Experimental approach to characterize soil-reinforcement composite interaction

Approche expérimentale pour caractériser l'interaction de sol-renfort composite

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ABSTRACT: The acceptance of soil reinforcement techniques has grown not only for conventional structures but also an increasingly large number of critical structures such as bridge abutments. Yet, while significant advances have been made in characterizing the soil-reinforcement interaction of individual reinforcement layers, additional evaluation is still needed into the complex interactions that may develop between contiguous layers, particularly if the reinforcement spacing is comparatively small. Accordingly, a study was conducted to assess the effect of reinforcement vertical spacing by developing a new soil-reinforcement interaction equipment that simulates the interaction between adjacent reinforcement layers. This paper provides a description of the newly developed testing equipment, which was designed to comprehensively assess soil-reinforcement interaction, particularly under working stress conditions. Typical results are presented to illustrate the suitability of the measurement techniques adopted for an experimental evaluation aimed at quantifying the interaction between contiguous reinforcements. The new equipment was found to adequately quantify key aspects of the soil-geosynthetic interaction, including the impact of reinforcement tension on the straining of adjacent reinforcements, the effect of dilatancy, and the development of soil shear bands induced by tensioning of the reinforcement.

RÉSUMÉ: Le renforcement des sols est maintenant une technologie acceptée pour un nombre de plus en plus un grand de structures critiques. Bien que des progrès significatifs ont été réalisés pour caractériser l'interaction sol-renfort des couches de renforcement indivuduelles, les interactions complexes qui peuvent se développer entre couches contiguës, menant à un comportement composite de la masse de terre renforcée, n'a pas été entièrement caractérisée. Par conséquent, une étude a été menée pour évaluer les multiples aspects qui devraient être pris en considération pour concevoir un équipement d'interaction sol-renfort qui compte pour l'interaction entre les couches de renforcement adjacentes. Ce document fournit une description d'un nouvellement développé équipement d'essai conçu pour évaluer de manière exhaustive l'interaction sol-renfort. Des résultats typiques sont présentés pour illustrer l'adéquation des techniques adoptées pour une évaluation expérimentale visant à quantifier l'interaction entre des renforts contigus. Le nouvel équipement a été trouvé pour adéquatement quantifier les aspects clés de l'interaction sol-géosynthèse, y compris l'impact de la tension de renfort sur les renforts adjacents, l'effet de la dilatance, et le développement des bandes de cisaillement du sol induites par la tension du renfort.

KEYWORDS: soil-reinforcement interaction; geosynthetic-reinforced soil composite; reinforcement pullout.

1 INTRODUCTION

The use of soil reinforcement has been widely recognized as an alternative in many structural disciplines. The interaction between the soil and reinforcement plays a key role in load transfer forming a composite material that has the appropriate strength to bear the applied loads. The spacing between reinforcement layers governs the degree of interaction not only between the reinforcement layer and surrounding soil, but also between the soil-reinforcement interfaces of neighboring reinforcement layers. This complex interaction has revealed that vertical spacing between reinforcement layers may play a key role in the overall mechanical response of the reinforced soil composite mass. Reinforcement spacing has been reported to have a greater effect on the reinforced soil composite strength than that of the reinforcement tensile strength. This observation was reported as occurring in conditions where reinforcement spacing was small (e.g. Nicks et al. 2013). However, there is need for further understanding of the mechanisms and extent of such effect.

This paper presents a new experimental approach to assess the behavior of reinforced soil structures. This evaluation includes: (1) a review of the soil-reinforcement interaction experimental modeling of reinforced soil structures based on pullout loading; (2) a description of newly developed testing equipment used in soil-reinforcement interaction behavior assessment; and (3) typical testing results.

2 BACKGROUND

The interaction of reinforcements with the surrounding soil involves complex shear stress transfer mechanisms, the manifestation of which is a shear band that develops in the vicinity of the reinforcement (e.g. Palmeira 2009). Beyond this zone, the soil is no longer affected by the reinforcement. The thickness of this band may be affected by a number of factors, including the reinforcement tensile stiffness, the deformability and shear strength of the backfill material, and the characteristics of the soil-geosynthetic interface. A composite response is expected to result when the shear bands of two contiguous reinforcements interact with each other (Leshchinsky et al. 1994). Accordingly, the thickness of the shear band represents the limit beyond which the composite behavior of reinforcements no longer occurs. That is, the shear bands of closely-spaced reinforcements interfere with each other and change the interaction from a simple tie-back mechanism to a more complex, composite mechanism that has been reported to include increased confinement, reduced lateral movements and reduced soil dilation (e.g. Adams et al. 2012).

According to ASTM D6706, the length of a pullout box should exceed 60 cm, and should be larger than 5 times the maximum aperture size if a geogrid reinforcement is used. The width of the box should be larger than 75 cm in devices with rough side walls, and 45 cm in devices with smooth side walls. Also, the width should exceed 20 times the D_{85} of the soil, as well as 6 times the maximum soil particle size. The box depth should accommodate soil thickness above and below the geosynthetic and be greater than 15 cm, greater than six times the D_{85} of the soil, and greater than three times the maximum soil particle size. Ladeira (1995) developed a box measuring 1.53 m long by 1.00 m wide by 0.80 m high, and demonstrated that these dimensions minimized lateral and horizontal boundary effects.

In addition to lateral boundary effects, interaction may develop between the upper and lower boundaries and the soil-reinforcement interface. Farrag et al. (1993) developed a box measuring 1.52 m long by 0.90 m wide by 0.76 m high. They reported that this interaction increased as soil thickness decreased, and thus influenced test results. They also reported the development of shear forces between the soil and horizontal boundaries, and the bottom boundary in particular. Brand & Duffy (1987) studied the effect of soil thickness on pullout resistance. Based on a limited number of tests, the authors observed that pullout resistance decreased as soil thickness increased, but only up to a certain value, beyond which there was no further change. Lopes & Ladeira (1996) showed that the predicted friction angle of the soil may increase beyond values measured using conventional techniques due to an increased confining pressure as a result of repressing soil dilatancy (Lopes & Ladeira 1996; Farrag et al. 1993). Lopes & Ladeira (1996) reported that specimen length significantly affects the impact of the upper and lower boundaries on test results. Palmeira & Milligan (1989) reported that an increasing specimen length to soil thickness ratio led to greater influence of the upper and lower boundaries of the pullout box. Farrag et al. (1993) reported that soil thickness should exceed 30 cm above and 30 cm below the reinforcement to eliminate the effect of the horizontal boundaries. Farrag et al. (1993), Ladeira (1995), and Lopes & Ladeira (1996) used a modular structured box to facilitate changes in soil thickness in various tests

3 PROPOSED EXPERIMENTAL APPROACH

An experimental setup was designed and developed at the University of Texas at Austin to quantify the thickness of the soil shear band that develops in the vicinity of the soil-reinforcement interface. Figure 1 shows a schematic layout of the testing equipment, which was based on the framework of a large-scale pullout test. Of particular relevance, this experimental system has the ability to vary the thickness of the soil layer above and below the main reinforcement system, as well as the characteristics of the materials used as top and bottom boundaries of the reinforced soil mass.

The box was designed to accommodate soil specimens up to 120 cm deep, 150 cm long and 75 cm wide. Six pneumatic actuators are placed on wooden pyramids that cover the top surface of the reinforced soil mass. The actuators react against a stiff reaction frame, which conveys the reaction load exerted by the actuators to the bottom of the box. This normal pressure system allows for assessment of soil dilatancy. In addition, this system can maintain a zero-volume-change condition to allow for comparison of the soil-reinforcement interaction under conditions that either fully allow or fully suppress soil dilation.

The axial pullout loading system consists of two hydraulic actuators reacting against the front wall of the box. The pullout system is connected to a clamping system that conveys the applied tensile load to the main reinforcement. The embedded geosynthetic is subjected to increasing loads, with particular focus on the responses under loads representative of working stress and ultimate loads. In addition to the main reinforcement layer, two other layers of the same type are used as upper and lower boundaries to represent the presence of contiguous reinforcements. Soil is placed between the boundary geosynthetics and the top and bottom boundaries of the box. Note that tests conducted using varying soil thicknesses resulted in differences in the unit tension carried by the reinforcement. A combination of collars (to heighten the box) is used to control the soil thickness. Monitoring the displacement of the boundary reinforcements is key to assess the shear transfer between two contiguous reinforcements placed at small vertical spacing. The data collected from both the main and boundary reinforcement layers provided key information on the limits of the composite behavior of geosynthetic-reinforced systems.

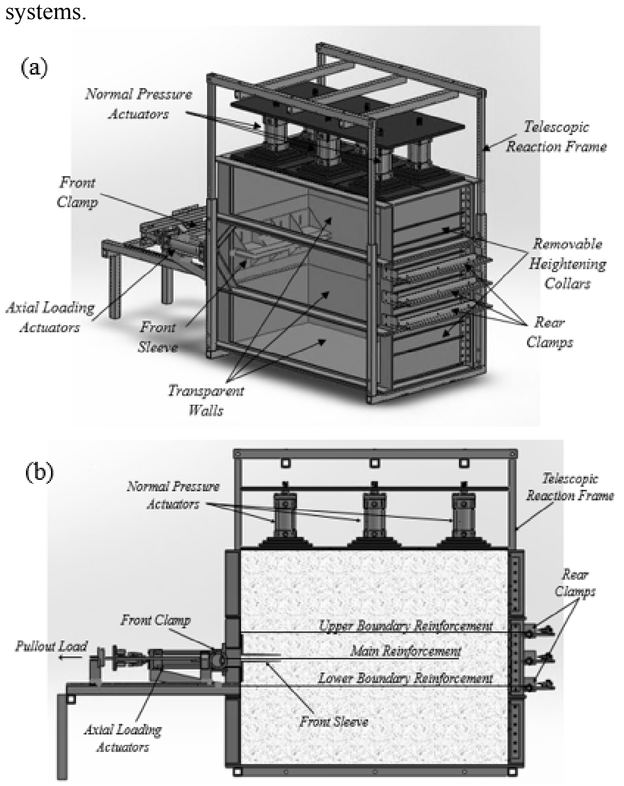


Figure 1. General layout of the new equipment: (a) 3D perspective; (b) sectional side view.

The instrumentation includes: (1) a load cell to measure the load applied to the main reinforcement; (2) load cells at the normal pressure pneumatic actuators to monitor the actual applied normal pressure on top of the soil throughout the test; (3) a camera that shoots against the transparent side wall that allows for measurement of the shear band as well as direct observation of the soil-reinforcement interaction. The camera used is a DSLR (Digital Single Lens Reflex) camera that has 24.1 million effective pixels. The camera image sensor is 23.5 × 15.6 mm CMOS (complementary metal-oxide semiconductor) sensor. The width of the reinforcements extends to the sides of the box in this case. On the inner surface of the box, Mylar sheets are used to minimize side friction against the fill soil. Markers are placed in the soil at the interface to follow soil movement as the tensile load in the geosynthetic is increased; (4) displacement sensors installed away from the sidewall, to allow for comparison of internal displacements with those obtained through the transparent wall; (5) displacement sensors on the surface that measure vertical displacements to assess the angle of dilation of the reinforced soil mass; (6) an earth pressure mat, placed on the floor of the box, to evaluate the normal pressures conveyed through the reinforced soil mass; (7) lateral earth pressure sensors, fixed to the inside of the front wall, that monitor the change in lateral earth pressure on the front wall during testing to allow for evaluation of the front wall rigidity effect on generated soil-reinforcement shear stresses; (8) displacement sensors to measure displacements at multiple locations within the main reinforcement, as well as within the boundary reinforcements; and (9) a camera that measures displacement within the unconfined portion of the main reinforcement to evaluate the tensile behavior of the geosynthetic corresponding to the interaction test.

4 TYPICAL RESULTS AND ANALYSIS

This section presents typical results for one of the tests. The results are presented to illustrate the capabilities of the proposed experimental approach. Note that this experimental approach proposes significant redundancy in various measurements for the purposes of validation.

4.1. *Pullout Resistance*

Figure 2 shows the frontal load-displacement behavior of the main reinforcement layer. The frontal load, defined as the total pullout force applied per unit width of the main reinforcement layer, was measured by the load cell mounted in the loading system. The frontal displacement, defined as the movement of the front end of the confined length of the main reinforcement layer, was measured by a linear potentiometer attached to a tell-tale, which was then attached to the front end of the confined reinforcement zone. The test reached failure in pullout mode, which enabled a full-range investigation of the soil-reinforcement interface behavior (i.e., at working stress and failure conditions).

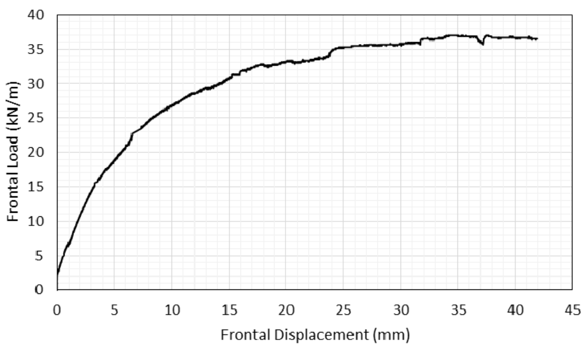


Figure 2. Frontal pullout load-displacement behavior

4.2. *Confined reinforcement straining*

Reinforcement deformation was measured at various nodes along the embedment length. These nodes were connected to tell-tales, which were then connected to linear potentiometers at the rear of the box. Figure 3 shows the displacement of the various nodes on the reinforcement layers at several load levels. Figure 3a shows the nodal displacement for the main reinforcement layer; and Figures 3b and 3c show the nodal displacement for the upper and the lower boundary reinforcement layers, respectively.

4.3. *Reinforced soil straining*

Soil deformation was measured through the transparent side of the equipment, which allowed for direct visualization of the kinematic response of soil particles adjacent to the reinforcement layers as well. Figures 4 and 5 show the displacement field of the reinforced soil mass in horizontal and vertical directions, respectively. To validate the measurements taken from the boundary of the reinforced soil mass, artificial gravel particles of a size and shape similar to those of the backfill material were employed. These particles were attached to tell-tales, which were then attached to linear potentiometers to measure the displacement of the artificial particles in real-time during testing.

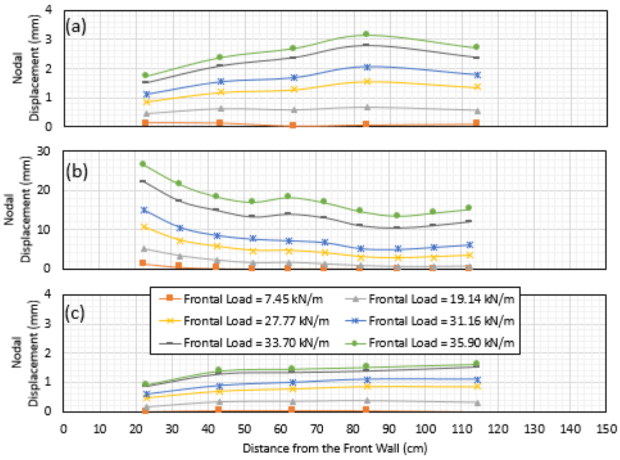


Figure 3. Reinforcement nodal displacement: (a) Main layer; (b) Upper boundary layer; and (c) Bottom boundary layer

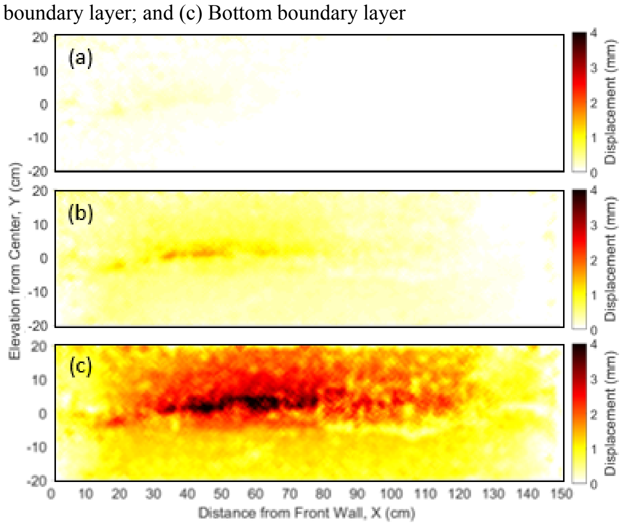
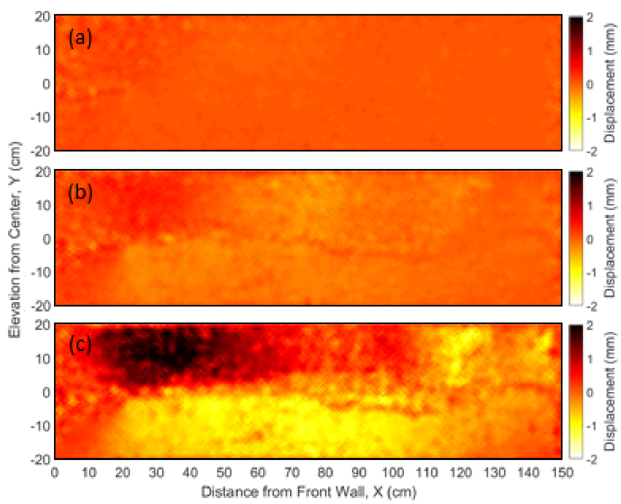


Figure 4. Horizontal displacement field: (a) at 7.4-kN/m frontal load; (b) at 19.1-kN/m frontal load; (c) at 35.9-kN/m frontal load

Figure 5. Vertical displacement field: (a) at 7.4-kN/m frontal load; (b) at 19.1-kN/m frontal load; (c) at 35.9-kN/m frontal load



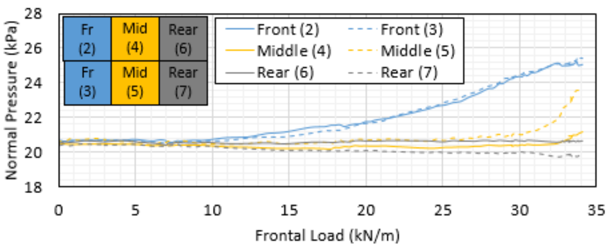
Six artificial gravel particles were stacked in a vertical array, centered in the box and located 30.5 cm (X = +30.5 cm) from the front wall to measure the horizontal deformation. Soil displacement measurements for these particles showed good agreement when compared to displacements measured by analyzing images tethered from the side transparent wall at various load levels. That is, the evolution of the shear band with increases in the soil-reinforcement interface load could be identified by analyzing images tethered from the side of the reinforced soil mass, as long as proper precautions were maintained. In addition, the displacement observed at the front wall of the box (X = 0) was negligible over the depth of the reinforced soil. This demonstrates that the sleeve minimized significantly potential problems related to front wall rigidity.

Three other artificial gravel particles were placed on top of the reinforced soil mass and underneath the normal pressure system (at Y = +21.5 cm) to measure the vertical deformation on a horizontal line centered in the box and located near the top of the reinforced soil mass. The displacement measurements showed good agreement when compared to measurements taken from analyzing images tethered from the side transparent wall at various load levels. That is, the dilative/compressive behavior observed with increases in the soil-reinforcement interface load could be identified by analyzing images tethered from the side of the reinforced soil mass, as long as proper precautions were maintained.

4.4. *Confining pressure*

Figure 6 shows the pressure measured on top of the reinforced soil mass. This pressure was estimated from the load measured by the load cells mounted on the reaction frame at the reaction point of each pneumatic actuator. The figure shows that normal pressure remained constant until 30% of the ultimate pullout load was applied. However, beyond this load level, the normal pressure at the front of the reinforced soil mass increased, up to about 30% at the original normal pressure. Note that limited dilation was allowed during testing to highlight the capabilities of the equipment in assessing the fully-allowed and fully-suppressed volume change conditions. The investigation of intermediate conditions facilitated understanding the full-scale behavior of the volume change, which would most likely happen in real structures.

Figure 6. Normal pressure on the top of the reinforced soil mass



4.5. *Reinforcement unconfined tensile behavior*

The experimental approach aimed at including an unconfined portion of reinforcement so that the unconfined tensile behavior of the reinforcement specimen used in each test could be evaluated. This was done by analyzing tethered images taken of the unconfined portion of the reinforcement. The exposed portion of the reinforcement was speckled by spray paint and randomly dappled with a white paint marker. This served to create two levels of pattern that enhanced the accuracy of the image analysis. The average strain rate was deliberately maintained at less than 0.1% throughout testing. The average strain rate in the test conducted was approximately 0.02 %/min. Figure 7 shows the strain data measured from images at various locations in the reinforcement unconfined zone. The average of the measured points is plotted as well. The figure also shows two data points provided in the technical specifications of the reinforcement manufacturer, which show good agreement with the measured values.

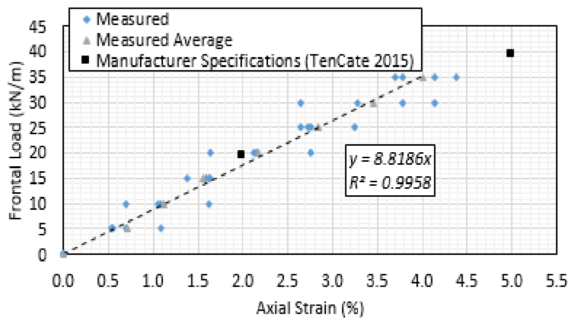


Figure 7. Reinforcement unconfined tensile behavior

5 CONCLUSIONS

A new equipment was developed at the University of Texas at Austin to evaluate soil-reinforcement composite behavior. The equipment includes a geosynthetic-reinforced soil mass that contains three reinforcement layers. The new device was found to provide suitable measurements of reinforcement straining in both a loaded geosynthetic reinforcement and in the adjacent reinforcement layers. In addition, the device allowed measurement of soil deformation field via digital image analysis, which was found to provide good basis for determination of the shear band. Finally, the equipment was found to be able to successfully monitor the dilatant behavior of the reinforced soil mass, which is expected to provide significant insight into the effect of reinforcement vertical spacing on the performance of geosynthetic-reinforced soil structures.

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