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NONISOTHERMAL RESPONSE OF REINFORCING GEOSYNTHETICS IN THERMALLY-ACTIVE GEOTECHNICAL SYSTEMS

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ABSTRACT

This study focuses on the effects of thermal softening on geosynthetics confined in compacted soil based on the results from a series of tests performed using a thermo-mechanical pullout device. Thermal softening of geosynthetics has been characterized using in-air creep tests, but softening behavior in confined conditions is important when considering the overall effects of this mechanism on the deformation response of thermally active MSE walls. The pullout box incorporates standard elements such as roller grips, a motor for displacement-control pullout or creep testing, instrumentation for pullout force and internal displacement measurement. The box also incorporates heating elements at the top and bottom of the box, along with an array of dielectric sensors for measurement of soil temperature and volumetric water content. The pullout results indicate the importance of considering the combined roles of unsaturated conditions and temperature on the pullout response of reinforcing geosynthetics.

1. INTRODUCTION

Several recent studies have focused on investigating issues that may be encountered when incorporating geothermal heat exchangers into mechanically stabilized earth (MSE) walls to form thermally-active MSE walls (Stewart and McCartney 2013; Stewart et al. 2014a). These systems can be used to dissipate excess heat from power plants or buildings, making the MSE wall more environmentally friendly and potentially economical due to the cost offsets associated with building cooling system requirements. 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. However, the injection of heat into MSE walls may lead to a change in the behavior of the soil and geosynthetic reinforcements, which must be understood before this technology is implemented in practice. On the positive side, thermally induced flow of water away from the heat exchangers is expected to occur in the unsaturated soil, leading to a lower degree of saturation, increased suction, and increased effective stress in the backfill soil at the locations of the heat exchangers (Coccia and McCartney 2013). If geotextiles are used as the reinforcing geosynthetic in the MSE wall, they may also act as lateral vapor drains, helping to expel water from the backfill (Stewart et al. 2014b). Despite the positive effects of heating, it is well known that heating of geosynthetics in confined conditions leads to accelerated creep (Zornberg et al. 2004; Bueno et al. 2005; Karademir 2011) and thermal softening (Stewart et al. 2014a).

Accordingly, the behavior of geosynthetics confined in unsaturated backfill soil under nonisothermal conditions is important to consider to determine whether the positive influence of a decreased degree of saturation in the soil offsets the negative aspects of thermal softening. As a first step in characterizing the effects of thermal softening on the behavior of reinforcing geosynthetics confined in compacted soil, this study presents the results from a series of tests performed using a thermo-mechanical pullout device developed by Carpenter et al. (2015). The pullout box incorporates standard elements such as roller grips, a motor for displacement-control pullout or creep testing, instrumentation for pullout force and internal displacement measurement. The box also incorporates heating elements at the top and bottom of the box, along with an array of dielectric sensors for measurement of soil and volumetric water content. Results are presented to show the baseline pullout behavior as well as the effects of transient heat transfer and water flow in the backfill soil on the pullout creep of a woven polypropylene geotextile. 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. MATERIALS

2.1 Soil

Bonny silt was used in the tests performed in this 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 has a specific gravity of 2.6. The silt was compacted into the pullout box using an impact hammer to a dry unit weight of 14.5 kN/m^3 at a gravimetric water content of 17%. This corresponds to an initial volumetric water content of 0.25 m^3/m^3, a porosity of 0.45, and a degree of saturation of 0.55. Under these conditions, the drained friction angle of the soil is 33° (Khosravi et al. 2011). The initial thermal conductivity of the silt was 1.2 W/m·K, measured using a KD2Pro thermal needle from Decagon Devices. The soil-water retention curve (SWRC) parameters are presented in Coccia and McCartney (2013).

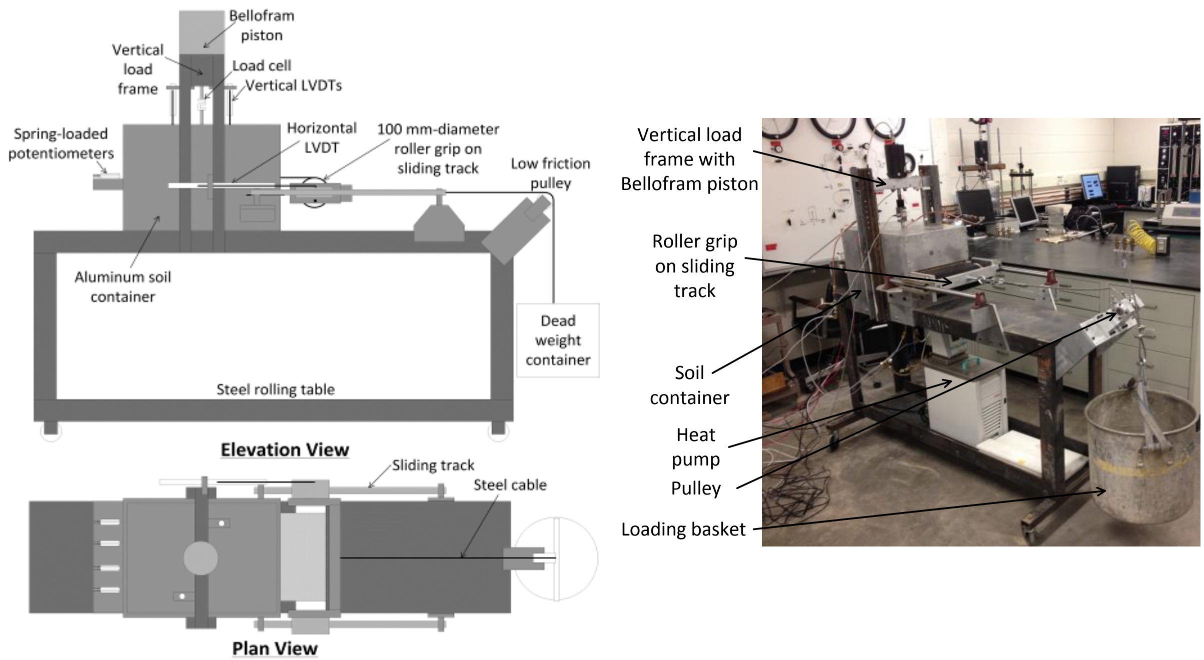
2.2 Geosynthetic

The geosynthetic used in this study is a woven polyethylene terephthalate (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. 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. The PET geotextile has a value of T_g of 70°C. The temperature in most geothermal heat exchange applications is less than 60 °C, so it is assumed that the stiffness of the geotextile will remain constant for temperatures below this level. An analysis of the magnitude of thermal softening on the tensile modulus for different geosynthetics was performed by Stewart et al. (2014a).

3. EXPERIMENTAL METHODS

3.1 Experimental Setup and Instrumentation

Schematics of the thermo-hydro-mechanical pullout box developed by Carpenter et al. (2015) are shown in Figure 2(a), while a picture is shown in Figure 2(b). The pullout load is applied to the geosynthetic using a dead-weight system, which facilitates the performance of creep loading tests. A roller grip on a sliding frame is used to grip the geosynthetic and to apply uniform horizontal pullout loads. A Bellofram pneumatic piston is used to apply vertical 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, along with the locations of the different instrumentation embedded in the soil mass. 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 while still permitting temperatures to be applied to the upper boundary of the soil layer through the aluminum loading plate. Although tell-tales can be incorporated to measure internal deformations, as shown in Figure 3, the results from these sensors are not presented in this study.

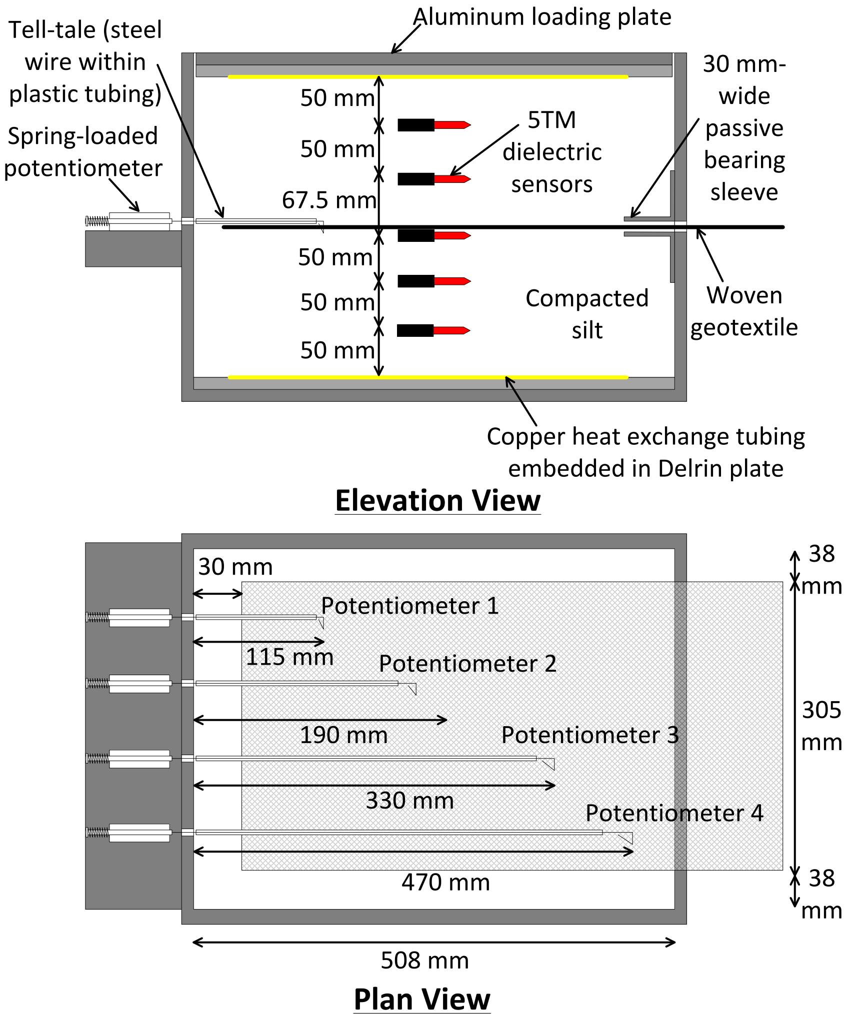


Figure 3. Schematics of the inside of the pullout device

Heat is 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, which has a low thermal conductivity compared to the aluminum 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. This means that the soil within 75 mm of the front and back edges of the container are not directly heated. However, the interaction zone of the geosynthetic is expected to only be in the center portion of the box due to the presence of the 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 and are not affected by thermally-induced creep. A circulating heat pump (model F25-ME from Julabo, Inc) was used to circulate heated fluid through the loading plates to reach a given boundary temperature applied to the soil.

3.2 Experimental Procedures

The silt was compacted 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 placed at the interfaces between lifts, taking care to ensure that the sensors were 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. 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 as uniform of a stress to the soil layer as well as applying a boundary temperature. Negligible tilting was observed during compression and pullout, indicating that relatively uniform stresses were applied. After application of a vertical stress of to the system, 24 hours was provided for consolidation to occur, which was sufficient to reach at least 90% of the consolidation settlement in all of the tests. Next, a seating pullout load of 0.67 kN/m was applied to the geotextile. The geotextile was then massaged to relieve any stress concentrations on the grips. Four tests were performed as part of this ongoing study. In two of the tests, horizontal loads were then applied to the geotextile having a negligible vertical stress in constant time increments for two different average changes in soil temperature. In the other two tests, a vertical stress of 22 kPa was applied and the geotextile was permitted to creep under a pullout load of 7 kPa. The creep deformations were then monitored over a period of 10 to 11 days.

4. RESULTS

Two tests were performed to evaluate the pullout behavior of the PET woven geotextile in compacted silt under different temperatures and negligible vertical stress. The pullout load per unit width as a function of the horizontal face displacement is shown in Figure 4. The first test was performed under room temperature conditions (an average change in soil temperature of 0), during which the horizontal load was applied to the grid in constant time intervals to keep the rate of load increase as constant as possible. After reaching a pullout load of 7 kN/m, no further masses were available for continued pullout testing and the test was stopped. The second test was performed by first heating the soil to an average change in soil temperature of 15 °C and maintaining this temperature for a duration of approximately 100 hours while the geosynthetic was under a seating pullout load of 0.67 kN/m. After this point, the geosynthetic was loaded monotonically to failure. Although the results in Figure 4 indicate that the geosynthetic initially shows a softer response than the geotextile tested under room temperature conditions, it has a similar slope after about 10 mm of displacement. Additional masses were available to load the geotextile to failure, at a pullout capacity of approximately 9 kN/m.

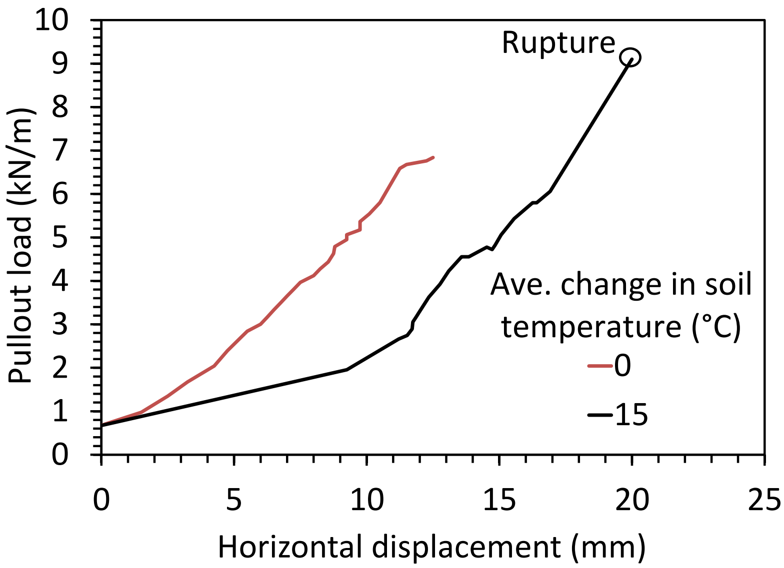


Figure 4: Results from a load-controlled pullout test at room temperature

As no vertical stress was applied in these two tests, the results from the pullout test that was loaded to failure need to be interpreted in terms of the coefficient of interaction so that the results can be applied to estimate the pullout capacity at different normal stresses. The coefficient of interaction C_i can be calculated as follows:

$$C_i = \frac{T}{2A\sigma_n tan\phi} \quad (1)$$

where T is the pullout capacity, A is the area of interaction, σ_n is the applied normal stress, and ϕ is the drained friction angle. The suction stress is required to estimate the effective stress in the unsaturated soil at the interface, so Equation 1 was used to calculate the coefficient of interaction in terms of total stress. The applied total normal stress in the first two tests due to the weight of the soil and the aluminum loading plate is approximately 3.35 kPa. The coefficient of interaction calculated for this case is equal to 6.8. Although the coefficient of interaction typically ranges from 0.7 to 0.9 for geogrids in granular material, this number is greater because it incorporates the effects of matric suction. It is not recommended to use a total stress approach in design of retaining walls in unsaturated soils, but this value is suitable for estimating the percentage of the ultimate capacity for the other tests in this study.

Next, two creep tests were performed under a pullout load that was a fraction of the pullout capacity estimated at room temperature conditions under a vertical total stress of 22 kPa (25.6 kN/m). After reaching equilibrium under the applied vertical stress of 22 kPa, a pullout load of 7 kN/m was applied to the geotextile (27% of the pullout capacity). After reaching this pullout load, the heating system was turned on. This testing sequence likely replicates the construction sequence of a thermally active MSE wall, where the wall would be built and self-weight stresses are imposed, after which the heating system would be turned on. Next, the soil temperature, creep displacements were monitored as a function of time. The temperature versus time is shown in Figures 5(a) and 5(b) for the tests having average changes in soil temperature of 14 and 22 °C. In both tests, the soil temperature rose quickly in less than a day and remained approximately constant. The temperature at the base of the container was slightly greater than at the top of the container due to experimental issues in controlling the fluid flow rates through the top and bottom plates.

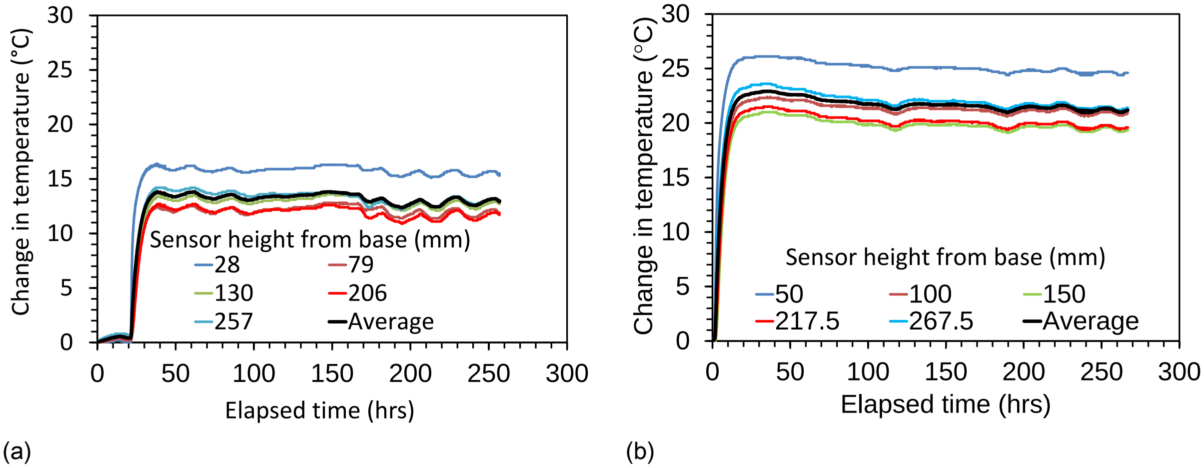


Figure 5: Temperature versus time for the two creep pullout tests having different average changes in soil temperature of: (a) 14 °C; (b) 22 °C

The change in water content of the unsaturated soil during heat injection from the top and bottom of the box is shown in Figure 6(a) and 6(b) for the tests with an average change in soil temperature of 14 and 22 °C, respectively. The volumetric water content values obtained from the dielectric sensors were corrected for temperature effects using the model of Iezzoni and McCartney (2015), which indicates that the sensors show a spurious increase in water content of 0.0031· T that needs to be removed from the measured results to accurately reflect changes in water content in non-isothermal conditions. The results from the two figures indicate that the soil in the bottom half of the box consistently dries during heating, while the soil above the geotextile shows an increase followed by a decrease. These trends are due to upward water vapor flow due to buoyancy, but also possibly water vapor flow through the geotextile, indicating that the geotextile reinforcement may be an effective water vapor barrier. Although a change in volumetric water content on the order of 3% may not seem significant, the relationship between the volumetric water content and matric suction is highly nonlinear, so this small change may result in more significant changes in the stress state at the soil-geotextile interface. In the first test, the driest soil conditions were closest to the geotextile.

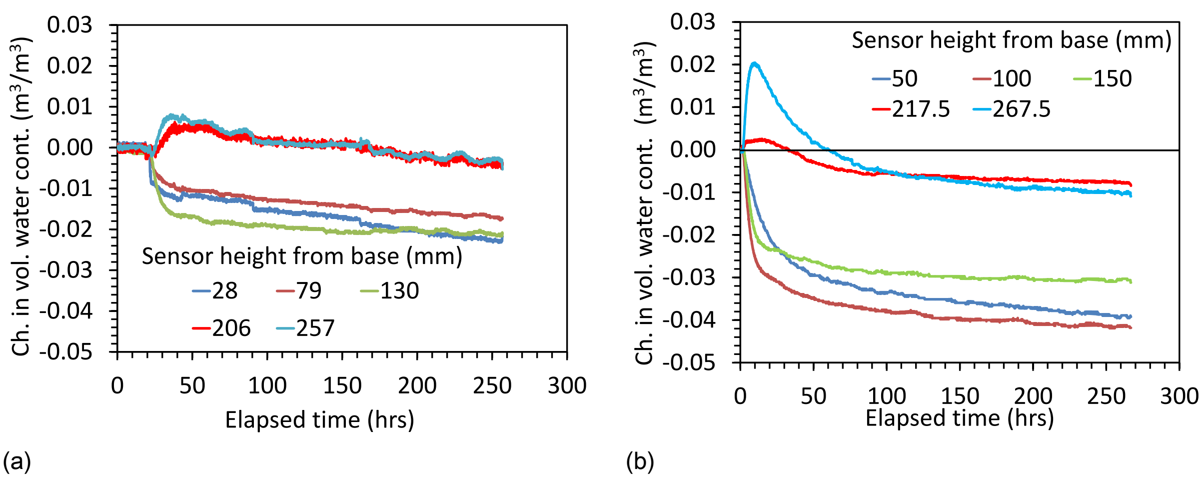
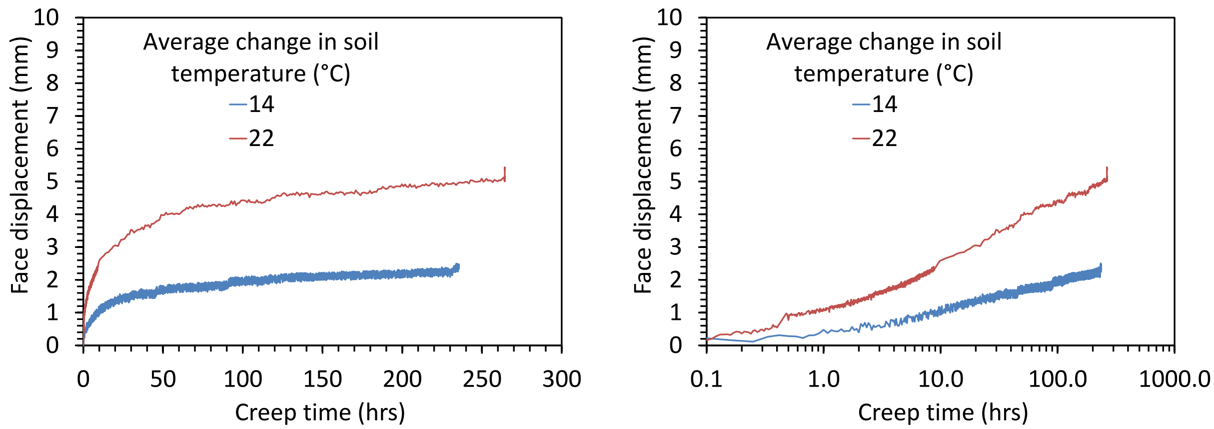


Figure 6: Change in volumetric water content versus time for the two creep pullout tests having different average changes in soil temperature of: (a) 14 °C; (b) 22 °C

The horizontal face displacement as a function of time during the two creep tests is shown in Figure 7. The first observation is that the geotextile with a greater change in temperature shows greater creep displacements during the test, and a slightly steeper logarithmic slope. This confirms that temperature has a negative effect on the creep pullout of geotextiles. Although both interfaces experienced drying of the surrounding soil, this was not sufficient to alleviate the creep potential of the soil. These tests will be complimented in future studies by in-air creep tests at the same temperatures and loads to assess if the external confinement and the increase in effective stress due to drying of the soil help to reduce the amount of geosynthetic creep.



(a) (b)

Figure 7: Face displacements due to pullout creep for geosynthetics in unsaturated soil at different average changes in temperature: (a) Natural scale; (b) Logarithmic scale

5. CONCLUSIONS

This study presents results from a new thermo-hydro-mechanical pullout device that can be used to characterize the soil-geosynthetic interaction mechanisms in thermally-active MSE walls. Results are shown to compare the creep response of a PET woven geotextile in unsaturated compacted silt during different load fractions and boundary temperatures. The results 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 27% of the pullout capacity, the creep displacements were observed to follow an asymptotic trend indicating that creep rupture was not likely. Although the increase in effective stress associated with drying of the soil at the geosynthetic interface was not sufficient to prevent temperature effects on geosynthetic pullout creep, it is possible that the increased confinement reduced the amount of pullout creep beyond that measured in in-air tests.

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