The effect of subsurface volume loss on the bearing capacity of reinforced granular material

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ABSTRACT
In this study, an experimental investigation that has been conducted to measure changes in the load-displacement response of a strip footing due to the introduction of subsurface volume loss are presented. A new test setup that has been designed and built to simulate the development of a controlled volume loss under an existing footing supported by granular subgrade material is described. The role of soil reinforcement on the footing response to subgrade weakening is examined. Preliminary results indicated the presence of a geogrid layer can improve the performance of the granular material and reduce the adverse effects of the unexpected development of local soil weakening under an existing foundation system.

RÉSUMÉ
Dans cette étude, un programme expérimental a été traité afin d'évaluer des changements dans la réponse du déplacement de la charge d'une semelle filante sujet à une perte de volume en profondeur. Un nouveau modèle expérimental qui a été conçu pour simuler le développement d'une perte de volume contrôlée sous une semelle existante appuyée sur un sol de fondation granuleux est décrit. Le rôle de renforcement du sol sur la réponse d'une semelle à l'affaiblissement du sol de fondation est examiné. Les premiers résultats montrent que l'introduction d'une couche renforcée par géogrille améliore le fonctionnement du matériel granuleux et réduit les effets défavorables imprévu d'une zone de sol affaiblissante sous un système de fondation existant.

1 INTRODUCTION

Shallow foundations are generally designed such that they are in full contact with the supporting soil throughout the service life of the structure. Granular subgrade is usually compacted to a specified density before construction to ensure sufficient bearing capacity and minimum settlement. Reinforcement layers placed within the granular subgrade material are sometimes used to improve the bearing capacity and the overall performance of the foundation system. Several researchers (e.g. Guido et al., 1985; Hirokawa and Miyazaki, 1992) suggested that the implementation of a geogrid layer can lead to an increase in the shear strength of the soil by up to 25%. The improvement in the bearing capacity of the reinforced soil has been explained by two different mechanisms: (1) friction between soil and the geogrid, and (2) passive resistance due to the particle interlocking in the geogrid ribs. Hirokawa and Miyazaki (1992) experimentally investigated the effect of installing a geogrid reinforcement layer in dense sand supporting square footings. It was recommended that the geogrid should be placed at a depth that is equal to the footing width. It was also concluded that the geogrid reinforcement has insignificant effects if placed at a depth more than twice the foundation width.

After construction, however, volume loss and local weakening of the subsurface soil may develop due to several reasons including underground construction activities, the dissolution of the underlying karst limestone or dynamic loading. This can lead to ground movement directly under the footing and consequently a reduction in the bearing capacity of the supporting soil. Figure 1 shows an example of soil disturbance due to weakening process in the vicinity of an existing footing.

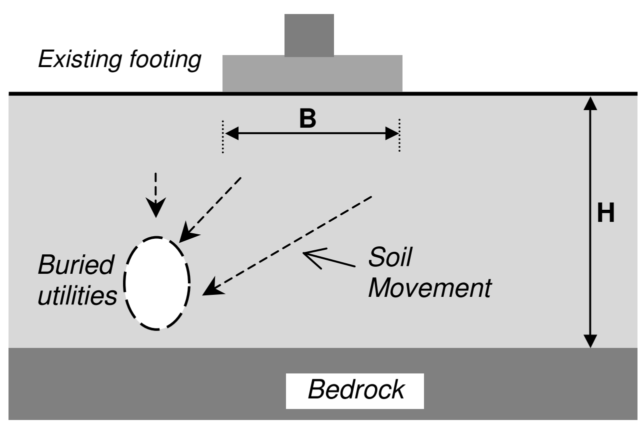

Figure 1 Schematic of the investigated problem

Wang and Badie (1983) studied the effect of introducing subsurface voids in silty clay material on the bearing capacity of an overlying strip footing. Various parameters were examined including footing dimension and void shape, orientation and location. It was concluded that at a depth of about twelve times the footing width the presence of the void would not affect the footing performance. This was attributed to the soil arching around the void. It was also concluded that as the void moved closer to the foundation, the bearing capacity decreased significantly.

Khing et al. (1993) investigated the effect of subsurface void in clayey soils overlain by granular material supporting a strip footing. Tests were conducted in a tank (915 mm x 915 mm x 152 mm) and were repeated using a geogrid sheet located at the interface between the two soil layers as well as at different heights within the granular material. It was concluded that soil reinforcement is highly effective when the length of the geogrid layer is 6 times the footing width and is placed at a depth of 2/3 the footing width. Omar and Das (1993) investigated the ultimate bearing capacity of strip and square footings on sand with geogrid inclusion. A geogrid length of 8 times the footing width was recommended for both footings. It was also recommended that the geogrid layer be placed at a distance of 2B below surface.

Das and Khing (1994) noted that creating voids in a clay subgrade causes drop in the bearing capacity and increase in settlement. They highlighted that if the void is located at a depth equal to or greater than 2.5 times the footing width the increase in bearing capacity can reach a maximum of 25%. Meguid and Menaa (2009) investigated the effect of erosion voids on the contact pressure distribution under slabs-on-grade and concluded that the presence of erosion voids can lead to rapid increase in the contact pressure in the immediate vicinity of the void in addition to an increase in tensile stresses at the outermost fibers of the slab.

The above studies contributed significantly to the understanding of the response of existing shallow foundation systems to subsurface voids. However, the reported investigations focused mainly on voids created in clayey soil. This is attributed to the difficulty associated with void creation in granular material. The objective of this study is to describe the experimental setup that has been developed to investigate the effect of introducing a controlled subsurface ground loss on the bearing capacity and settlement of a strip footing supported by granular material. To evaluate the role of geogrid reinforcement on the measured response, the cases of reinforced and non-reinforced sand are examined.

2 EXPERIMENTAL SETUP

The tests were conducted in a rigid steel test tank (1400 mm in length, 300 mm in width, and 1300 mm in depth). The dimensions of the tank and the loaded area were selected to simulate the two-dimensional nature of the problem and minimize the effects of the lateral boundaries on the measured displacements. The tank was constructed using 6 mm thick steel plates and reinforced with 100 mm HSS sections. A 6 mm thick Plexiglas sheet replaced the steel plate at the front of the tank to enable full visibility of the sand movement throughout the test. The internal sides of the tank were painted and lined with plastic sheets to reduce friction between the sand and the sides of the tank. Two circular openings 150 mm in diameter located 400 mm above the base of the tank were made in the front and back sides to facilitate the installation of the volume loss mechanism. The volume loss was created inside the sand layer by placing a shrinkable segmented cylinder across the entire width of the tank as shown in Figure 2. The diameter of this cylinder can be reduced incrementally up to a maximum of 6 mm (about 8% volume loss). This was achieved by rotating an external wheel (see Figure 3) attached to a mechanical system inside the steel cylinder.

It is worth noting that the location of the segmented cylinder below the model footing has been chosen such that the load transferred to the cylinder is kept to a minimum value through out the experiments. This was monitored through 4 load cells installed at different locations along the pipe circumference and readings were continuously taken during each test.

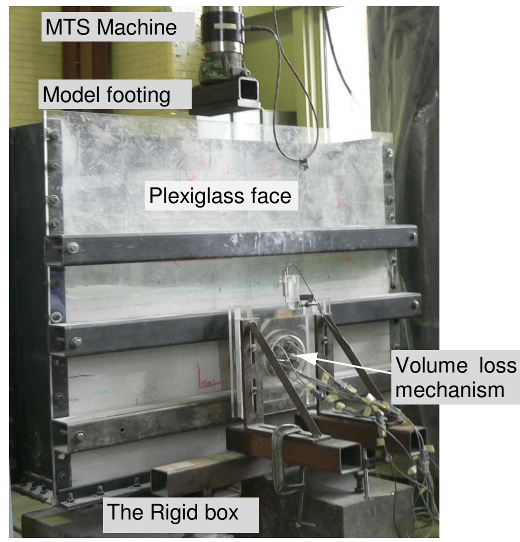

Figure 2 Front view of the experimental setup

In addition the shrinkable cylinder was allowed to move vertically through a sliding mechanism made out of plexiglass plate attached to the pipe and sliding freely on along plexiglass grooves as shown in Figure 3.

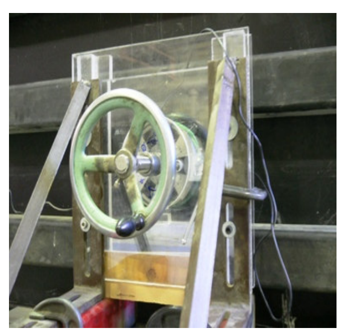

Figure 3 The controlled volume loss mechanism

Details of the test setup and the shrinkable cylinder are provided in Figures 4 and 5, respectively.

The soil used was uniform fine sand with 100% passing through sieve 40 with 0% passing from sieve 200. The sand was poured into the tank using the raining technique and compacted using tampers every 100 mm layer. The final height of sand before testing was 950 mm. The average unit weight of the sand was measured to be 15 kN/m^3. The geogrid used was BX 1100 with elastic modulus of 528 MPa. The length of the geogrid sheet was 600 mm and was placed at a depth of 70 mm below the base of the footing.

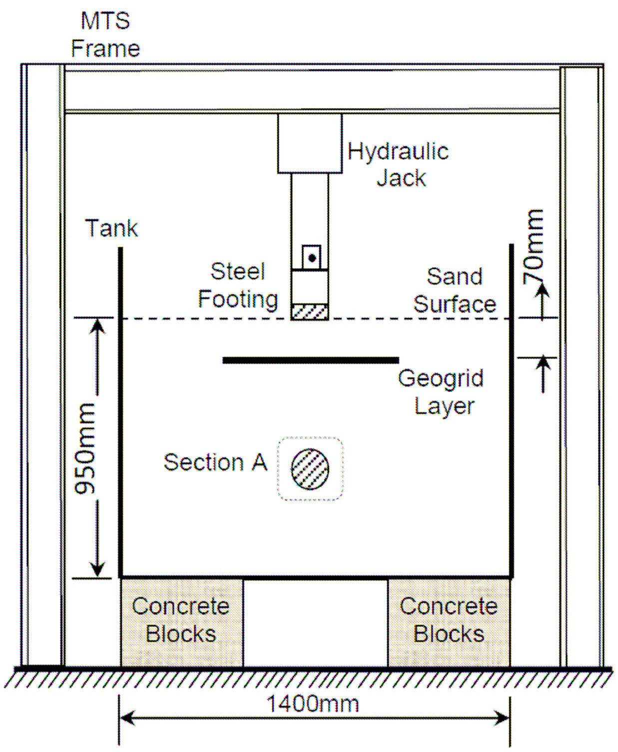

Figure 4 Schematic drawing of the test setup

The model footing had the dimensions of 100 mm wide x 290 mm long x 20 mm thick. It was made of steel and was welded to a 5 mm thick x 100 mm high steel section. The strip footing was attached to an MTS machine with a maximum capacity of 640 kN and a stroke of 1000 mm. Displacement control at a rate of 1.3 mm/minute was employed for all the conducted tests. The Load-settlement relationship of the footing was recorded using a computer system attached to the MTS machine.

A total of four tests were conducted in this preliminary phase of the study including two control tests with no volume loss for comparison purposes. Table 1 summarizes the conditions of each test.

Table 1 Tests Conducted

Test	Geogrid	Void
Test 1	No	No
Test 2	Yes	No
Test 3	No	Yes
Test 4	Yes	Yes

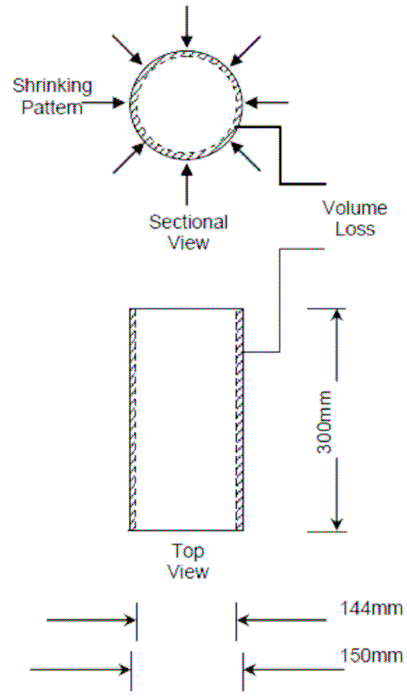

Figure 5 Detailed dimensions of the cylinder (Section A)

3 PRELIMINARY RESULTS

Figure 6 shows the load settlement curves of two control tests (Tests 1 and 2) conducted without introducing the subsurface volume loss. Test 1 represents the case of non-reinforced soil whereas Test 2 represents the reinforced soil. An increase of about 20% in the maximum load at failure was measured due to the presence of the geogrid layer as indicated by the trend lines shown in Figure 6. This is consistent with the results reported in the literature.

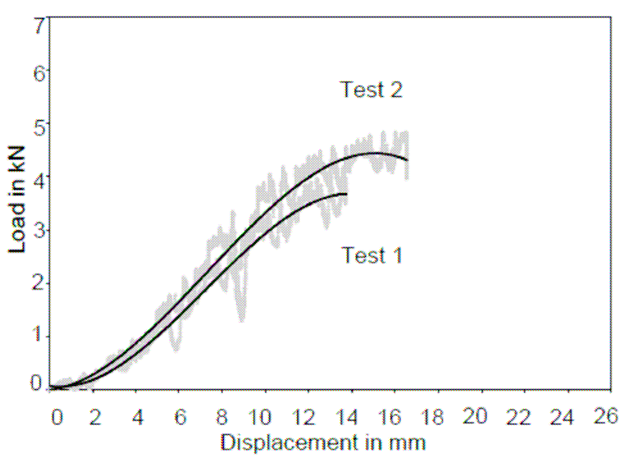

Figure 6 Load-Settlement curves without volume loss

In tests 3 and 4, a volume loss of about 8% was introduced during the load application process. To ensure the repeatability of the tests, the footing was loaded and allowed to displace initially using the same displacement rate used in tests 1 and 2. When the measured displacement reached 5% of the footing width, the subsurface volume loss was introduced. This was achieved by reducing the diameter of the segmented cylinder by 6 mm at a rate of 1mm/sec. The load displacement relationship measured after the completion of volume loss in Tests 3 (non-reinforced) and 4 (reinforced) are shown in Figure 7.

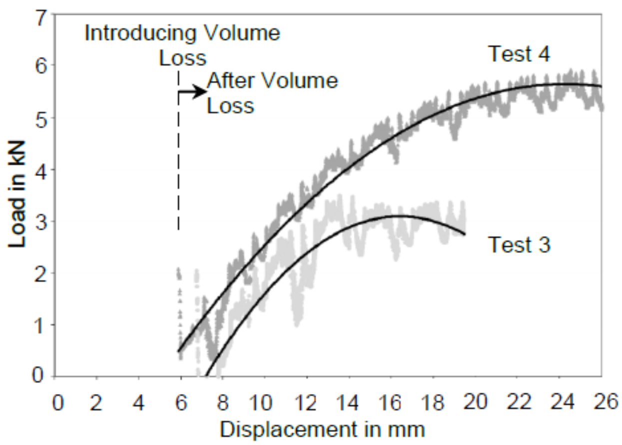

Figure 7 Load-Settlement Curves after volume loss

It can be seen that the volume loss has lead to significant reduction in the bearing capacity momentarily (at a displacement of 7 mm). For the non-reinforced case (Test 3), the load dropped from 2 kN to 0 and then increased to a maximum of about 3 kN before failure whereas in the reinforced case (Test 4) the load dropped from 2 kN to a minimum of 0.5 kN and increased to 6 kN before failure. It can be concluded that even a small volume loss (6 mm) in the granular subgrade under an existing footing can cause a complete loss of support and a sudden drop in the contact pressure under the footing. It can also be concluded that the placement of the geogrid sheet reduced the impact of the volume loss but did not completely eliminate its effect.

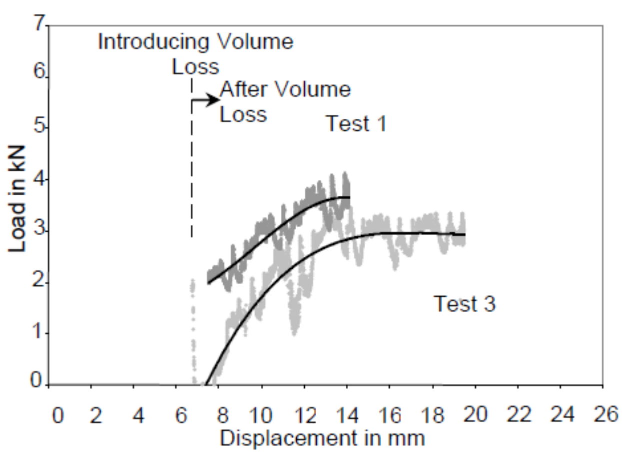

Figure 8 Load-Settlement curves for non-reinforced soil

To further understand the impact of volume loss on the footing bearing capacity the measured responses for the two unreinforced cases (Tests 1 and 3) were examined as shown in Figure 8. A drop in the bearing capacity by about 30% and increase in settlement after the introduction of volume loss is evident in this figure. Figure 9 shows a comparison between the load-displacement relationships for the two reinforced cases (Tests 2 and 4). It can be seen that the presence of the geogrid layer improved the bearing capacity by about 35%. This is attributed to the mobilization of stresses in the geogrid layer due to the additional soil movement induced by the volume loss at the location of the cylinder.

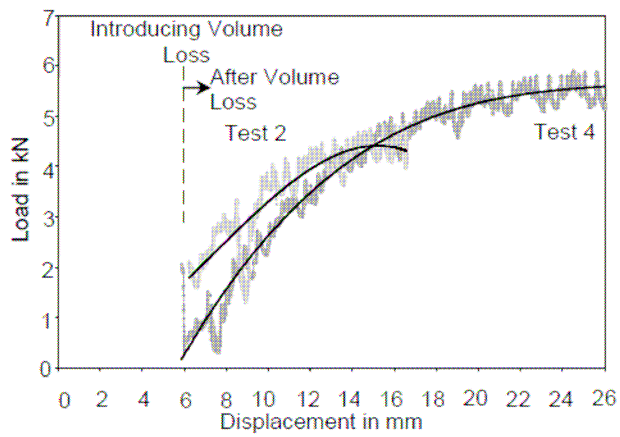

Figure 9 Load-Settlement Curves for reinforced soil

It is worth noting that in all conducted tests the load cells installed around the cylinder did not record substantial increase in stresses. This was consistent with the assumption made regarding the effect of the cylinder stiffness on the response of the footing during the experiments.

4 CONCLUSIONS AND RECOMMENDATIONS

An experimental setup has been designed and built to investigate the effect of subgrade weakening on the performance of an existing foundation system.

Four experiments have been conducted to investigate the effect of local volume loss under an existing footing on the bearing capacity of the subgrade material. Two cases have been examined namely; reinforced and non-reinforced soil.

The following could be concluded from the tests conducted:

- As little as 6 mm of volume loss in a local area below an existing strip footing could cause a loss of contact with the foundation and consequently an increase in settlement.
- The reduction in the bearing capacity of the footing could reach up to 30% in non-reinforced soil.

- The placement of the geogrid sheet within the subgrade reduced the impact of the volume loss but did not completely eliminate its effect.
- The contribution of the geogrid was found to be more significant when a volume loss occurs due to the larger strains developing in the soil.
- The presence of the geogrid increased the overall bearing capacity by about 45% compared to the case of volume loss without geogrid.

This study presents experimental results conducted under 1g conditions using a specific volume loss configuration under the centerline of a strip footing. Additional research is, therefore, needed to further examine the effect of footing size and location of volume loss with respect to the supported footing on the bearing capacity and surface settlements.

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