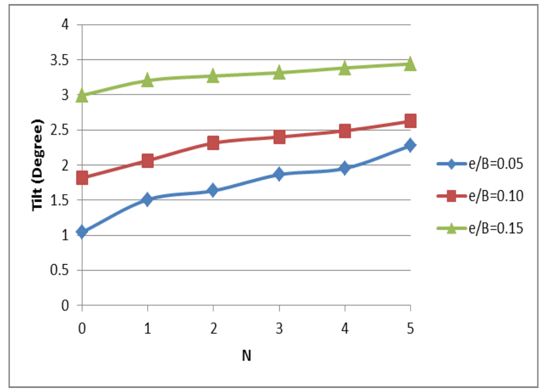

Fig. 14. Tilt (Degree) versus Number of reinforcement layer (N) for (e/B = 0, 0.05, 0.10 and 0.15) and (RD= 80%)

Figures (7) to (14) show the effect of the relative density (R_D) on the bearing capacity ratio (BCR) and on horizontal displacements and on the tilt for different values of load inclination (α) and load eccentricity ratio (e/B) for relative densities 60% and 80%, respectively. It can be seen that the increase of the relative density (R_D) decreases the (BCR) and decreasing the optimum number of reinforcement (N) and reduce the horizontal displacement and decrease the tilt of the footing, because the soil has been improve and it was observed for the two chosen values of (R_D). In addition, it is noticed that the (BCR) for the medium sand is larger than that for dense sand. This means that the reinforcement is more sufficient for medium sand than for dense sand considering the unreinforced loaded case for each of them as a reference, according to the definition of (BCR).

It should be mentioned that Figures (3) to (10) could be used by practicing engineers as design charts to obtain the number of reinforcement layers required to cancel or to reduce the effect of load inclination and eccentricity or even to increase the factor of safety.

Optimum Depth of first sheet

The optimum value of topmost layer of reinforcement (U/B) is obtained by changing the position of a single layer of reinforcement until we reach no change in the bearing capacity ratio.

Figures (15) and (16) show the relationship between the topmost layer (U/B) and the bearing capacity ratio (BCR) for different load inclination (α) for two relative densities 60% and 80% respectively.

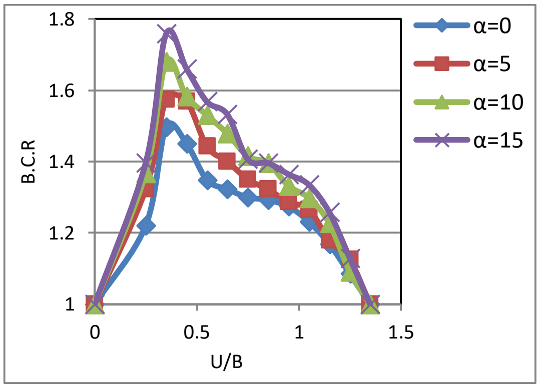

Fig. 15. Bearing capacity ratio (BCR) versus the depth ratio of the first sheet of reinforcement , for (α = 0°, 5°, 10° and 15°) and (RD = 60%)

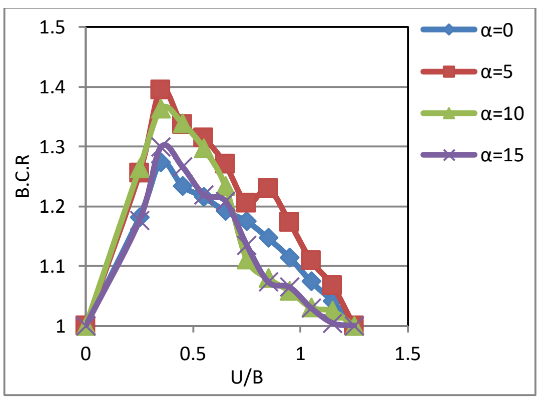

Fig. 16. Bearing capacity ratio (BCR) versus the depth ratio of the first sheet of reinforcement , for (α = 0°, 5°, 10° and 15°) and (RD = 80%)

Figures (17) and (18) show the relationship between the topmost layer (U/B) and the bearing capacity ratio (BCR) for different eccentricity ratio (e/B) for two relative densities 60% and 80% respectively.

It can be seen that with increasing the depth of first sheet (U/B) , the bearing capacity ratio (BCR) increases until reach the maximum value of (U/B)(0.35), then after this point with increasing the depth of first sheet (U/B), the bearing capacity ratio (BCR) decreases.

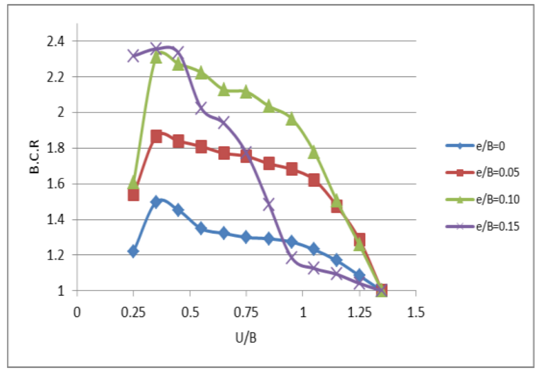

Fig. 17. Bearing capacity ratio (BCR) versus the depth ratio of the first sheet of reinforcement, for (e/B = 0, 0.05,0.10and 0.15)and (RD=60%)

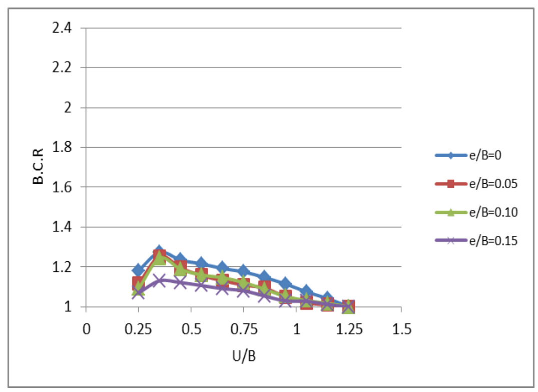

Fig. 18. Bearing capacity ratio (BCR) versus the depth ratio of the first sheet of reinforcement, for (e/B = 0, 0.05, 0.10 and 0.15) and (RD = 80%)

Figures (15) to (18) show the effect of the relative density (R_D) on the value of (U/B) for inclined and eccentrically loaded strip footing. It is obvious that the variation of (R_D) has no effect on the optimum value of (U/B) but has a major effect on the value of (BCR).

Optimum Vertical Space between Geogrid Sheets.

For two layers of reinforcement, it has been kept the first layer at (U/B=0.35) the second layer location was changed with varying (h/B) (0.25, 0.35, 0.45, 0.55, 0.65, 0.75 and 0.85).

Figures (19) and (20) show the relationship between the vertical space ratio between consecutive sheets of geogrid (h /B) and the bearing capacity ratio (BCR) for different load inclination (α) for two relative densities 60% and 80% respectively.

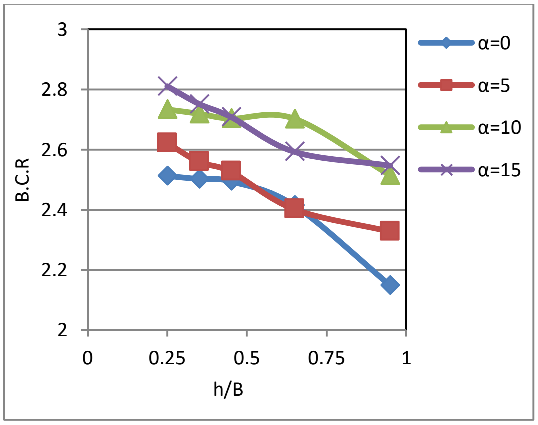

Fig. 19. Bearing capacity ratio (BCR) versus the vertical space ratio between consecutive sheets of geogrid (h/B), for (α = 0°, 5°, 10° and 15°) and (RD= 60%)

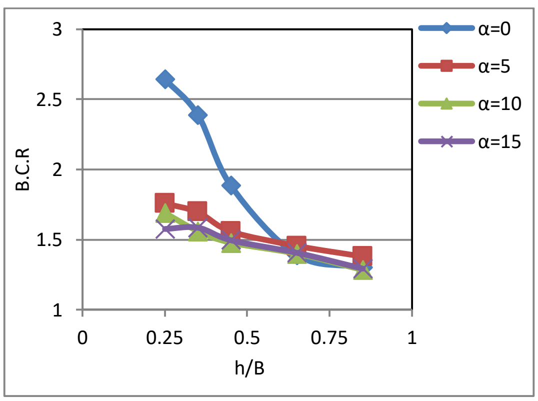

Fig. 20. Bearing capacity ratio (BCR) versus the vertical space ratio between consecutive sheets of geogrid (h/B), for (α=0°, 5°, 10° and 15°) and (RD= 80%)

Figures (21) and (22) show the relationship between the vertical space ratio between consecutive sheets of geogrid (h/B) and the bearing capacity ratio (BCR) for different eccentricity ratio (e/B) for two relative densities 60% and 80% respectively .

It can be seen that maximum value of (h/B) is 0.25. After this point with increasing, the vertical distance (h/B) the bearing capacity ratio (BCR) decrease.

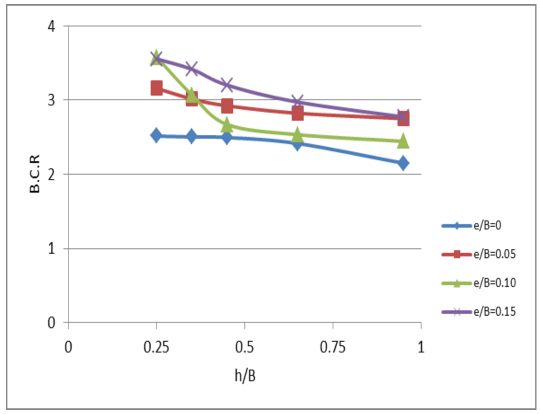

Fig. 21. Bearing capacity ratio (BCR) versus the vertical space ratio between consecutive sheets of geogrid (h/B), for (e/B = 0, 0.05, 0.10 and 0.15) and (RD= 60%)

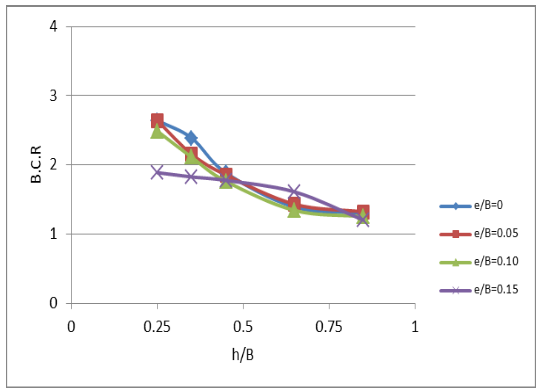

Fig. 22. Bearing capacity ratio (BCR) versus the vertical space ratio between consecutive sheets of geogrid (h/B), for (e/B = 0, 0.05, 0.10 and 0.15) and (RD= 80%)

Figures (19) to (22) show the effect of the relative density (R_D) on the value of (h/B) for inclined and eccentrically loaded strip footing. It is obvious that the variation of (R_D) has no effect on the optimum value of (h /B) but has a major effect on the value of (BCR).

For three and four layers of reinforcement, the first layer was kept at (U/B=0.35), also, the vertical distance (h/B) was kept constant 0.25.

Effective Depth Zone of Reinforcement

The effective depth zone of the reinforcement (d) is the depth beneath the footing base, under which no longer effect of the reinforcement on the bearing capacity is noticed. This depth could be calculated as follow:

$d = U + (N-1)\,h$ ………………....……… (2)

Where:
d: effective depth zone of reinforcement.
U: depth of first layer of reinforcement beneath the footing base.

Since the optimum values of (U/B, h/B and N) for inclined and eccentrically loaded footing were found to be (0.35, 0.25 and 4) for a relative density (80%), the value of effective zone will be (d =1.1B). For a relative density (60%) case, the optimum values of (U/B, h/B and N) are (0.35, 0.25 and 5), in which the effective depth zone of reinforcement (d =1.35B). So that, the effective depth zone (d=1.1B-1.35B) depending on the relative density (R_D).

Statistical Analysis of the Results

A computer software program called (SPSS19)(statistical package social science) which provides a powerful statistical analysis and data management system had been used to analyze the results obtained from the previous tests in order to get a new empirical equation to calculate the ultimate bearing capacity of the strip footing under inclined and eccentric loading on geogrid reinforced sand. Using the curve estimation of linear regression analysis option, the equation is :

$q_{ur} = q_u\,(C + e^x)$ …………………………..…….(3)

Where:
$X = a_0 + a_1 U + a_2 h + a_3 N + a_4 e + a_5 \alpha + a_6 \phi$
($C, a_0, a_1, a_2, a_3, a_4, a_5, a_6$):constants which their values are shown in Table (2)

Table 2. The value of constant (a) with their standard error

Symbol	Value
C	-126.8761
a_0	4.81629
a_1	-0.002123
a_2	-0.000401
a_3	0.002431
a_4	0.026254
a_5	-0.000175
a_6	0.000947

Conclusions

From the experimental results and their discussion stated in the previous sections, the major conclusions that could be drawn on the behavior of inclined and eccentrically loaded strip footing resting on geogrid reinforced sand are outlined below:

1- The results showed that, using geogrid as a reinforcement material has a significant increased on the ultimate bearing capacity .
2- The results show that, increasing the number of geogrid sheets (N), lead to increase the ultimate bearing capacity, but there is an optimum value after which no effect is noticed. This optimum value is varied from 4 to 5 for relative densities (80% and 60%), respectively.
3- Increasing the number of reinforcement layers (N) decreases the horizontal displacement but increases the footing tilt
4- .The optimum value of (U/B) is (0.35) and it is independent on the load inclination (α), eccentricity ratio (e /B) and relative density (R_D).
5- The optimum value of the vertical distance between layers is (h/B=0.25) and it is independent on the load inclination (α), eccentricity ratio (e /B) and relative density (R_D).
6- The effective depth zone of reinforcement (d/B) is varied from 1.1 to 1.35 depending on the value of the relative density (R_D) of the soil.
7- From statistical analysis a new equation to calculate the ultimate bearing capacity of the strip footing under inclined and eccentric loading on geogrid reinforced sand was developed, for domain (α) from 0^o to 15^o, (e/B) from 0 to 0.15 and (ϕ) from 34.5° to 38°.

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