Load-Carrying Geosynthetic Mechanically Stabilized Earth (GMSE) Bridge Abutments: Lessons Learned from Experimental Evaluations

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ABSTRACT

This paper presents the findings of an experimental study conducted to define the boundary conditions of composite behavior of Geosynthetic Mechanically Stabilized Earth (GMSE) bridge abutments. The study involved the development of a new soil-geosynthetic interaction device capable of generating data required to assess the mechanical interactions between soils and reinforcing inclusions within a reinforced soil mass. These interactions are key to understanding the effect of reinforcement vertical spacing on the behavior of GMSE bridge abutments. The soil-geosynthetic interaction device was designed to accommodate a reinforced soil mass with three reinforcement layers. One reinforcement layer was subject to increasing tensile loads through an external loading system, while the other two neighboring reinforcement layers were not subject to external loads. An extensive instrumentation program was implemented to monitor the mechanical behavior of the soil and the three reinforcement layers during testing. It was observed that the neighboring reinforcement layers experience increasing passive tension with increasing active tension on the loaded reinforcement layer. The interaction among reinforcement layers was found to increase with decreasing the reinforcement spacing. For the testing program implemented in this study, one actively loaded reinforcement layer can transfer shear loads to a distance up to 0.20 m normal to its plane with a zone of shear influence of 0.15 m. That is, the interaction between two neighboring reinforcement layers could be observed for a reinforcement spacing corresponding to 0.30 m, a spacing capable of forming a composite reinforced soil mass.

INTRODUCTION

Soil-reinforcement interaction is the key property to the mechanical behavior of reinforced soil structures such as retaining walls and bridge abutments. The interactions between soils and reinforcing inclusions are governed by several load transfer mechanisms that have studied extensively over the past few decades (*e.g.*, Palmeria 2009). In design of reinforced soil walls and bridge abutments, soil-reinforcement interaction has always been considered to be of importance in restraining soil mass and has often been ignored in the driving mass. This simplification has been deemed conservative and thus has been acceptable by researchers and practitioners.

Vertical reinforcement spacing in geosynthetic-reinforced soil structures was reported to control the degree of interaction not only between soil and reinforcement layers, but also among neighboring reinforcement layers. This interaction was found to enhance the overall mechanical behavior of reinforced soil structures (Leshchinsky *et al.* 1994; Leshchinsky and Vulova 2001; Adams *et al.* 2011; Morsy 2017; Zornberg *et al.* 2018, 2019; Shen *et al.* 2019). Reinforcement spacing has been reported to have a greater effect on the stability of a reinforced soil structure than reinforcement tensile strength at ultimate states (Nicks *et al.* 2013), and greater than the reinforcement tensile stiffness under working stresses (Morsy 2017). The interaction mechanisms that result from the confinement of reinforcements were observed to exhibit behaviors not necessarily consistent with results predicted by limit state analyses (Ziegler 2011). However, the need for a greater understanding of the mechanisms and extent of such an effect remains.

This paper presents the findings of an experimental study that involved the development of a new device to comprehensively assess the soil-reinforcement interaction under both working stress and failure conditions considering varying reinforcement vertical spacings. The device was used to conduct a comprehensive testing program that aimed at investigating the effects on the interaction among neighboring reinforcements in relation to: (1) the normal stress at the soil-reinforcement interface; (2) the vertical spacing between reinforcements; (3) the reinforcement properties; and (4) the fill type. Analysis of the experimental results revealed that the existence of the zone of shear influence and its extent can be directly related to the interaction between neighboring reinforcement layers.

EXPERIMENTAL APPROACH

A new experimental device was designed and implemented by Morsy (2017) at the University of Texas at Austin to evaluate soil-reinforcement composite behavior and quantify the thickness of the zone where shear stresses propagate into the soil adjacent to the interface with a reinforcement where shear stresses are imposed. The device was used to conduct soil-geosynthetic interaction tests with various geosynthetic and soil materials under varied testing conditions. This section provides a descriptive summary of the soil-geosynthetic interaction device and its instrumentation. The detailed description of the device is presented in Morsy (2017) and Morsy *et al.* (2019a).

Soil-geosynthetic interaction device. The device consisted of a steel box 1200 mm in depth, 750 mm in width and 1500 mm in length that accommodates geosynthetic-reinforced soil specimens with three reinforcement layers. A general layout of the soil-geosynthetic interaction device is presented in Figure 1. One side of the box was made of transparent acrylic. The normal stress was applied on the geosynthetic-reinforced soil specimens using six pneumatic actuators placed on load distributing wooden pyramids, as shown in Figure 1a. Tensile loading was applied to middle reinforcement layer (active reinforcement) using a hydraulic loading system mounted on smooth liner guides, as shown in Figure 1b. The two other reinforcement layers act as upper and lower boundaries to represent the presence of neighboring reinforcements. These layers are passively loaded (passive reinforcements) through the load transfer from the active reinforcement layer. The soil-geosynthetic interaction device could detect the load transfer amongst neighboring reinforcements that occur when these layers deform differently (Morsy 2017; Zornberg *et al.* 2018; Morsy *et al.* 2019a, 2019b, 2020; Morsy and Zornberg 2020). The active reinforcement was attached to a loading system at its front end and was free at its rear end; whereas, the passive reinforcements were anchored at their rear ends.

Instrumentation and monitoring techniques. The instrumentations used in the soil-geosynthetic interaction device included the following: (1) a load cell measuring the increasing tensile load applied to the active reinforcement; (2) a camera capturing the soil displacement field; (3) artificial gravel particles buried within the soil mass and connected to linear potentiometers via horizontal telltales, which provided a comparison of displacements from internal particles with those obtained from particles adjacent to the transparent wall; and (4) linear potentiometers measuring displacements at numerous locations within the three reinforcement layers. Detailed information about the instrumentation and monitoring techniques is presented in Morsy (2017) and Morsy *et al.* (2019a).

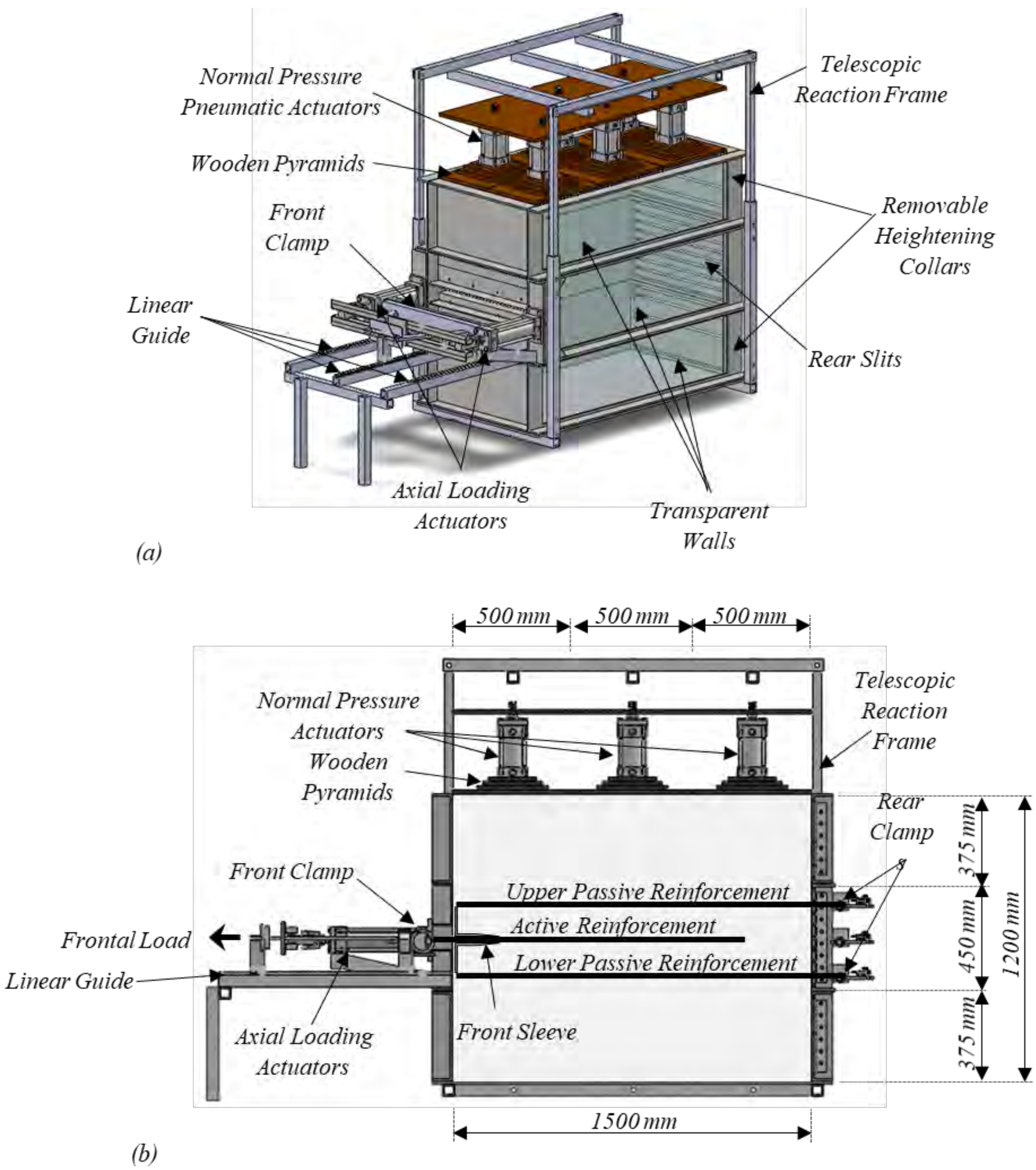

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Figure 1. Soil-geosynthetic interaction device: (a) general layout; and (b) schematic cross-sectional side view (Morsy and Zornberg 2020).

EXPERIMENTAL PROGRAM

A comprehensive experimental program was conducted using the new soil-geosynthetic interaction device. Table 1 summarizes the tests conducted as part of this program (Morsy *et al.* 2019b, 2020), which shows several testing series that explored the effects of various parameters on soil-reinforcement interaction. These testing series included repeatability assessment, varying normal stress levels for two reinforcement spacings, varying reinforcement vertical spacings for three normal stress levels, and varying geosynthetic and soil types. The results of the soil-geosynthetic interaction tests are presented in Morsy *et al.* (2019b, 2020).

The baseline soil used in the soil-geosynthetic interaction tests was a pea gravel that conforms to No. 8 gradation. Another soil type that confirms to sand No. 30 gradation was used. Characteristic properties of the two soils used in the testing program are summarized in Table 2. The baseline reinforcement used in the soil-geosynthetic interaction tests was a polypropylene woven geotextile. Other geosynthetic types including geogrids and geotextiles were used in the testing program to cover various geosynthetic characteristics (Morsy *et al.* 2020). Characteristic properties of geosynthetic reinforcements used in the testing program are summarized in Table 3.

Table 1. Summary of soil-geosynthetic interaction tests (after Morsy and Zornberg 2020).

*Testing Scheme **	*Test ID*	*Testing Variables*			
		Soil	*S_v (m)*	*σ_v (kPa)*	*Reinforcements*
Repeat Tests	GP-04-07-G1-G GP-04-07-G1-G(R)	Gravel	0.10	50	W1-GT
Tests with Varying Normal Stress Level	GP-06-02-G1-G GP-06-03-G1-G GP-06-05-G1-G GP-06-07-G1-G	Gravel	0.15	15 21 35 50	W1-GT
	GP-04-03-G1-G GP-04-07-G1-G	Gravel	0.10	21 50	W1-GT
	GP-02-03-G1-G GP-02-07-G1-G	Gravel	0.05	21 50	W1-GT
Tests with Varying Reinforcement Vertical Spacing	GP-02-07-G1-G GP-04-07-G1-G GP-06-07-G1-G GP-08-07-G1-G GP-12-07-G1-G GP-16-07-G1-G	Gravel	0.05 0.10 0.15 0.20 0.30 0.40	50	W1-GT
	GP-02-03-G1-G GP-04-03-G1-G GP-06-03-G1-G	Gravel	0.05 0.10 0.15	21	W1-GT
Tests with Varying Geosynthetic and Soil Types	GP-06-03-G1-G GP-06-03-G2-G GP-06-03-G4-G GP-06-03-G5-G SP-06-03-G1-G	Gravel Gravel Gravel Gravel Sand	0.15	21	W1-GT W2-GT EX-GG KN-GG W1-GT

* Note: Some tests are mentioned more than once in different testing schemes to show the extent of variation in each scheme.

Table 2. Characteristics of soils used in soil-geosynthetic interaction tests (after Morsy and Zornberg 2020).

Properties	***Gravel***	***Sand***
Particle Size Range, D	1.0-13.0 mm	0.2-2.0 mm
Mean Particle Size, D_{50}	7.0 mm	0.7 mm
Uniformity Coefficient, C_u	1.6	1.9
Curvature Coefficient, C_c	0.9	1.3
Specific Gravity, G_s	2.62	2.65
Range of Void Ratio, e_{min}-e_{max}	0.50-0.73	0.56-0.76
AASHTO Classification	A-1-a	A-3
USCS Classification	GP	SP

TEST RESULTS AND ANALYSIS

Soil displacement profiles. Figure 2 shows the horizontal displacement profiles normal to the reinforcement planes near the location of the frontal load at various loading stages for a representative test (Morsy *et al.* 2019a). The displacements were measured using the artificial gravel particles at the center of the reinforced soil mass, as well as using digital imaging at the side boundary of the reinforced soil mass.

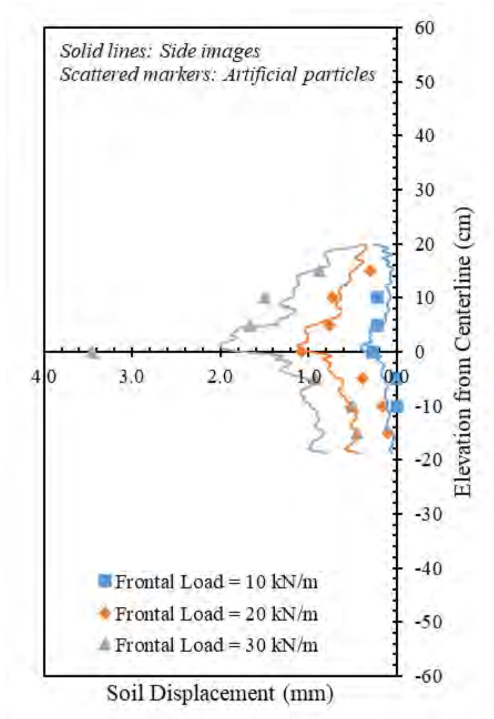

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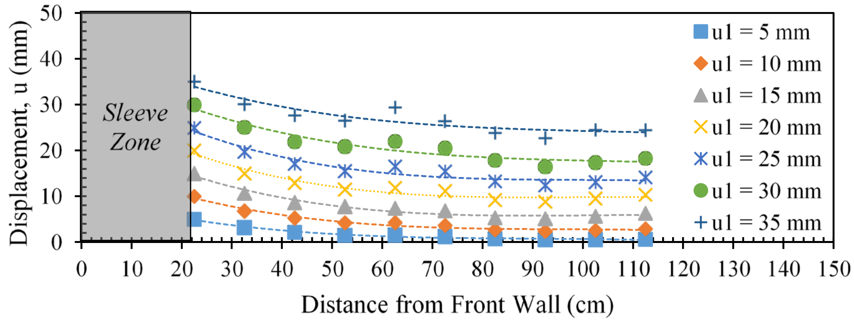
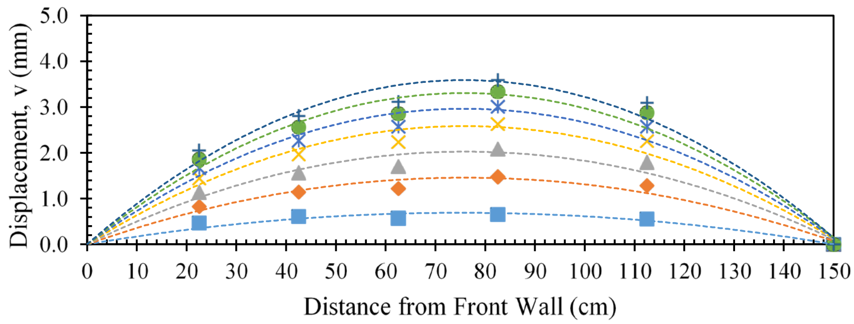
Figure 2. Horizontal soil displacement.

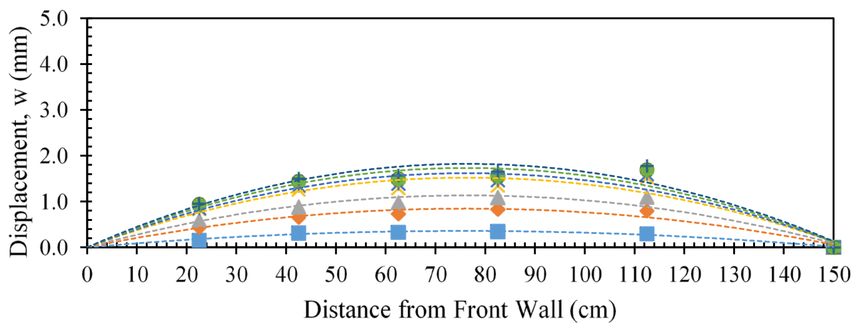
Reinforcement displacement profiles. Figure 3 shows the displacement profiles of the three reinforcement layers at various loading stages in a representative test (Morsy *et al.* 2019a). Specific frontal displacements, u1, were used to generate displacement profiles. Figure 3a shows the displacement profiles for the active reinforcement layer at increasing values of the frontal displacement. Figures 3b and 3c show the displacement profiles for the upper and lower passive reinforcement layers, respectively. It should be noted that the stresses generated at the soil-reinforcement interface of the active reinforcement layer shed at an angle. This results in maximum displacement magnitudes towards the middle of the passive reinforcement layers.



(a)



(b)



(c)

Figure 3. Reinforcement displacement profiles: (a) active reinforcement; (b) upper passive reinforcement; and (c) lower reinforcement.

Effect of reinforcement spacing. The experimental data generated as part of this study was used to evaluate the vertical reinforcement spacing below which the loading of a geosynthetic reinforcement affects the deformation response and load magnitude of adjacent reinforcement layers (Zornberg *et al.* 2019). Figure 4 shows the experimental data that was used to quantify the effect of reinforcement spacing on the interaction between neighboring reinforcement layers. Specifically, the ratio between the reinforcement displacements measured in a passive reinforcement, v, to the corresponding displacement measured in the active reinforcement, u, was used as an indicator to the degree of interaction between neighboring reinforcement layers. Figures 4a through 4c show the ratio adopted as indicator (v/u) as a function of reinforcement vertical spacing for different stages or loading levels in a test corresponding to u1 of 2, 5, and 10 mm. Two inflexion points can be observed in the relationships shown in the figures: (1) at a vertical spacing $S_{v,c}$ (*i.e.*, composite threshold) below which full interaction occurs between adjacent reinforcements; and (2) vertical spacing $S_{v,nc}$ (*i.e.*, non-composite threshold) beyond which no interaction occurs between adjacent reinforcements. Varying degrees of interaction between adjacent reinforcements can be observed for vertical spacing values ranging from $S_{v,c}$ to $S_{v,nc}$. The results indicate that maximum interaction between neighboring reinforcements occurred below a reinforcement spacing of approximately 0.10 m (*i.e.*, $S_{v,c}$ = 0.10 m) and minimum interaction between adjacent reinforcements occurred beyond a reinforcement vertical spacing value of approximately 0.20 m (*i.e.*, $S_{v,nc}$ = 0.20 m).

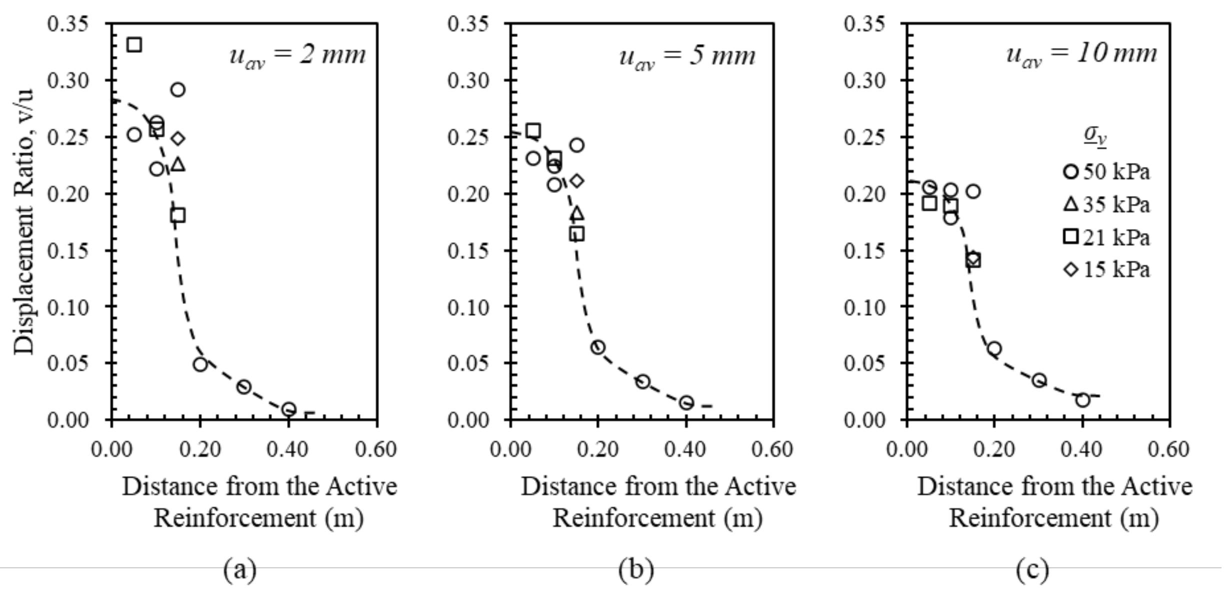


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Figure 4. Average displacement ratio of upper passive reinforcement layers at various average displacements of active reinforcement layers: (a) u_{av} = 2 mm; (b) u_{av} = 5 mm; and (c) u_{av} = 10 mm.

According to these experimental results, interaction between neighboring reinforcements occurred up to an average distance from active reinforcement (*i.e.*, reinforcement vertical spacing) of 0.15 m from the soil-reinforcement interface. In Figure 4, the reinforcement spacing at which a significant change in the interaction between neighboring reinforcements occurred can be used to define the boundary for the composite behavior of a geosynthetic-reinforced soil mass. It should be recognized that load in the experimental testing setup was mobilized in only one active reinforcement. In the case of multiple active (*i.e.*, loaded) reinforcements, the soil between would be mobilized in shear by the two neighboring reinforcement layers. Consequently, according to these experimental results, composite behavior could be observed for vertical spacing values corresponding to twice the distance from the active reinforcement layer shown in Figure 4. That is, an average of 0.30 m for select soil (AASHTO No. 8 gravel). This value is in good agreement with current limits for reinforcement spacing established by Adams *et al.* (2011) for geosynthetic-reinforced soil structures.

CONCLUSION

An experimental study was conducted to investigate the interactions that take place in geosynthetic-reinforced soils under both working stress and failure conditions considering varying reinforcement vertical spacings. A device was developed to perform this study designed to measure displacement fields of soils and reinforcing inclusions. The newly developed experimental device was used to conduct a comprehensive testing program to study the effects of normal stress, vertical reinforcement spacing, reinforcement type, and fill type on soil-reinforcement interaction. The following conclusions could be made:

- The device was capable of measuring tensile strains developing in both actively tensioned and neighboring geosynthetic reinforcement layers. It allowed direct visualization of the kinematic response of soil particles adjacent to the geosynthetic layers, which facilitated evaluation of the soil displacement field via digital image analysis. Evaluation of the soil displacement field allowed quantification of the extent of the zone of shear influence around a tensioned reinforcement layer. Finally, the device allowed monitoring of dilatancy within the reinforced soil mass, providing additional insight into the effect of reinforcement vertical spacing on the reinforced soil mass.
- Analysis of the experimental results revealed that the existence of the zone of shear influence and its extent can be directly related to the interaction between neighboring reinforcement layers.
- The interaction between adjacent reinforcement layers was found to increase with decreasing reinforcement vertical spacing. A minimum reinforcement vertical spacing threshold was identified below which the interaction between adjacent reinforcements develops fully. In addition, a maximum reinforcement vertical spacing threshold was identified beyond which the interaction between neighboring reinforcements becomes negligible. For the testing program implemented in this study, the minimum and maximum threshold vertical spacings were identified as 0.10 and 0.20 m (4 and 8 in.), respectively.
- According to these experimental results, the zone of shear influence extends an average distance of 0.15 m (6 in.) from the soil-geosynthetic interface. That is, interaction between adjacent reinforcements could be observed for a vertical spacing value corresponding to 0.30 m (12 in.), or twice the average distance from the reinforcement for which interaction occurs.

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