HBRC Journal (2015) 11, 240–245

Housing and Building National Research Center

HBRC Journal

http://ees.elsevier.com/hbrcj

Behavior of circular footing resting on laterally confined granular reinforced soil

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Received 27 November 2013; revised 8 March 2014; accepted 25 March 2014

KEYWORDS

Soil confinement;
Reinforcement;
Physical model;
Bearing capacity

Abstract Three dimensional physical laboratory models were examined to investigate the influence of soil confinement on circular footing behavior resting on granular soil. A total of 23 model footing tests were performed. Nine hollow cylinders with various heights and diameters were installed around the footing model for soil confinement purpose. Square geogrid layers were placed at different depths beneath the bottom edge of the cylinder. Different parameters such as height, diameter, and depth of the cylinder were studied. Moreover, number, width, and position of the geogrid layers were, also, investigated. The response of a non-confined footing model was set as reference for comparison purpose. The results showed enhancement in the bearing capacity of the soil as well as a reduction in its settlement in all used configurations compared with the reference case. It is, however, observed that on increasing the number of geogrid layers more than one layer had a small significant effect on the footing behavior. Moreover, placing geogrid layers underneath the cylinders improves the bearing capacity up to 7.5 times that of the non-confined case. Footing with cylinder of a diameter nearly equal to the footing diameter behaves as one unit like a deep foundation. This behavior pattern was no longer observed with large cylinder diameter and small height. Finally, the study ends up with recommendations for selection of cylinder dimensions to maximize the bearing capacity. The benefits of using geogrid layers were also highlighted.

Introduction

Several methods for soil improvement have been applied to improve soil characteristics. Confinement of soil in shallow depths might have a significant effect in enhancing soil bearing capacity. Skirted foundations form an enclosure where the soil is strictly confined. This allows the confined soil to work as one unit transferring the superstructure loads to the soil at the skirt tip level. For foundations resting on cohesive soil, [1] concluded that increase in bearing capacity due to the presence of rigid walls was small. On the other hand, several

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Peer review under responsibility of Housing and Building National Research Center.

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http://dx.doi.org/10.1016/j.hbrcj.2014.03.011

investigators reported that a significant increase in bearing capacity and a reduction in settlement of footing models were obtained by confining the sand. Results of [2] showed that the existence of skirt leads to enhancement of soil bearing capacity and reducing footing settlement. Mahiyar and Patel [3] found that the bearing capacity of circular footings on sand increases with rising of the confinement depth. They observed that the effectiveness of confinement decreased by increasing its diameter. Confined soil underneath the footing resists its lateral displacement which consequently leads to an improvement in the load-settlement behavior; all the details are shown in reference [4]. The effect of confinement on the bearing capacity of sand was studied by [5]. They found an improvement in bearing capacity up to 17 times higher than that of unconfined case with noticeable reduction in settlement values. Inserting discontinuous vertical dowels around existing foundation was carried out by [6]. The dowels were close enough to prevent the escaping of soil through the gaps. A marked increase of 20% in the bearing capacity and a reduction of settlements were found. Al-Aghbari and Zein [7] carried out tests on strip footings with structural skirts resting on sand. They observed that the skirts improved the bearing capacity by a factor up to three. A large number of triaxial compression tests on confined sand were done by [8]. Enhancement in granular soil strength and stiffness was found due to the influence of geocell confinement. Tests on strip footing resting on homogeneous dense sand beds of 70% relative density were conducted [9]. They indicated that an 8 times increase in bearing capacity was achieved with the provision of geocell. Model tests were performed on a circular footing supported on a dense sand layer overlying a soft clay bed [10]. Results showed about a six times rise in bearing capacity with the provision of geocell.

Limited literature is available on numerical simulations of confined foundation beds. The results revealed that soil confinement upgrades the footing load-settlement behavior. The soil confinement conduits using GEOFEM program were simulated [11,12]. The confinement layer has been modeled as an equivalent composite material having higher stiffness and shear strength. The effect of introducing a skirt in the soil around the footing by using SAPIV package program was studied analytically [13]. The analysis concluded that insertion of a skirt leads to a substantial gain in bearing capacity and reduction in settlement. Regarding the skirt thickness, the benefit of skirting is realized substantially even at lower thickness. Also, the skirt benefit was found to be rather insensitive to skirt material. Finite element method is used to study the effect of skirted foundation shape on the response of various loads [14]. The analyses indicated that the vertical circular footing capacity was higher than that of the strip footing.

The aim of the present study is to investigate experimentally the behavior of soil footing system due to installing hollow cylinder surrounding isolated circular footing model on granular soil. The effect of adding geogrid layers with the confinement cylinder was also studied. To achieve this objective, 23 model plate loading tests were carried out with a wide range of variables.

Materials and methods

The materials used in this study were clean sand, circular footing model, plastic hollow cylinders with different height and diameter, and geogrid inclusion having the following properties:

Sand: it was brought from Khatatba city, north of Cairo, Egypt. The specific gravity as determined by the pycnometer method as per IS: 2720, 1980, was 2.63. The grain size distribution is 27% coarse sand, 52% medium sand, and 15% fine sand. The sand is classified as SP according to the USCS and has a maximum and a minimum dry density of 19.3 and 15.6 kN/m^3, respectively. The effective size (D_{10}), the mean grain size (D_{50}), coefficient of uniformity (C_u), and coefficient of curvature (C_c) were 0.19 mm, 0.50 mm, 2.9 and 1.0, respectively. The bulk density of the sand was kept constant during model tests at 18.0 kN/m^3 with a relative density of 70%, for which the friction angle from direct shear test was found to be 36°.

Footing model: circular stiff steel footing model with 200 mm diameter and 20 mm thickness having a rough base was used in all tests.

Plastic hollow cylinders: nine plastic hollow cylinders of thickness 5 mm open at both ends were used to confine the soil under the circular footing model. The cylinders having different heights and diameters are shown in Fig. 1.

Reinforcement: the inclusion used in this research is a geogrid sheet which is made of high density polyethylene produced by El-Sherif Company, commercially known as CE131, which is shown in Fig. 2. It is manufactured in a sheet form of 2.0 m width and 30.0 m length, with unit mass = 6.6 N/m^2, mesh opening size = 27×27 mm, mesh thickness = 5.2 mm, tensile strength at maximum load = 5.8 kN/m, load at 10% extension 5.2 kN/m, strain at maximum load = 16.5%, and strain at 1/2 peak strength 3.7%.

Test set-up: the model steel circular footing, 200 mm diameter, was tested in a three dimensional stiffened framed tank of inner dimensions of 1000 mm length, 1000 mm width, and 600 mm depth. The tank's height and width were chosen equal to three and five times the footing width, respectively. The tank dimension was designed to minims its boundary effect on the footing pressure settlement behavior, as stated by [15]. Two opposite sides of the tank were made of perspex, 18 mm thickness, and the other two sides were made of stiff wood, 12 mm thickness. The outer sides of the tank were fixed by rigid steel frames and restrained by steel stiffeners to prevent deflection in the tank sides during tests. The vertical load was transmitted axially to the footing through a hydraulic jack

Fig. 1 Plastic cylinders.

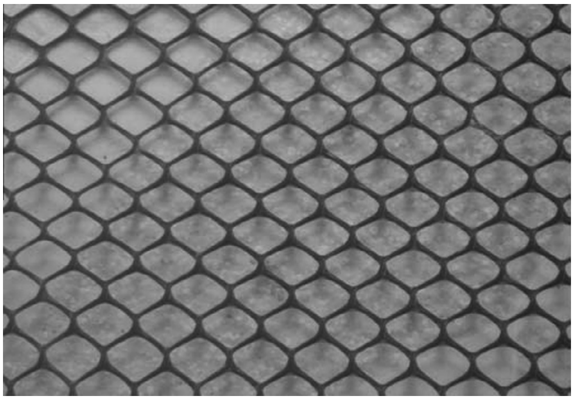

Fig. 2 Geogrid sheet.

10 ton centered between the model footing and the loading frame. A dial gauge with sensitivity 0.01 mm was used to measure the footing settlement. The arrangement of the test rig set up is shown in Fig. 3.

Testing procedure

The test model was prepared by compacting the sand in layers, each of 100 mm thick up to 600 mm height. The sand was compacted at a relative density of 70% .The accuracy of the sand density inside the tank was checked by conducting three preliminary density tests. The variation of the sand relative density was found to be 70% ± 0.50%. The sand unit weight and, thus, the required relative density was controlled by pouring a pre-calculated weight of dry sand into the testing tank, to fill each layer, and then the sand surface was leveled and compacted. Reference markers on the perspex sides were used to form the required sand model. The geogrid layer was placed at the desired height and location on the compacted level surface. The sand filling process continued above the geogrid layer up to filling the tank. The cylinder is pushed vertically into the deposits at the desired location after filling the model. The model footing was placed, centrally with the cylinder, in the top surface of the sand and the dial gauge was placed on the footing. The verticality of the hydraulic jack and horizontality of the footing model were set up with the help of plumb bob as decided by [16]. After taking the zero loading, the load was applied in small increments and the dial gauge recorded the footing settlement at the end of each increment until failure.

Fig. 3 Test set up.

The experimental program consists of carrying out twenty-three load bearing tests on the circular model footing. The study investigated the effect of soil confinement on soil-footing response. Each test was carried out to study the effect of one parameter while the other variables were kept constant. The variables studied are the height (h) and diameter (d) of the cylinder, Position (X), length (L), and number (N) of the embedded geogrid reinforced layers placed under the cylinder. The confining hollow cylinders used in the tests had different diameters of 205, 250, and 300 mm i.e. (d/D = 1.02, 1.25, and 1.50) and with variant heights of 50, 100, and 200 mm i.e. (h/D = 0.25, 0.50, and 1.0). The inner and outer surface of the cylinder was smooth to prevent the effect of the interface friction between the soil particles and the cylinder. The additional enhancement on the load carrying capacity and settlement response, obtained from placing a geogrid reinforcement sheet under the cylinder was studied. A geogrid sheet of width varying from L/D = 1.50, 3.0, and 4.0 was placed at a depth varying from X/D = 0.25, 0.50, and 1.0 under the cylinder. The effect of installing more than one square geogrid layer at constant vertical spacing X/D = 0.25 under the bottom of the cylinder was studied (i.e. N = 1.0, 2.0, and 3.0). A typical sketch of the apparatus and the geometry setup of the model footing tests are illustrated in Fig. 4.

Results and discussion

Load-settlement experimental footing model tests were conducted for isolated circular footing, 200 mm in diameter,

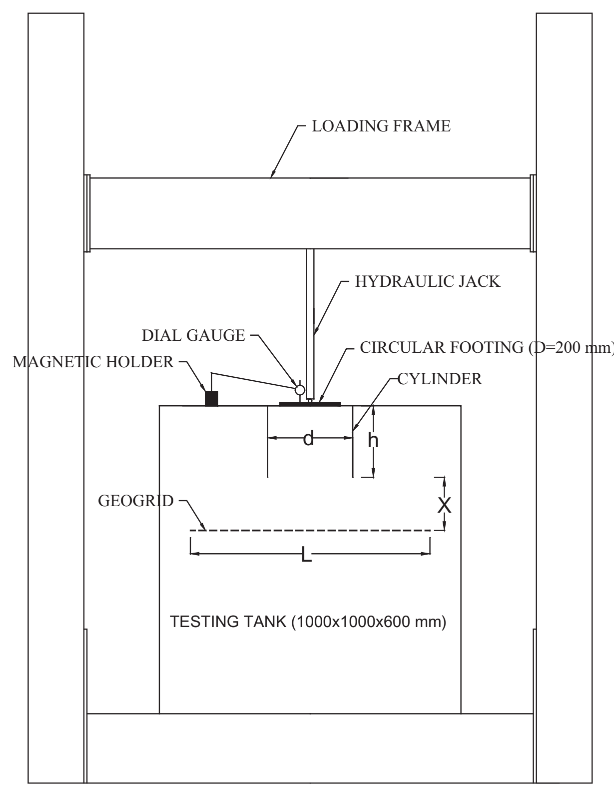

Fig. 4 Geometry set-up of the model footing tests.

resting on the top surface of unconfined and laterally confined clean sand bed. In addition, the combined effect of using confinement cylinder with geogrid layers placed underneath the bottom of the cylinder was studied. The model sand cushion inside the testing tank was compacted to a relative density of 70%. The failure pressure was marked by the sudden considerable steepness in the load-settlement curves and/or by using the intersection tangent method. The footing settlement (S) is also expressed in non-dimensional form in terms of the footing diameter (D) as the settlement ratio, ($S/D\%$).

Effect of cylinder diameter

The load-settlement relationships for confined sand model are shown in Figs. 5–7. Each figure is plotted for fixed cylinder height and variant cylinder diameters. The load-settlement relationship for unconfined case is shown in the same graphs, as a basic case for comparison. The cylinder around the footing resists the lateral displacement of soil particles underneath the footing so the soil gets more confined leading to a significant decrease in settlement and therefore improving the load-settlement behavior. The improvement increases as the cylinder diameter decreases because the soil inside the cylinder and the footing behaves as one unit and settle together. This allows the depth of the failure surface to increase which increases the load carrying capacity of the footing. This behavior was not noticed in the tests carried out with large cylinder diameters, d/D more than 1.0, and small cylinder height, $h/D = 0.25$. The footing settled down while the cylinder was unaffected with the increase of the load. Cylinders with small height decreases the lateral confinement and allows escaping a high percent from the soil underneath the footing.

The load-settlement relationships in the case of single geogrid layer of length $L/D = 4.0$ and placed at the bottom of the cylinder at fixed locations, $X/D = 0.25$ are shown in Figs. 8 and 9. Each figure is plotted for fixed cylinder height and variant cylinder diameters. The load-settlement relationship for unconfined case is shown in the same graphs for comparison. The graphs of the combined system of cylinder and geogrid showed the same trend as using the confined cylinder only. The combined system of cylinder and geogrid improves the grade of the load-settlement behavior than the confined case.

The soil confinement could be considered as a method of bearing capacity improvement for isolated footings on sandy soil. As the footing pressure is increased, the plastic state is developed initially around the edges of the footing and then spreads downward and outward. The mobilized vertical friction between the soil and the inside cylinder wall increased

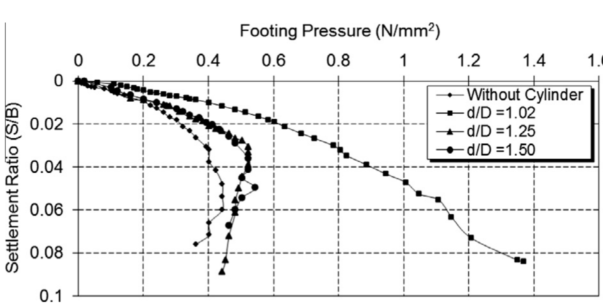

Fig. 5 Load-settlement relationship for ($h/D = 0.25$).

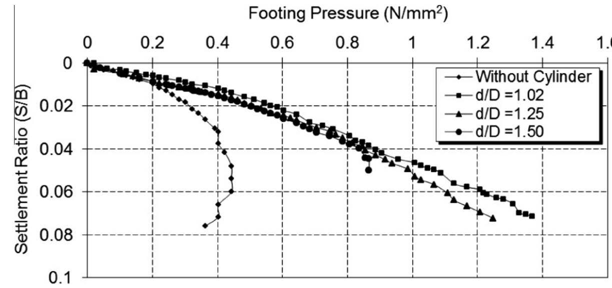

Fig. 6 Load-settlement relationship for ($h/D = 0.50$).

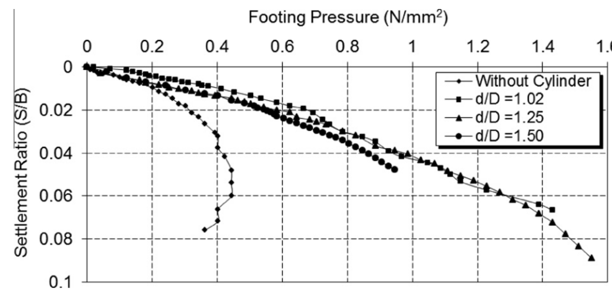

Fig. 7 Load-settlement relationship for (h/D = 0.50).

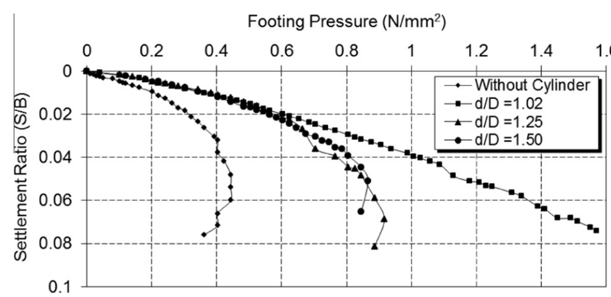

Fig. 8 Load-settlement relationship for single geogrid layer ($L/D = 4.0$, $X/D = 0.25$, and $h/D = 0.25$).

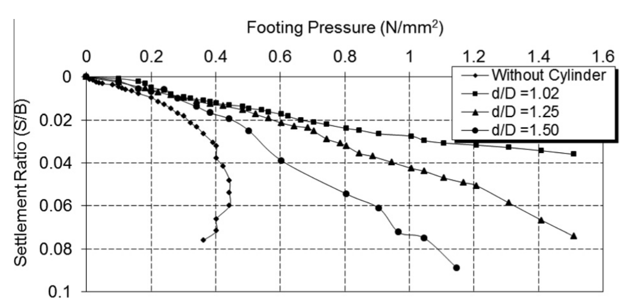

Fig. 9 Load-settlement relationship for single geogrid layer ($L/D = 4.0$, $X/D = 0.25$, and $h/D = 0.50$).

with the increase of the acting active earth pressure until the point at which the system (the cylinder, the soil, and the footing) behaves as one unit. This behavior is similar to those observed in deep foundations in which the bearing capacity increases due to the shear resistance of the foundation surface.

The improvement due to the soil confinement is represented using a non-dimensional factor, called improvement factor

(If), which is defined as the ratio of the footing ultimate load with cylinder as a lateral confinement to that of the footing ultimate load without confinement. Comparing the figures from 5 to 7, it can be seen that the soil confinement improved the footing bearing capacity from 0.20 to 0.664 N/mm^2 (i.e. If = 3.30) with installing a cylinder, $d/D = 1.02$ and $h/D = 1.0$. Also, the settlement reduced up to 43% at the same pressure level 0.20 N/mm^2.

Experimental tests indicated that a cylinder with defined height and diameter could easily be manufactured and placed around the individual isolating footing leading to a significant improvement in the load-settlement behavior. When the excessive settlement is the controlling factor for the bearing capacity, the confinement cylinder has a significant benefit to decrease the footing settlement.

Effect of cylinder height

The effect of the cylinder height on the soil-footing response is shown in Fig. 10. The figure shows the test results of samples from three different heights of each cylinder diameters. The plot shows the same pattern of behavior for the different cylinder diameters. It is clear that increasing the cylinder height led to a greater improvement in the load-settlement behavior due to enlargement in the contact confined soil volume under the footing. The failure plane moves in the downward direction to the bottom edge of the cylinder which leads to an increase in the area of the resisting soil around the cylinder. The deeper locations of the failure wedge increase the surface area of the cylinder-model footing. This enhanced the soil carrying capacity and improved the load-settlement behavior of the footing.

Effect of geogrid reinforcement

The objective of this test series is to investigate the effect of placing a geogrid reinforcement layers under the bottom edge of the cylinder on the load-settlement footing behavior .The variables studied in this test series are the geogrid position, geogrid width, and the number of geogrid layers.

Geogrid position

The main objective of this test series is to determine the optimum position of placing centrally a single geogrid layer under the bottom of the cylinder. The optimum position of geogrid layer that gives the maximum improvement in the load-settlement behavior was determined. The load-settlement relationship is shown in Fig. 11 for the case of single geogrid layer of width $L/D = 4.0$ and placed at the bottom of the cylinder at three different locations, X/D, ranged from 0.25 to 1.0. The height and diameter of the cylinder in these tests is $d/D = 1.02$ and $h/D = 0.25$. Moreover, results for case of unreinforced soil as a reference test are shown in the same graph. Results indicated that the bearing capacity increases as the depth of the geogrid layer decreases. The optimum depth for placing a single geogrid layer under the bottom of the cylinder was found equal to quarter of the footing width. This was due to the deepness of the failure wedge down to the bottom of the cylinder as the lateral soil confinement. The existence of geogrid layer near the bottom of cylinder cut prompts the failure wedge which improves the soil strength. This resists the soil escaping which is the reason for enhancing the load -settlement behavior.

Geogrid width

The objective of these test series is to investigate the optimum reinforced width for one geogrid sheet placed centrally under the bottom edge of the cylinder. The load-settlement relationships for one geogrid layer of width $L/D = 0.0$, 1.50, 3.0, and 4.00 are shown in Fig. 12. The load settlement curve for the case without reinforcement is shown in the same graph for comparison. It can be seen that the bearing capacity increased as the reinforcement width increased up to $L/D = 4.0$ and the improvement factor (If) reached about 7.5. The improvement is achieved from the anchorage length of the geogrid sheet. The improvement in the ultimate bearing capacity due to the combined effect of both lateral confinement and geogrid layer was about 227% of that without reinforcement.

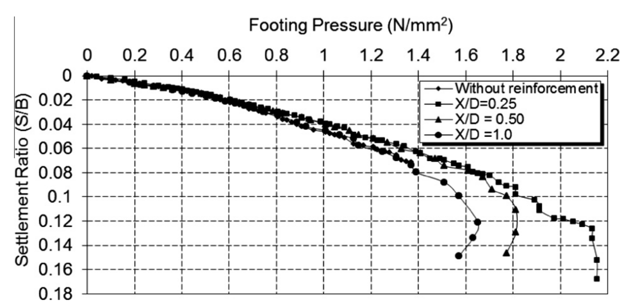

Fig. 11 Load-settlement relationship for single geogrid layer ($L/D = 4.0$, $d/D = 1.02$, and $h/D = 0.50$).

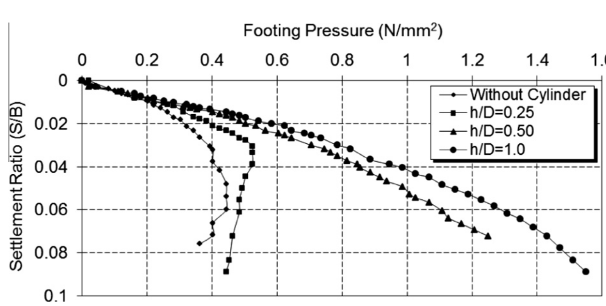

Fig. 10 Load-settlement relationship for ($d/D = 1.25$).

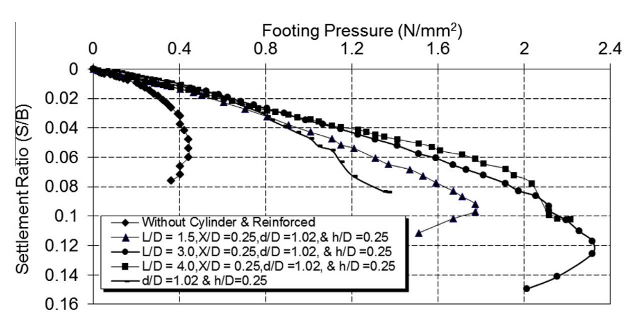

Fig. 12 Effect of geogrid width.

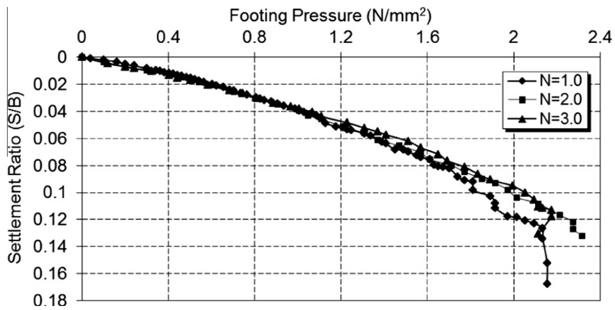

Fig. 13 Load-settlement relationship for multi geogrid layer ($L/D = 4.0$, $h/D = 0.25$ and $d/D = 1.02$).

Number of geogrid layers

One of the important parameters is to investigate the effect of geogrid layer number placed under the bottom of the cylinder. The load-settlement curves for a number (N) of one, two, and three geogrid layers are shown in Fig. 13. The width of geogrid layer in these tests is kept constant at $L/D = 4.0$. The position of the first geogrid layer is at $X/D = 0.25$ and the vertical spacing between the geogrid layers is equal to $X/D = 0.25$. No improvement in the load-settlement behavior due to using multi geogrid layer up to a stress level of about 1.0 kN/mm^2, and little improvement thereafter was observed. The first reinforcement layer cuts the failure wedge in addition the soil particles interlock with the mesh of the geogrid leading to an increase in the soil sheer strength parameters. The movement of the soil particles is greater at the first geogrid layer. This movement decreases downward; placing additional geogrid layers with little effect since the improvement obtained from the geogrid depends on soil movement.

Conclusions

Based on experimental study, the following conclusions are drawn.

1. Soil confinement enhances the influence of the load-settlement behavior of circular footing resting on granular soils.
2. The load-settlement behavior depends on the diameter and height of the confinement cylinder relative to the footing diameter.
3. The maximum improvement factor was reached when the cylinder has a width equal to the footing diameter, as the cylinder-footing system acts as one unit.
4. Increasing the confining cylinder height transfers the footing loads to deeper levels and enhances the soil behavior.
5. The optimum depth for placing a single geogrid layer under the bottom of the cylinder was found equal to quarter of the footing width.
6. Increasing geogrid width under the confined cylinder up to $L/D = 4.0$, increased the improvement factor (If) up to 7.5.
7. On increasing the geogrid layer number under the confined cylinder more than single layer has little significant effect on the response of footing-cylinder systems.

Conflict of interest

None declared.

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