A tensile test device for evaluation of load-strain behavior of geosynthetics under operational conditions of reinforced soil walls

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ABSTRACT: In many cases, design of geosynthetic-reinforced soil walls requires analyses involving deformation that are supplied by deformation parameters of the geosynthetic, soil and/or geosynthetic-soil systems. The load-strain characteristics of geosynthetic reinforcements should be measured under the soil-confinement condition. Most of the research studies reported in literature revealed the effect of soil confinement on the tensile strength and deformability of geosynthetic reinforcements by means of laboratory tests devices in which the load is directly applied to the geosynthetic. However, little research has been focused on devices that properly reproduces the typical operational conditions of geosynthetic-reinforced soil walls, in which load is transferred to the geosynthetic through the surrounding soil. This paper describes a tensile test device for evaluation of load-deformation responses of geosynthetics based on a load-transfer mechanism from surrounding soil to reinforcement. The tensile load and deformation captured by the test device consider the interface soil response with the elongation of the reinforcement during loading transfer and reflect the strain compatibility between the soil and the reinforcement. A reinforced layer composed of a geogrid reinforcement and sand as backfill soil was tested. The device allowed to reveal that confined geogrid modulus is twice of unconfined. The novel tensile test device demonstrates to properly simulate an operational condition of geosynthetic-reinforced wall layer in terms of displacement and strains distributions and mobilized tensile loads.

Keywords: Geosynthetic, confined tensile test, tensile modulus, deformability.

1 INTRODUCTION

Geosynthetic-reinforced soil structures have been extensively used during the last decades in geotechnical engineering. Generally, analytical design methods are based on the limit equilibrium method or the finite element method. For analysis using the finite element method, it is generally required to supply the deformation parameter of the geosynthetic for a linear elastic model, and the deformation and strength parameters for a non-linear elastic or elasto-plastic model. The exact required parameters should be defined in a manner of simulating the operational condition of geosynthetic-reinforced soil structures. In operational conditions in GRS walls, mobilized tensile stresses are due to the transference from the backfill soil subjected to a service limit state and not ultimate limit state as adopted in conventional design analyses.

Some researchers have suggested that the tensile characteristics of geosynthetics should be measured under the soil-confinement condition (McGown et al. 1981, 1982, Christopher et al. 1986, Tatsuoka et al. 1986, Kokkalis & Papacharisis 1989, Wu and Arabian 1988, Ballegeer et al. 1993, Wilson-Fahmy et al. 1993, Boyle et al. 1996, Yuan et al. 1998, Won and Kim 2007, 2014). One of the important findings obtained from these in-soil tests was that there was a significant increase in the stiffness and strength of the geotextiles confined with soil compared with the unconfined condition more than other geosynthetics.

However, most of the research studies revealed the effect of soil confinement on the tensile strength and deformability of geosynthetic reinforcements by means of tensile test devices that the load is directly applied to the geosynthetic reinforcement. Little research has been focused on devices that properly reproduces the typical operational conditions, in which load is transferred to the geosynthetic through the surrounding soil. Ling et al. (1992) report that it is very likely that these in-soil tests did not simulate the operational conditions of a geosynthetic in a reinforced soil structure. In fact, in these tests, the soil was kept stationary inside a box, and the geotextile had to overcome the frictional resistance against the stationary soil before the tensile load in the geotextile could be mobilized. As a result, the measured load reflects the combined effects of the frictional force and the stress confinement. As the slippage at the soil-geosynthetic interfaces will not occur until a failure state is approached, most of conventional in-soil tensile devices did not simulates a geosynthetic-reinforced soil structures under typical operational conditions. Consequently, conventional in-soil devices overestimate the strength and stiffness of geosynthetics and might render the design unsafe.

Ling et al. (1992) developed a device capable of measuring the strength and deformation properties of geotextiles under confinement condition using membrane or soil. The device differed from conventional in-soil test devices in that during the soil-confinement test the soil was allowed to deform with the geotextile while being confined by a prescribed pressure simulating the predominant operational condition of geotextiles in reinforced soil structures.

Similarly, Whittle et al. (1993) developed a laboratory device that provides accurate measurements of load-transfer for a planar reinforcing inclusion as the surrounding soil matrix is deformed in a plane strain compression mode of shearing. Differently of other cited works, the device properly simulates operational conditions of reinforced soil structures as the load is applied to the geosynthetic through the surrounding soil. In this study, the data demonstrate the importance of the inclusion length on the load-transfer mechanism. In addition, the performance of these composite soil structures depends, in large part, on the interaction between the soil matrix and the inclusions, which determines the magnitude of loads carried by the reinforcement.

This paper describes the development of a tensile test device in which loads and deformations in geosynthetic reinforcement are developed due to load-transfer from surrounding soil to reinforcement stablishing an operation condition of geosynthetic-reinforced soil walls. This device considers that an appropriate soil-reinforcement load-transfer model should couple the interface soil response with the elongation of the reinforcement during loading transfer and should verify the strain compatibility between the soil and the reinforcement. The device is capable of measuring directly the tensile stresses within the reinforcement and imposes well-defined boundary conditions on the soil specimen. Measurements provide a method for comparing load-transfer characteristics for different types of geosynthetic reinforcements and backfill soils.

2 TESTING PROGRAM

This section describe the device used for determination of in-soil deformability of a geogrid, as well as the geosynthetic and backfill materials evaluated.

2.1 *Confined tensile test device*

A confined tensile test device for determining the confined load-deformation properties of geosynthetics was developed. The device simulates a geosynthetic reinforced-soil layer for measuring the maximum tensile load transferred to a planar reinforcement due to plane strain shearing of the surrounding soil. The geosynthetic mobilizes the maximum tensile load at the potential failure surface along the reinforced-soil structure length.

The reinforced soil system, with internal dimensions of 600 x 750 x 700 mm (width x length x height), basically involves geosynthetic reinforcement between two compacted soil layers located within a rigid metal box, of which one of the sides is a transparent glass wall. The device setup is illustrated in Figure 1. The boundary conditions are well defined by zero lateral displacement in both the soil and reinforcement due to lateral wall confinement. The rear and lateral walls of the cell is rigid and lubricated to minimize friction along the center plane of the unit element. The front wall is free to move in the horizontal direction by using wheels running along rails that are located at the bottom of the metallic container. The reinforced soil is compacted over two cars (plates with wheels) and is consequently free to move horizontally. The cars run internally along rails of which the spacing between both cars imposes a failure surface. The wheels system allows the cars running over the rails with insignificant friction (2 degrees). The key design feature of the confined tensile test device is that one of the reinforcement ends is clamped externally to the metallic wall restricting the displacements, while the opposite end is clamped to a load cell that measures the force mobilized by the reinforcement at a location equivalent to the centerline of the inclusion. The load cell is connected to a portico attached to the front wall, and the relative displacements between the portico and the front geosynthetic clamp allow for measurement of the mobilized tensile loads during testing.

Vertical stress is applied over a rigid plate on top of the reinforced soil unit by using a hydraulic piston, as shown in Figure 1. The working principle of this equipment consists of applying vertical stress on the top of the reinforced soil unit, resulting in horizontal forces being transferred to the moving wall and external porticos. While the geosynthetic is strained, the internal clamp tends to restrict the wall movement, resulting in a reaction force between the clamp and portico. This measured force consists of that mobilized by the reinforcement.

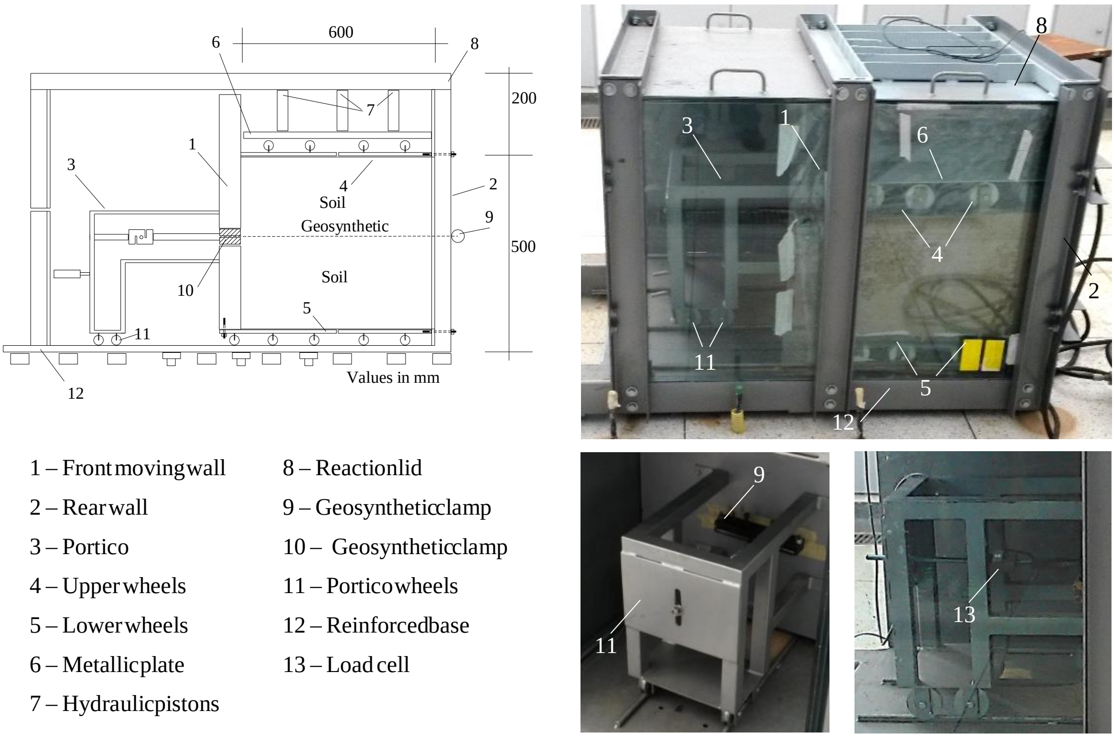

Figure 1. The confined tensile test device.

2.2 *Instrumentation*

Instruments were used to monitor tensile loads and internal displacements (Figure 2a). A load cell located between the external portico and clamps allowed for measurement of the horizontal loads mobilized by the geosynthetic reinforcements as previously described. Furthermore, internal displacements were obtained by using wire extensometers. This technique involved one end of inextensible wires being attached to different points along the geotextile length, while the other end of the inextensible wires was attached to positioning sensors (potentiometers) with 0.001 mm precision (Figure 2b). The relative displacements between two wire extensometers allowed for the calculation of reinforcement strains. An external displacement transducer measures the moving wall displacements at the frontal clamp, corresponding to the total displacement. Earth pressure cells were used to monitor vertical stresses at the proximity of the reinforcement line and horizontal stresses at the contact between soil and the frontal wall. Figure 2 provides details of instruments location.

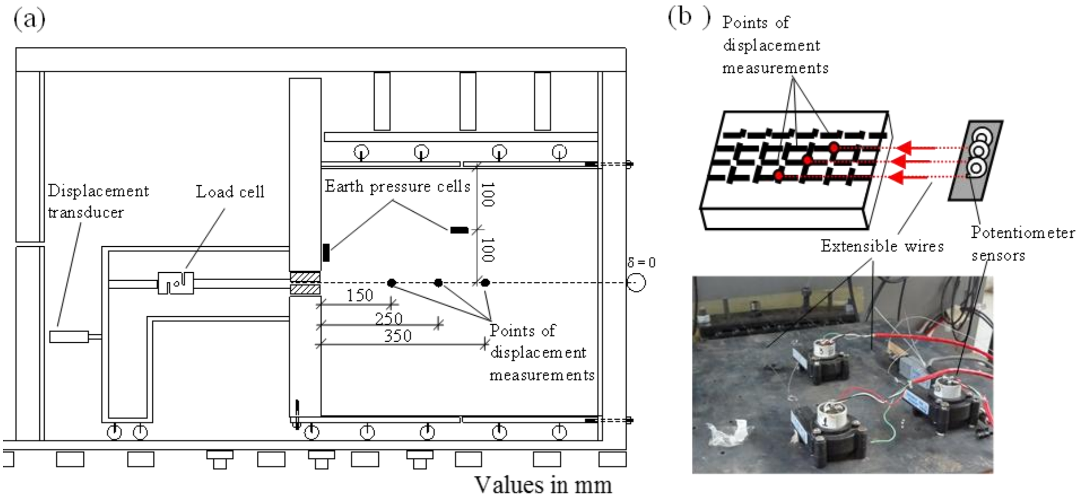

Figure 2. Schematic detail of instruments location: (a) Overall; (b) Internal displacement measurements.

2.3 *Testing materials*

The soil used in this study was a clean medium to course sand (quartz poorly graded sand, G_s = 2.67). Its maximum and minimum dry densities were 17.6 kN/m^3 and 15.7 kN/m^3, respectively. The grain size distribution is shown in Figure 3.

To determine the internal friction angle of this sand, direct shear tests have been conducted on sand samples compacted to the dry density of 16 kN/m^3 and normal stresses of 15, 30, 60 and 120 kPa. Results show that the direct shear friction angle of the sand is 31^o.

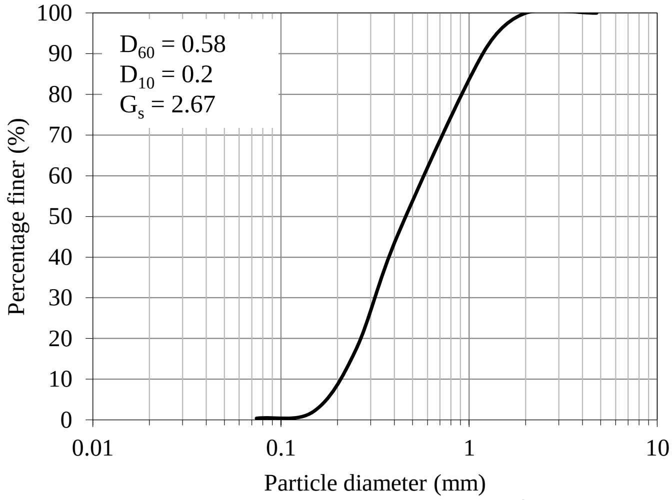

Figure 3. Grain size distribution of the sand.

The geosynthetics used for the tensile tests included a polyester woven geogrid (named here as GG. Table 1 summarizes the physical and mechanical properties of the geogrid used in the tests. To be used in the tensile tests, geogrid was cut in specimens of 550 mm length and 700 mm width.

Table 1. Physical and mechanical properties of geosynthetics used in the experiment.

Properties	Standard	Values
Weight per unit area (g/m^3)	ASTM D5261	-
Thickness (mm)	ASTM D5199	1.3
Ultimate tensile strength (kN/m)	ASTM D4595/D6637	42
Elongation at failure (%)	ASTM D4595/D6637	13
Tensile strength at 2% strain (kN/m)	ASTM D4595/D6637	3.0
MD Yarn width (mm)	-	3.0
CMD Yarn width (mm)	-	8.5
MD aperture (mm)	-	27
CMD aperture (mm)	-	19

* MD – Machine direction, CMD – Cross-machine direction.

2.4 *Testing procedure*

The tensile tests were performed in order to simulate a reinforced layers of geosynthetic-reinforce soil walls. Sand specimens were prepared by raining particles through an assembly of sieves (dry pluviation) in order to achieve specimens of specified target density of 16 kN/m^3. The raining device for comprises a sand hopper with a perforated base mounted on a 1.4 m high chimney which contains a series of wire mesh screens. Sand was compacted over the bottom cars that were previously covered with a thin plastic sheet used to avoid sand run off during tests. The geosynthetic sample (550 x 700 mm) was embedded between two 150 mm-thick soil layers. To ensure a plane strain condition throughout the test, the adhesion between the sidewalls and soil was reduced by creating a lubrication layer at the interface, which consists of a latex transparent sheet and thin layer of silicon grease. The upper wheels were positioned over the surface of compacted sand. Vertical stresses were applied over a rigid plate located over the upper wheels by using two hydraulic pistons.

Tests consisted of applying increments of vertical stresses of 50 kPa, which were maintained for five minutes. The final vertical stress reached was of 200 kPa. During tests, instrumentation monitored internal and front wall displacements, earth pressures, and tensile loads as described previously.

3 RESULTS

Figure 4 shows the responses of earth pressures cells installed in vertical and horizontal positions. The horizontal earth pressure cell was installed in contact with the front wall to allow the calculation of the reinforced active stress coefficient. This coefficient can be compared to the theoretical coefficient used in design analyses as that obtained from the Rankine`s theory. Vertical and horizontal measured earth pressures are plotted against the external displacement at the front moving wall. Results show that the vertical earth pressure cell properly responded the applied vertical stresses (increments of 50 kPa with maximum of 200 kPa). Horizontal pressures cells presented responses varying from 10 to 30 kPa, which reduced with the front wall displacements. These measurements resulted in an average stress coefficient of 0.1. This value is low values when compared to the Rankine`s pressure coefficient of 0.33, which indicates that the horizontal stresses conventionally adopted can be overestimated when using conventional design analyses of reinforced soil walls.

As regards the horizontal measurements, lateral pressures were found to reduce with vertical pressures increases. The reduction is attributed to the lateral displacement of the front wall resulting in relative displacement between soil and front wall. Therefore, lateral pressures captured by the cells should be relocated to proper responses.

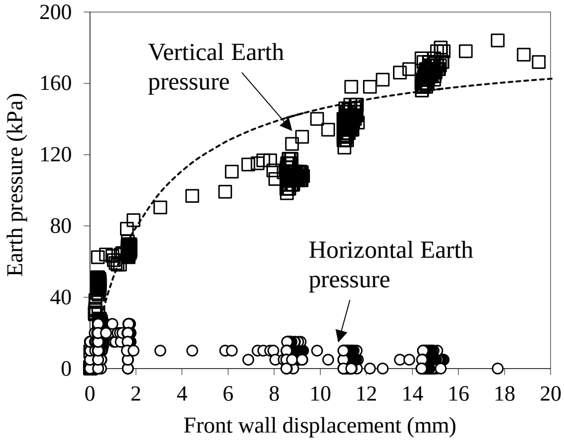

Figure 4. Vertical and lateral earth pressures measured during confined tensile tests at the proximity of the geogrid and at the interface between soil and front wall.

The distribution of internal displacements measured along the reinforcement length is shown in Figure 5a. Internal displacement tend to increase as closer the measured points are from the front wall. This behavior agrees to the distributions of displacements observed in many reinforced soil walls reported in literature (Portelinha and Zornberg 2017, Portelinha et al. 2014, Zornberg and Arriaga 2003). This is an evidence that the proposed device properly simulates the displacements behavior of reinforced soil layers of geosynthetic reinforced soil walls. Figure 5b shows the strain distribution along the geosynthetic reinforcement. The strains were calculated based on the relative displacement measured in consecutive points. Strains were obtained dividing the relative displacements by the distance between consecutive points. It should be noted that the peak strain occurred at the distance of 300 mm from the front wall. This is the exact position of the spacing between both cars that imposes failure surface, demonstrating most of straining occurring at this point, as expected. This behavior validates the proposed tensile test device. During tests, reinforcement strains reached maximum value of 7%, half of the total strain at failure of 14% (Table 1).

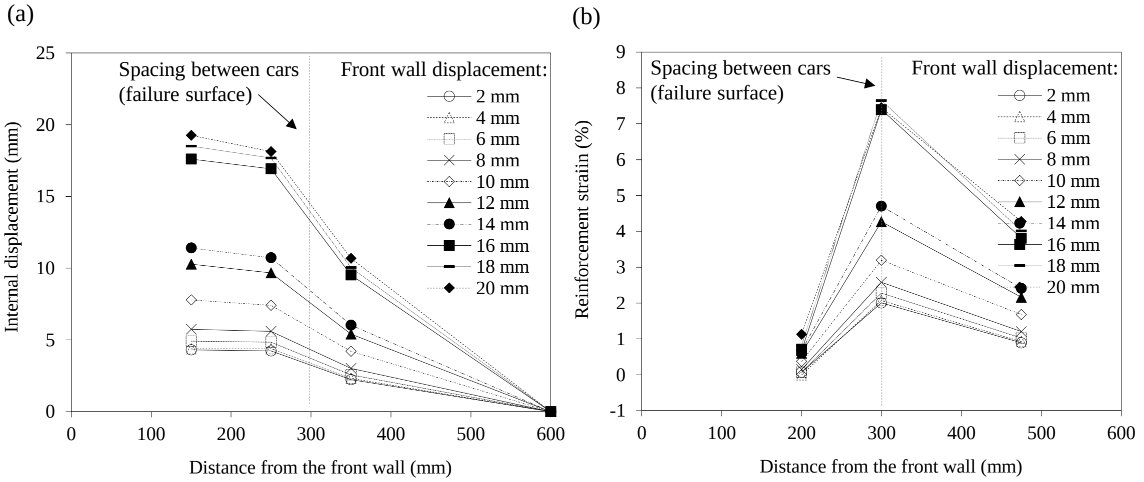

Figure 5. Distribution of displacements (a) and strains (b) during confined tensile tests of a geogrid in sand.

Figure 6 shows the tensile load measured by the load cell fixed at the geosynthetic clamp and the moving external portico as previously detailed. These values correspond to tensile loads mobilized by the geogrid during applied vertical loading. In Figure 3a, tensile loads are related to the front wall displacements also monitored during tests. Results shows a well defined load-displacement curve, in which the maximum tensile load mobilized by the geogrid is 9 kN/m. In Figure 3b, the mobilized tensile load is plotted against the internal displacements measured at distances from the front wall of 150, 250 and 350 mm. higher displacements were observed at distances of 250 and 350 mm, which is expected as the spacing between running cars is located at the distance of 300 mm from the front wall. Observe that the lateral earth pressure from Rankine's theory would be around 25 kN/m, considering the pressure coefficient of 0.33, the final vertical surcharge of 200 kPa, and and reinforced layer of 300 mm thick. Therefore, Rankine's theory was found to overestimate in 80% the horizontal load when compared to the mobilized tensile load measured in the novel device.

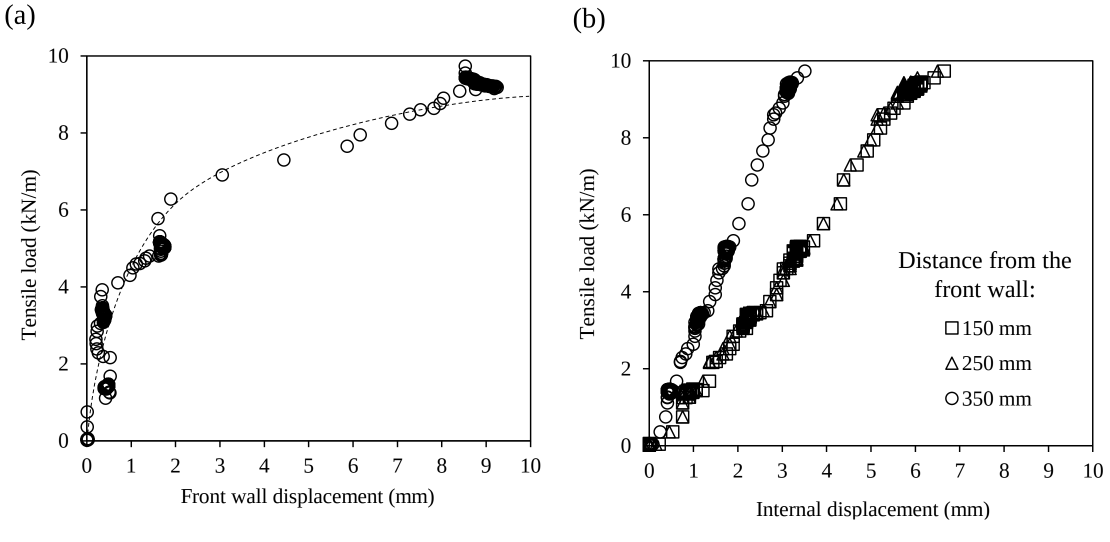

Figure 6. Mobilized tensile load of the geogrid in sand: (a) tensile load *versus* front wall displacements; (b) tensile load *versus* internal displacements.

Confined tensile curves obtained from the novel device is compared to the in-isolation tensile loads from conventional wide-strip tensile tests in Figure 7. Note that the geogrid deformability is improved by the confinement as reported by many studies in literature (Juran et al. 1989, França et al. 2014). An interesting aspect is that the improvement of geogrid stiffness occurs for small strains up to 5%. From 5% of straining, the in-soil and in-isolation tensile load were found to have similar values. Results shows that from 3% of strains, which is a regular magnitude of strains in operational conditions, the geogrid secant modulus is 233 kN/m from confined tests, while the value is 115 kN/m from in-isolation conventional tensile tests. In conclusion, the novel device demonstrates that the confined geogrid modulus is twice of unconfined stiffness. Juran and Christopher. (1989) observed similar level of improvement in laboratory geogrid models. França et al. (2014) also presents a development of a device for confined tensile tests. The authors reports that the confined stiffness of a geogrid is 1.7 higher than that obtained from conventional tensile tests. However, the in-soil tensile test device developed by França et al. (2014) applied the tensile load directly to the confined geogrid. The present device describe herein simulates the operational conditions by the transference of stresses by the soil to the embedded geosynthetic. Unexpectedly, both device demonstrated similar improvement on geogrid deformability.

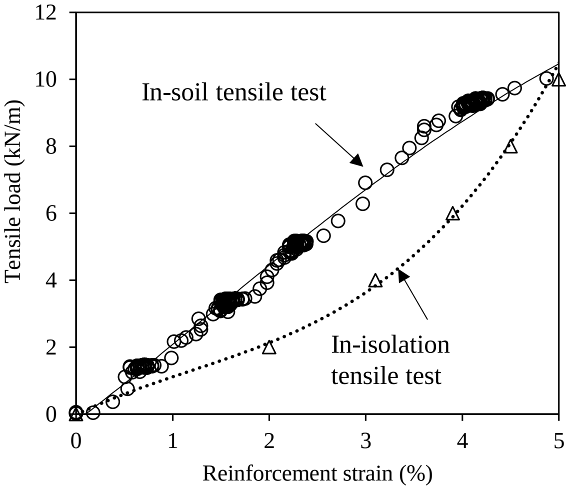

Figure 7. Comparison of confined and unconfined tensile load-deformation of the geogrid in sand.

4 CONCLUSIONS

The present study reports a novel device for determination of tensile modulus of geosynthetic under typical operational conditions of geosynthetic-reinforced soil walls. The test equipment simulates a geosynthetic-reinforced layer subjected to increment of surcharge loads. Specific system was deployed to impose the failure surface by a set of running wheels located at the base of the reinforced layer. The tensile test device allows the measurement of mobilized tensile loads and geosynthetic straining during loading. In addition, earth pressure cell were installed inside the backfill soil to measure vertical and horizontal stresses acting in the reinforced system. This study is part of an extensive research project that investigates the effect of wetting front on the mobilized tensile load of geosynthetics. However, the present paper describes the preliminary results of a confined tensile test of a geogrid in a sandy backfill soil. Based on the results presented, the following conclusion can be drawn:

- The novel tensile test device demonstrates to properly simulate a typical operational condition of a geosynthetic-reinforced soil wall layer as the displacements and strains distributions were consistent to those observed in GRS walls in literature. Additionally, differently of other conventional confined tensile test devices, the proposed device impose lateral earth stresses proportional to vertical stresses differently of conventional confined tensile tests reported in literature.
- The earth pressures measured inside the backfill, at vertical position and at the horizontal contact with the front wall indicates that the conventional earth pressure theories overestimate the lateral pressures in design analyses. Results indicated that Rankine’s theory overestimate the tensile load in 80%;
- The confined tensile test apparatus allowed to observe that geogrid modulus is improved by the soil confinement mainly for small strains up to 5%. From 5% of straining, the confined and in-isolation tensile load were found to have similar values, which is expected in operational conditions of GRS walls.

- The novel tensile test device demonstrates the in-soil geogrid modulus (at 3% of strains) as twice of unconfined modulus. Similar conclusions were observed in other tensile test device even not simulating operational conditions. Although similar results were obtained among the different confined tensile test devices cited in the present paper, those in which the tensile load is directly applied to the reinforcement are questionable once the mechanisms involving the operational condition of a reinforced layer are not simulated as the device proposed herein.

Although the tensile test device has indicated to proper determine the geogrid deformability, additional tests including other types of geosynthetics and backfill soils must be conducted to better validate the equipment functioning.

ACKNOWLEDGEMENTS

Sao Paulo Research Foundation (FAPESP) provided financial support for this study in the form a research grant awarded to the first author (Grant No. 2015/05807-5).

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