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Experimental and Numerical Behavior of Shallow Foundations on Sand Reinforced with Geogrid and Grid Anchor Under Cyclic Loading

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Abstract. *There are many cases where the foundations of structures are subjected to cyclic loading in addition to static loading. Oil reservoir foundations with frequent discharges and filling or road embankments under repeatable traffic loads are examples of such foundations. Although the amplitudes of the cyclic load is usually less than the permissible static load, the concern still exists for the amount of uniform and non uniform settlement of such structures. The soil under such foundations may be reinforced with geosynthetics to improve their engineering properties. This paper deals with the effects of using the new generation of reinforcements, grid-anchor, for the purpose of reducing the permanent settlement of these foundations under the influence of different proportions of the ultimate load. Other items, such as the type and number of reinforcements, as well as the number of loading cycles, are studied experimentally. In all cases, the foundation is first under the influence of a fixed static load equal to the weight of the structure itself and, then, the cyclic load in different proportions of the ultimate load is applied to it. The results show that by using grid-anchor and increasing the number of their layers in the same proportion as that of the cyclic load applied, the amounts of permanent settlements are reduced and the numbers of loading cycles to reach it are decreased. For comparison with the experimental findings, similar to the conditions of the tests conducted, numerical models were made using a 3-D finite element software. The numerical results showed good agreement with the test results.*

Keywords: *Reinforced soil; Shallow footing; Cyclic loading; Grid-anchor; Geogrid.*

INTRODUCTION

More than 40 years have elapsed since reinforcements were used for the first time to improve the mechanical properties of soils. Since then, the type and quality of reinforcements have been changed dramatically and the use of polymeric reinforcements, such as geotextiles [1], geogrids [2], geocells [3,4] and tire shreds [5], has been increasingly expanding.

Up to now, many experimental and numerical studies have been made to determine the loading capacity of shallow foundations on different soils reinforced by different elements, such as metal strips, metal rods and geosynthetics. Figure 1 shows the classical scheme of a system of reinforced soil for a square foundation with $B \times B$ dimensions and N reinforcement layers. The dimensions of reinforcements are $b \times b$ and the distance between their first layer and the foundation bottom is denoted by u. The depth of the reinforcement area can be found using the following

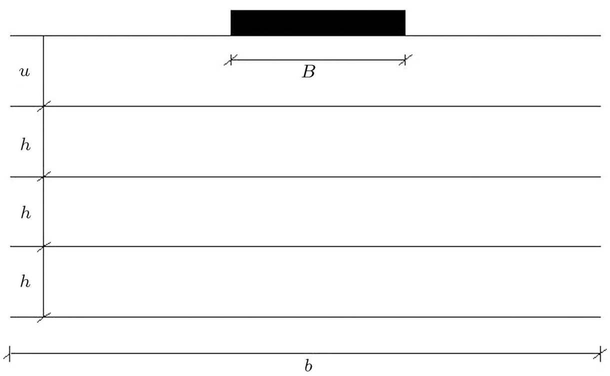

Figure 1. Shallow square foundation supported by geogrid-reinforced sand.

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equation:

$$d = u + (N - 1)h. \quad (1)$$

Previous studies have given different optimal values for the ratios u/B, b/B and h/B for optimizing the bearing capacity of shallow foundations. Binquet and Lee [6] and Guido et al. [7] showed that the ratio, u/B, for the most suitable state possible under the influence of using reinforcement must be chosen as less than 0.67. Also, they provided the values of $(b/B)cr$ and $(d/B)cr$ for a square foundation on sandy soil reinforced by the geogrid as follows:

$$(b/B)cr = 2 \text{ to } 3, \qquad (d/B)cr = 1.25.$$

Yetimoglu et al. [8] found that the critical value of u/B, h/B and b/B were equal to 0.25, 0.2 and 4.5, respectively. Adams and Collin [9] also conducted a comprehensive study on geogrid and geocell reinforced foundations on 34 large-scale models. The bearing capacity ratio ($BCR = qr/qur$), which is defined as the ratio of the bearing capacity of the reinforced soil (qr) to that of the unreinforced soil (qur), was reported to be 2.63 for the geogrid reinforced foundations, while BCR equals 1.27 for the geocell-reinforced foundations. Das and Shin [10] investigated the behavior of strip footing on geogrid reinforced sand. They found that full depth geogrid reinforcement may reduce the permanent settlement of a foundation by about 20% to 30% compared to one without reinforcement. Unnikrishnan et al. [11] conducted laboratory triaxial tests to investigate the behavior of reinforced clay under monotonic and cyclic loading. They found that due to the provision of sand layers on either side of the reinforcement (sandwich technique) within reinforced clay soils, the response of the reinforced clay soil by way of an enhanced interfacial bond was improved. Boushehrian and Hataf [12] studied experimentally and numerically the effect of depth to the first layer of reinforcement (u), the spacing between reinforcements (z) and reinforcement stiffness (EA) on the bearing capacity of circular and ring foundations on sand.

Chang and Cascante [13] have shown that a critical zone between $0.3B$ and $0.5B$ is identified for maximizing the benefits of soil reinforcement [13]. They found that if the reinforcements are placed within one footing width (B) below the foundation, BCR and the low strain stiffness of the reinforced system are increased by transferring the foundation load to deeper soil layers and, thus, reducing the stresses and strains underneath the foundation. Mosallanezhad et al. [14] deal with the influence of a new generation of reinforcement (named by them Grid-Anchor) on an increase in the bearing capacity of a square foundation. This new reinforcement layer can be put in place and covered with a compacted soil layer. Therefore, in the laboratory or in practice, each layers of grid-anchor can be assembled beforehand in a specific dimension (not in roll shape) and then put in place. Therefore, there is no difference between the placing time of this system of reinforcing and an ordinary geogrid, while the production cost of this type is only about 20% more than a conventional geogrid. They found that the critical values of u/B, h/B and b/B were equal to 0.25, 0.25 and 4.5, respectively. They also showed that the BCR for this system was greater than an ordinary geogrid and equal to 3.0. Table 1 shows the result of their research. Shin et al. [15] showed that for the same maximum depth of reinforcement under a cyclic loading test, the shear modulus increases with the number of layers in depth.

As revealed by previous studies, little research has been performed to obtain the cyclic behavior of shallow footings on reinforced soils. Most studies have been done on reinforced soil under static loads. Although a number of theoretical approaches have been presented by researchers, there are few cyclic loading experiments on reinforced soils.

In this study, the effect of various factors, such as the amplitude of the cyclic load applied, type and number of reinforcements on the amount of permanent settlement of square foundations and the number of cycles required to achieve such an amount of settlement, was examined experimentally.

EXPERIMENTAL MODEL

A steel foundation with a dimension of 200×200 mm and a thickness of 25 mm in a metal box with dimensions of $1.0 \times 1.0 \times 1.0$ m and a well graded sand (SW) with the grading as shown in Figure 2 was used.

All tests were conducted on sand with a relative density of 70$\pm$ 5 percent. Reinforcement of the soil was undertaken in two states: once using common geogrids and then using the grid-anchor system.

The grid-anchor is a 3-dimensional reinforcement system that is made adding anchors at an angle of 45° with a plastic belt material ending at two polymer cubes with dimensions of $10 \times 10 \times 10$ mm (Figure 3), to an ordinary geogrid sheet according to the pattern shown in Figure 4. The system was used for the first time by Mosallanezhad et al. [14]. The characteristics

Table 1. Summary of experimental results [14].

Characteristic	Value
h/B	0.25
u/B	0.25
b/B	5.0
c/B	4.0
N	4

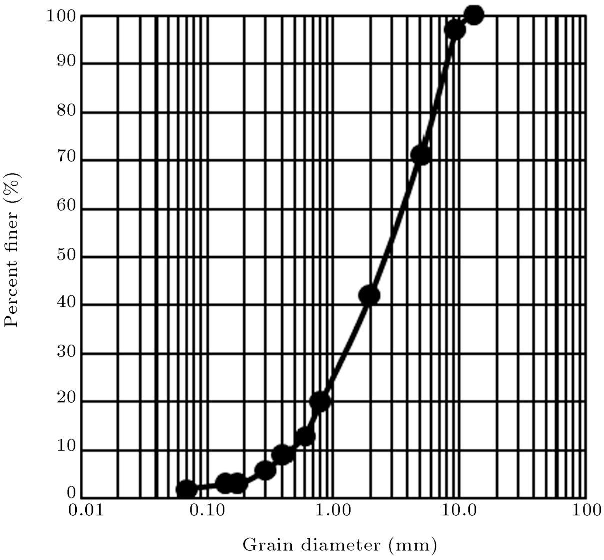

Figure 2. Grain-size distribution curve for sand.

Figure 3. Grid-anchor layout.

of the materials used in this study are shown in Tables 2, 3 and 4.

The bottom of the foundation was chosen appropriately rough using a thin sandpaper sheet glued to it using aquarium glue. The sand was poured in 70 mm layers into the box by the raining technique and after the surface of each layer was leveled, the sand was compacted by tempering with a smooth wooden board dropped from 300 mm height, 20 times. To make sure of achieving the concentration degree in question, a small metal vessel with a given volume was placed randomly in different layers. The geogrids and grid-anchors were placed based on the values obtained from the studies of Mosallanezhad et al. [14] on the same soil with fully similar characteristics. For all tests conducted, the values of $u/B = (h/B)cr$, $(b/B)cr$ and $(d/B)cr$ were taken as 0.25, 5.0 and 1.25, respectively.

The load application system is in the form of a hydraulic jack, as shown in Figure 5, with the possibility of applying a controlled pressure stepwise up to 95 kN. The details of the loading system that consists of a jack and its hydraulic unit are shown in Figure 6.

The amount of settlement due to load application was measured using gauges with an accuracy of 0.01 mm, connected to the box body using a magnetic base. The amount of settlement due to load application was measured using gauges with an accuracy of 0.01 mm connected to the box body using a magnetic base.

TEST PROCEDURE

The procedure of the tests was as follows: In the first step, the initial fixed load, in the form of a metal cylinder (with a weight of 125 N) with a load per

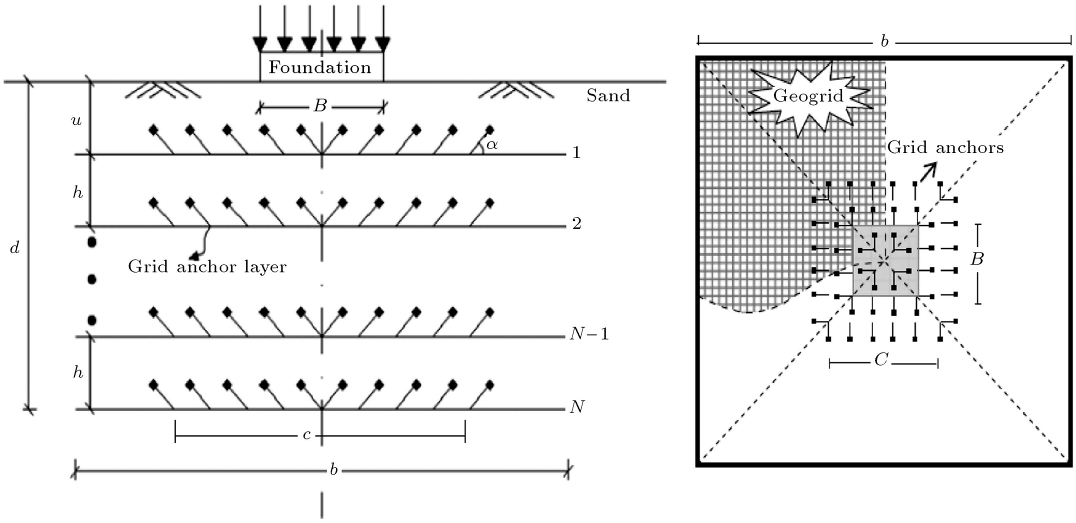

Figure 4. Arrangement of anchor elements on ordinary geogrid [14].

Table 2. Soil parameters.

Parameter	Value
Friction angle (degree)	43.0
Cohesion (kPa)	0.0
Maximum dry unit weight (kN/m^3)	18.8
Minimum dry weigh (kN/m^3)	13.9
Coefficient of uniformity (C_u)	7.8
Coefficient of curvature (C_c)	1.8
D_{60} (mm)	3.5
D_{30} (mm)	1.5
Effective grain size (mm)	0.35

Table 3. Properties of reinforcement.

Parameter	Value
Elastic axial stiffness (kN/m)	7.80
Axial stiffness of anchors (kN)	0.18
Geogrid opening size (mm)	27*27
Length of anchors (mm)	50.00

Table 4. Properties of model foundation.

Parameter	Value
Thickness (mm)	25.0
Width and length (mm)	200.0

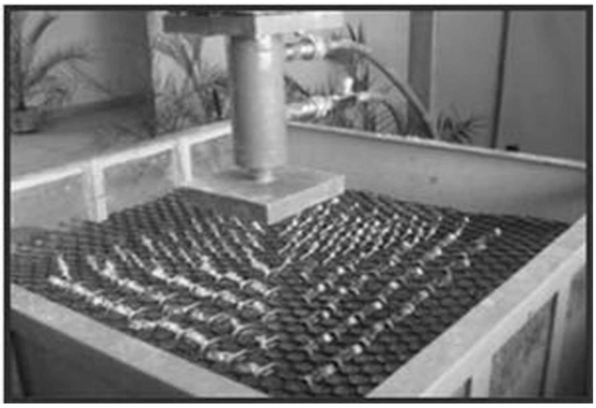

Figure 5. Test box and hydraulic jack.

area unit of 4 kN/m^2 that represents the weight of the structure and its accessories, was applied to the foundation (qs). In the second step, the cyclic load, in the form of a percentage of the ultimate load on the unreinforced condition, was added to the previous fixed load (qd). The two-above mentioned steps were repeated for both reinforcement types with a different number of layers. Table 5 shows the details of tests conducted in the laboratory. The selected percentages are 6, 20 and 33 percent (with respect to allowable bearing capacity), respectively.

NUMERICAL MODELING

For comparison with the experimental findings, similar to the conditions of the tests conducted, numerical

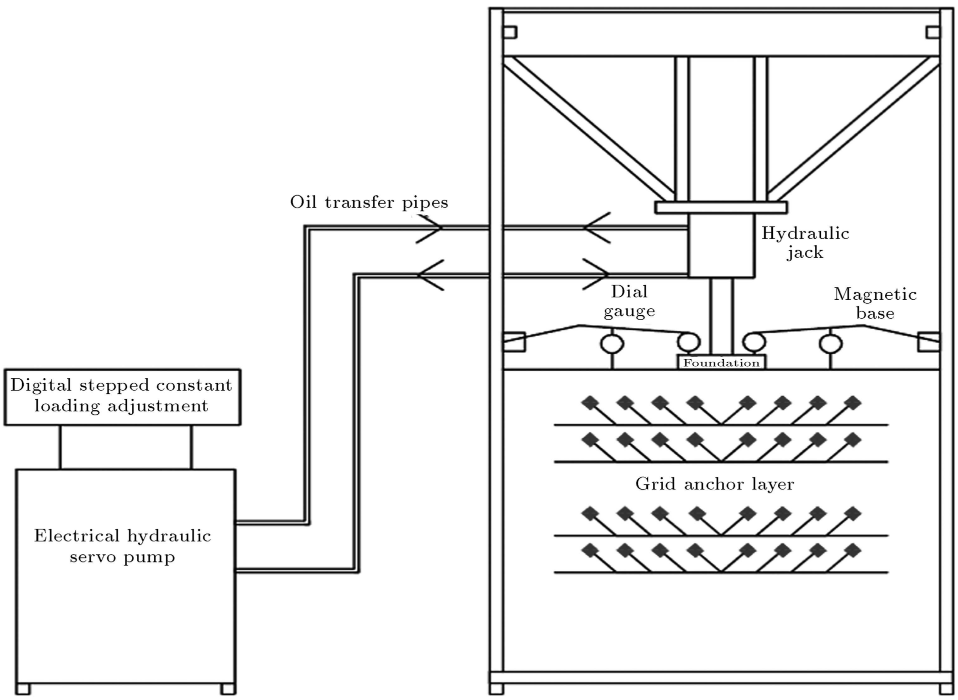

Figure 6. Schematic of laboratory test setup, loading and reaction system.

Table 5. Details of experiments in the laboratory.

Test Series	Reinforcement Condition	Percent of Applied Load (q_d/q_{ur})	N
A-1 to A-3	Unreinforced	6,20,33	-
B-1 to B-3	Reinforced with geogrid	6,20,33	1
B-4 to B-6	Reinforced with geogrid	6,20,33	2
B-7 to B-9	Reinforced with geogrid	6,20,33	3
B-10 to B-12	Reinforced with geogrid	6,20,33	4
C-1 to C-3	Reinforced with G-A	6,20,33	1
C-4 to C-6	Reinforced with G-A	6,20,33	2
C-7 to C-9	Reinforced with G-A	6,20,33	3
C-10 to C-12	Reinforced with G-A	6,20,33	4

models were made using the PLAXIS 3-D TUNNEL finite element software. The software can model and analyze most geotechnical problems in 3-D form. Among other features of the software, one can mention the modeling of the geogrid sheets and anchors connected to them in the grid-anchor system by assigning them axial stiffness. Figure 7 shows one of the models made using this software.

Another feature of the software is its ability to simulate the testing process, such as the application of two groups of load, one in static form (load system A) and the other in cyclic form (load system B) with amplitudes equal to selected percentages of the ultimate bearing capacity of an unreinforced condition. The number of load cycles is specified by staged construction modeling. The hypotheses used in the numerical modeling are given in Table 6. A hardening soil model was chosen based on two different models, which provide a reasonable prediction by the

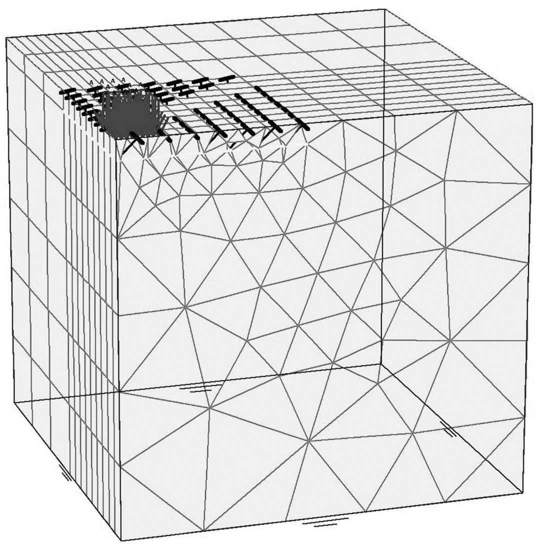

Figure 7. 3-D modeling created with PLAXIS 3-D TUNNEL.

Table 6. Material set and parameters used in the numerical modeling.

Characteristic	Value
Material model	Hardening soil model
Material type	Drained
E_{50}^{ref}	10e3 (kN/m^2)
E_{ur}^{ref}	30e3 (kN/m^2)
$E_{\text{ode}}^{\text{ref}}$	7000 (kN/m^2)
ν_{ur}	0.2
Power	0.5

E_{50}^{ref}: Reference secant stiffness modulus for mobilization of 50% of the maximum shear strength.

$E_{\text{ur}}^{\text{ref}}$: Unloading-reloading modulus of elasticity.

$E_{\text{ode}}^{\text{ref}}$: Odeometric modulus of elasticity.

code, namely the Mohr-Coulomb (elastic-ideal plastic model) and hardening soil model. The parameters in the hardening soil model were obtained from several attempts to match the laboratory data to the computer model. There are many phases in the analysis which are as follows:

Phase 0: The initial stress field through which the initial stresses, due to soil self weight, are computed;

Phase 1: Activation of grid-anchors and a load application up to a certain level (e.g., 20% ultimate load);

Phase 2: Unloading;

Phase 3: Loading up to a certain level;

Phase 4: Unloading.

The analyses phases were continued to reach a reasonably constant settlement at the final stage of loading and unloading. Therefore, the number of phases was a bit different for different analyses under different loading conditions, number of reinforcement layers and other parameters. Standard fixities, i.e. a horizontal fixity for vertical boundaries and a total fixity for the bottom boundary of the model, were chosen as the boundary conditions for the analyses. To model the reinforcements, the standard geogrid elements of PLAXIS were used, which are elastic elements, and the elastic axial stiffness of geogrids per unit length was chosen in accordance with the manufacturer's manual of the product.

To evaluate these hypotheses and to determine parameters, a laboratory small scale load test was performed over the desirable material and the test was modeled simultaneously with the program. After that, the results were calibrated in such a way that actual hardening soil model parameters were obtained.

TEST RESULTS AND DISCUSSION

Unreinforced Sand (Series A)

The bearing capacity of foundations on unreinforced soil was calculated by the tangent method depicted in Figure 8. By this method, the bearing capacity is determined at the intersecting point of two tangent lines that pass through the beginning and end of the load-settlement curve (Figure 8).

The bearing capacity was found to be 220 kPa by this method. In test results, the final settlement due to the cyclic load, is denoted by $(S_d)_f$. This is the permanent settlement, due to the sum of fixed and cyclic loads. Figure 9 provides variations of (S_d/B) with the number of cycles for Series A (Unreinforced soil) tests in different load percentages.

Soil Reinforced by Grid-Anchor and Geogrid (Series B and Series C):

Figures 10 through 13 show the variations of the dimensionless settlement with the number of load cycles for soils reinforced by common geogrids with different numbers of layers, and Figures 14 through 17 show the same for grid-anchors with up to 4 reinforcement layers.

Figure 18 illustrates that by using the grid-anchor system to reach a constant value of the amount

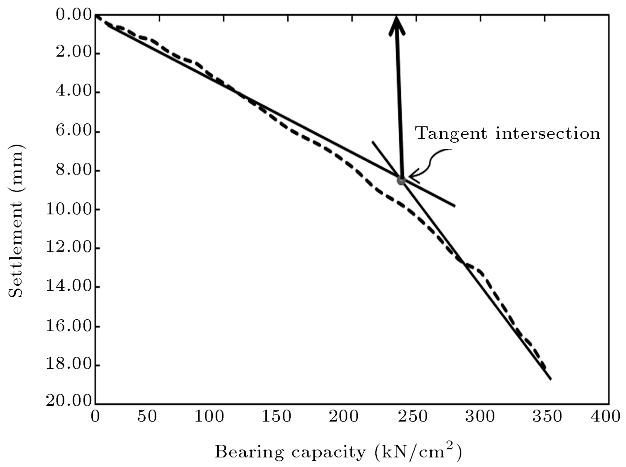

Figure 8. Load settlement curve for unreinforced soil.

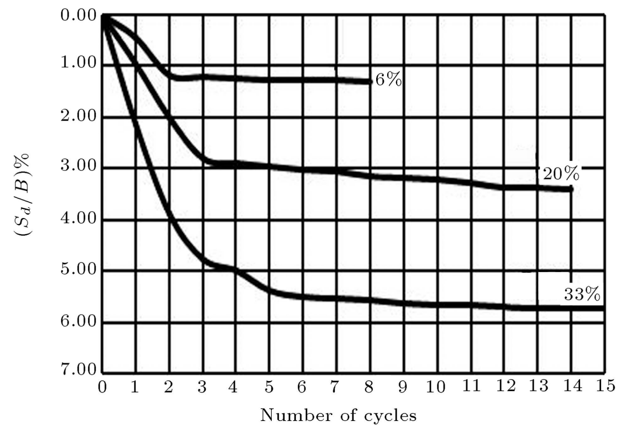

Figure 9. Variations of (S_d/B) with the number of load cycles for Series A tests.

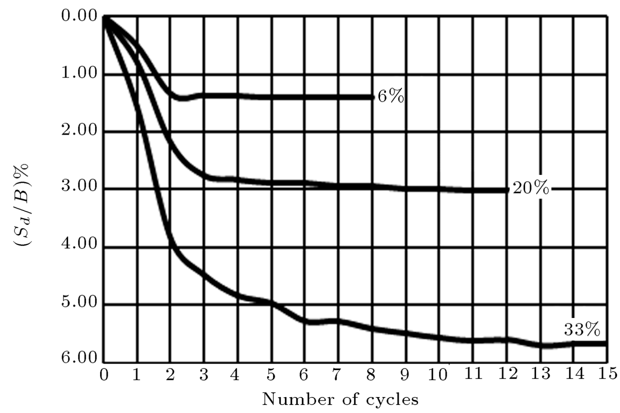

Figure 10. Variations of (S_d/B) with the number of load cycles for Series B1-B3 tests.

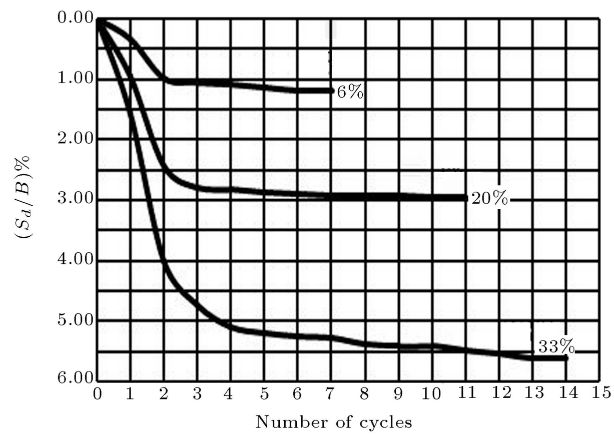

Figure 11. Variations of (S_d/B) with the number of load cycles for Series B4-B6 tests.

of dimensionless settlement, it decreases up to 17% relative to ordinary reinforcements and up to 50% relative to an unreinforced condition depending on the number of reinforcement layers and the percent of applied load. Also by using the grid-anchor system, the number of loading cycles to reach a constant value of dimensionless settlement decreases up to 33% relative to ordinary reinforcements and up to 57% relative to an unreinforced condition depending on the number of reinforcement layers and the percent of applied load

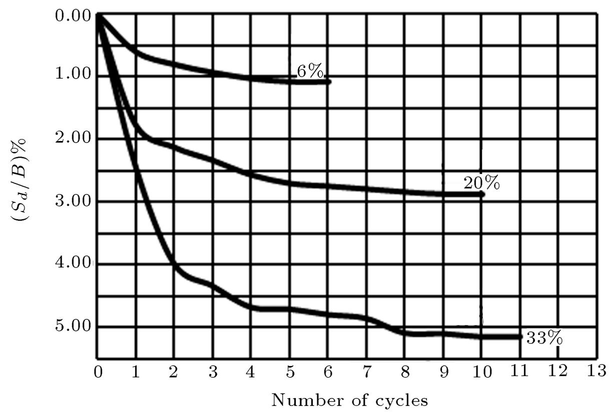

Figure 12. Variations of (S_d/B) with the number of load cycles for Series B7-B9 tests.

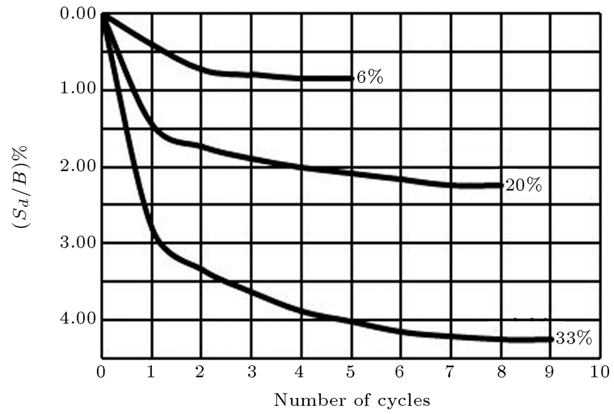

Figure 13. Variations of (S_d/B) with the number of load cycles for Series B10-B12 tests.

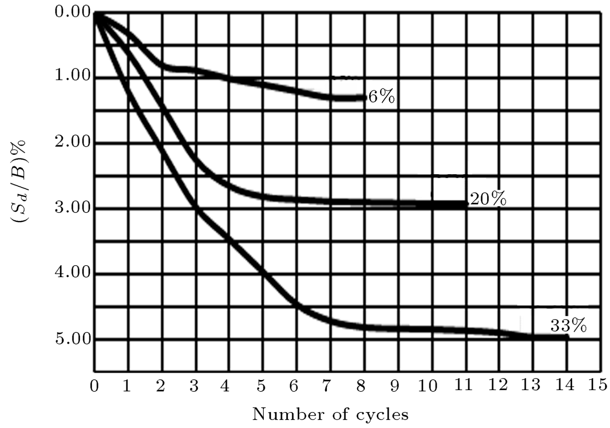

Figure 14. Variations of (S_d/B) with the number of load cycles for Series C1-C3 tests.

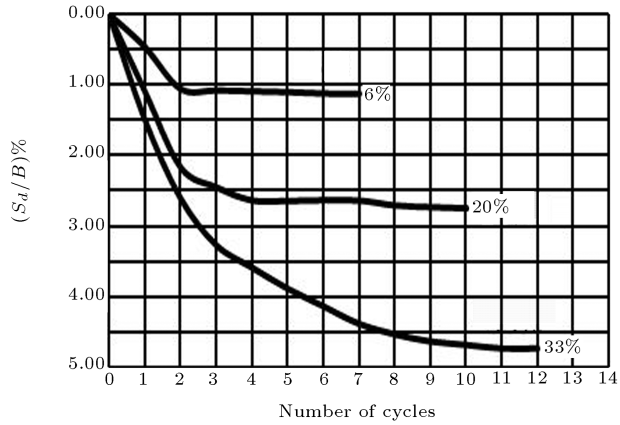

Figure 15. Variations of (S_d/B) with the number of load cycles for Series C4-C6 tests.

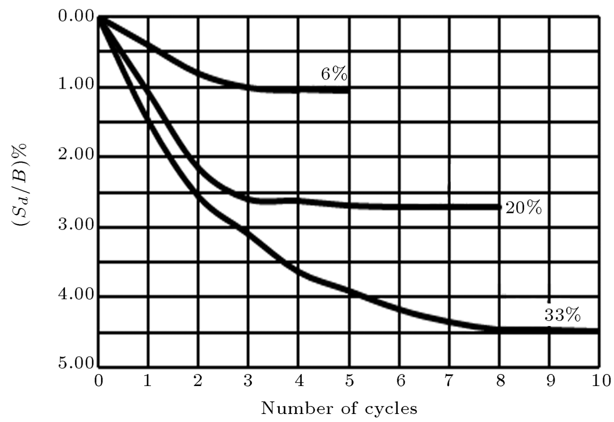

Figure 16. Variations of (S_d/B) with the number of load cycles for Series C7-C9 tests.

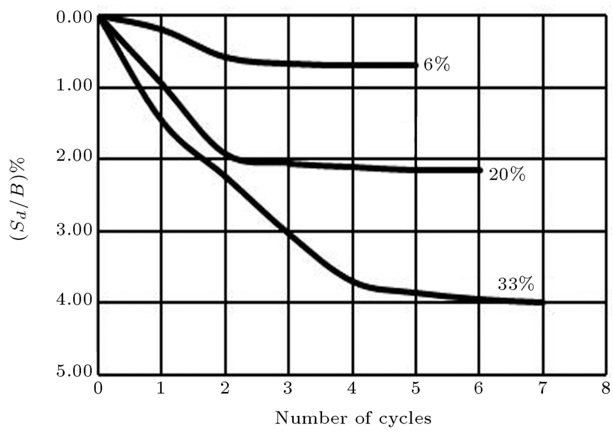

Figure 17. Variations of (S_d/B) with the number of load cycles for Series C10-C12 tests.

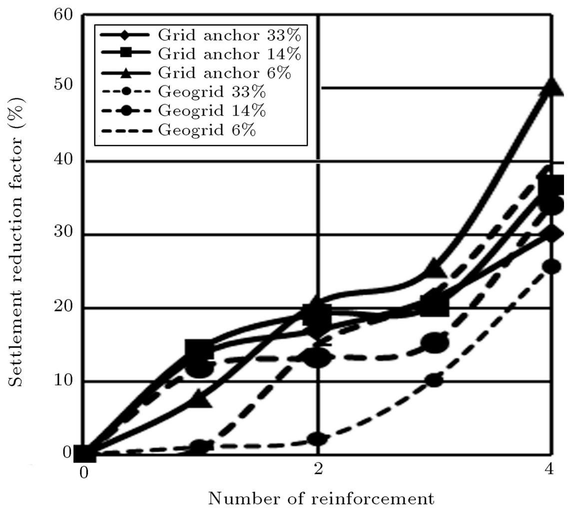

Figure 18. Variations of settlement reduction factor (experimental result) with the number of reinforcement layers.

(Figures 9 and 17).

A careful examination of the figures reveals that more than 50% of settlement occurs in the initial cycles of loading. By increasing loading cycles due to the soil beneath the foundation getting more compact and, consequently, more engagement of soil grains with the reinforcements, the settlement is reduced. An increase in loading cycles more than by a given number, denoted by n_{cr}, will have no effect on reducing the settlement.

Figures 19 and 20 indicate a variation of number of load cycles with a number of reinforcement layers for common reinforcements and the grid-anchor system, respectively. Comparing the findings provided in these figures, one can conclude the higher ability of the grid-anchor system in reducing the settlement. This effect is more noticeable for higher values of cyclic load. The reason is more engagement of this 3-D system with the soil and their further involvement against a pull-out of reinforcement layers.

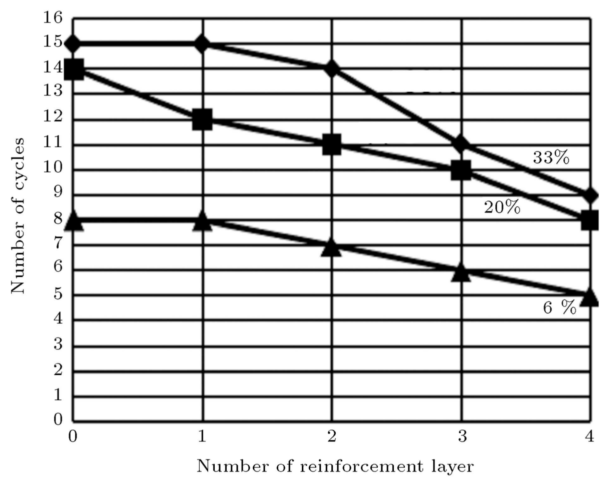

Figure 19. Variations of the number of load cycles with the number of reinforcement layers (geogrid).

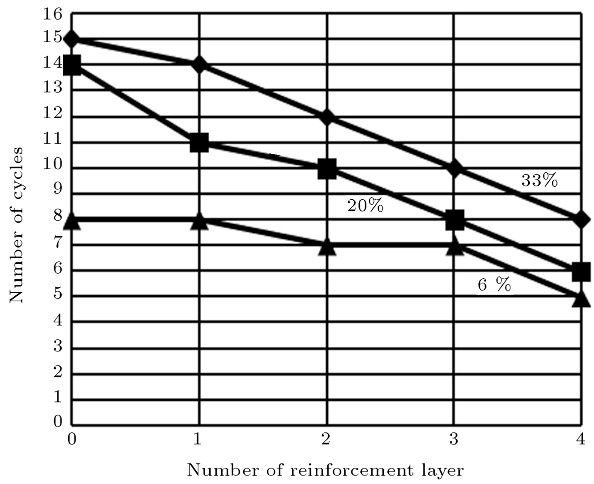

Figure 20. Variations of the number of load cycles with the number of reinforcement layers (grid-anchor).

The optimal number is found from Mosallanezhad et al. [14]. Tests were limited to 4 layers. They found that if more than 4 reinforcement layers were used, no improvement in the BCR ratio would follow.

As revealed by the figures, by increasing the number of reinforcements, due to the soil stiffness getting higher, the number of loading cycles needed to achieve a constant permanent settlement is reduced.

Figures 21 and 22 show the load variations with the final permanent settlement ratio for cases of geogrid and grid-anchor reinforcement. A careful examination of the figures reveals the fact that the slope of the deformation load diagram in the case of using reinforcement layers will increase up to an effective depth (1.25 times the foundation width) [14]. This increase

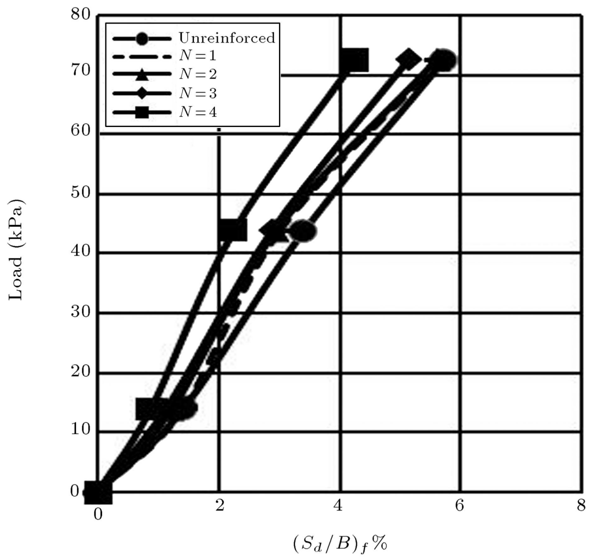

Figure 21. Variations of load with the final permanent settlement ratio (geogrid).

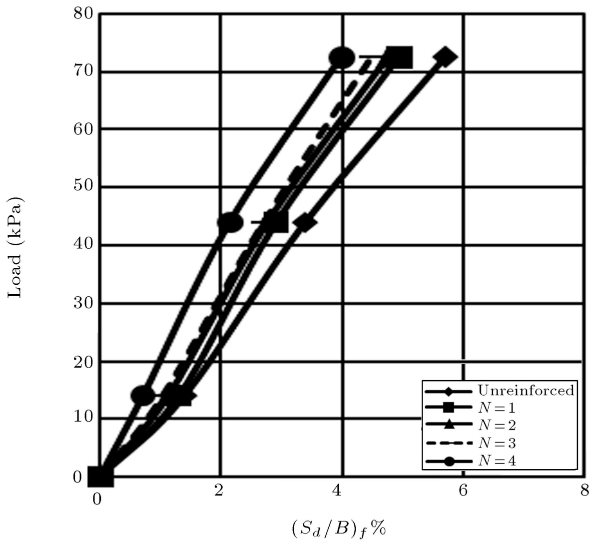

Figure 22. Variations of load with the final permanent settlement ratio (grid-anchor).

would be higher in cycles with more amplitude due to the mobilization of more tensile force in the anchors (Figures 21 and 22).

Figure 23 shows the variation of load with a final permanent settlement ratio for grid-anchor reinforced soil based on test results and numerical analysis. As illustrated in the figures, the value of (S_d/B) remains constant after a given number of loading cycles.

Soil Reinforced by Grid-Anchor and Geogrid (Series B and C)

Figure 24 shows variations in the settlement ratio with the number of load cycles based on test results and numerical analysis. Figures 25 and 26 show variations

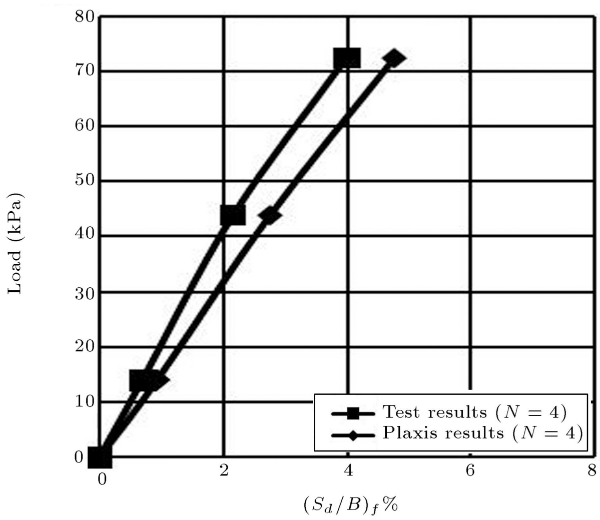

Figure 23. Variations of load with the final permanent settlement ratio (grid-anchor), experimental and numerical results.

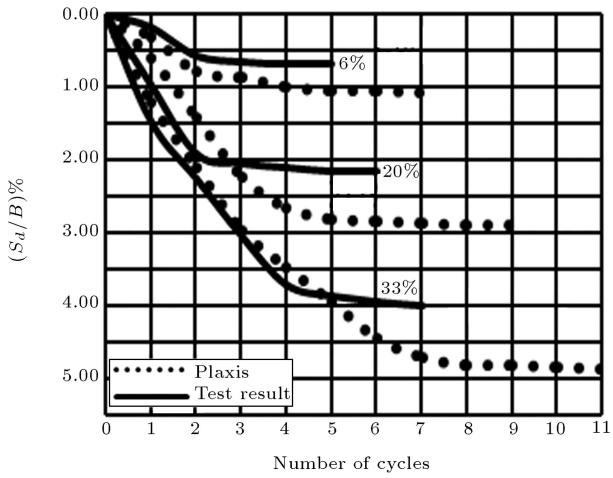

Figure 24. Variations of (S_d/B) with the number of load cycles for Series C10-C12, experimental and numerical.

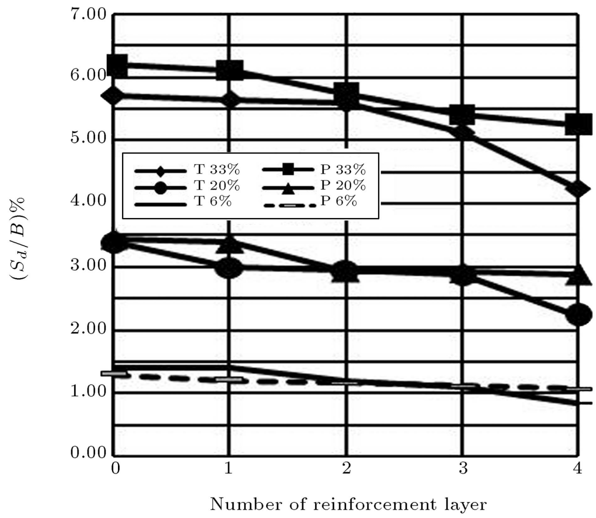

Figure 25. Variations of (S_d/B) with the number of reinforcement layers (geogrid), experimental and numerical results.

in the settlement ratio with the number of geogrid reinforcement and grid-anchor layers, respectively, based on test results and numerical analysis. Test results show a good agreement with the numerical results.

CONCLUSIONS

According to the test results and numerical analysis, one can mention the following:

1. For a given initial fixed load, the dimensionless settlement of the foundation increases with the cyclic load amplitude.
2. For a given initial fixed load, the number of loading cycles needed to reach a constant value of dimensionless settlement decreases with an increase in the number of reinforcement layers.

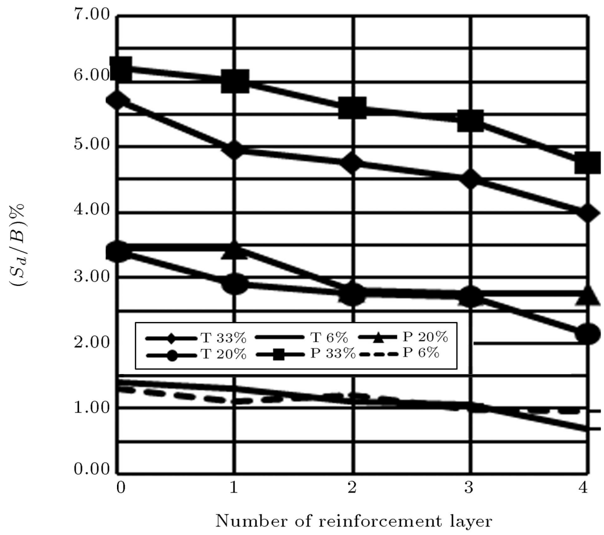

Figure 26. Variation of (S_d/B) with number of reinforcement layers (grid-anchor), experimental and numerical results.

3. By using the grid-anchor system, the amount of dimensionless settlement needed to reach its constant value decreases up to 17% relative to ordinary reinforcements and up to 50% relative to an unreinforced condition, depending on the number of reinforcement layers and the percent of applied load.

4. Also, by using the grid-anchor system, the number of loading cycles to reach a constant value of dimensionless settlement decreases up to 33% relative to ordinary reinforcements and up to 57% relative to an unreinforced condition depending on the number of reinforcement layers and the percent of applied load.

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