Pullout Device for Nonisothermal Response of Reinforcing Geosynthetics in Thermally-active Geotechnical Systems

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ABSTRACT
This study focuses on the development of a pullout device that can be used to evaluate the effects of thermal softening on geosynthetics confined in compacted soil. The new pullout box incorporates standard elements such as roller grips, a setup to apply tensile loads in load-control conditions for pullout or creep testing, instrumentation for measurement of vertical displacements under constant normal stress conditions, and instrumentation to measure global and internal pullout displacements. The box also incorporates heating elements at the top and bottom of the soil layer, along with an array of dielectric sensors for measurement of soil temperature and volumetric water content. Results are presented to show the effects of transient heat transfer and water flow in the backfill soil on the pullout creep of a woven polypropylene geotextile. The preliminary results indicate the importance of considering the combined roles of unsaturated conditions and temperature on the pullout response of geosynthetics.

1. INTRODUCTION

Mechanically-stabilized earth (MSE) walls consist of alternating layers of compacted soil backfill and geosynthetic reinforcements. These composite systems allow for the mobilization of both tensile and compressive resisting forces to withstand self-weight and external loads. Although the mobilized resistance of these structures depends on the shear strength of the soil, the tensile strength of the geosynthetic, and soil-geosynthetic interaction, the deformation response of MSE walls is closely linked to the effective stress state within the backfill. Interaction with the environment or changes in the groundwater level may lead to changes in pore water pressure, which will affect the effective stress state. To minimize corresponding changes in backfill behavior, most design codes require freely draining backfills.

As the cost and availability of freely draining backfills can be prohibitive for some projects, the use of poorly draining backfills in MSE walls has been evaluated (Zornberg and Mitchell 1994, Zornberg et al. 1995). These studies indicate that under the right conditions, MSE walls with poorly draining backfills will have acceptable performance. However, there is still some concern over their deformation response due to the effects of infiltration of water and relatively slow rates of drainage. Increases in pore water pressure or degree of saturation that may occur in poorly draining backfills will lead to decreases in effective stress (Lu et al. 2010). A method that is being investigated for control of the stress state in poorly draining backfills is the incorporation of geothermal heat exchangers within the reinforced soil mass (Stewart and McCartney 2013, Stewart et al. 2014a). In this case, thermally induced water flow is expected to occur in the unsaturated soil away from the heat exchangers, leading to a lower degree of saturation, increased suction, and increased effective stress in the backfill at the locations of the heat exchangers (Coccia and McCartney 2013). The reinforcing geosynthetics may also act as lateral vapor drains, helping to expel water from the backfill (Stewart et al. 2014b). This soil improvement technique has the added advantage that MSE walls could be used to dissipate excess heat from power plants or buildings, making these systems more environmentally friendly and potentially less expensive due to the cost offsets associated with the cooling system requirements. In this sense, the MSE wall with geothermal heat exchangers would become a thermally active geotechnical system. As MSE walls already incorporate several subsurface technologies including geosynthetics and additional drainage components (i.e. blanket or chimney drains), inclusion of additional plumbing for heat exchangers should not create a significant increase in cost or complexity.

A schematic of a thermally active MSE wall is shown in Figure 1(a), showing how geothermal heat exchangers can be placed in between the lifts at which reinforcing geosynthetics are placed. Heat is injected into the system by circulating hot fluid through the closed-loop heat exchange tubing. Shallow geothermal heat exchangers are a well-established technology, with a typical configuration shown in Figure 1(b). Using the reinforced zone of a MSE wall as a heat sink for the cooling of nearby industrial facilities or buildings is different from the classical use of GSHPs, where the soil subsurface is used as a heat source in the winter and heat sink in the summer. Accordingly, a potential drawback of using the MSE wall as a heat sink is that the efficiency of heat injection may decrease as the mean soil temperature increases and the backfill dries. However, heat will be continuously lost into the atmosphere for this near-surface system. Further, MSE walls are often long, linear structures so they represent a substantial volume of soil that can be used as a heat sink. With any new technology, the fundamental soil-geosynthetic system response should be characterized, design details need to be developed, and long-term simulations need to be performed before being implemented into practice.

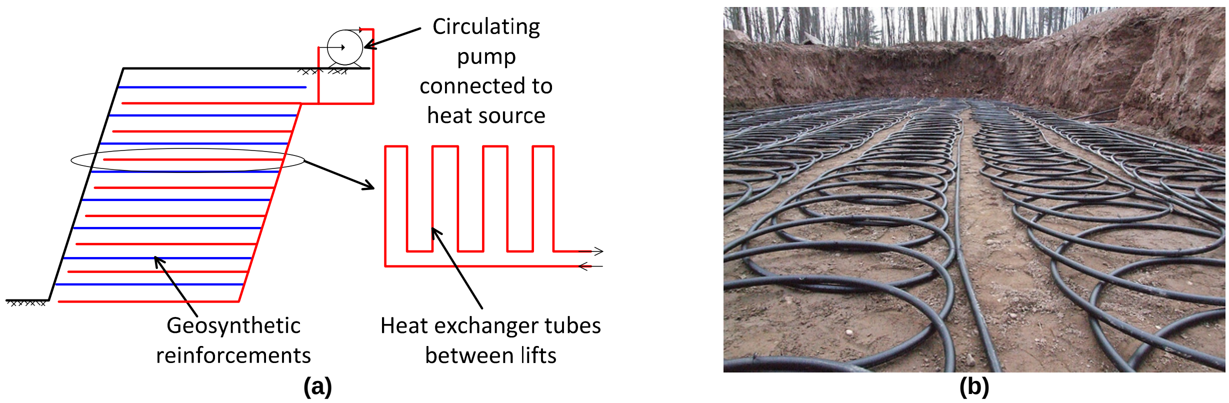


Figure 1. (a) Schematic of a thermally-active MSE wall; (b) Shallow geothermal heat exchange loops.

Despite the potential positive effects of thermally induced water flow on the shear strength and stiffness of the reinforced soil mass, studies on geosynthetics indicate that there may be negative effects of temperature on the stress-strain response of reinforcing geosynthetics. Thermal softening (i.e., a decrease in tensile modulus) may be encountered when geothermal heat exchange elements are incorporated into mechanically stabilized earth (MSE) walls. Although thermal softening has been characterized in the past using in-air creep tests (Zornberg et al. 2004), thermal softening of geosynthetics in confined conditions may be different due to geometrical restraint of the geosynthetic provided by the soil. Accordingly, the confined behavior of geosynthetics under nonisothermal conditions is important to consider whether the positive influence of a decreased degree of saturation in the soil offsets the negative aspects of thermal softening. Along these lines, the objective of this study is to present the details a new pullout device that can consider the thermo-hydro-mechanical response of a soil-geosynthetic system. Results from this device will not only be able to provide new insight into geosynthetic behavior, but can be used to validate and enhance simplified analytical models to predict the face deflections of thermally active MSE walls, such as the model developed by Stewart et al. (2014a).

2. BACKGROUND

2.1 Thermal Effects on Unsaturated Soils

During heating of unsaturated soils, water will move from regions of high temperature to regions of lower temperature in the liquid form due to gradients in surface tension and in vapor form due to vapor pressure gradients and buoyancy (Thomas et al. 1996). Water vapor will evaporate from the heating front, and will condense on liquid water islands in the soil layer. The zone of influence of this liquid and vapor movement will vary as a function of initial saturation, hydraulic conductivity, thermal conductivity, and porosity (Thomas et al. 1996; Coccia and McCartney 2013). Coccia and McCartney (2013) performed a numerical investigation using VADOSE/W to understand the influence of heat exchange on the thermo-hydro-mechanical response of a layer of unsaturated silt at different initial degrees of saturation with heat horizontal heat exchangers at a spacing of 1 m. They found that the more thermally induced water flow occurred as the degree of saturation decreased, and observed discrete zones of drying of about 0.3 m above and below the location of heat exchanger. A less predominant zone of wetting was observed away from the heat exchanger. The decrease in degree of saturation (or increase in suction) near a heat exchanger will result in an increase in effective stress. The effective stress in unsaturated soils can be represented by many models, but the model of Lu et al. (2010) is useful to use in conjunction with water flow analyses as it uses the effective saturation as the effective stress parameter. The effective saturation is directly linked with the soil-water retention curve (SWRC) of soils, making it simple to link changes in the water content during water flow with changes in effective stress. It is well established that an increase in effective stress leads to increases in the shear strength and stiffness of the soil (Lu et al. 2010).

Uchaipichat and Khalili (2009) observed that heating leads to a decrease in the preconsolidation stress of unsaturated compacted silt. This leads to a decrease in the peak shear strength for a given net stress and suction. However, the shear strength at critical state was unaffected by temperature. Further, Uchaipichat and Khalili (2009) observed that an increase in suction leads to a greater increase in peak shear strength than the decrease in peak shear strength due to heating. Drained heating of unsaturated soil will cause elasto-plastic volume changes, which can be either expansive or contractive depending on the stress history of the soil (Uchaipichat and Khalili 2009). Normally consolidated to lightly overconsolidated soils exhibit plastic contraction during heating due to complex collapse mechanisms (i.e., a reduction in the preconsolidation stress due to thermal softening when the specimen is at or near the preconsolidation stress), while over-consolidated soils exhibit elastic thermal expansion. As the preconsolidation stress induced by compaction of poorly draining backfill is generally much greater than the effective overburden stress from soil self-weight, it is likely that the unsaturated backfill in MSE walls will expand during heating. For a change in temperature of 40 °C, soils having OCRs ranging from 2 to 4 (typical of backfill in MSE walls) should experience thermal volumetric expansions up to 0.12%.

2.2 Thermal Effects on Geosynthetics

In the effort to accelerate the time required for obtain creep data for various geosynthetics, several studies have evaluated the non-isothermal behavior of these materials (Zornberg et al. 2004, Bueno et al. 2005, Karademir 2011). These studies found that some geosynthetic polymers are susceptible to changes in stiffness at elevated temperatures. The most important property governing the thermal response of a polymer is the glass transition temperature (T_g), defined as the temperature at which the polymer shows a reduction in tensile stiffness or ceases to behave as a brittle material. Two common polymers used in geosynthetics are polyethylene terephthalate (PET) and polypropylene (PP), and have values of T_g of 70°C and 0°C, respectively. Generally, the stiffness of a polymer is unaffected by changes in temperature until the temperature of the polymer approaches or exceeds T_g. As such, PET based geosynthetics are expected to maintain their original stiffness up to 70 °C. However, PP is much more susceptible to temperature changes, with thermal softening occurring at small changes from ambient temperature. An analysis of the magnitude of thermal softening on the tensile modulus for different geosynthetics was performed by Stewart et al. (2014a).

3. MATERIALS

3.1 Soil

Bonny silt was used in this experimental study. The liquid and plastic limits of the silt are 26 and 24 and the fines content of this soil is 84%, so it has a USCS classification of ML (inorganic silt). The silt, which has a specific gravity of 2.6, was compacted into the container using an impact hammer to a dry unit weight of 13.72 kN/m^3 at a gravimetric water content of 17%. This corresponds to an initial volumetric water content of 0.24 m^3/m^3, a porosity of 0.47, and a degree of saturation of 0.51. The initial thermal conductivity of the compacted silt was measured to be 1.2 W/m·K using a KD2Pro thermal needle from Decagon Devices. The SWRC parameters are presented in Coccia and McCartney (2013).

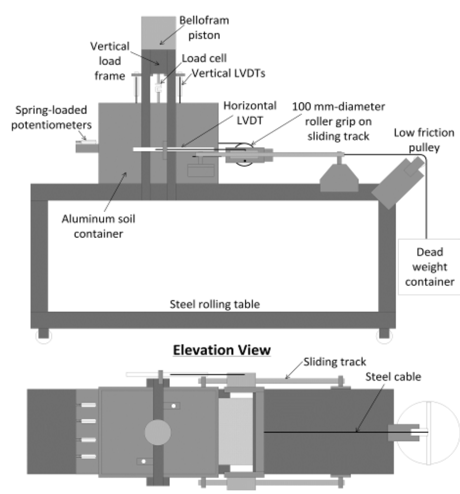
3.2 Geosynthetic

The geosynthetic used in this study is a woven PET 70/70 geotextile manufactured by TenCate-Mirafi Inc. The geotextile has an ultimate tensile strength of 70 kN/m, and a creep-reduced tensile strength of 42 kN/m according to the manufacturer specifications. The geotextile has a permittivity of 0.1 s^{-1}, which indicates that it should not provide a significant barrier to water or gas flow during the heating process.

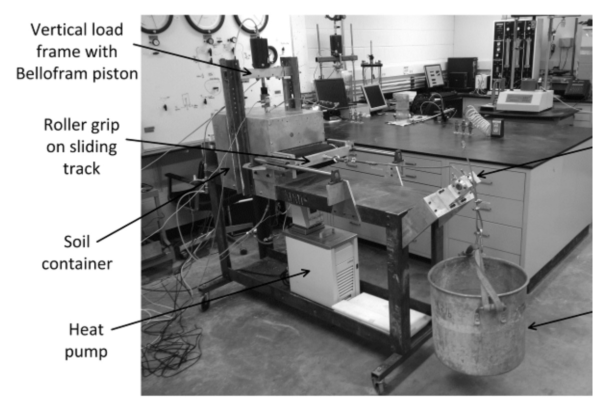
4. EXPERIMENTAL METHODS

4.1 Experimental Setup and Instrumentation

Schematics of the thermo-hydro-mechanical pullout box is shown in Figure 2(a), and a picture is shown in Figure 2(b). Although future versions of the pullout device will involve a servo-motor with feedback control that can be operated in displacement- and load-control conditions, this version was developed with load-control conditions. A Bellofram pneumatic piston is used to apply vertical loads, and a dead weight container is used to apply horizontal loads. A roller grip on a sliding frame is used to grip the geosynthetic and to apply uniform horizontal pullout loads.



(a)



(b)

Figure 2. Thermo-hydro-mechanical pullout device: (a) Schematics of the outside of the device; (b) Picture.

Schematics showing the internal dimensions of the pullout box are shown in Figure 3(a), along with the locations of the different instrumentation embedded in the soil mass. The pullout box has dimensions which meet or exceed those in ASTM D6706, and has several features that are consistent with the standard. Four spring-loaded potentiometers are mounted to tell-tales that are embedded in the soil layer to measure displacements of the geotextile during pullout. The potentiometers are mounted on a table on the back side of the container as shown in Figure 3(b). The tell-tales consist of heavy gage wire within a 0.175 mm-diameter plastic tube, and the wire is attached to the geotextile ribs with a hook.

The pullout box was developed to impose temperatures in a similar manner expected in the MSE wall in Figure 1(a), with heat being applied to the top and bottom of the soil layer through copper heating coils in a spiral formation embedded within a 12 mm-thick plate of Delrin. Delrin is a relatively low thermal conductivity plastic that was used to apply heat to the soil without losing heat to the outside of the metal box. The heating coils do not extend across the entire top and bottom width of the loading plates, but were placed in a spiral form across the center of the plate. Although this means that the soil at the left and right edges of the container are not heated by as great of a temperature, the geosynthetic is expected to only be in the center portion of the box due to the presence of a passive bearing sleeve at the face of the container and the fact that the geosynthetic does not extend all of the way to the back of the container. An advantage of this approach is that the geosynthetic loading system (i.e., the roller grips and unconfined geotextile) are unheated are not affected by thermally-induced creep. A heat pump was used to control the temperature within the loading plates, as shown in Figure 2. The heat pump used in this study was the F25-ME refrigerated/heated circulator designed by Julabo, Inc. The heat pump consists of an automated temperature control system and circulating pump, with a working temperature range of -28 to 200 °C. The circulating pump supplies a flow rate of approximately 16 l/min during testing.

Dielectric sensors (model 5TM from Decagon Devices) embedded at different depths are used to monitor changes in temperature and volumetric water content in the soil layer during heating. The container was not designed to control the suction within the soil layer during testing, so the sensors are needed to infer changes in degree of saturation (and therefore the suction) during the heating process. A long-stroke (150 mm) linear variable differential transformer (LVDT) was used to measure the face displacements of the grip. A load cell was used to monitor the vertical load, and two vertical LVDTs were used to measure the settlement and possible tilt of the top cap. The Bellofram piston permits vertical stresses to be applied in load-control conditions.

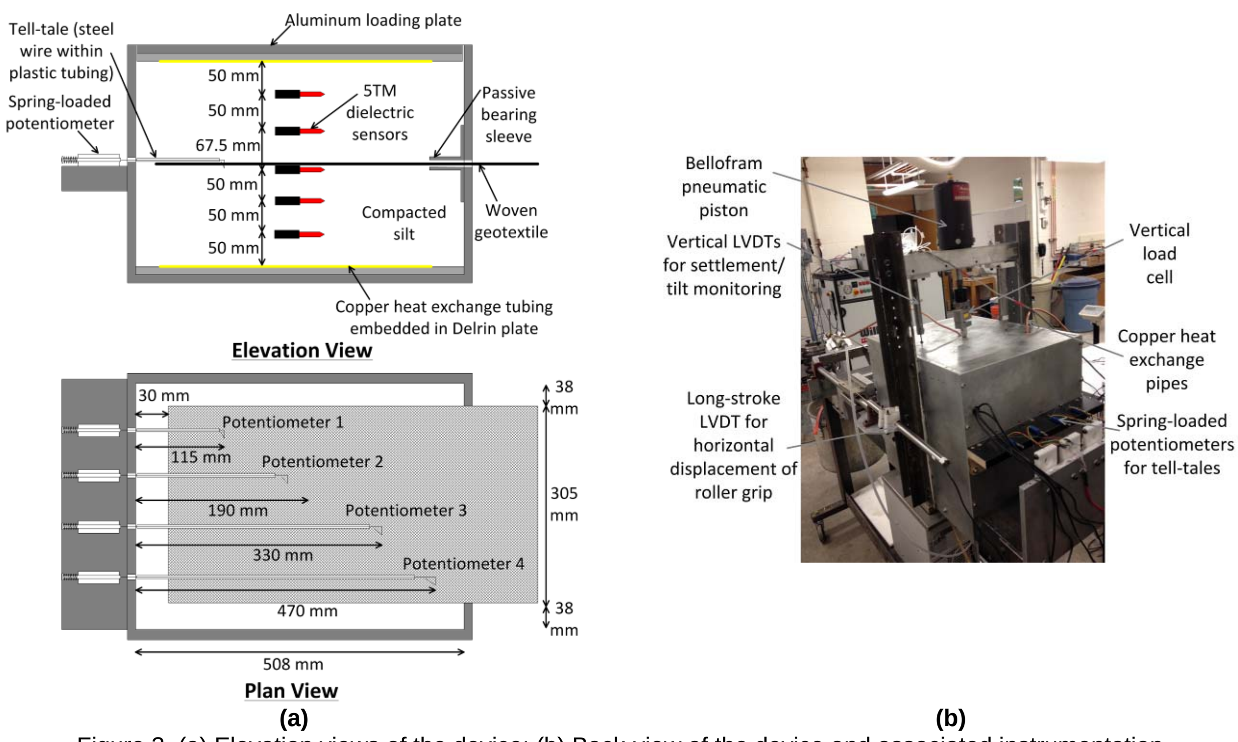


Figure 3. (a) Elevation views of the device; (b) Back-view of the device and associated instrumentation.

4.2 Experimental Procedures

The soil layer was prepared in 25 mm-thick lifts using dynamic compaction with an impact hammer. The soil was compacted directly atop the heating coils on the bottom of the container, as shown in Figure 4. The dielectric sensors were place at the interfaces between lifts, taking care to ensure that the sensor was horizontal. The sensors were placed in such a manner that the cable would not provide tensile resistance to pullout. The wires of the sensor exit from the back side of the container, in the upper half of the container to avoid damage from the vertical stress application. At the depth of the geosynthetic, the tell-tales were attached to the geosynthetic, taking care that the tell-tales were initially pre-loaded in tension by the spring-loaded potentiometers attached to the back wall of the container. The wire hooks were securely attached to the ribs of the geotextile. The geosynthetic was wrapped around a soft polypropylene geotextile to ensure uniform slippage from the roller grip. After compaction of the soil layer, the top surface was carefully leveled so that the top plate would apply a uniform stress to the soil layer. This was a challenging aspect as the goal of the container was to apply uniform temperatures to the top and bottom of the soil layer, which precluded the use of a bladder or layer of gum rubber to assist in uniform stress distribution. Nonetheless, negligible tilting was observed during compression and pullout, which indicates that relatively uniform stresses were applied.

After placement of the top plate and assembly of the vertical loading apparatus, a normal stress of 22.1 kPa was applied to the top plate. This stress corresponds to the stress associated with that at the mid-height of a MSE wall having a height of 1.5 m. A period of 24 hours was provided for consolidation, which led to a degree of consolidation of approximately 90%. Next, a seating pullout load of 2.1 kN/m was applied to the geosynthetic, after which it was massaged to remove any stress concentrations at the grips. The horizontal face displacements were zeroed after the application of the seating load. Next, a horizontal load of 5.85 kN/m was applied to the geosynthetic at a rate of 0.002 kN/m/s by pouring tungsten pellets into a hanging basket. This loading rate was chosen to result in drained conditions. The horizontal load of 5.85 kN/m is equal to 40% of the maximum pullout resistance of the geotextile at this normal stress, which was evaluated using a pullout test performed at room temperature. Next, the top and bottom of the box were heated to approximately 50 °C, and the temperature and pullout load were maintained for a period of approximately one week. After this, the pullout load was increased until reaching failure (defined by movement of the tell-tales).

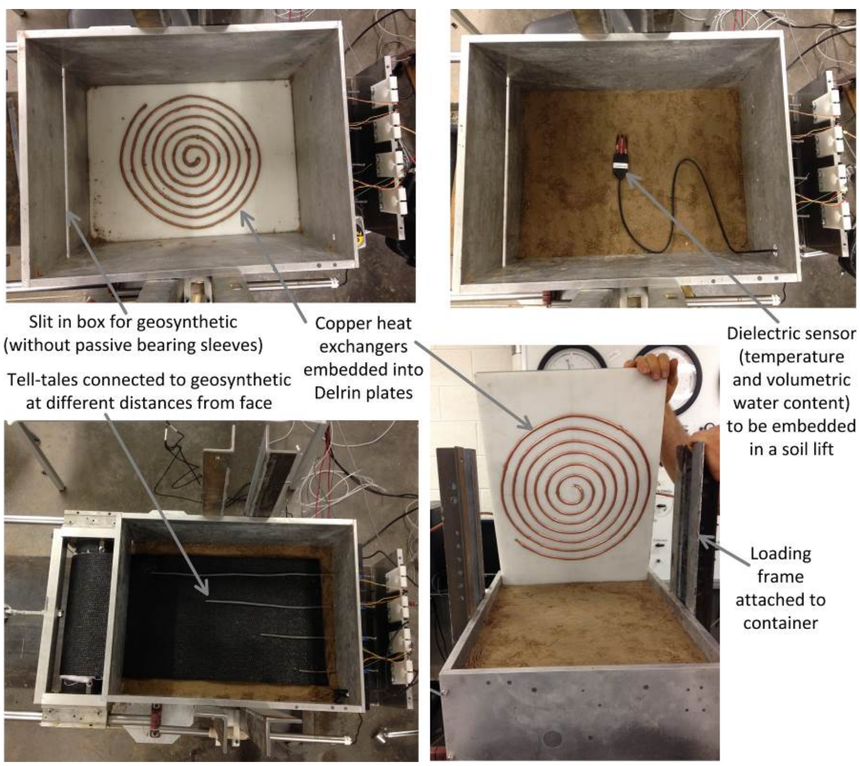


Figure 4. Views of the setup during preparation.

5. RESULTS

The applied load and the face displacement during the duration of the test is shown in Figure 5(a), while the geosynthetic displacements from the tell-tales are shown in Figure 5(b). The face displacement was observed to increase proportionally to the application of the pullout load of 5.85 kN/m. After application of the pullout load, the horizontal displacement continued throughout the rest of the test, with a diminishing amount of displacement over time. After a period of one week, the pullout load was applied at a constant rate of 0.006 kN/m/s until movement of the tell-tales was observed. The results in Figure 5(b) indicate that the front half of the geosynthetic started to move during application of the initial pullout load, potentially due to the increase in temperature, the details of which will be discussed later. However, the tell-tales did not show the continuous displacement observed at the face of the geosynthetic. Close-ups of the load and displacements during initial loading are shown in Figures 6(a) and 6(b), while a close-up of the load and displacements during final loading are shown in Figures 6(c) and 6(d). During final loading, all of the tell-tales showed movement, albeit inconsistent in some of the cases potentially because of stress concentrations. A single large weight was applied at the end of loading (266.5 hrs), which caused the large increases in the measured displacements.

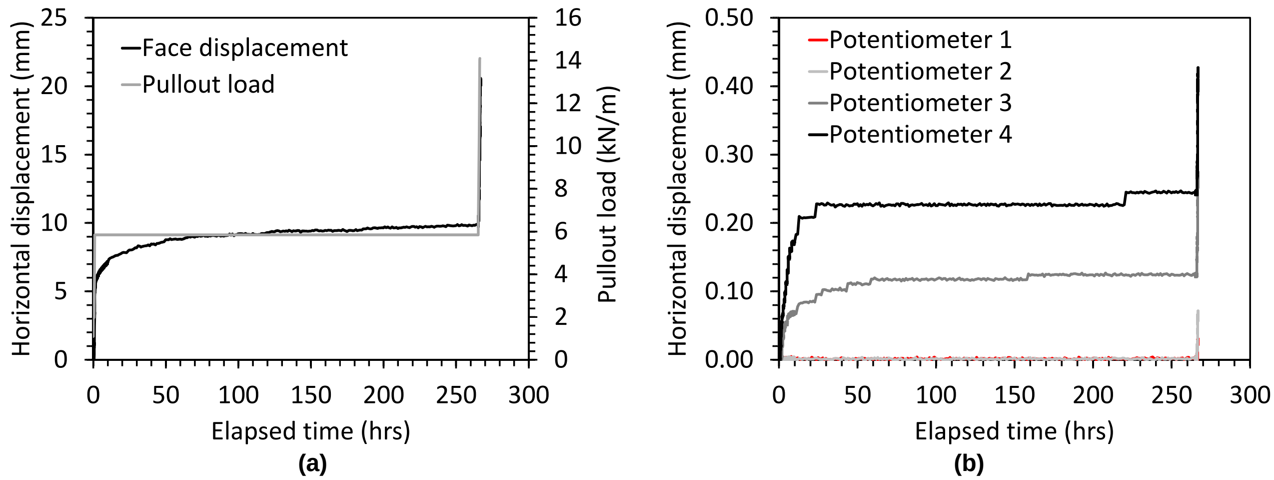


Figure 5. (a) Pullout load and face displacement for the full test; (b) Tell-tale displacements for the full test

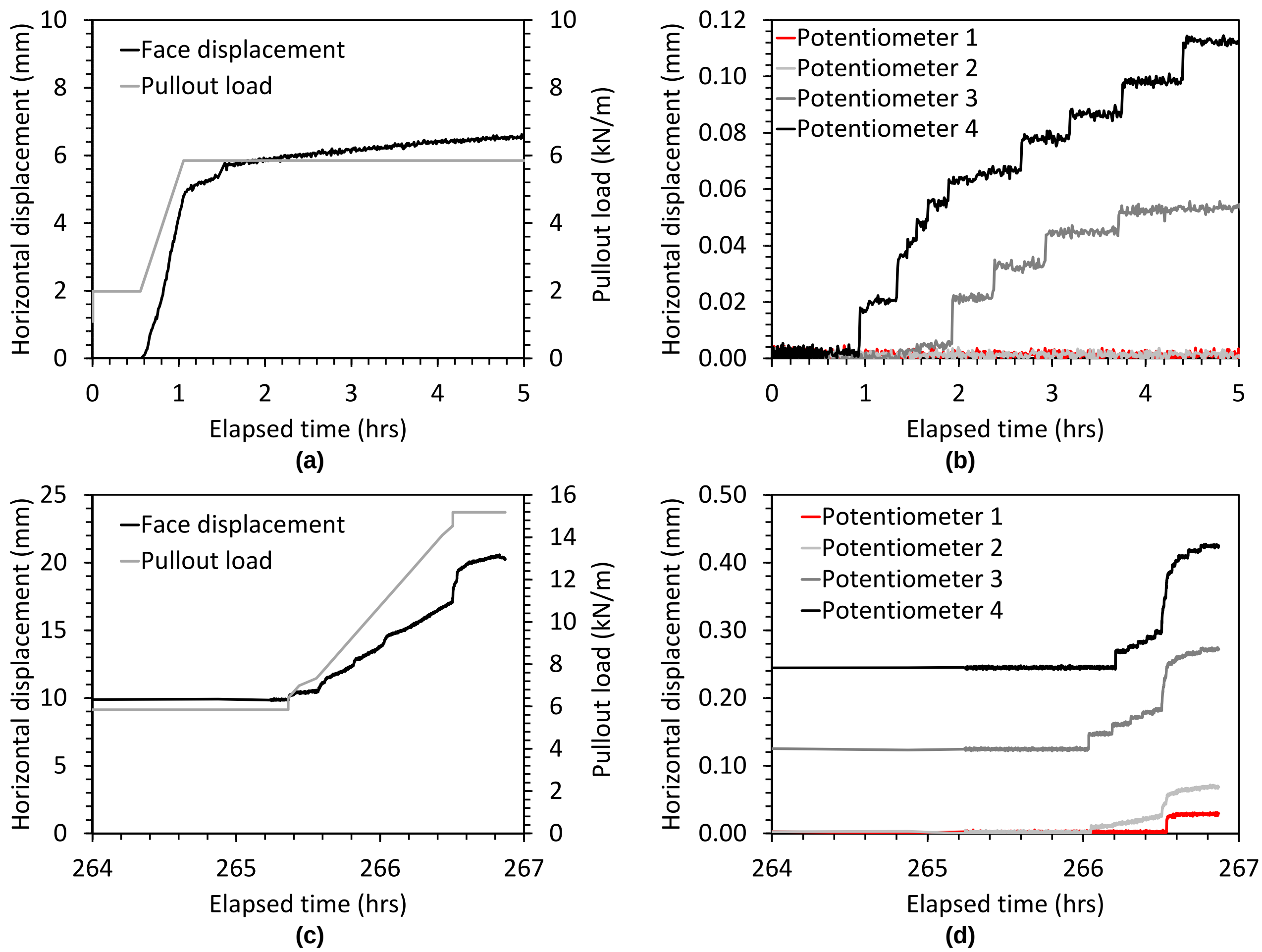


Figure 6. Close-up views of pullout load and displacement results: (a) Pullout load and face displacement during seating load; (b) Tell-tale displacements during seating load; (c) Pullout load and face displacement during final load; (d) Tell-tale displacements during final load

The temperatures of the fluid entering and exiting the heat plates are shown in Figure 7. Unfortunately one of the temperature sensors malfunctioned at the beginning of the test. The heat exchange system also did not supply the same amount of fluid to the top and bottom loading plates because the length of tubing to reach the upper plate was longer. This means that the top of the plate had a lower boundary temperature than the bottom loading plate.

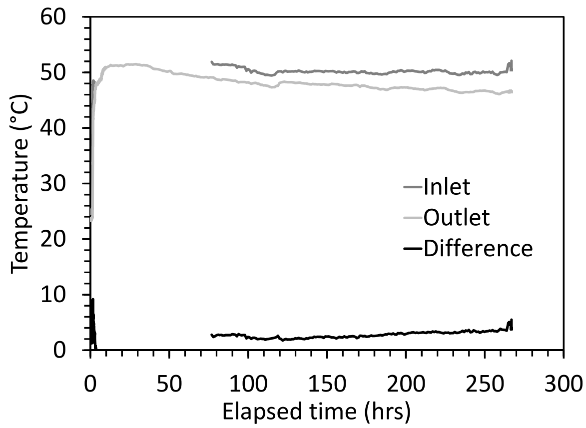
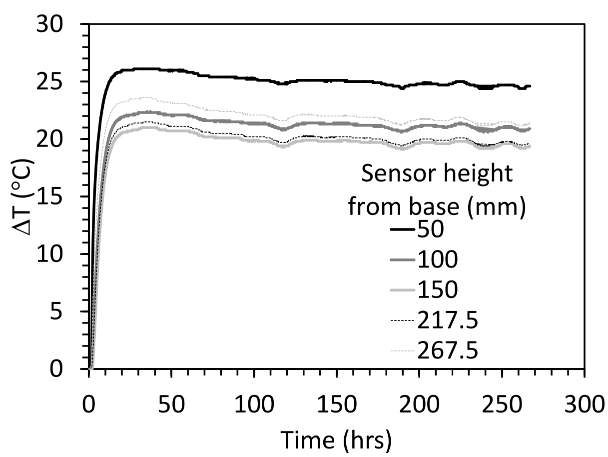
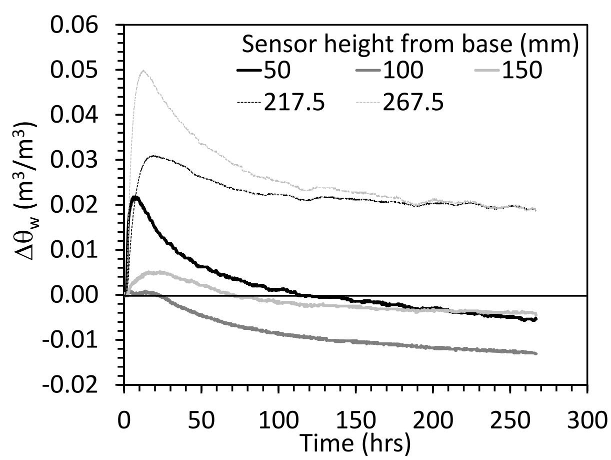


Figure 7. Fluid temperatures (inlet represents the temperature of the lower face and outlet that of the upper face).

The temperature of the soil at different depths is shown in Figure 8(a). The temperature of the soil was observed to increase relatively, reaching a relatively steady value after approximately 20 hours. During this time period, the volumetric water content (θ_w) at different depths was observed to change, as shown in Figure 8(b). The dielectric sensor readings were corrected to account for the effect of temperature as follows: $\theta_w = \theta_{w,measured} - 0.001725\Delta T$, where ΔT is the change in temperature at a given depth measured by the sensors. At most depths, the soil increased in water content briefly, after which it decreased. Because the temperature at the top and bottom were different, the soil near the base was observed to dry by a greater amount than the soil in the upper portion of the container.



(a)



(b)

Figure 8. Dielectric sensor results: (a) Changes in temperature over time at different heights from the base; (b) Changes in volumetric water content over time at different heights from the base.

Profiles of temperature at different times during heating are shown in Figure 9(a). It is clear that the temperature at the base of the container is slightly greater than that at the top of the container. The difference in temperature between the top and bottom of the soil layer decreases over time. The volumetric water content profiles in Figure 9(b) indicate that the soil reached the greatest value after approximately 10 hours of heating, after which the soil layer started to dry. The bottom half of the soil layer experienced a greater amount of drying due to the greater temperature. The sensor at the depth of the geosynthetic indicates that the soil-geosynthetic interface became drier. During this entire process, the geosynthetic showed creep displacements (both in terms of the face displacement and the internal geosynthetic displacements). However, the rate of creep displacements seems to decrease over time, which may indicate that that the drying of the soil starts to arrest the creep behavior. Further research and additional testing is needed to confirm this observation for a wider range of conditions.

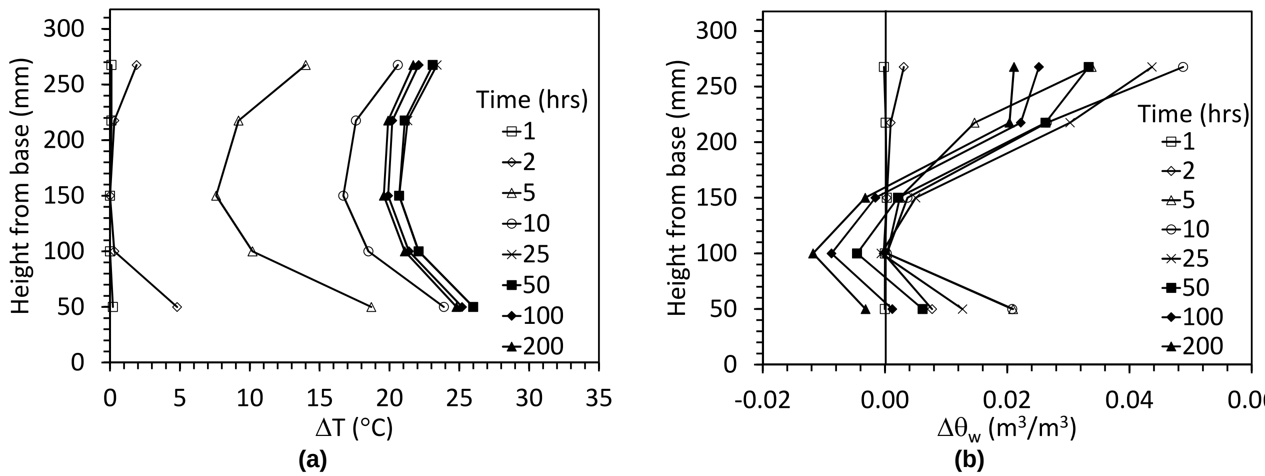


Figure 9. (a) Profiles of changes in temperature; (b) Profiles of changes in volumetric water content.

6. ANALYSIS

The pullout load-displacement curve for the geosynthetic is shown in Figure 10. The horizontal displacements were zeroed after application of the seating load of 2.1 kN/m. After application of 40% of the ultimate pullout resistance of the geosynthetic, a creep displacement of approximately 5 mm was observed. This was associated both with the sustained horizontal load as well as the heating of the soil layer. After heating, the geosynthetic was loaded further until movement of the tell-tales was observed, which was defined as failure. It is interesting to note that the pullout stiffness was observed to increase after heating, potentially due to the greater effective stress at the location of the geosynthetic. Further testing and comparison against a baseline test is needed to fully characterize the complex and coupled phenomena observed in these tests, but this study shows that heating may not lead to a negative response.

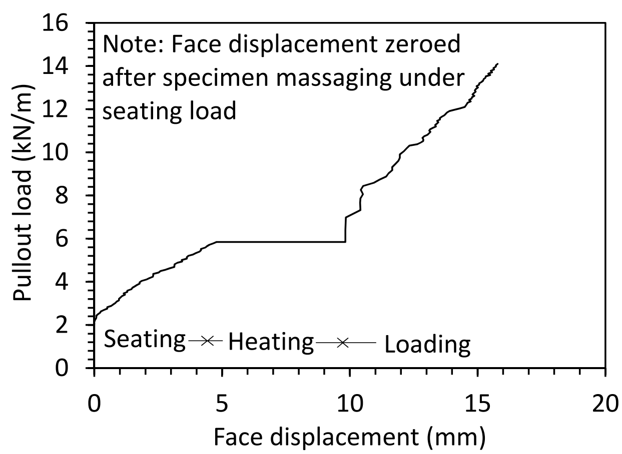


Figure 10. Load-displacement curve before and after the heating process.

7. CONCLUSIONS

This study presented the details of a new thermo-hydro-mechanical pullout device that can be used to characterize the soil-geosynthetic interaction mechanisms in thermally-active MSE walls. Preliminary results were presented for a single test on a PET geotextile in unsaturated, compacted silt which show the capabilities of the device and instrumentation in characterizing the coupled heat transfer and water flow process and the combined mechanical response. Although additional testing is required, the results from this preliminary test indicate that heating of the soil layer led to a drying effect, which led to an increase in the effective stress state in the soil surrounding the geosynthetic. Although pullout creep was observed after an application of a pullout load equal to 40% of the pullout capacity, the creep displacements were observed to decrease in rate as a function of time. This supports the hypothesis that thermally induced water flow and increased effective stress in poorly draining backfill may be sufficient to overcome the negative effects of thermally induced creep. It is possible that the use of geosynthetics with a lower glass transition temperature such as polypropylene may not have as favorable response as the PET geotextile tested in this study.

ACKNOWLEDGEMENTS

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