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Experimental and Numerical Studies of Square Footing on Weak Clay Stabilized with Geosynthetics-Reinforced Granular Replacement

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ABSTRACT

This paper presents experimentally and numerically the bearing capacity and settlement characteristics of shallow footings rested on geogrid reinforced crushed limestone over weak clay soil. The effects of thickness of the crushed limestone, the depth and types of geogrid on bearing capacity and settlement characteristics of reinforced soil foundation (RSF) are investigated in laboratory, whereas numerical simulations are used to study the reinforcement-foundation interaction. Test results indicate that the footing performance could be appreciably improved by the inclusion of layer of geogrid leading to an economic design of the footing. However, the efficiency of RSF system is dependent on reinforcement parameters. A close agreement between the experimental and numerical trend lines is observed. Based on the numerical and experimental results, critical values of geogrid parameters for maximum reinforcing effect are established.

***Keywords**:* Geogrid, crushed limestone, finite element analysis, reinforcement, bearing capacity ratio

1. INTRODUCTION

In many cases of construction in city centers which have shortages of availability of proper construction sites, shallow foundations are built on top of existing cohesive soils of low to medium plasticity, which is leading to in low bearing capacity and/or excessive settlement problems. To the effective solution, construction on soft soils often requires utilization of reinforced soil foundation (RSF). This can be done by either reinforcing cohesive soil directly [1-2] or replacing weak soils with stronger granular fill, in combination with geosynthetics. The resulting composite zone (reinforced soil mass) will improve the bearing capacity of the footing and provide the better pressure distribution on top of the underlying the weak soils, so reducing the associated excessive settlements. Construction of geogrid reinforcement incorporated at the base of a layer of granular fill placed on a soft clay subgrade is commonly used for low-cost unpaved roads such as temporary site access roads, low embankments, and large stabilized areas such as car parks or working platforms for oil drilling [3-6]. Rowe and Soderman [3] investigated the potential effects of geotextile reinforcement upon the stability of embankments constructed on peat which is underlain by a soft clayey layer. The use of a geotextile in conjunction with lightweight fill appears to be the most satisfactory means of improving the performance of embankments on these very poor foundations. It was shown that reinforcement can significantly reduce the maximum lateral deformations, vertical deformation and foundation soil heave during embankment construction [4]. Fannin and Sigurdsson [5] investigated the stabilization of unpaved roads on soft ground with geosynthetics. It was shown that the combination of geosynthetic reinforcement and fill help to spread the concentrated vertical loads and to inhibit large deformations and local failures. Geosynthetics reinforcing unpaved roads on soft subgrade have been shown to reduce the necessary fill thickness by approximately 30% [6]. One of the applications is the use of RSF in the design of approach slab for highway engineering applications to minimize the resulting differential settlements [1]. Since the state of Louisiana is well-known for its weak original soil formations, the common result of excessive differential settlement of the concrete approach slab currently has created one of the major highway maintenance problems. To solve this problem, the Louisiana Quality Initiative (LQI) study recommended changing the design of approach slabs by increasing their rigidity. As a result, the slab and traffic loads will be carried by the two ends of the slab rather than distributed over the length of the slab. Accordingly, a footing will be needed at the far end of the approach slab, away from the bridge. To increase the soil's bearing capacity and minimize settlement due to concentration load, the soil underneath the footing needs to be replaced with crushed limestone, in combination with geogrid reinforcement. In comparison with other applications of geosynthetic-reinforced soil, for example, geosynthetic reinforced soil embankments, roads or retaining walls; relatively less emphasis has been placed on reinforced soil footings. There have been many studies of shallow foundations on reinforced soil systems, most of them concentrating on sandy soil [7-10]. However, results of a limited number of studies are available at the present time relating to the bearing capacity of shallow foundations on reinforced granular material of limited thickness overlaying weak clay [11-12]. This paper relates to some laboratory tests results which were conducted to determine the bearing capacity and settlement behavior of circular footing supported by a reinforced stiffer granular layer of limited thickness over weak clay. The behavior of a rigid circular footing on reinforced granular material underlain by weak soil has been also simulated by 2D numerical analysis based on the finite element method. In order to verify accuracy of the numerical analysis, the results of numerical analysis are compared with the results of laboratory tests.

2. LABORATORY MODEL TESTS

2.1. Model Box and Footing

The small-scale laboratory tests were conducted at the Geotechnical Engineering Research Laboratory (GERL) of the Louisiana Transportation Research Center (LTRC). The model tests were carried out inside a steel box with dimensions of 1.5m (length) × 0.91m (width) × 0.91m (height). The model footing used in the tests was 25.4mm thick steel plates with dimensions of 152mm × 152mm. The rough footing condition was achieved by cementing a thin layer of fine particles of limestone onto the base of the model footing. The test setup is shown in Figure 1.

Figure 1 Laboratory test setup

2.1. Material properties

2.1.2. Granular fill material

The granular fill material used in this investigation was Kentucky crushed limestone, which has a uniformity coefficient of 20.26 and a coefficient of curvature of 1.37. It was obtained from the sieve analysis that the crushed limestone had 100% passing 37.5 mm opening sieve, 81% passing 19 mm opening sieve, 47% passing No.4 opening sieve, and 4% passing No. 200 opening sieve with an effective particle size (D_{10}) of 0.465 mm and a mean particle size (D_{50}) of 5.662mm. The maximum dry density of the soil was 22.47kN/m^3, with an optimum moisture content of 6.6%, as determined by Standard Proctor test in accordance with ASTM D698. This crushed limestone was classified as GW according to the Unified Soil Classification System (USCS) and A-1-a according to the AASHTO classification system. Large scale (304.8mm×304.8mm×130.9mm) direct shear tests on this crushed limestone at its maximum dry density under three different normal stresses (25kPa, 50kPa, 75kPa) indicated an internal friction angle of 53[1].

2.1.3. Subgrade material

In many coastal areas of the United States, high quality embankment soils are not locally available and marginal cohesive soils are often encountered. The silty clay soil used in the present study was a marginal embankment soil with low to medium plasticity that is often encountered in embankments in Southern Louisiana. The physical properties of the silty clay are summarized in Table 1. The maximum dry density of soil is 16.70kN/m^3, with an optimum moisture content of 18.75%, as determined by the standart proctor test. The silty clay soil was classified as CL according to the USCS and A-6 according to the AASHTO classification system.

Table 1. Soil profile in test area

Property	**Value**
Liquid limit	31
Plastic index	15
Silt content	72%
Clay content	19%
Maksimum dry density#	16.70 kN/m^3
Optimum moisture content#	18.75%

#Standard Proctor test

2.1.4. Geogrid

Three different geogrids, GG1, GG2 and GG3, were used to reinforce the granular fill layer in the reinforced soil foundation (RSF). These geogrids have a punched structure and are made from polypropylene with different properties. The physical and mechanical properties of these geogrids, as provided by the manufacturers, are listed in Table 2.

Table 2. Properties of geogrids

Type	**Reinforcement**	**Polymer Type**	**T^a, kN/m**		**J^b, kN/m**		**E, kN/m^2**	**Aperture size, mm**
			MD^c	**CD^d**	**MD^c**	**CD^d**	**Average**	
GG1	BX4100 Geogrid	Polypropylene	4.0	5.5	200	275	190000	33x33
GG2	BX4200 Geogrid	Polypropylene	5.5	7.4	275	370	258000	33x33
GG3	BX1500 Geogrid	Polypropylene	8.5	10.0	340	500	370000	25x30.5

[a] Tensile strength (at 2% strain), [b] Tensile modulus (at 2% strain), [c] Machine direction, [d] Cross machine direction

2.3. Test Setup and Procedures

The experimental set-up has been used extensively for the bearing capacity of shallow foundations on reinforced clay soils. The schematic view of the test is shown in Figure 2, where, B is the foundation diameter, H is the thickness of the granular fill layer and N is the number of geogrids.

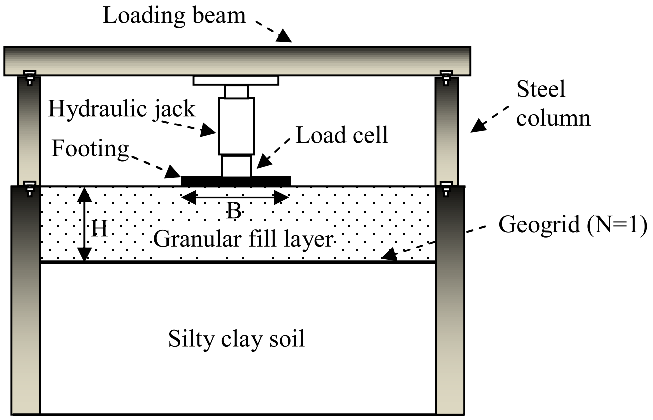


Figure 2 Schematic view of the test (unscaled)

In the tests, the silty clay soil was first placed and compacted in lifts inside the steel test box. The thickness of each lift was 152mm. The target dry density and water content of the subgrade were set to 16.0kN/m^3 and 23%, respectively to achieve a weak subgrade of about CBR=1% (estimated based on the DCP tests). The subgrade was prepared by using a tiller to mix the silty clay and water. Then, the silty clay was raked level and compacted using a

203mm×203mm plate adopted to a vibratory jack hammer to the predetermined height to achieve the desired density. After the completion of subgrade preparation, the pressure cells were installed in different depths to measure stress changing in the subgrade. In reinforced tests, the granular fill layer was similarly prepared by placing the crushed limestone mixing with the desired water and then predetermined height. The target dry density and water content of the granular fill layer were 22.10kN/m^3 (i.e. 98% degree of standard proctor compaction) and 6%, respectively. The geogrid layers including different properties were installed at the interface. After the soil preparation, steel loading beam was rested on steel columns. Then model foundation, hydraulic jack, a ring load cell and two dial gauges were placed. The testing procedure was performed according to the ASTM D 1196-93, where the load increments were applied and maintained until the rate of settlement was less than 0.03mm/min for three consecutive minutes. The load and the corresponding footing settlement were measured using ring load cell and two dial gauges, respectively. In the tests, granular fill layer with different thicknesses was located under the foundation. A total of 11 tests were performed in the experimental studies and the details of the tests are given in Table 3. In the reinforced tests, the thicknesses of the granular fill layer were changed as 0.50, 1.00 and 1.50, according to the footing size.

Table 3. Details of the laboratory test program

Test Series	Test Conditions	Number of Tests
I	Unreinforced	1
II	H/B=0.50, 1.00, 1.50 and 2.00	4
III	N=1; u/B=0.50; H/B=0.50, GG1	3
	N=1; u/B=1.00; H/B=1.00, GG1	
	N=1; u/B=1.50; H/B=1.50, GG1	
IV	N=1; u/B=0.50; H/B=0.50, GG1	3
	N=1; u/B=0.50; H/B=0.50, GG2	
	N=1; u/B=0.50; H/B=0.50, GG3	

3. INTERPRETATION OF TEST RESULTS

3.1. Series I: Natural Clay (Unreinforced)

These tests were conducted using square foundation with dimensions of 152mm × 152mm. The aims of carrying out these tests are to investigate the bearing capacity of clay soils with different foundation sizes and to create a reference for the oncoming tests with granular fills and geogrids.

3.2. Series II: The Effect of Granular Fill

Figure 3 shows the test results for square footing on the compacted granular fill layer of different thickness over the soft clay. It is shown that the granular fill layer helps increase the load bearing capacity of the footing and decreases the settlement allowable load since the granular fill layer is stiffer and stronger than the natural clay.

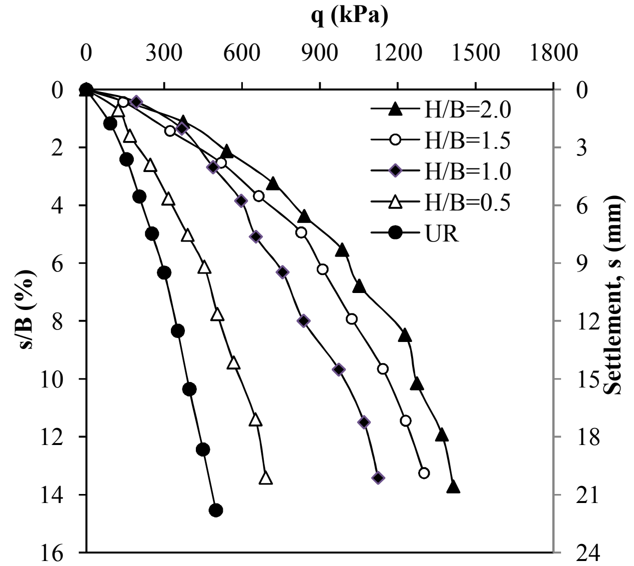
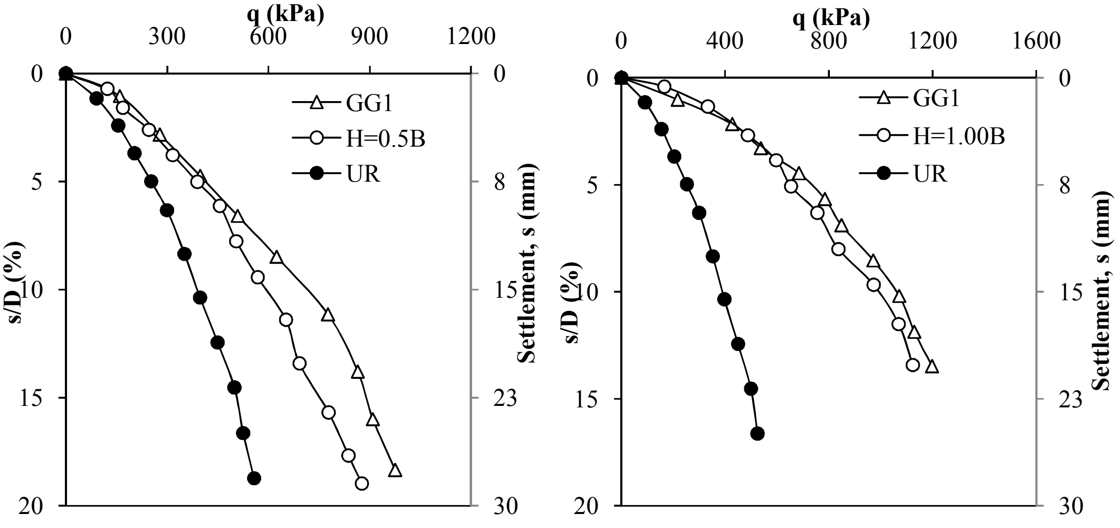


Figure 3 The Effect of granular fill in Series I and II

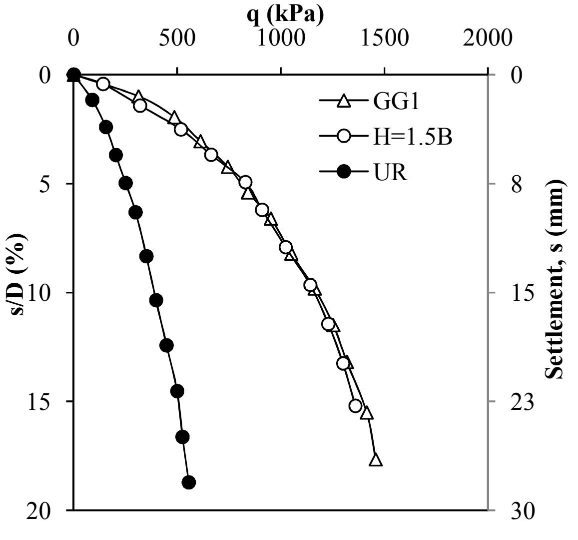
3.3. Series III: The Effect of Geogrid Reinforcement at Granular Fill-Soft Clay Interface

The tests in this series were conducted to determine the effect of geogrid reinforcement at the granular fill-soft clay interface on bearing capacity. In reinforced tests, the thickness of granular fill layer, H was changed as 0.50, 1.00 and 1.50B and GG1 geogrid was used at the interface of soft clay and the compacted granular fill. Figure 4 shows the load-settlement curves for all the tests performed in Series I and III, respectively. It is seen in Figure 4 that a single layer of reinforcement at the interface of soft clay and the compacted granular fill does not bring further improvement on BCR values, as granular fill thickness increases.



a) H=0.5B

b) H=1.0B



c) H=1.50B
Figure 4 The load-settlement curves in Series III

3.4. Series IV: The Effect of Geogrid Rigidity

The tests in this series were carried out to determine the effect of different geogrid rigidities at the granular fill-soft clay interface on bearing capacity. For this purpose, three different types of geogrid were used at the interface of soft clay and the compacted granular fill in the tests. In reinforced tests, the thickness of granular fill layer, H was kept constant as 0.50B. Figure 5 shows the load-settlement curves for all the tests performed in Series I and III, respectively. As shown in Figure 5 that RSF with GG3 geogrid reinforcement at the interface of soft clay and the compacted granular fill performed better than GG1 and GG2 geogrid reinforcement.

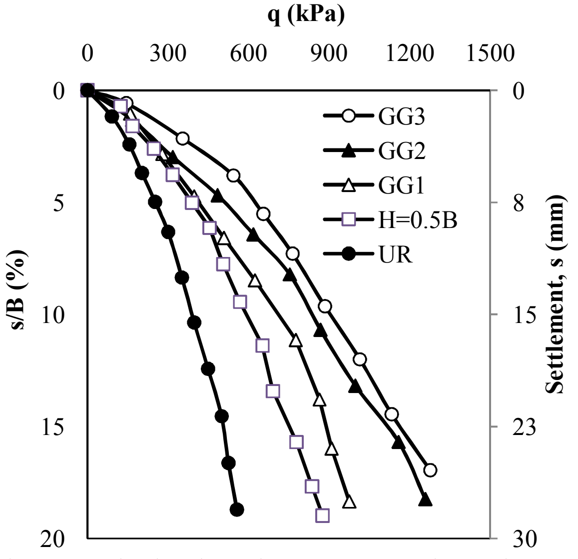


Figure 5 The load-settlement curves in Series III

4. FINITE ELEMENT ANAYSIS

The commercial FEM program ABAQUS was used in this study [13]. A two-dimensional axisymmetric model was adopted to simulate the square footing on reinforced crushed limestone over soft clay. The geomaterials were discretized using eight-node (CAX8R) isoparametric elements, while the reinforcement was modeled using two-node (MAX2) isoparametric membrane elements. The reinforcement-crushed limestone interaction was simulated by two fully bonded contact surface. The boundary dimensions for the finite element model were determined by conducting several analyses on different mesh sizes to select the dimension of the mesh in which the footing's bearing capacity is not affected by the boundary conditions. Sensitivity analysis was also conducted to find the degree of mesh refinement to minimize mesh-dependent effects and converge upon a unique solution. Finally it was adopted finite element model, which has the dimensions of 5B x 5B and includes 11,500 elements. Linear Drucker-Prager Model was used to define clay soil and granular fill behavior in this study. Model parameters used in the analysis for clay soil, granular fill and reinforcement are given in Table 4.

Table 4 Material and interface properties

Materials	**Model**	**Mechanical properties**	**Elastic Modulus, E**	**Poisson ratio, ν**
Silty clay	Linear Drucker-Prager	c=10kPa, ϕ =20°	7500kPa	0.35
Crushed limestone		ϕ =53°	12000kPa	0.35
Reinforcement	Linear Elastic	N/A	GG1, 190000kPa GG2, 258000kPa GG3, 370000kPa	0.30
Soil-reinforcement interface	Tied contact	N/A	N/A	N/A

5. COMPARISON BETWEEN TEST AND NUMERICAL RESULTS

In this study, laboratory tests and numerical analyses were carried out on granular fill beds with and without geogrid overlying soft clay soil. After the tests and analyses were completed, bearing capacity – displacement curves for various arrangements were obtained and discussed. The bearing capacity was defined as a pressure across a specific settlement which is s/D=%10 in relation to the foundation diameter. The term “bearing capacity ratio” (BCR) is commonly used to express and compare the test data of the reinforced and unreinforced soils. The following well-established definition [14] is used for BCR:

$$BCR= q_R / q_0 \qquad (1)$$

Where q_R and q_0 are the bearing capacity for the reinforced and unreinforced soils, respectively. The parameters investigated, including the settlement of foundation plate, s, are normalised by the diameter of the foundation plate, D.

5.1. Series I: Natural Clay (Unreinforced)

Typical plots for the load–settlement behavior obtained from the test and numerical analysis of the unreinforced natural clay soil case are shown in Figure 6. As seen from the figure that there is a similar tendency between test and numerical results.

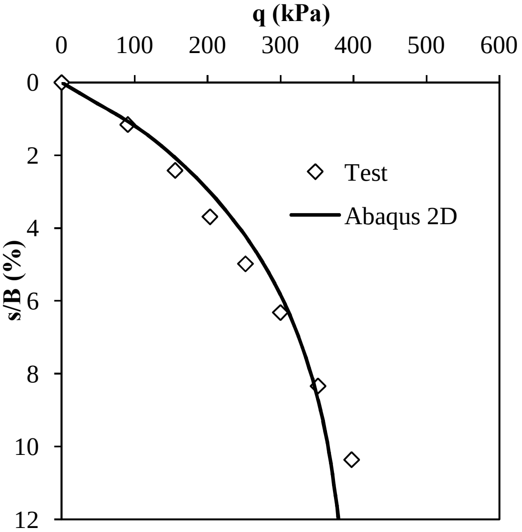
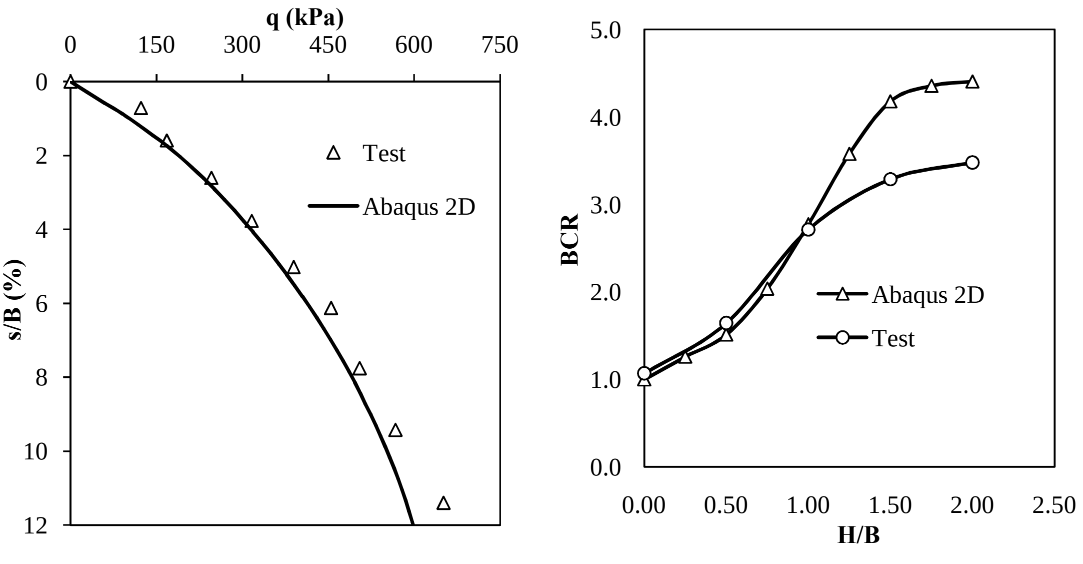


Figure 6. Comparison of the load-settlement curves obtained experimentally and numerically in Series I

5.2. Series II: The Effect of Granular Fill

Figure 7 (a) shows that typical plots for the load–settlement behavior obtained from the test and numerical analysis of compacted granular fill layer of different thickness over the soft clay. There is a similar tendency between test and numerical results. The test and FEM results were defined using bearing capacity ratios (BCR), as seen in Figure 7 (b). As seen from the figure, the BCR predicted in the analysis is agreed well with the test results for especially less than H/B=1.00.



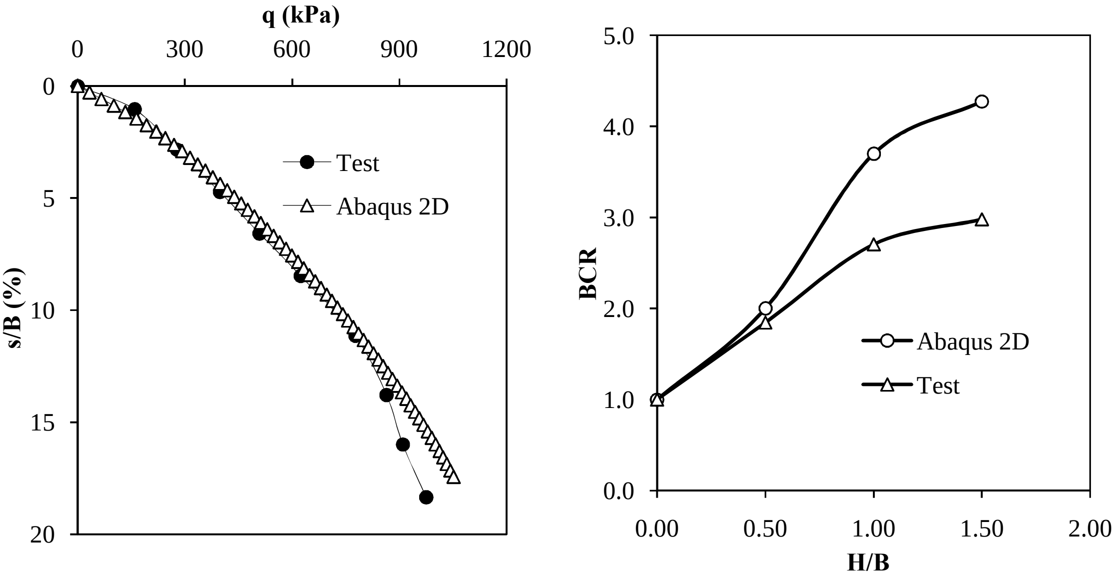
a) H=0.50B

b) BCR versus H/B

Figure 7. Comparison of the load-settlement curves and BCR obtained experimentally and numerically in Series II

5.3. Series III: The Effect of Geogrid Reinforcement at Granular Fill-Soft Clay Interface

The experimental and FEM analysis in this series were conducted to determine the effect of GG1 geogrid reinforcement at the granular fill-soft clay interface on bearing capacity. The thickness of granular fill layer, H was changed as 0.50, 1.00 and 1.50B. Figure 8 (a) shows a typical the load-settlement curves obtained from test and FEM analysis results. It is seen in Figure 8 (b) that GG1 reinforcement at the interface of soft clay and the compacted granular fill does not bring further improvement on BCR values, as granular fill thickness is higher than 1.0B. it is also seen that the BCR obtained from the FEM results give the higher results than the test results As seen from Figure 8, although the bearing capacity values obtained from numerical analyses do not fit completely with the experimental results and give greater bearing capacity, especially after H/B=1.00, but the agreement is reasonably well. This discrepancy may be related to the model and foundation parameters chosen in numerical and experimental model.



a) H=0.50B-GG1 b) BCR versus H/B

Figure 8. Comparison of the load-settlement curves and BCR obtained experimentally and numerically in Series III

5.4. Series IV: The Effect of Geogrid Rigidity

The analyses in this series were carried out to determine the effect of different geogrid rigidities at the granular fill-soft clay interface on bearing capacity. For this purpose, three different types of geogrids were used at the interface of at the interface of soft clay and the compacted granular fill in the tests. The thickness of granular fill layer, H was kept constant as 0.50B. Figure 9 shows BCR variations versus elastic modulus of geogrid, E_G in Series IV. The results of model tests and FE analyses show that the values of bearing capacity ratio, BCR increases almost linearly until the elastic modulus of geogrid (E_G) is 200000kPa. However, after the value of E_G is 200000kPa, the value of BCR increases decreasingly.

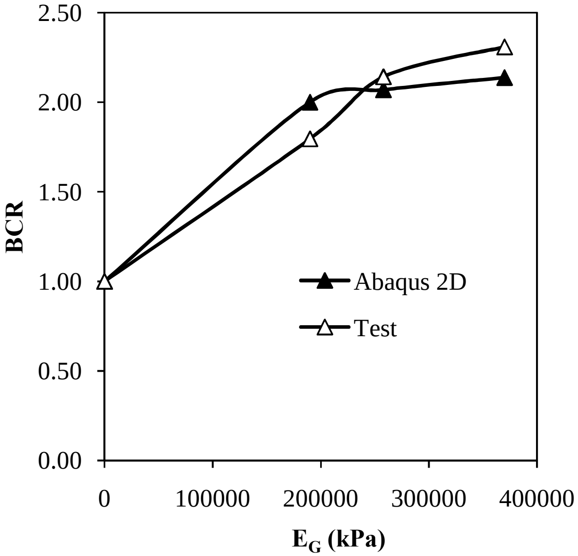


Figure 9. Comparison of BCR versus E_G for Series IV

4. CONCLUSIONS

The bearing capacity of shallow foundation on compacted granular fill layer underlain by soft clay with and without a layer of geogrid at the granular fill-clay interface was investigated using non-linear FEM program ABAQUS, and by physical model tests. Based on this investigation the following conclusions can be drawn:

- Finite element solutions gave results that closely match those from physical model tests.
- Clay soil deposit replaced partially by stiffer granular fill increases the bearing capacity. The increment is about %100 at H=0.50D. A single layer of geogrid reinforcement at the interface of soft clay and the compacted granular fill does not bring further improvement on BCR values, as granular fill thickness increases.
- The results of model tests and FE analyses show that the values of bearing capacity ratio, BCR increases almost linearly until the elastic modulus of geogrid (E_G) is 200000kPa. However, after the value of E_G is 200000kPa, the value of BCR increases decreasingly.
- This investigation is considered to have provided a useful basis for further research leading to an increased understanding of the application of soil reinforcement to bearing capacity problems.

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