A Study on the effect of scale and testing method on soil-geosynthetic interaction

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ABSTRACT: A proper understanding of the soil-geosynthetic interaction is essential to the design of soil-geosynthetic systems under both ultimate (or large displacement) and service (or small displacement) conditions. Pullout and interface direct shear tests have been among the most widely used experimental techniques to evaluate this interaction. However, correlation between the results obtained using each testing method and the suitable testing scale have remained unclear. A pilot experimental program was conducted using pullout and direct shear devices of various scales. Experimental data obtained in the tests was analyzed to gain insight into the effect of the scale and testing method on the soil-geosynthetic interaction behavior. Specifically, load and displacement data, average interface shear values, and normalized displacements were compared for a baseline geosynthetic and backfill material tested in three testing scenarios: (1) large- and small-scale pullout tests, (2) large- and small-scale direct shear tests, and (3) same-scale pullout and direct shear tests. Overall, the ultimate interface shear was found to be similar in various testing scales and devices. However, the slope of the relationship between the interface shear and relative displacement between soil and geosynthetic was found to be sensitive to both test method and testing scale. Implication of the experimental observations in modeling soil-geosynthetic interaction was evaluated by simulation of a small-scale pullout test using a t-z analysis approach. Comparison of the simulation results with the experimental data further underlined significance of adopting suitable test method and testing scale for calibration and validation of analytical and numerical soil-geosynthetic interaction models.

Keywords: Soil-geosynthetic interaction; Pullout test; Interface direct shear test; numerical modeling; t-z analysis.

1 INTRODUCTION

A proper understanding of the soil-geosynthetic interaction is essential to the design of soil-geosynthetic systems. Characterization of soil-geosynthetic properties at ultimate states (i.e., at large displacements) would be relevant in soil-geosynthetic systems that are designed using limit states conditions (e.g., geosynthetic-reinforced soil walls) (e.g., Bathurst 2005; Morsy et al. 2017). On the other hand, stiffness properties of soil-geosynthetic interaction, which are characterized under small displacements, would be relevant in soil-geosynthetic systems that are designed using deformability or serviceability criteria (e.g., geosynthetic-stabilized base roadways) (e.g., Roodi and Zornberg 2017; Zornberg et al. 2017).

Soil-geosynthetic interaction has typically been evaluated using interface direct shear and pullout tests. The two tests mobilize the soil-geosynthetic interface shear in two different modes. While in the direct shear test soil is forced to slide on a stationary geosynthetic, in the pullout test the geosynthetic is subjected to increasing tension and is pulled out of a stationary soil mass. While both tests have been used to evaluate soil-geosynthetic interaction (e.g., Chen and Abu-Farsakh 2012; Weldu et al. 2016; Xiao et al. 2015), pullout test would be relevant in cases where elongation of the geosynthetic specimen is considered and direct shear test would be relevant in cases where the geosynthetic does not strain.

Various factors have been identified to affect the soil-geosynthetic interaction test results (e.g., Palmeira 2009). However, the effect of testing scale and the test method on soil-geosynthetic interaction have remained unclear. As part of an ongoing research study at the University of Texas at Austin, various soil-geosynthetic interaction testing equipment of different scales have been used to characterize soil-geosynthetic interaction properties for a wide range of backfill materials, geosynthetics, and testing conditions. This paper presents results obtained in a pilot testing program. Specifically, the soil-geosynthetic interaction data was analyzed in three testing scenarios: (1) large- and small-scale pullout tests, (2) large- and small-scale direct shear tests, and (3) same-scale pullout and direct shear tests. In the end, implication of the experimental observations in modeling soil-geosynthetic interaction was evaluated by simulation of a small-scale pullout test using a t-z analysis approach.

The experimental data presented in this paper was obtained using a baseline geosynthetic, and backfill material. This data will continue to be completed using a wide range of backfill materials, geosynthetics, and testing conditions.

2 BASELINE MATERIAL

Characteristics of the baseline materials used in the pilot testing program are presented in this section.

2.1 *Fill material*

The backfill material was Monterey No. 30 sand. This soil is uniformly graded clean sand classified as SP (poorly graded) according to the Unified Soil Classification System (USCS). This sand has rounded to sub-rounded particles and consists predominantly of quartz with a trace of feldspars and other minerals. The grain size of Monterey No. 30 sand ranges from 0.2 to 2 mm with a mean grain size of 0.7 mm (Figure 1). The coefficients of uniformity and curvature are 1.9 and 1.3, respectively. The backfill has a specific gravity of 2.65 and its minimum and maximum dry unit weight of 14.76 and 16.70 kN/m^3, respectively. The peak friction angle for Monterey No. 30 sand at relative density of 70% is estimated to be 36.7 degrees. This value is estimated from data obtained in triaxial testing condition.

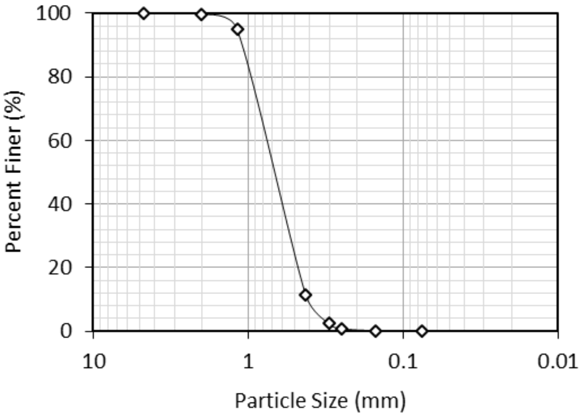


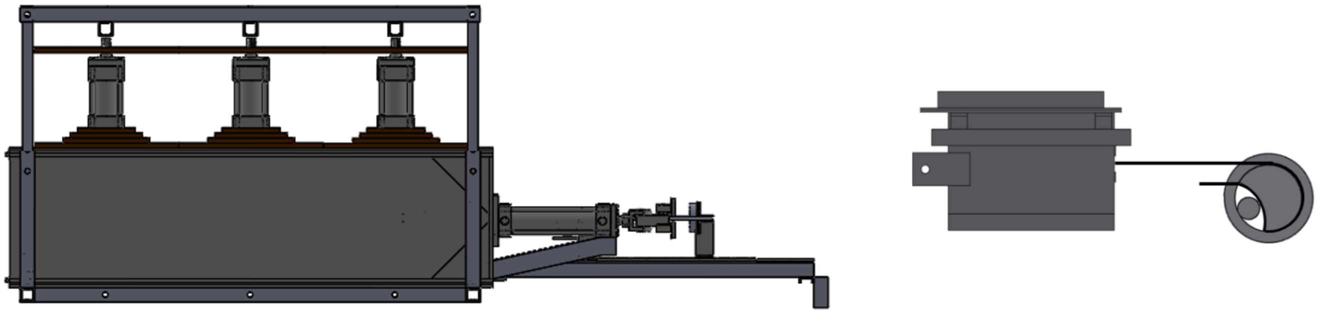
Figure 1. Grain size distribution of Monterey No. 30 sand

2.2 *Geosynthetic*

The geosynthetic material used in the pilot tests was a polypropylene woven geotextile. This geotextile has multi-filament yarns oriented in the machine direction and mono-filament yarns oriented in the cross--machine direction. Yarns in the machine direction are connected to each other forming a squeezed rhombic network. As reported by the manufacturer, the ultimate tensile strength of the geotextile in both machine and cross-machine directions is 70 kN/m. The tensile strength in cross-machine direction at 2 and 5 % strain was reported 19.3 and 39.4 kN/m, respectively, and the tensile strength in machine direction at 2 and 5 % strain was reported as 14 and 35 kN/m, respectively. The tensile properties were obtained in accordance with ASTM D4595. However, these properties are susceptible to variability results from manufacturing, transportation, and storage. In addition, tensile strength and stiffness vary with the strain rate during axial loading.

3 EFFECT OF SCALE IN PULLOUT TEST: LARGE VS. SMALL SCALE PULLOUT TEST

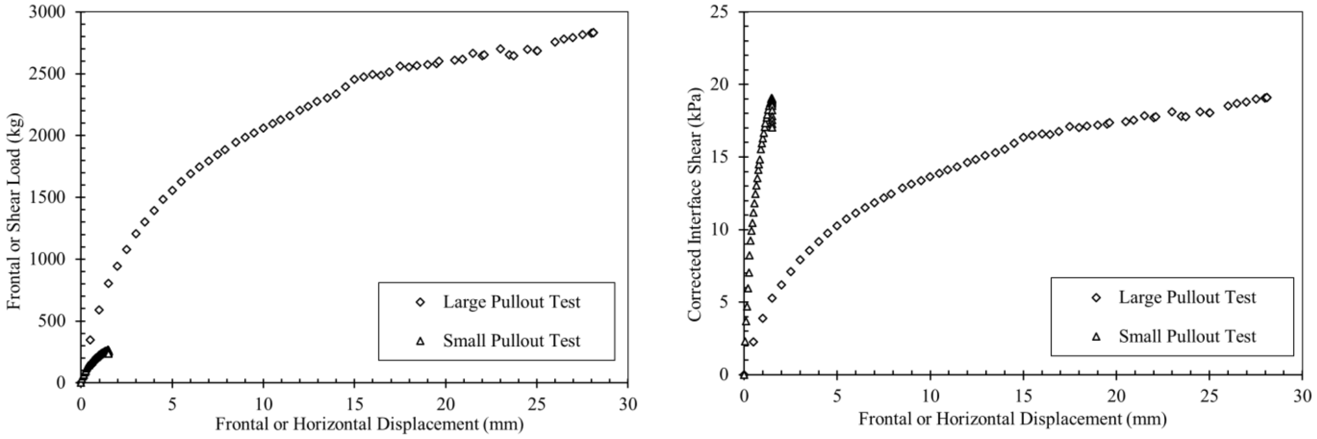
Effect of scale in pullout test was evaluated using two pullout devices of significantly different scales: a large-scale equipment with inner dimensions of 1,500 mm (length), 750 mm (width), and 450 mm (depth) (Figure 2a); and a small-scale equipment with inner dimensions of 250 mm (length), 300 mm (width), and 280 mm (depth) (Figure 2b). Smooth sheets were used on inner walls of the pullout boxes to minimize friction at boundaries. The dimensions of the geosynthetic specimen were approximately 750 x 1,000 mm (width x length), in the large-scale test, and 280 x 250 mm (width x length), in the small-scale test. Both specimens were tested in the cross-machine direction. The backfill material was placed and compacted using hand tampers to reach a target dry unit weight of 16.05 kN/m^3 in both tests. A normal pressure of 21 kPa was applied and geosynthetic specimens were pulled at a displacement rate of 1 mm/min.



(a) (b)

Figure 2. Schematic of pullout equipment used in the pilot testing program: a) large-scale; b) small-scale

Figure 3a presents the frontal load vs. frontal displacement obtained in the small- and large-scale pullout test. Expectedly, both ultimate frontal load and ultimate displacement in the large-scale test were significantly higher than those in the small-scale test. However, a more relevant comparison involves evaluation of the interface shear and shear strain between the two scales. The average interface shear was estimated by dividing the frontal load over the soil-geosynthetic contact area. The contact area was also corrected for the loss of contact results from the geosynthetic portion that is pulled out of the backfill. The corrected average interface shear versus displacement is presented in Figure 3b. The ultimate interface shear was found to be very close in the two testing scales as approximately 20 kN/m^2. The small-scale test, however, was found to show a higher slope of soil-geosynthetic interaction defined as the slope of the relationship between interface shear and displacement. This observation was expected because mobilization of the interface shear in pullout tests differs in various testing scales (Roodi et al. 2018). When geosynthetic specimen is comparatively small, the soil-geosynthetic interface shear is mobilized mainly by rigid movement of the geosynthetic, while the tensile strains remain comparatively small. Therefore, the ultimate interface shear in the small-scale test is expected to be reached at relatively small displacements when the entire geosynthetic displaces. However, in a large-scale test, the soil-geosynthetic interface shear is mobilized by both movement and deformation of the geosynthetic. Therefore, additional frontal displacements (and elongation of the front portion of the geosynthetic) is expected in the large-scale test as the mobilize length advances to the end of the geosynthetic.



(a) (b)

Figure 3. Comparison of test results obtained in small- and large-scale pullout tests: a) load versus displacement; b) average interface shear versus displacement.

As an additional effort to further compare consistency between the results obtained in the small- and large-scale pullout test, the interface shear values were compared using a normalized displacement. Frontal pullout displacements in each testing scale were normalized by the ultimate frontal displacement obtained in that scale. Results are presented in Figure 4. A reasonably good agreement was found between the results obtained in the two testing scales for both average interface shear values and the soil-geosynthetic interaction slopes.

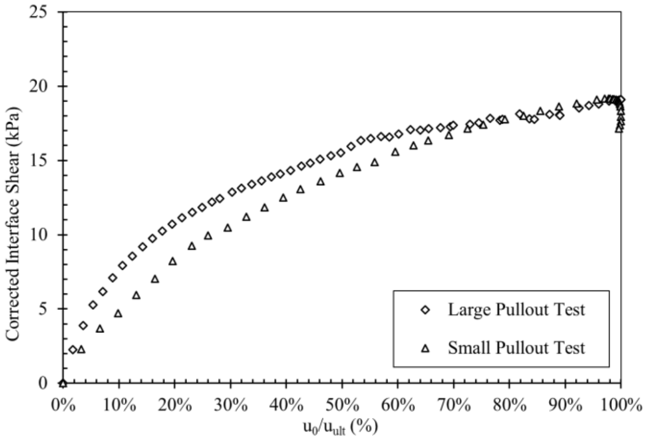
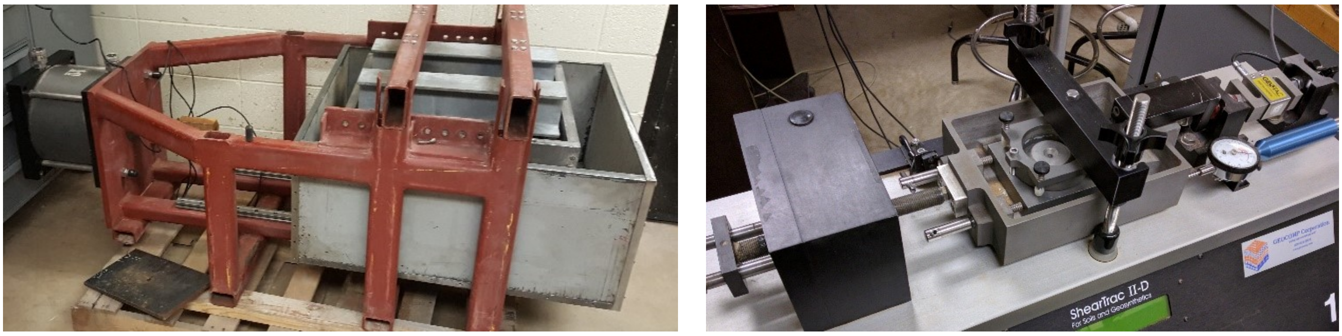


Figure 4. Average interface shear versus normalized displacements in small- and large-scale pullout tests

4 EFFECT OF SCALE IN DIRECT SHEAR TEST: LARGE VS. SMALL SCALE DIRECT SHEAR TEST

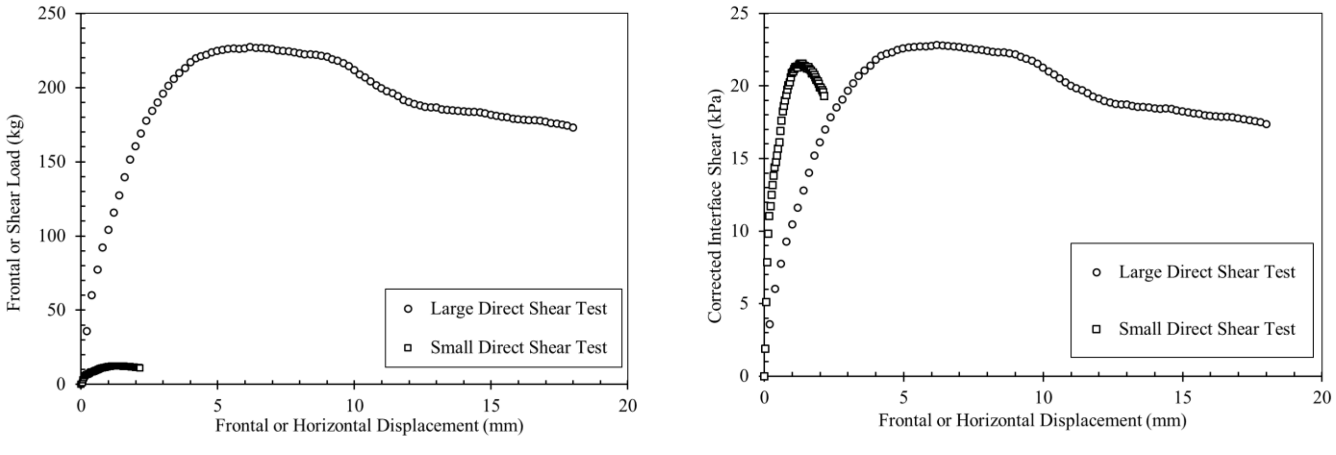
Effect of scale in direct shear test was evaluated using two direct shear setups of different scales. The large-scale setup included a shear box with inner dimensions of approximately 330 mm (length) and 300 mm (width) (Figure 5a). The small-scale equipment had inner dimensions of 75 mm (length) by 75 mm (width) (Figure 5b). The geosynthetic specimens were placed in the cross-machine direction and securely glued to the bottom half of the setups to minimize their deformation. Backfill material was placed and compacted in the top haves of the setups. The thickness of the soil layer was 75 mm and 25 mm in the large- and small-scale setups, respectively. Although a target dry unit weight of 16.05 kN/m^3 was set, the backfill density in the small-scale test was found to be slightly larger than the target. A normal pressure of 21 kPa was applied and the bottom halves of the setups were pulled at a displacement rate ranging from 0.5 to 1 mm/min. Vertical displacement was also measured at the center of the soil to evaluate dilation.



(a) (b)

Figure 5. Direct shear equipment used in the pilot testing program: a) large-scale; b) small-scale.

Figure 6a presents the shear load vs. horizontal displacement obtained in the small- and large-scale direct shear test. As expected, the test conducted in the large-scale setup resulted in significantly larger ultimate shear load and ultimate displacement. Average interface shear was obtained by dividing the shear load over the soil-geosynthetic contact area. Reduction in the contact area was also taken into account in the small-scale test where the box movement resulted in the loss of contact between the geosynthetic and backfill. Results are presented in Figure 6b. The ultimate interface shear was found to be very close in the two testing scales as approximately 22 kN/m^2. Consistent with the observation in the pullout tests, the small-scale test was found to have a higher slope of soil-geosynthetic interaction defined as the slope of the relationship between interface shear and soil-geosynthetic relative displacement.



(a) (b)

Figure 6. Comparison of test results obtained in small- and large-scale direct shear tests: a)load versus displacement; b) average interface shear versus displacement.

A clear distinction was found between the peak and the residual shear resistance (22.5 vs. 17.5 kN/m^2) in the large-scale test (Figure 6b). The peak interface shear was recorded at a relative displacement of approximately 5 mm, whereas the residual interface shear was observed at displacements exceeding 11 mm. Results obtained in the small-scale test exhibited a similar distinction between the peak and residual interface shear but at significantly smaller displacement range. Evaluation of the vertical displacement of backfill materials confirmed the observations of the soil-geosynthetic interaction behavior in the two testing scales. The vertical displacement data is presented in Figure 7. Note that the scales of the secondary horizontal and vertical axes, presented on the right and on the top, respectively, differs from the primary axes, presented on the left and in the bottom. The primary axes were used to present the data corresponds to the large-scale test and the secondary axes were used to show the data corresponds to the small-scale test. The large-scale test initially showed comparatively small amount of compression at displacement range of 0 to 10 mm. A significant dilation was then observed toward the end of the test when residual state was reached. In the small-scale test, however, compression was insignificant. This can be attributed to the comparatively larger soil density in the small-scale test. Similar to the large-scale test, substantial soil dilation was observed towards the end of the small-scale test. However, soil dilation in the small-scale test was significantly smaller than that in the large-scale test.

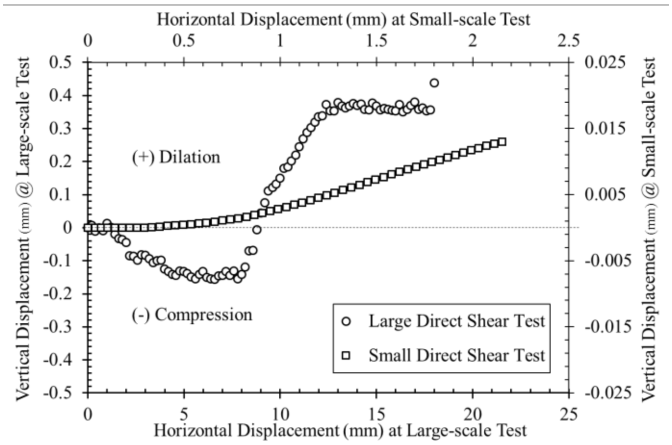


Figure 7. Dilation and compression of backfill in small- and large-scale direct shear tests

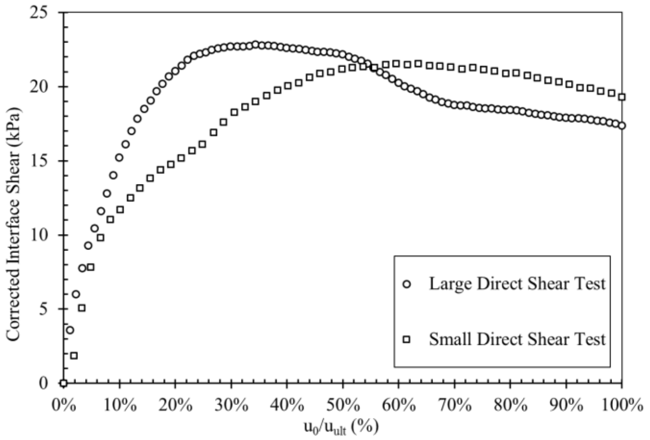


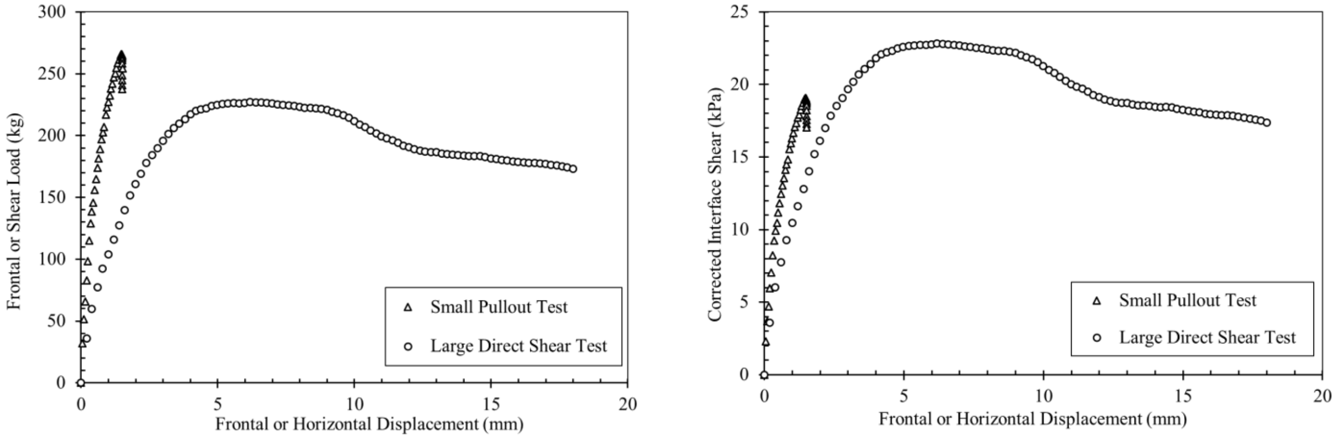
Figure 8. Average interface shear versus normalized displacements in small- and large-scale direct shear tests

Consistent with the analysis conducted on pullout test results, average interface shear values obtained in the direct shear tests were evaluated using normalized shear displacements. Results are presented in Figure 8. Shear displacements in each testing scale were normalized by the ultimate shear displacement obtained in that scale and presented as percentage on the horizontal axis in this figure. A reasonably good agreement was found between the results obtained in the two testing scales. Specifically, the slope of the soil-geosynthetic interaction curves were found to be similar in the initial portion.

5 EFFECT OF TEST METHOD: DIRECT SHEAR VS. PULLOUT TEST

Effect of test method on the soil-geosynthetic interaction response was evaluated by comparison of pullout and direct shear test results conducted using the same scale. Specifically, the test results obtained using the small-scale pullout device (300 mm (width) x 250 mm (length)) was compared to the test results obtained using the large-scale direct shear device (300 mm (width) x 330 mm (length)). The soil-geosynthetic interaction curves were found to be significantly different. This observation was expected as the two tests mobilize the soil-geosynthetic interface shear in different modes.

The load vs. displacement and interface shear vs. displacement data are presented in Figures 9a and b, respectively. As presented in Figure 9a, a significantly larger displacement was required in the direct shear test, as compared to the pullout test, to reach the ultimate interface shear (5 mm in the direct shear test vs. 1 mm in the pullout test). As presented in Figure 9b, the peak interface shear was found to be larger in the direct shear test. However, the ultimate interface shear (i.e., in the residual states) was expectedly found to be similar between the two tests. The slope of the soil-geosynthetic interaction defined as the slope of the relationship between the interface shear and relative displacement between soil and geosynthetic was found to be generally larger in the pullout test.



(a) (b)

Figure 9. Comparison of test results obtained in direct shear and pullout tests of the same scale: a)load versus displacement; b) average interface shear versus displacement.

6 IMPLICATION IN SOIL-GEOSYNTHETIC INTERACTION MODELING

Analytical modeling of soil-geosynthetic interaction requires suitable constitutive relationships to be defined for soil-geosynthetic interface. The soil-geosynthetic interface constitutive relationships typically relate the shear stress mobilized at the soil-geosynthetic interface to the relative displacement between the two materials. Some of the models adopted in previous studies to describe the interface interaction include: linear elastic (e.g., Yuan 2011); linear elastic-perfectly plastic (e.g., Bergado and Chai 1994); rigid-perfectly plastic (e.g., Roodi 2016); bilinear and hyperbolic models (e.g., Wilson-Fahmy and Koerner 1993); and more complex nonlinear multiphase models such as elasto-plastic strain hardening and softening models (*e.g.,* Perkins and Cuelho 1999). The soil-geosynthetic interface models have typically calibrated by experimental data obtained in direct shear tests. However, as presented in this study (Figure 6b), soil-geosynthetic interface shear vs. displacement relationship is not unique and is sensitive to the testing scale.

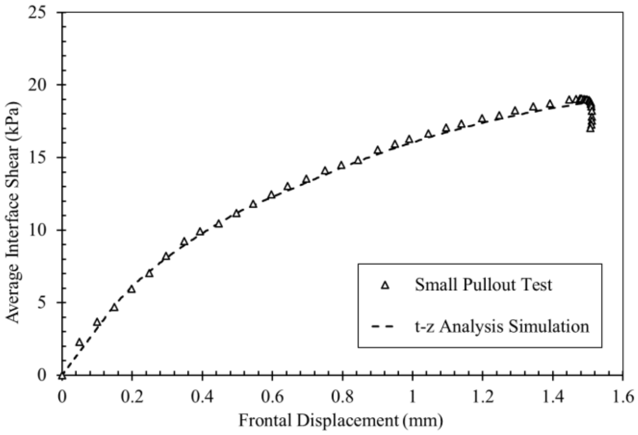
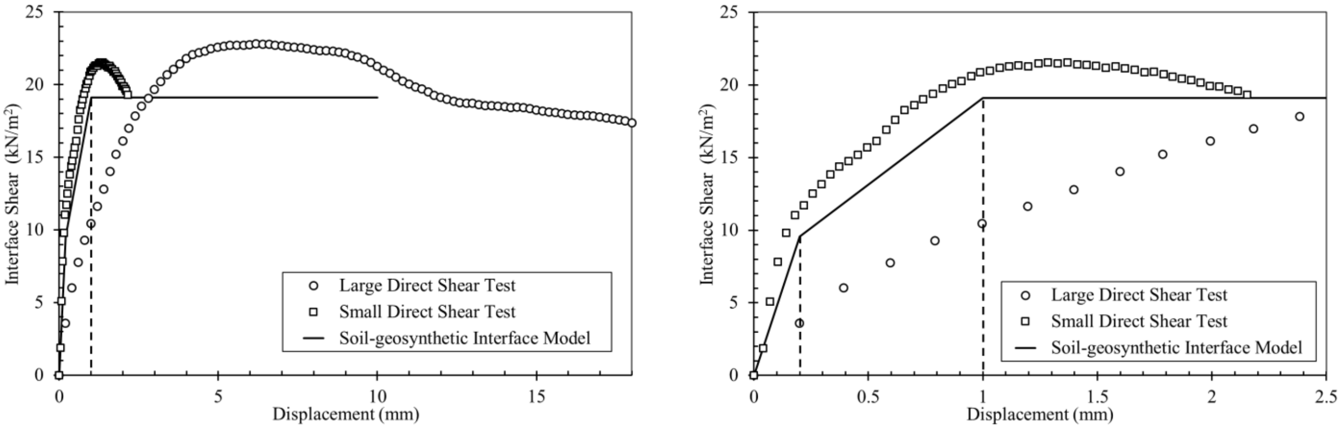


Figure 10. Simulation of pullout test results using t-z analysis approach

Experimental data obtained in this study was used in a pilot evaluation to identify suitable testing scale for soil-geosynthetic interface relationships. As part of this evaluation, an iterative procedure based on t-z analysis approach was implemented to simulate soil-geosynthetic interaction data obtained in the small pullout test presented in this paper (Refer to Roodi et al. (2018a and b) for more details regarding implementation of the t-z analysis approach). Specifically, constitutive models were assumed for geosynthetic and soil-geosynthetic interaction and the small pullout test was simulated. Various soil-geosynthetic interface models were then tried to identify the best fit to the experimental data obtained in the small pullout test. As presented in Figure 10, the iterative procedure resulted an excellent agreement between simulated data and the experimental data obtained in the small pullout test.

The soil-geosynthetic interface model that resulted the best fit to the experimental pullout data involved a bilinear-plastic model. The displacement that corresponded to the beginning of the plastic portion of the model was 1 mm and the displacement corresponded to the end of the first linear portion of the model was 0.2 mm. Figure 11a compares this model against the experimental data obtained in this study using direct shear setups of different scales. Figure 11b shows a close view of the same data in the displacement range of 0 to 2.5 mm. Evaluation of the data presented in this figure indicates that the small-scale direct shear test provided a significantly more suitable data (as compared to that provided by the large-scale direct shear test) to be used for soil-geosynthetic interface modeling. This observation underlines significance of adopting suitable testing scales for calibration and validation of analytical and numerical soil-geosynthetic interaction models.



(a) (b)

Figure 11. Soil-geosynthetic interface model obtained for pullout test as compared to direct shear test results: a) general view; b) close view in displacement range of 0 to 2.5 mm.

7 CONCLUSIONS

Effect of scale and testing method on the soil-geosynthetic interaction data was evaluated through a series of various soil-geosynthetic interaction tests conducted in various scales. Specifically, large- and small-scale pullout devices and large- and small-scale direct shear devices were used. Load and displacement data, average interface shear values, and normalized displacements were compared among the tests.

Overall, a reasonably good consistency was found among the ultimate interface shear values obtained in various testing scales and devices. However, absolute value of displacements in the large-scale tests significantly differed from those in the small-scale tests. Nonetheless, reasonably good agreement was found between average interface shear versus normalized displacement data for the same type of tests conducted in different scales.

Stiffness of the soil-geosynthetic interaction data, defined as the slope of the relationship between average interface shear and relative displacement between soil and geosynthetic, was found to be higher in the small-scale tests as compared to that in the large-scale tests. Furthermore, comparison of the results obtained using pullout and direct shear tests of the same scales indicated that this slope was higher in the pullout test.

Experimental data obtained in this study was used to evaluate suitability of soil-geosynthetic interface shear models typically used in soil-geosynthetic interaction modeling. Specifically, as part of an iterative procedure, various soil-geosynthetic interface models were tried and the model that could produce the best fit to the experimental pullout data was identified. The identified model was then compared to the experimental data obtained in the direct shear tests. This comparison indicated that the small-scale direct shear test data was indeed a more suitable data to predict soil-geosynthetic interaction response. This observation underlines significance of adopting suitable testing scales for calibration and validation of analytical and numerical soil-geosynthetic interaction models.

Conclusions drawn in this paper have been based on the experiments conducted using a baseline soil, geosynthetic type, and testing condition. This research is currently ongoing at the University of Texas at Austin aimed at generalizing these conclusions for a wider range of materials and testing conditions. Experimental data, findings, and conclusions will be updated accordingly.

REFERENCES

Bathurst, R.J., Allen, T.M., & Walters, D.L. (2005). “Reinforcement loads in geosynthetic walls and the case for a new working stress design method.” *Geotext. Geomembr* , 23(4):287-322.

Bergado, D.T., and J.C. Chai. Pullout force–displacement relationship of extensible grid reinforcements.” G&G, Vol.13, No.5, 1994, pp.295–316.

Chen, Q., and M. Abu-Farsakh. Structural contribution of geogrid reinforcement in pavement. Proc. Geo-Congress 2012, 2012, pp.1468–1475.

Morsy, A.M., Leshchinsky, D., and Zornberg, J.G. (2017), “Effect of Reinforcement Spacing on the Behavior of Geosynthetic-Reinforced Soil,” Proceedings of Geotechnical Frontiers, ASCE, Orlando, Florida, pp. 112-125.

Palmeira, E.M. (2009), “Soil-Geosynthetic Interaction: Modelling and Analysis,” Geotextiles and Geomembranes, Vol. 27, No. 5, pp. 368-390.

Perkins, S.W., and E.V. Cuelho. Soil-geosynthetic interface strength and stiffness relationships from pullout tests. Geosynth. Int., Vol.6, No.5, 1999, pp.321–346.

Roodi, G.H. Analytical, experimental, and field evaluations of soil-geosynthetic interaction under small displacements. Ph.D. dissertation, Univ. of Texas, Austin, 2016.

Roodi, G.H., Morsy, A. M., and Zornberg, J. G. (2018a). “Soil-Geosynthetic Interface Shear in Different Testing Scales.” Transportation Research Board (TRB), Annual Meeting, Washington, D.C.

Roodi, G.H., Morsy, A. M., and Zornberg, J. G. (2018b). “Implementation of T-Z Analysis Approach to Predict Pullout Test Results.” Proceedings International Foundations Congress and Equipment Exposition (IFCEE 2018), ASCE, Orlando, Florida.

Roodi, G. H., and Zornberg, J.G. (2017), “Stiffness of Soil-Geosynthetic Composite under Small Displacements: II. Experimental Evaluation,” Journal of Geotechnical and Geoenvironmental Engineering, ASCE, Vol. 143, No. 10.

Weldu, M.T., J. Han, S.M. Rahmaninezhad, R.L. Parsons, J.I. Kakrasul, and Y. Jiang. Effect of aggregate uniformity on pullout resistance of steel strip reinforcement. Transportation Research Record 2579, 2016, pp.1–7.

Wilson-Fahmy, R.F., and R.M. Koerner. Finite element modeling of soil-geogrid interaction with application to the behavior of geogrids in a pullout loading condition. G&G, Vol.12, No.5, 1993, pp.479–501.

Xiao, M., Ledezma, M., and Hartman, C. (2015). “Shear resistance of tire-derived aggregate using large-scale direct shear tests.” J. Mater. Civil Eng., 10.1061/(ASCE)MT.1943-5533.0001007, 04014110.

Yuan, Z. Pullout response of geosynthetic in soil-theoretical analysis. Proc. Geo-Frontiers, 2011 pp.4388–4397.

Zornberg, J.G., Roodi, G.H., and Gupta, R. (2017), “Stiffness of Soil-Geosynthetic Composite under Small Displacements: I. Model Development,” Journal of Geotechnical and Geoenvironmental Engineering, ASCE, Vol. 143, No. 10.