EXPERIMENTAL TESTS ON STRIP FOOTINGS RESTING ON GEOSYNTHETIC REINFORCED REPLACEMENT SOIL OVERLYING LOOSE SAND*

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ABSTRACT

This paper presents the results of laboratory model tests to investigate the performance of shallow footings resting on geosynthetic reinforced replacement soil overlying loose sand. The model tests are conducted in a 1250 mm long, 400 mm wide, and 800 mm deep steel tank. A strip footing is simulated using a 30 mm thick, 100 mm wide, and 380 mm long steel plate. The purpose of the testing program is to determine the effect of the configuration of reinforced replacement soil on improvement in bearing capacity and settlement of the strip footing. The number of reinforcement layers (N = 1, 2, 3), length of reinforcement (L = 6B, 4B, 2B), and thickness of the replacement soil relative to footing width (d/B = 1.2, 1.5, 1.8) are varied. A punching shear failure mechanism is observed in the laboratory tests for unreinforced soil, which tends to fade as the number of reinforcement layers increase. Improvements in observed settlement occurred at settlements beyond 10% of the footing width. Increase in bearing capacity ratios due to increasing the number of reinforcement layers, length of reinforcement, and thickness of replacement soil is discussed.

1. INTRODUCTION

The use of shallow foundations may be limited in many conditions due to excessive settlement and /or bearing capacity concerns resulting from the underlying soil. A reinforced soil foundation may enhance the performance of shallow foundations to acceptable limits. This involves replacing the existing weak soil up to a shallow depth with a compacted granular soil with inclusions of geosynthetic reinforcement layers to improve the ultimate bearing capacity and decrease settlements.

Few experimental studies were performed to inves-tigate the bearing capacity of reinforced granular material underlain by soft clay [6,8,11,13, and 14]. Experimental study was performed using strip foundation resting on dense sand layer overlying soft clay reinforced with a layer of geogrid at the sand/clay interface [8]. They concluded that the optimum length of geogrid was 6B and the maximum benefit of the bearing capacity ratio was achieved by inclusion a layer at the sand/clay inter-face where the depth ratio (H/B) equal 0.67. The optimum width of the reinforcement was 5B for strip footing and 3B for rectangular footings [14]. The optimum number of layers was three which resulted in an increasing in bearing capacity by 45% and reduction in settlement by 15.7% [14].

Limited researches are available on the bearing capacity of reinforced layered sand [7, 9, and 10]. Experimental investigation was executed to study the bearing capacity of reinforced layered sand using strip footings with thickness of top dense layer varies from 0 to 2B [9]. The ultimate bearing capacity increased up to 4 times the unreinforced case by inclusions of reinforcement layers up to 4 and the bearing capacity at settlement level (s/B) of 2% increased up to 3 times of unreinforced case [9]. However, the effect of using reinforcement layer has a minimal effect on the bearing capacity ratio at lower settlement value due to mobilizing membrane effect.

The present study investigates the improvement of ultimate bearing capacity and settlement reduction for a strip footing resting on geosynthetic reinforced replacement soil overlying loose sand with varying the number of geogrid layer, geogrid length, and thickness of replacement soil.

2. TEST CONFIGURATION

2.1 Materials Properties

The tested soil used in this study is poorly gra-

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*Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy ded sand. Grain size distribution was established according to ASTM D6913 [2]. Firstly, the soil was passed through a sieve No.4 (4.75mm) to separate the coarse particles. The grain size distribution curve was illustrated in Fig. (1). The soil is classified as poorly graded sand (SP) according to the unified soil classification system [1]. Some of the index properties of the tested soil can be summarized in Table (1). The angle of shearing resistance was determined using consolidated-drained triaxial tests [3] on samples prepared at relative densities of 36% and 78%, representative of the relative densities used in the physical model. The measured soil properties are summarized in Table (1). A commercially available biaxial geogrid made from woven polyester yarns having the properties summarized in Table (2) is used for soil reinforcement.

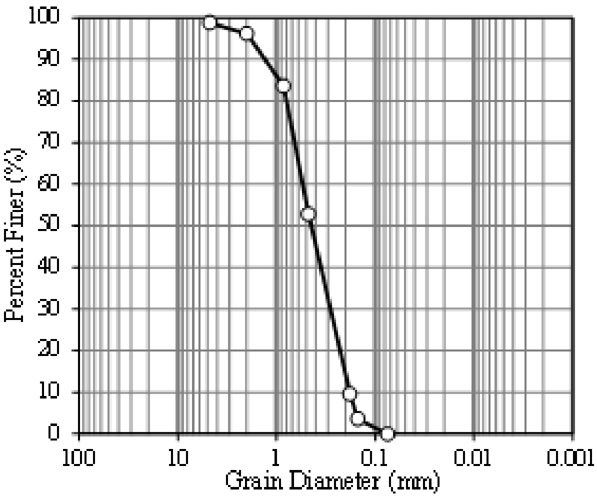


Fig. 1- Grain size distribution of used sand. Source: Researcher

Table 1- Properties of sand material.

Soil Property	Value
Maximum dry unit weight (kN/m^3)	18.30
Specific gravity	2.65
Maximum void ratio	0.87
Minimum void ratio	0.43
Shearing resistance of dense sand ϕ (deg.)	42
Modulus of dense sand at σ'_3=50kPa, E_{50} (kPa)	10000
Shearing resistance of loose sand ϕ (deg.)	31
Modulus of dense sand at σ'_3=50kPa, E_{50} (kPa)	2000

Table 2-Properties of geogrid material

Geogrid Property	Value
Ultimate tensile strength (kN/m)	15
Strain at ult. tensile strength (%)	18
Secant stiffness @strain 2% (kN/m)	160
Secant stiffness @strain 5% (kN/m)	105
Opening size (mm)	3.5

2.2 Test Device

The model tests are conducted in a 1250 mm long, 400 mm wide, and 800 mm deep steel tank (Figure 2). The tank is fabricated from 5 mm thick steel sheet. One side of the tank is fabricated from 10 mm thick acrylic sheet to allow for visual observation. The tank is braced with steel angles to avoid lateral deformation during loading. The model footing used in the tests is 30 mm thick steel plate with dimensions of 100 mm x 380 mm representing a rigid strip footing. A loading groove was carved at the centre of the model footing to ensure concentric loading and minimal rotation. The loading frame consists of 6.0 m long horizontal steel arm pivoted on a vertical steel beam. The loading arm is loaded at the far end, and applies a load on the model close to the pivot with an arm ratio of 10. Counter weights are loaded at the opposite end of the beam to balance the own weight of the arm.

Figure 2- Arrangement of the test device.Source: Researcher

2-3- Test Procedure

The tank was filled with loose sand to a certain depth representing a natural formation and then a reinforced dense sand layer representing replacement soil was placed to the target soil surface. The loose sand representing a natural formation was placed using a funnel and was allowed to fall by gravity for a height of 600 mm, then the surface of the sand was levelled. The amount of sand was predetermined to achieve the required relative density of 36%. Dense sand representing compacted replacement soil was placed in layers of 30 mm compacted thicknesses. The required weight of sand was placed and compacted using a 10 mm x 38 mm wooden plate and hand rammer to achieve the predetermined height of 30 mm at the target relative density of 78% representing 95% of maximum dry unit weight obtained from modified Proctor test. The procedure was repeated for subsequent layers to achieve the total thickness of dense sand. The weight of the hand rammer was maintained for all tests and number of blows adjusted based on trials in order to minimize the effective compaction depth and minimize potential densification of the underlying loose sand. Geogrid reinforcement of required width was placed at the target depth centered with the footing. Sand layers above the geogrid were placed at the center of the geogrid and spread outwards to ensure the geogrid was stretched. The tank was fully emptied and refilled with sand between tests.

The model footing is placed on the soil surface at the center of the tank and extends from edge-to-edge of the tank along the short direction. The model footing was axially loaded in 500 kN increments applied using a vertical hinged rod as illustrate in Figure (2). The corresponding average stress increment below the footing is 13.2 kN/m^2. The axial load increments were added after footing settlements ended. An MTS 661.19 Force Transducer of 25 kN capacity was used to monitor the applied load. The footing settlement was measured using two linear voltage displacement transducer (LVDT) located at the footing edges. The tests were carried out up to a settlement of 80 mm. Data were logged using a data acquisition system.

2-4- Testing Program

A series of tests were conducted to determine the effect of the configuration of reinforced replacement soil on improvement in bearing capacity and settlement of the strip footing. The testing program was organized to study the effect of the number of reinforcement layers (N = 1,2,3), length of reinforcement as a function of footing width (L = 6B, 4B, 2B), and thickness of the replacement soil as a function of footing width (d = 1.2B, 1.5B, 1.8B) on improvement in bearing capacity and reduction in settlement. All tests were performed at constant spacing between layers (h = 0.3 B) and first layer spacing from footing base (u = 0.3 B). Some tests were repeated at least twice to ensure repeatability of the test results. The testing program is summarized in Table (3). Each test is identified using a string (d-N-L-u/B-h/B) representing the test configuration.

Table 3- Testing program

Test No.	N	u/B	h/B	L/B	d/B
1-3	0	-	-	-	1.2,1.5,1.8
4-12	1,2,3	0.3	0.3	2,4,6	1.2
13,14	3	0.3	0.3	6	1.5,1.8

3- RESULTS AND ANALYSIS

A series of tests were performed on strip footing resting on geosynthetic reinforced soil overlying loose sand. The purpose of testing program was to evaluate the improvement in bearing capacity and settlement of the strip footing due to inclusion of geogrid layers. The effect of the number of reinforcement layers, reinforcement length, and thickness of the replacement soil were discussed below. There are two available methods to show the improvement in bearing capacity and settlement; ultimate bearing capacity ratio and bearing capacity ratio at certain settlement.

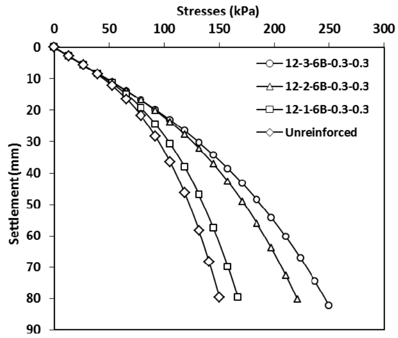
$BCRu = q_{uR}/q$ ……… ……………………… (1)

$BCRs = q_{Rs}/q_s$ ……………………………….. (2)

Where q_{uR} and q are the ultimate bearing capacity for the reinforced and unreinforced soil respecttively that determined based on tangent intersection method [15] and q_{Rs} and q_s are the bearing capacity values at the same settlement for the reinforced and unreinforced soil, respectively.

3-1- Effect of Number of Reinforcement Layers

Tests were performed for reinforced soil including a variable number of layers (N=1, 2, 3). The first layer is located at 30 mm below the footing and the spacing between each layer is 30 mm. The total thickness of the dense sand layer is 120 mm. At low vertical stresses (below 50 kPa) minimal differences were observed between tests including different number of geogrids. At moderate to high applied vertical stresses (above 50 kPa), increasing the number of geogrids resulted in a decrease in measured footing settlements and increase in stresses at the maximum settlement of 80 mm as illustrated in Fig. (3). The failure mode of unreinforced soil was observed to be a punching shear failure through the dense sand. A similar failure mode was observed in case of one geogrid layer as shown in Figure (4a). However, the punching shear failure mode faded in case of three geogrids (Figure 4c). As the soil under the footing settled downward, the reinforcement layer deformed and developed tension having an upward force component supporting the external applied loads. Mobilizing membrane effect requires some settlement and reinforcement pullout resistance resulting from interlocking and friction between the soil and geogrid. This membrane effect reduces the occurrence of soil punching and distributes the stresses on a larger area beneath the footing (Fig. 4b & 4c). It is believed that the increase in number of layers combined with the larger depth extent of reinforcement for multiple layers contribute to the increase in membrane action and fading of the punching failure.



12-3-6B-0.3-0.3 represents d-N-L-u/B-h/B
Fig.3-Stresses versus settlement curves ford=1.2B
Source: Researcher

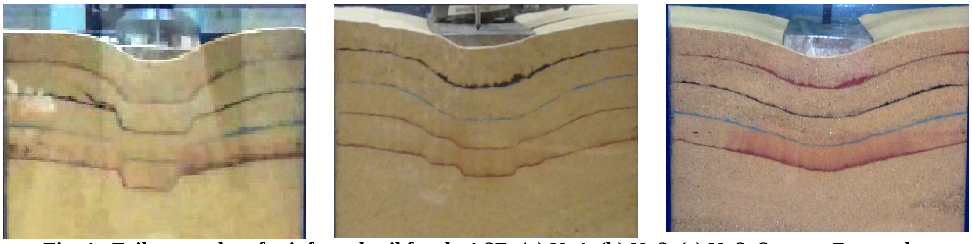
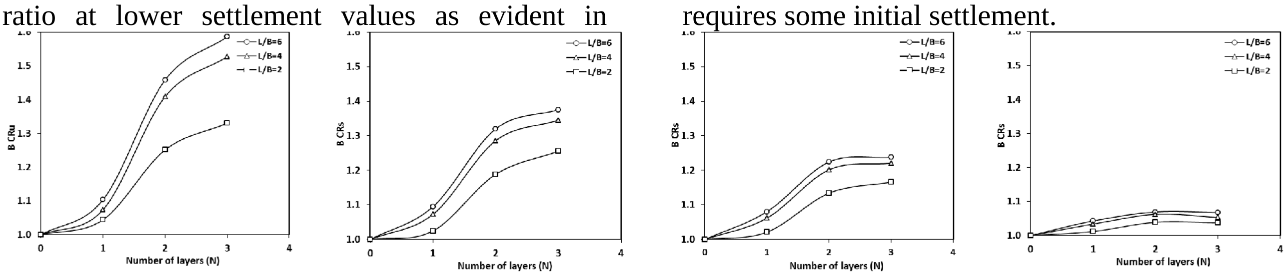


Fig. 4- Failure modes of reinforced soil for d =1.2B. (a) N=1, (b) N=2, (c) N=3. Source: Researcher

Figure (5a) shows that the ultimate bearing capacity ratio increased by 10%, 46%, and 59% when using one, two, and three layers of width 6B, respectively. However, the number of geogrid layers has a decreasing effect on the bearing capa-city ratio at lower settlement values as evident in Figures (5b, 5c, and 5d). The bearing capacity ratio at s/B of 30% increased by 9% to 38%, and at s/B of 10% increased by 4% to 7% when using one to three layers of reinforcement having a width of 6B. This is because mobilizing the membrane effect requires some initial settlement.

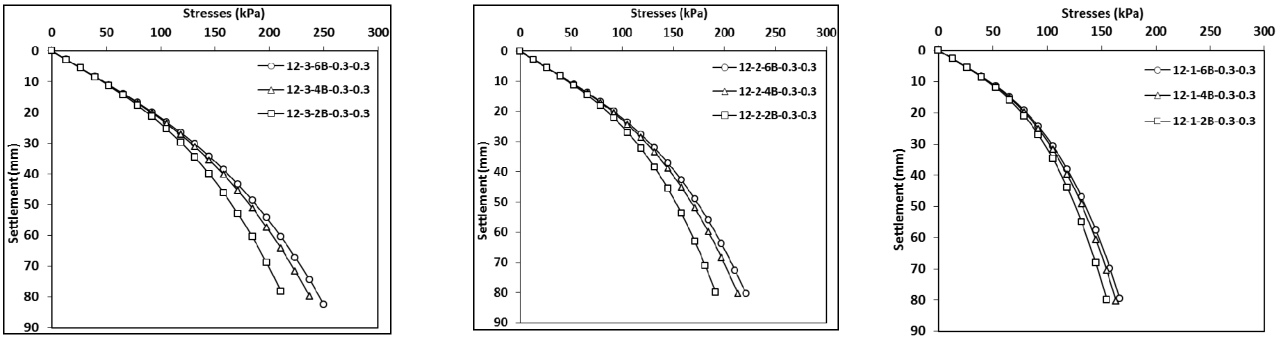


A B C D

Fig. 5- Bearing capacity ratio versus number of layers for d =1.2B: (a) BCRu, (b) s/B=0.3, (c) s/B=0.2, and (d) s/B=0.1. Source: Researcher

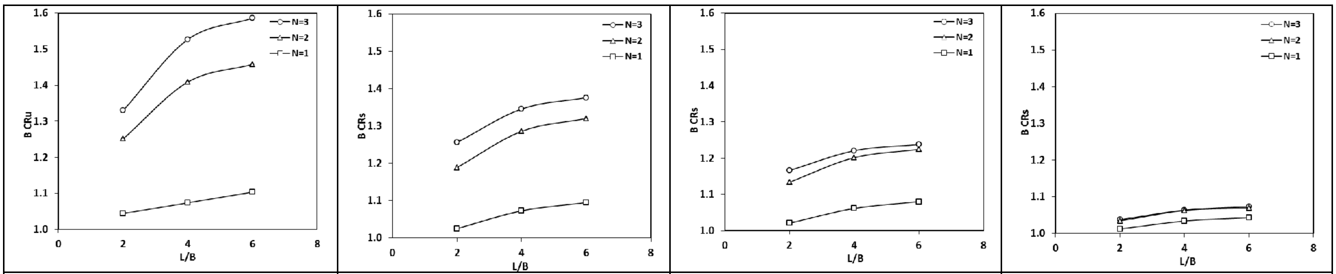
3-2- Effect of Reinforcement Width

Typical stress – settlement curves from model tests that illustrate the effect of reinforcement width are shown in Fig. (6). The tests were executed at different reinforcement width of 2B, 4B, and 6B and the thickness of dense layer of 120 mm. It is observed from Figure (6) that the different reinforced soil configurations have the same initial stiffness and the effect of inclusion of geogrid layers appears at large deformation. Figure (7) shows that the ultimate bearing capacity ratio increased with increasing geogrid length; the BCRu for reinforced soil including three reinforcement layers improved by 33%, 53%, and 59%for geogrid length of 2B, 4B, and 6B respectively. For two layer of geogrid, the BCRu increased by 25%, 41%, and 46%for geogrid length of 2B, 4B, and 6B, respectively. It is noted that the improvement of geogrid length have a minimal effect beyond 4B. The improvement resulting from increasing the reinforcement length beyond the shear zone is due to increasing geogrid anchorage length that increases the pullout resistance. The effect of geogrid length for reinforced soil using one reinforcement layer at 30 mm below the footing base was insignificant due to the low effective stresses acting along the anchorage length; therefore pull out resistance increased insignificant as the geogrid length increased. However, the reinforcement width has a decreasing effect on the bearing capacity ratio at lower settlement values as evident in Figure (6).



A B C

Fig. 6- Stresses versus settlement curves for d =1.2B. (a) N=3, (b) N=2, (c) N=1. Source: Researcher



A B C D

Fig. 7- Effect of geogrid length for d =1.2B on the bearing capacity ratio. (a) BCR_u, (b) s/B=0.3, (c) s/B=0.2, and (d) s/B=0.1. Source: Researcher

3-3- Effect of Replacement Soil Thickness

Figure (8) shows a typical stresses – settlement curves that showed the effect of replacement soil thickness. The tests were performed at different replacement soil thickness of 1.2B, 1.5B, and 1.8B, three reinforcement layers, the reinforcement width of 6B, spacing between reinforcement layer of 0.3B, and first layer spacing of 0.3B. It is noted that, the ultimate bearing capacity increased by 12 % and 26% when the thickness of replacement soil increased from 1.2B to 1.5B and 1.8B respectively. However, for the same reinforcement layers, the ultimate bearing capacity ratio decreased slightly by increased the thickness of dense layer where the BCRu increased by 59%, 50%, and 47% for 1.2B to 1.5B and 1.8B respectively. Nevertheless, the BCRs increased by approximately 7% at settlement ratio (s/B) of 10% as shown in Figure (9).

4- CONCLUSIONS

Series of laboratory model tests were fulfilled to study the behaviour of shallow footings resting on geosynthetic reinforced replacement soil over-lying loose sand to investigate the improvement of the ultimate bearing capacity and reduction in settlements. The test results show the following conclusions:

1- A punching shear failure mechanism is observed in the laboratory tests, However, inclusions of geogrid layers distribute the stresses on a large area beneath the footing and reduce occurrence of soil punching.

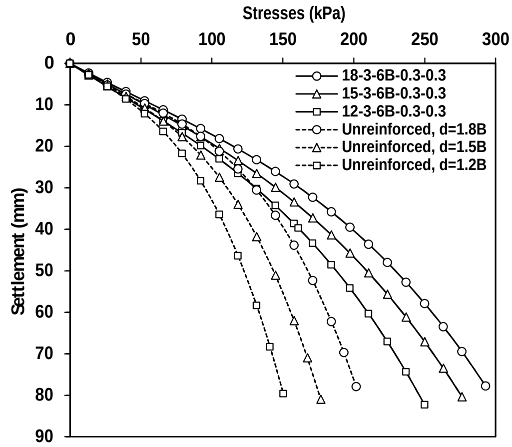


Fig. 8- Stresses versus settlement curves for reinforced and unreinforced soil cases using different replacement soil thickness Source: Researcher

2- The membrane action requires some initial deformations for the geogrid forces to develop, thus no significant improvement is observed at relatively low amplitudes of applied loads.

3- The potential benefits of using geosynthetic as reinforcement element is improvement the ultimate bearing capacity nonetheless no reduction in settle-ments occurred up to settlement ratio (s/B) of 10%.

4- Increasing the number of reinforcement layers results in an increase in the bearing capacity ratios (BCR_u, and BCR_s at s/B of 0.1, 0.2, and 0.3). However, the increase in bearing capacity was more pronounced up to two layers, and less significant to negligible at higher number of geogrids especially for BCR_s values at s/B ratios of 0.1 and 0.2.

5- Increasing the length of reinforcement layers up to l/B of 6 results in an increase in the bearing capacity ratios (BCR_u, and BCR_s at s/B of 0.1, 0.2, and 0.3) at a decreased rate. The maximum bearing capacity ratios occurred for reinforcement width of 6 times footing width.

6- The ultimate bearing capacity increased signify-cantly by increasing the thickness of replacement soil but the ultimate bearing capacity ratio decree-sed for the same reinforcement layers.

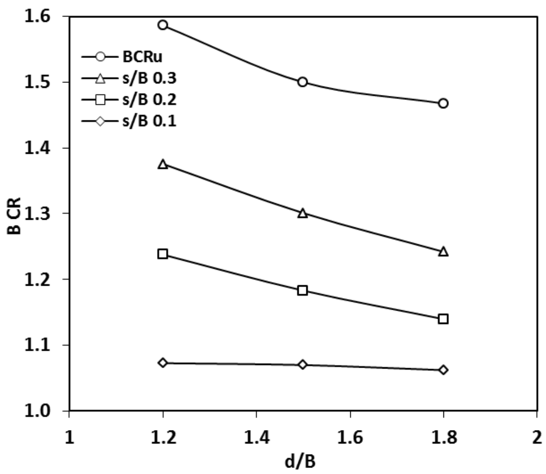


Fig. 9- Effect of replacement soil thickness on the bearing capacity ratio at different settlement ratios for L/B=6 and N=3
Source: Researcher

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