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Experimental and Numerical Study of a Model Strip Footing Resting on Geogrid-Reinforced Dune Sand

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ABSTRACT: This paper presents the results of experimental and numerical investigations on the behaviour of strip footing resting on geogrids-reinforced dune sand. The tests were performed on a rigid steel tank having glass sides and the model footing is made of steel. Footing depth, geogrids depth, and number of geogrid layers were studied. Footings were placed at the surface of the sand or at a depth of $0.25B$ below the surface of the sand. Geogrids were placed at different depths below the footing from $0.25B$ to B . The number of geogrids layers was varied from 0 to 4 layers. The results indicated that using more geogrids layers improved the ultimate bearing capacity of the strip footings and reduced the settlement. The bearing capacity improvement factor increased from 1.2 for the case of one geogrid layer to more than 3 for the case of 4 geogrid layers. For the case of one layer of geogrids the highest improvement is when the depth of the reinforcement below the footing was between $0.5B$ and $0.75B$. For the case of two layers of geogrids, the highest improvement is when the reinforcements are placed at depths of $0.25B$ and $0.75B$ below the footing. Results obtained from finite element analysis using the program MIDAS are generally in good agreement with those obtained from the laboratory model tests. Further, numerical analysis indicates that the geogrids redistribute the applied load on larger area of the soil, thus, reducing the settlement.

KEYWORDS: Bearing Capacity, Dune Sand, Geogrids, Model Footing, Reinforcement, Settlements.

I. INTRODUCTION

Dune sands are not suitable for support of structures and roads without the risk of bearing capacity failure or excessive settlement. Different techniques such as chemical stabilization and soil reinforcement are used to improve the properties of problematic soils. In the early stages of soil reinforcement, engineers used metal strips [1]. Since the 1990's the use of geosynthetic materials is popular because of the superior properties of these materials such as durability and ease of installation. Geosynthetic reinforcements include geogrids [2-5], prestressed geotextiles [6] and geocells [4].

A number of laboratory model tests and very few large scale tests were used to study the performance of footings bearing on a geosynthetic reinforced-soil. The foundations types were strip footings [2, 5, 7-10], square footings [2, 11], rectangular footings [3] or circular footings [6,12].

Analytical methods were also used to study the performance of footing bearing on geosynthetic-reinforced soils [13-14]. The performance of footings bearing on geosynthetic-reinforced soils was also studied using numerical methods such as finite elements and finite difference methods [6, 14-16].

The studies reported in the literature have shown that the bearing capacity of the reinforced soil increased by a factor of 1.5 to 4. The improvement depends on the type, depth, length and spacing of the reinforcement. Of special interest is the optimum depth of the first reinforcement below the footing (u), the spacing between the reinforcement (h) and the overall depth of the reinforcements (d_r). There is no agreement between different researchers on these design parameters (e.g. u , h and d_r). For strip footings on reinforced-sand, values of u reported in the literature varied from $0.3B$ to $0.5B$.

The objective of this paper was to study the settlement of a model strip footing on dune sand reinforced with geogrids. The study included laboratory model experiments and finite element analyses using MIDAS program. Parametric studies were performed to study the effect of different factors such as the footing depth, the depth of the geogrid layers and the number of geogrid layers on the performance of the reinforced footing on sand.

II. EXPERIMENTAL SETUP AND MATERIALS

Footing Model Test

The footing was tested in a large tank formed by a very heavily reinforced rigid steel frame and toughened glass sides (Figures 1 and 2). This test setup was intended to simulate the plane strain condition below strip footing. The main concern in simulating the plane strain condition is to avoid the side effects of the test tank. This was accomplished by maintaining rigidity of the test tank [17] and placing the model footing at a reasonable distance from the sides of the tank. The tank has a length of 1.0 m, a width of 0.23 m and a height of 0.64 m (Figure 1). The footing was placed centrally across the tank and was made from a metal plate with a width of 75 mm and a length of 230 mm.

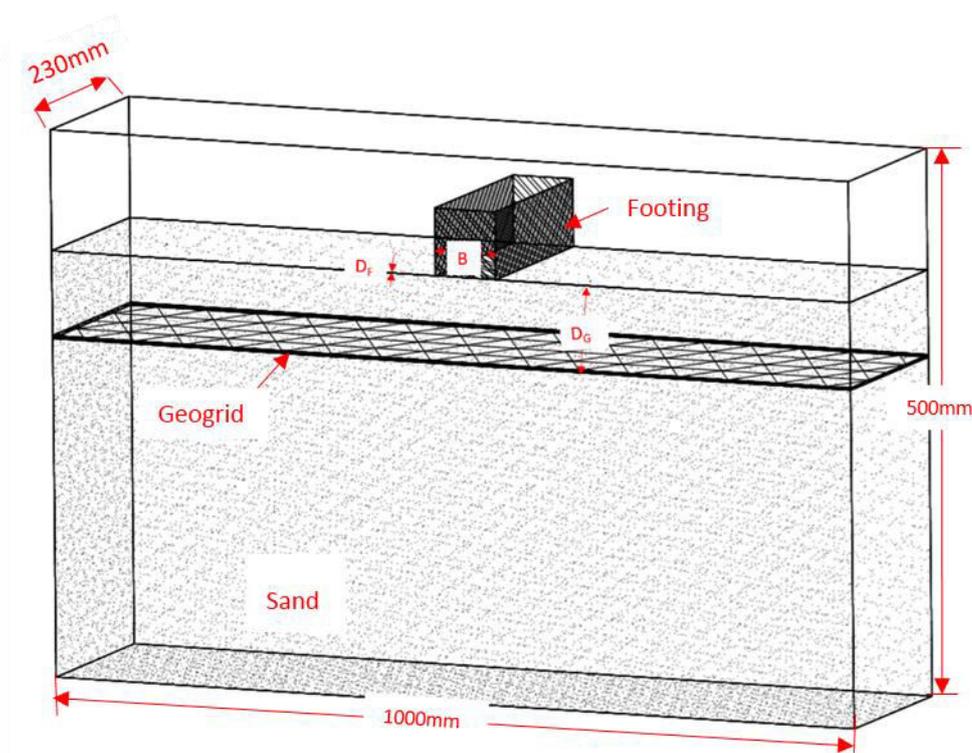


Figure 1. Schematic Diagram of the Experiment Setup



Figure 2. Experimental setup showing test tank with compacted sand

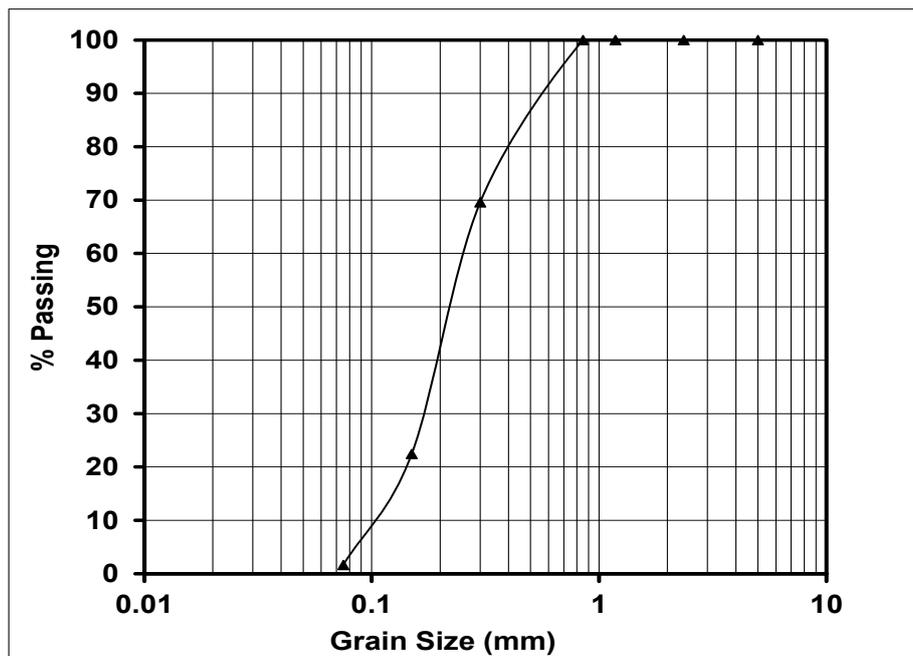


Figure 3. Grain size distribution of sand



Experimental Procedures

At the beginning of any test, the glass side plates were cleaned with acetone. To ensure side lubrication, silicon grease, and rubber membranes were used. The membrane was greased and left for at least one hour to allow the uniform spreading of grease over the surface and were then placed on the glass symmetrically along the center line of the tank. Care was taken to remove trapped air bubbles between the glass wall and the membrane.

The sand bed was prepared by pouring the grains uniformly across the width of the tank in layers using pouring method recommended by Kumar and Bhoi [18] so that any segregation of grains was avoided during the construction process. The loose sand was placed in seven layers and compacted using 200 blows per layer. The top surface of the sand layer was gently levelled off using a hand scraper. Care was taken not to disturb the compacted sand in any way before applying the axial loading.

The rigid footing was placed on the sand at two different depths: at the surface or at 0.25B below the sand surface. For the cases where geogrids were used, the layers of geogrids were placed at the appropriate depths during sand placement and before the placement of the footing.

The loading system consists of a hydraulic machine with a motor connected with an actuator capable of moving vertically upwards and downwards at a constant rate of deformation. The actuator applies a load at the center of the footing. The load is measured by using a ring with strain gages located at the top of the footing. A small ball of steel is placed between the foundation and the load cell or a ring. The vertical displacement (settlement) of the foundation that occurred at the center of the rigid footing is recorded by using LVDTs (Linear Variable Displacement Transducers) that is fixed to the top of the footing. A vertical compression loading was applied slowly on the footing center using a displacement rate of 0.05 mm/s. as shown in Figure 2.

Sand

The sand used in this study was a dune sand. The grain size distribution of the sand is shown in Figure 3. The sand can be classified as fine-grained, poorly-graded sand (SP) according to the Unified Soil Classification System (USCS). The sand has a specific gravity of 2.6. The results of the shear box tests for sand at different relative density values showed that the angle of internal friction (ϕ) of the sand varies from about 27° in the loosest state to about 36° in the densest condition. Table 1 lists a summary of the sand properties.

Geogrids

The bi-axial geogrids used in this research was a three, needle-punched, polypropylene geogrids manufactured by TENSAR International Co. These geogrids are extensively used in the region for soil reinforcement. The most important properties of these geogrids are summarized in Table 1.

Table 1. Properties of materials

Sand Properties (Model: Modified Mohr-Coulomb)

Density (kN/m ³)	Modulus of Elasticity E (loading) (kN/m ²)	Modulus of Elasticity E (unloading) (kN/m ²)	Possion's Ratio	Angle of internal friction (°)
16	7000	14000	0.25	27

Footing Material Properties

Footing Material	Material Model	Density γ (kN/m ³)	Possion's Ratio	Modulus of Elasticity E (MPa)
Steel	Elastic	78.50	0.2	210000



Geogrid Material Properties

Material Model	Density γ (kN/m ³)	Modulus of Elasticity E (MPa)	Shear Modulus G (MPa)
Orthotropic-Geogrid	13	210	190

III. THE TESTING PROGRAM

The testing program was designed to cover the three main factors considered in this research: the depth of the footing, the depth of the geogrid layers, and number of geogrid layers. Table 2 lists the tests performed where the footing depth ratio (D_F/B) was 0 or 0.25 (where D_F is the depth below the ground surface) and the geogrids depth ratio (D_G/B) were 0.25, 0.5, 0.75 or 1.0 (where D_G is the geogrid layer depth below the footing). Different combinations of D_F/B and D_G/B were studied with different numbers of geogrid layers (i.e. 0, 1, 2, 3 and 4 layers). A total of 18 tests were conducted in this study.

IV. FINITE ELEMENT MODELLING

A two-dimensional (2D) plane strain finite element analysis was developed to verify the conducted experimental work in the laboratory. MIDAS GTS NX Version 2019 [19] was employed to simulate the experimental work using plane strain model. The mesh has been generated using auto-face meshing option. Such option let the mesh to be automatically generated with a combination of the triangle and quadrilateral element shapes. All nodes on the bottom of the tank are constrained in both horizontal as well as vertical directions. While the side boundaries (which represent the tank side) were restrained only in the horizontal direction. Figure 4 shows a mesh for the case of footing bearing on 4 layers of geogrid-reinforced sand. The model consists of three materials: soil, steel plate (footing), and geogrid layers. The soil was simulated using Modified Mohr-Coulomb (MMC) material model [20]. This model is an improvement on the Mohr-Coulomb model. The footing material was simulated using linear elastic material model. Such model is appropriate in modelling structural steel, which have a much higher strength than the soil. The geogrid layers were modelled using orthotropic geogrid material model. In this model, users can define different values of stiffness along each direction. The properties of these materials are shown in Table 1.

The loads were applied into two loading stages. The self-weight of the soil was applied in the initial construction stage, followed by the applied pressure in the second loading stage. The self-weight was applied as a body force everywhere within the soil domain. The pressure load was applied on the top of the footing.

Table 2. Testing Program

Test Code*	Depth of footing D_F	Number of Geogrids layers	Depth of Geogrid D_G/B
S0	0	0	-
D0	0.25		-
S1(0.25)	0	1	0.25
S1(0.5)			0.5
S1(0.75)			0.75
S1(1.0)			1
D1(0.25)	0.25B	1	0.25
D1(0.5)			0.5
D1(0.75)			0.75
D1(1)			1
S2(0.25, 0.5)	0	2	0.25,0.5
D2(0.25, 0.75)	0.25	2	0.25,0.75
D2(0.5, 0.75)			0.5,0.75

D2(0.5, 1)			0.5,1
D2(0.25, 0.5)			0.25,0.5
S3(0.25,0.5, 0.75)	0	3	0.25,0.5,0.75
D3(0.25,0.5, 0.75)	0.25		0.25,0.5,0.75
S4(0.25,0.5, 0.75,1.0)	0	4	0.25,0.5,0.75,1

* The first letter S = surface footing, D = footing at 0.25B; the number after the first letter is the number of the geogrids layers; the numbers between the brackets are the depth of the geogrids layers D_G/B .

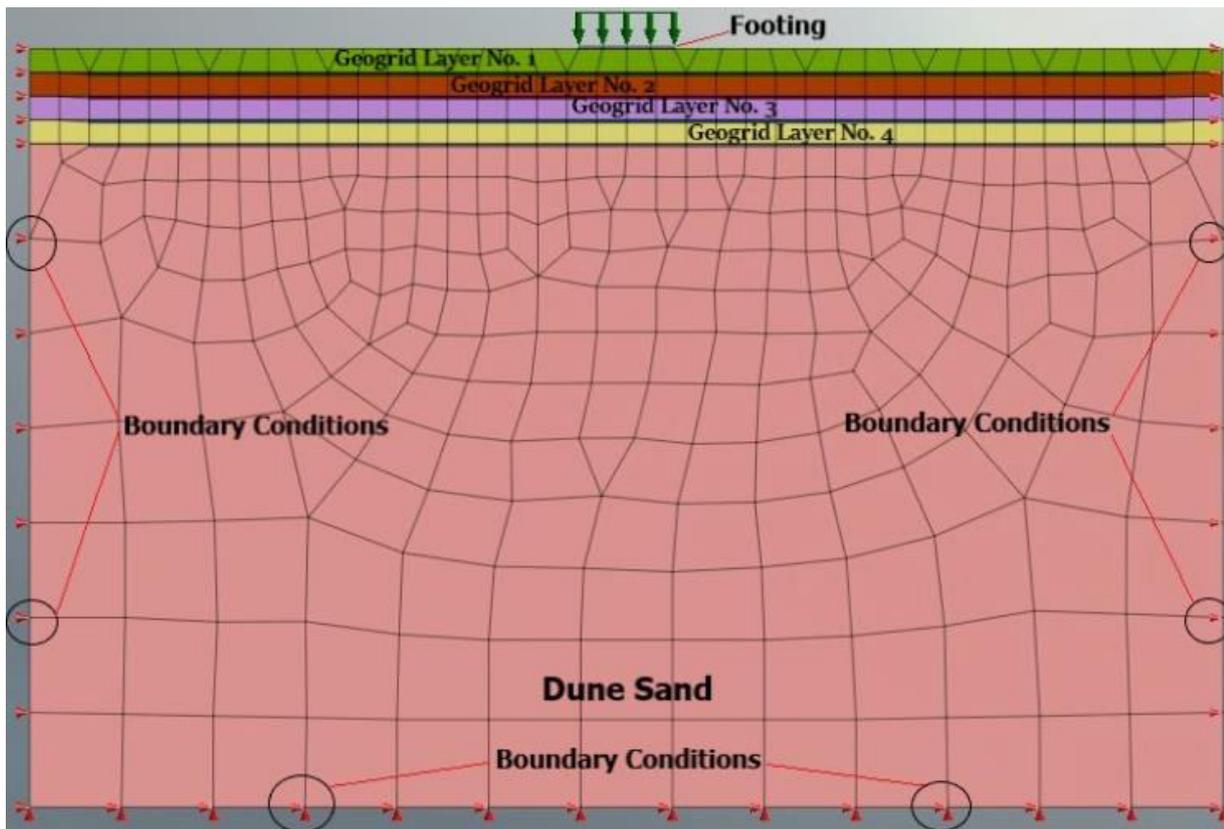


Figure 4. Typical finite element mesh

IV. RESULTS AND DISCUSSION

Model Test Results

To quantify the improvement provided by the geogrids, a parameter termed bearing capacity improvement factor (BCR) is used. The BCR is the ratio of the ultimate bearing capacity (q_u) of the footings with geogrids to that without geogrids [6], as given by Equation (1).

$$BCR = \frac{q_u \text{ with geogrids}}{q_u \text{ without geogrids}} \quad (1)$$

Table 4 shows a summary of all laboratory results. It shows that BCR for one layer of geogrid varies from 1.17 to 1.88. For 2 layers, the maximum BCR increased to 3.4. For 3 and 4 layers of geogrids no failure is seen, however, BCR is expected to be high (greater than 3). For a surface footing, the ultimate bearing capacity increased from 125 kPa for the case of no geogrid to > 410 kPa for the case of 4 layers of geogrids. Thus, it can be concluded that the improvement in bearing capacity and settlement increases with increase in the number of geogrid layers.



Footing with One Layer of Geogrid

Figure 5 presents the pressure-settlement curves of the surface footing with one layer of geogrid at depths of 0.25B, 0.5B, 0.75B and B below the footing, respectively. The use of one geogrid layer improved the load-settlement of the surface footing for all depths of the geogrid layers. However, the footing with a geogrid layer at a depth of 0.75B shows the stiffest response, followed by the footing with a geogrid layers at 0.5B, B and 0.25B, respectively. The maximum bearing capacity is 325 kPa and the maximum BCR (Table 3) is 1.8 for the footing with a geogrid layer at 0.75B.

Table 3: Summary of laboratory results

Test Code	q _u (kPa)	CBR	q _a (kN/m ²)
D0	175	-	125
S0	180	-	150
S1(0.25)	240	1.3	150
S1(0.5)	280	1.56	200
S1(0.75)	325	1.8	250
S1(1.0)	210	1.17	180
D1(0.25)	300	1.7	210
D1(0.5)	330	1.88	200
D1(0.75)	310	1.77	180
D1(1)	300	1.7	210
S2(0.25, 0.5)	375	2.1	150
D2(0.25, 0.75)	590	0.4	200
D2(0.5, 0.75)	320	1.83	190
D2(0.5, 1)	500	2.8	200
D2(0.25, 0.5)	-	- no failure	150
S3(0.25,0.5, 0.75)	>390	- no failure	210
D3(0.25,0.5, 0.75)	-	- no failure	150
S4(0.25,0.5, 0.75,1.0)	>410	- no failure	340

Similar pressure-settlement curves were obtained for footing at a depth of 0.25B and resting on sand reinforced with one geogrid layer at depths of 0.25B, 0.5B, 0.75B and B below the footing. However, the footing with a geogrid layer at a depth of 0.5B shows the stiffest response, followed by the footings with a geogrid layers at 0.75B, B and 0.25B, respectively. The maximum bearing capacity is 330 kPa and maximum the BCR is 1.88 for the footing with a geogrid layer at 0.5B.



Footing with Two Layers of Geogrid

Figure 6 shows the pressure–settlement curves of the footing at a depth of 0.25B with two layers of geogrid reinforcements at different depths below the footing, namely (0.5B and 0.75B), (0.5B and B), (0.25B and 0.75B) and (0.25B and 0.5B). From the figure the best combinations are for the case of depths of geogrids at (0.25B and 0.75B) followed by the combination of depths of (0.5B and B). The other two cases give softer response. It is clear that the cases where the spacing between the layers is 0.5B (i.e. the first two cases) are better than the latter two cases where the spacing is 0.25B. This implies at smaller spaces the geogrid layers are not effective. The maximum BCR value is 3.4 for the case with geogrid layers at (0.25 and 0.75) B and the minimum value is 1.83 for the case with geogrid layers at (0.5B and 0.75B).

Footing with Three Layers of Geogrids

The three layers of geogrids are placed at depths 0.25B, 0.5B and 0.75B below footings. Figure 7 shows the pressure–settlement curves for both surface footing and a footing at a depth of 0.25B. In both cases failure did not occur even for a pressure of about 375 kPa. The surface footing shows less settlement than the footing at a depth of 0.25B, indicating that the geogrids are more effective in reducing the settlement of the surface footing than that of the footing below the sand surface.

Footing with Four Layers of Geogrids

Four geogrid layers were installed at depths of 0.25B, 0.5B, 0.75B and B below a surface footing. Figure 8 shows for this case the load-settlement curve is linear elastic behaviour up to a pressure of about 400 kPa and the settlement is 5.4 mm.

Effect of the Number of Geogrid Layers

Figure 9 shows the load-settlement curves for surface footings with different number of geogrid layers (i.e. one, two, three, and four layers). The depths of the geogrid layers vary from 0.25 B to B under the footing. For one layer the depth is 0.25B; for 2 layers the depths are 0.25B and 0.5B; for 3 layers the depths are 0.25B, 0.5B and 0.75B; and for 4 layers the depths are 0.25B, 0.5B, 0.75B and B, below the footing. It is clear that the case with 4 layers is superior than other cases, followed by the cases with 3 layers. Also, there is no soil failure is seen for the cases of 3 and 4 layers of geogrids.

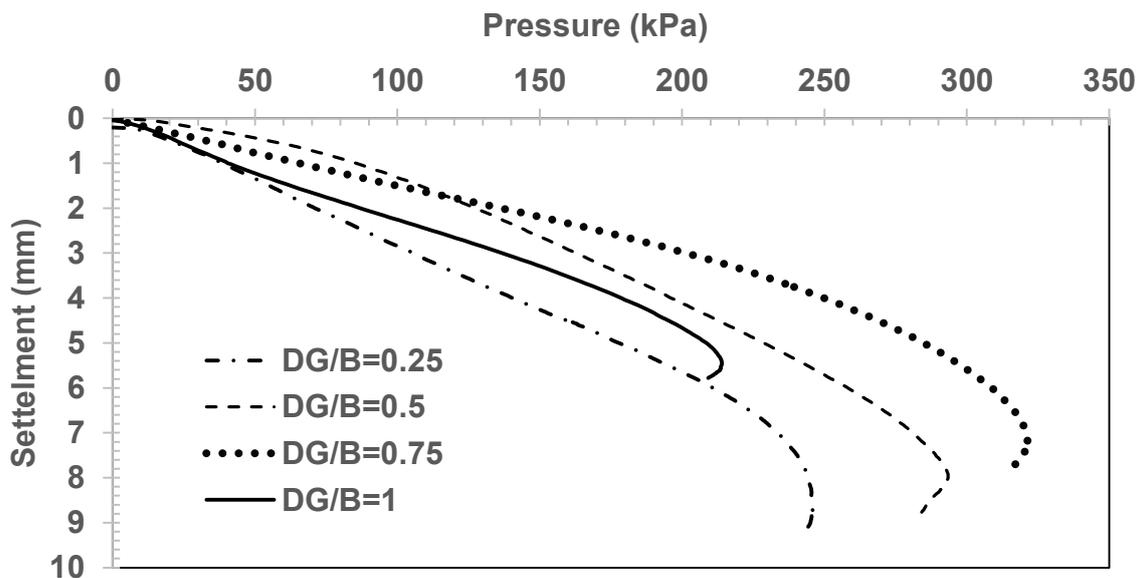


Figure5. Pressure-settlement curves for surface footing with one layer of geogrid.

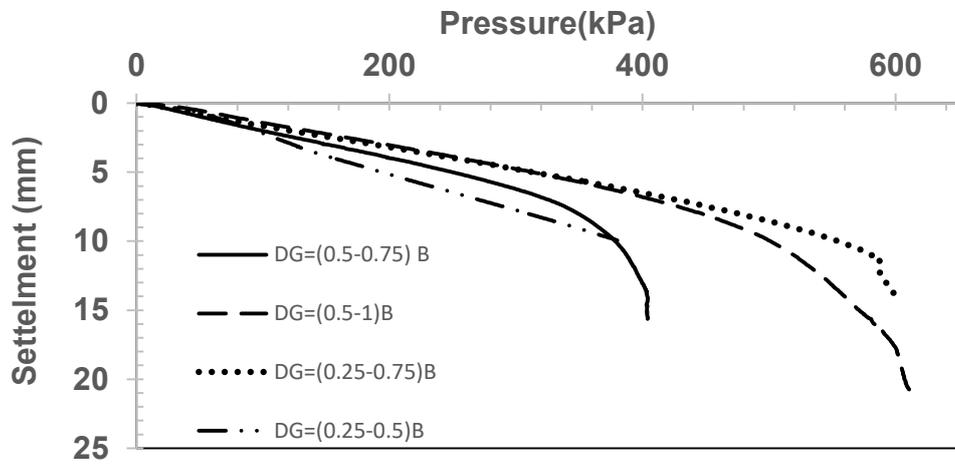


Figure 6. .Pressure-settlement curves for footing with two layers of geogrid ($D_f=0.25B$)

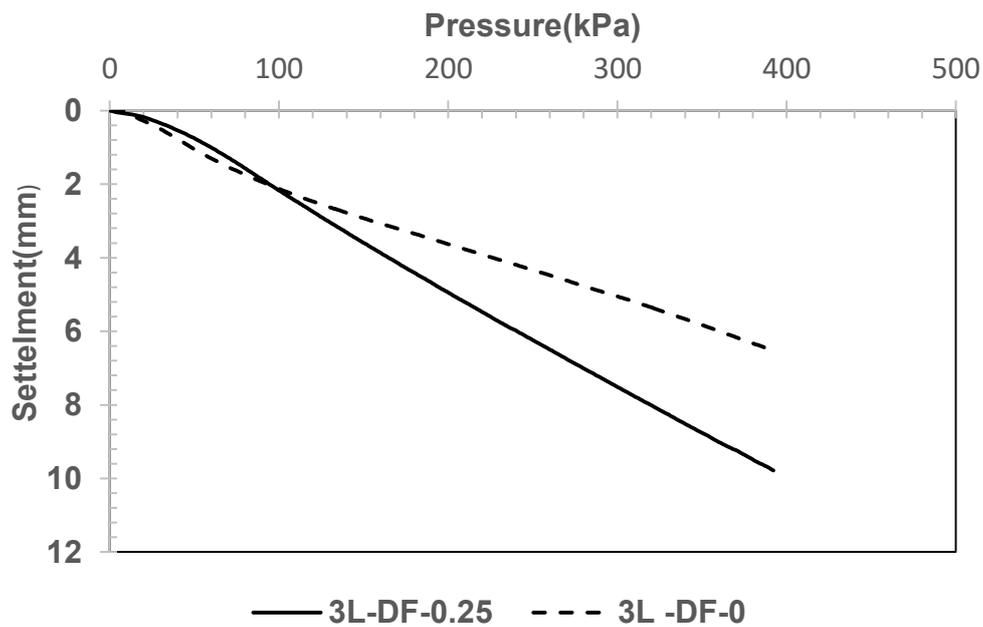


Figure 7. Pressure-settlement curves for footing with three layers of geogrid ($D_f=0.25B$ and $D_f=0$) ($DG/B = 0.25, 0.5$ and 0.75)

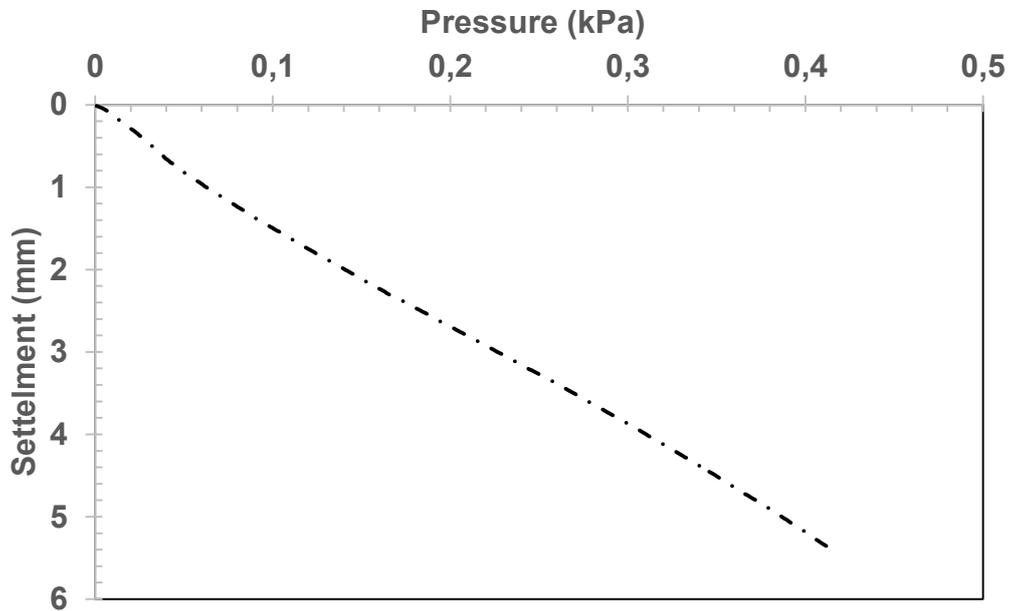


Figure 8. Pressure-settlement curves for footing with four layers of geogrid ($D_F=0$) ($D_G/B = 0.25B, 0.5B, 0.75B$ and B)

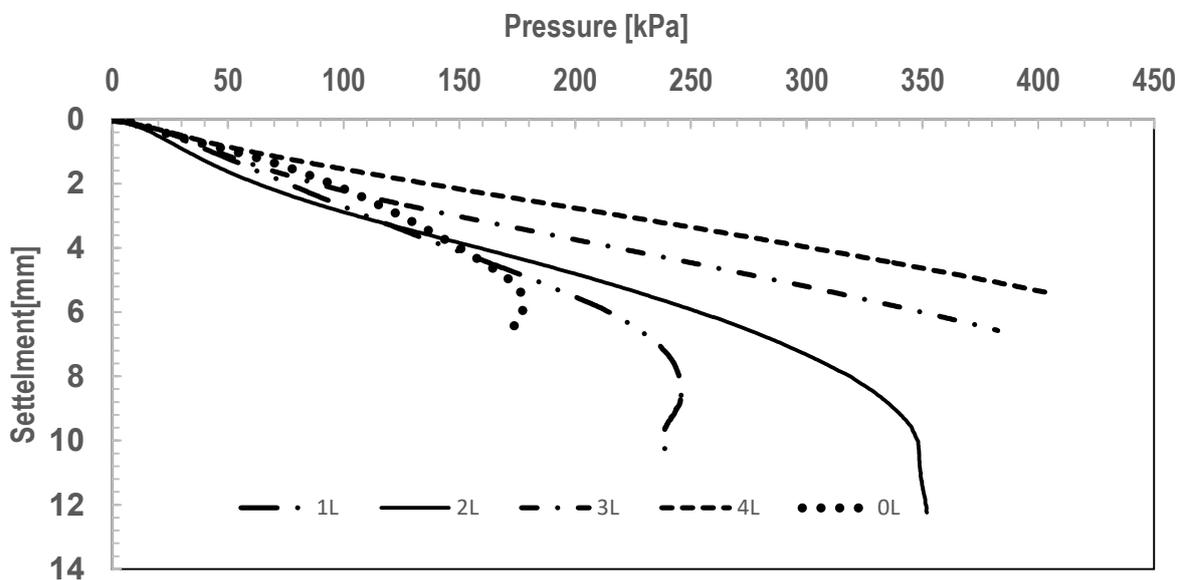


Figure 9. Pressure-settlement curves for surface footing with different layers of geogrid ($D_F/B=0$)

Results of Numerical Analysis

The results of the finite element model developed in this study using MIDAS software are compared to the results of the laboratory model tests for selected cases as shown in Figures 10 and 11. In general, there is a good agreement between the experimental and numerical results. This validates the numerical model outlined earlier.

The results from the numerical model can be used to gain insight into the behaviour of the strip footing bearing on geogrid-reinforced sand. As the number of geogrid layers increases, the area of the soil affected by the load increases. This indicates that the effect of the geogrids is to redistribute the applied load on larger area of the soil, thus, reducing the settlement.

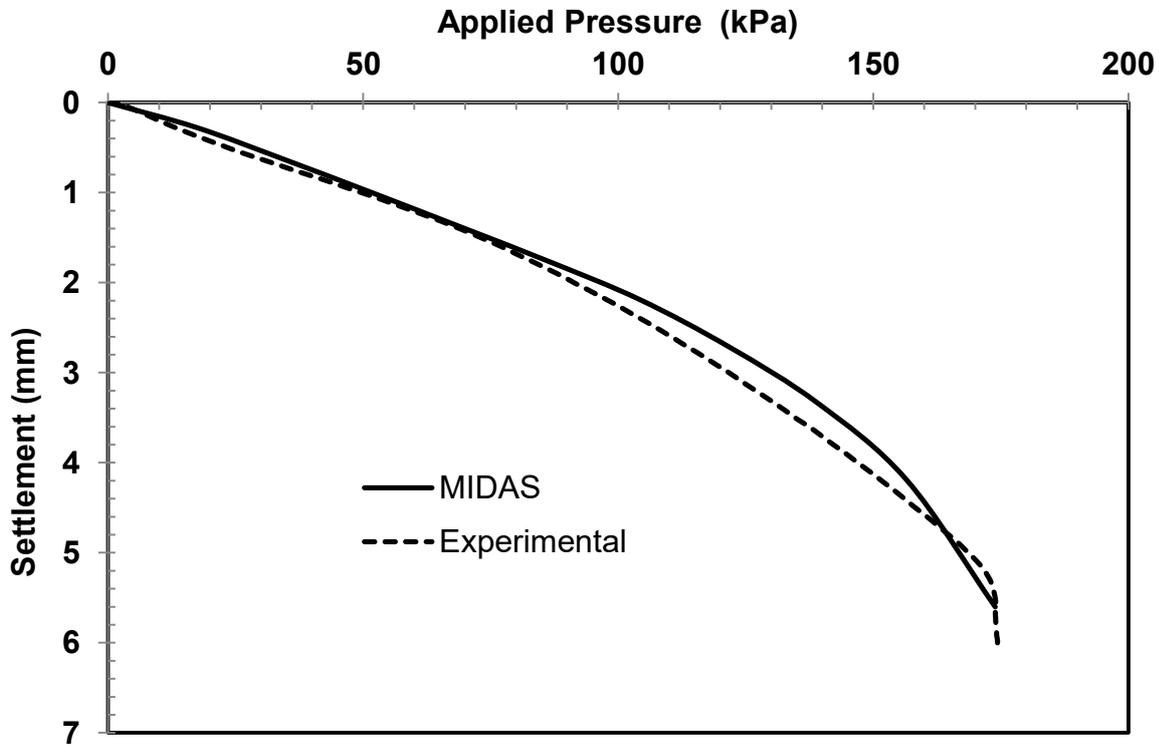


Figure 10. Pressure-settlement curves for surface footing with no geogrids

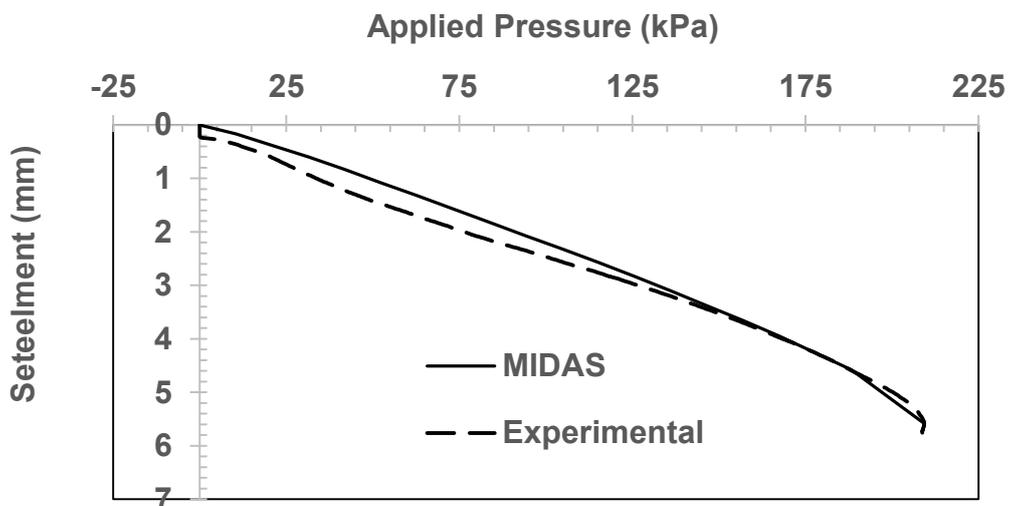


Figure 11. Pressure-settlement curves for surface footing with one geogrid layer ($G/B = 0.25B$)

V. CONCLUSIONS

A model test was conducted to study the behaviour of strip footing bearing on geogrid-reinforced dune sand. The conclusions from this investigation can be summarized as follows:

1. The geogrids improve and modify the pressure-settlement curve by increasing the strain at failure.
2. The allowable bearing capacity increased from 125 kPa for the case of no geogrid to more than 410 kPa for the case of 4 layers of geogrids.
3. For one layer of geogrid and a footing at the surface, the ultimate bearing capacity (q_u) and bearing capacity ratio (BCR) are highest when the depth of the geogrid-reinforcement is at 0.75B.
4. For one layer of geogrid and a footing at a depth of 0.25B below the surface, the ultimate bearing capacity (q_u) and bearing capacity ratio (BCR) are highest when the depth of the geogrid-reinforcement below the footing is at 0.5B.
5. For two layers of geogrids and a footing at the surface, the ultimate bearing capacity (q_u) and bearing capacity ratio (BCR) are highest when the depth of the reinforcement below the footing is at 0.25B and 0.75B.
6. For two layers of geogrids and footing at a depth of 0.25 m the surface, the ultimate bearing capacity (q_u) and bearing capacity ratio (BCR) are highest when the depth of the reinforcement below the footing is at 0.25B and 0.5B.
7. For three layer of geogrids, failure was not reached for both surface footing and the footing at depth of 0.25B. However, BCR is expected to be high (greater than 3).
8. The best improvements in q_u and BCR are for the case of four layers of geogrids.
9. Results obtained from the finite element analysis using the program MIDAS are generally in good agreement with those obtained from the laboratory model test.
10. The geogrids redistribute the applied load on larger area of the soil, thus, reducing the settlement.

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