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Authors

Stewart, Melissa A
Coccia, Charles JR
McCartney, John S

Publication Date

2014-02-24

DOI

10.1061/9780784413272.395

Issues in the Implementation of Sustainable Heat Exchange Technologies in Reinforced, Unsaturated Soil Structures

Melissa A. Stewart[1], M.S., S.M. ASCE, Charles J.R. Coccia[2], M.S., S.M. ASCE, and John S. McCartney[3], Ph.D., P.E., M. ASCE

[1]Doctoral Student, University of Colorado Boulder, Dept. of Civil, Env. and Arch. Engineering, UCB 428, Boulder, CO 80309; melissa.stewart@colorado.edu.
[2]Doctoral Student, University of Colorado Boulder, Dept. of Civil, Env. and Arch. Engineering, UCB 428, Boulder, CO 80309; coccia@colorado.edu.
[3]Associate Professor and Lyall Faculty Fellow, University of Colorado Boulder, Dept. of Civil, Env. and Arch. Engineering, UCB 428, Boulder, CO 80309; john.mccartney@colorado.edu.

ABSTRACT: This study involves an investigation into issues that may be encountered when using the backfill in mechanically stabilized earth (MSE) walls as a heat sink for spurious heat generated by nearby industrial facilities or buildings. The deformation behavior of thermally active MSE walls is evaluated using a simplified analytical model adapted to consider the effects of temperature, confining stress and unsaturated soil conditions on the stiffness of geosynthetic reinforcing elements. The major conclusions that can be drawn from the model results are that it is important to select a geosynthetic that has a high glass-transition temperature, and that confining effects of unsaturated backfill may lead to a reduction in the thermal deformations of the geosynthetic.

INTRODUCTION

Many infrastructure systems generate waste heat, including power plants, refineries, and buildings in cooling-dominated climates. For industrial applications, cooling towers are utilized to dissipate excess heat energy through phase change, while air conditioners are used for building cooling. An alternative approach to dissipate this excess heat energy is by circulating a heat exchange fluid through soil-borehole arrays (Mands et al. 2013) or nearby geotechnical structures such as soil embankments (Coccia and McCartney 2013) or mechanically stabilized earth (MSE) walls (McCartney and Stewart 2012). MSE walls are composite structures that utilize the tensile strength of geotextiles and the compressive strength of soil in order to create reinforced walls capable of maintaining a steeper face than soil alone. Most design standards dictate that MSE walls be constructed using free-draining backfill to eliminate potential negative impacts of water within the reinforced soil zone. However, reinforced walls and slopes with fine-grained, poorly draining backfills have been constructed in locations where free-draining backfill is expensive or not available, with excellent performance when properly designed (Zornberg and Mitchell 1994, Zornberg et al. 1995). Issues that may be encountered when using poorly draining backfill include positive pore water pressures due to poor drainage design or the effects associated with increases in the degree of saturation of the backfill due to environmental interactions. Changes in degree of saturation (or suction) lead to changes in effective stress (Lu et al. 2010), which can result in a change in shear strength or stiffness of the backfill. Although it is not expected that these changes will lead to catastrophic failure, undesirable deformations may occur. Incorporation of heat exchangers may help maintain lower degrees of saturation in the backfill through thermally induced water flow (Coccia and McCartney 2013). However, increased temperatures may also cause a decrease in tensile stiffness of the geosynthetic reinforcement (Zornberg et al. 2004, Bueno et al. 2005, Karademir 2011), requiring these interactions to be carefully considered in thermally active MSE walls.

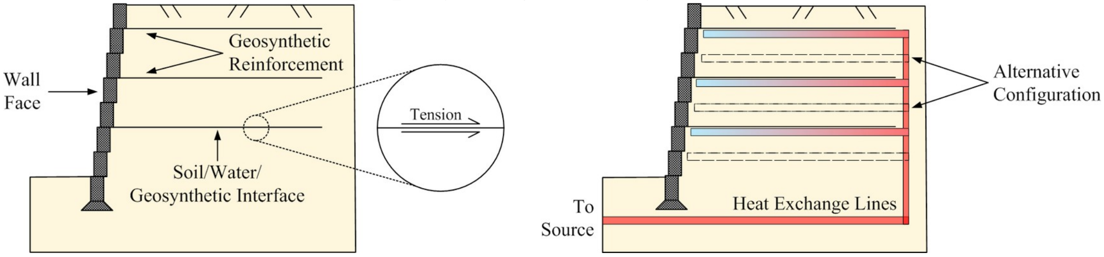
Although several studies have evaluated the impact of elevated temperatures on the engineering properties of unsaturated soils (Saix et al. 2000; Romero et al. 2005; Uchaipichat and Khalili 2009) and geosynthetics (Bueno et al. 2005; Zornberg et al. 2005), questions regarding the impact of temperature on soil-geosynthetic interaction remain. The objectives of this paper are to summarize the relevant results from studies that can be used to characterize the thermo-hydro-mechanical response of unsaturated soils and geosynthetics and to substitute the results of Coccia and McCartney (2013) into a modified Jewell-Milligan model (Stewart and McCartney 2013), to introduce some potential impacts these behaviors may have on the mechanical response of a typical MSE wall, and to consider potential configurations for heat exchange systems implemented into new construction MSE walls.

MSE WALLS AS THERMALLY-ACTIVE STRUCTURES

Concept and Operation

A schematic of a traditional MSE wall is given in FIG. 1(a). In general, the backfill soil and reinforcing layers make up the main constituents of an MSE wall. Geosynthetics may be arranged at varying lengths and spacing throughout the structure. The geosynthetic reinforcements are generally polypropylene (PP) or polyethylene terephthalate (PET) textiles and are attached to the wall face, extending back into the soil mass. Reinforcement of the MSE wall is maintained, primarily, by the friction between the soil and the geosynthetic, which is a function of effective stress and interface roughness. During construction, backfill is compacted in lifts resulting in an overconsolidated stress state with a uniform initial saturation.

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 exchange would not create a significant increase in cost or complexity. A schematic of a thermally active MSE wall is shown in FIG. 1(b), noting how heat is introduced into the system. Heat exchange loops may be placed directly along the geosynthetics or in between. Thermal changes could have a positive effect on the stress state of the soil as well as a negative effect on the mechanical properties of the geosynthetic. A more in-depth understanding of how the two interact is necessary to properly design these systems.



(a) (b)

FIG. 1. Simplified schematic with typical components of an MSE wall: (a) Conventional MSE wall; (b) Thermally-active MSE wall

Using the reinforced zone of a MSE wall as a heat sink for the cooling of nearby industrial facilities 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. A drawback of using the MSE wall as a heat sink is that the efficiency of heat injection may decay as the mean soil temperature increases. However, heat is continuously being lost into the atmosphere for this near-surface system. Another approach used by Mands et al. (2013) that can be used to address this issue would be to use water towers for cooling at night, and only inject heat into the subsurface during the day. Though this method still requires cooling towers, energy savings would still be observed due to the use of cooling via the MSE wall during the day.

Impact of Temperature on Unsaturated Backfill

Heating of a soil element in drained conditions can lead to both recoverable and irrecoverable volume changes. During drained heating tests on normally consolidated and lightly overconsolidated saturated soils, the differential expansion of water and soil particles leads to a generation of excess pore water pressure, which dissipates with time, resulting in an irrecoverable volumetric contraction of the bulk soil. For saturated soils with overconsolidation ratios (OCRs) greater than 1.5 to 3.0, thermal expansion is typically observed (Cekerevac and Laloui 2004). Similar behavior has been observed for unsaturated soils (Tang et al. 2008, Uchaipichat and Khalili 2009). The results from these studies reinterpreted in terms of OCR are presented in FIG. 2.

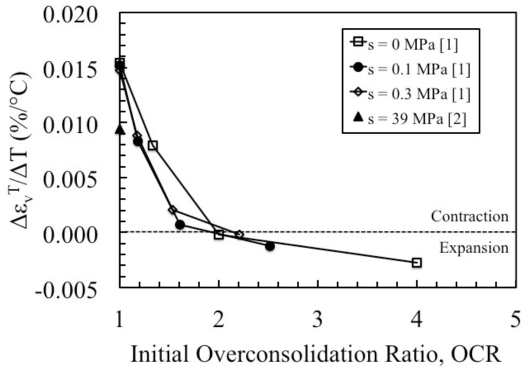


FIG. 2. Ratio of thermal volumetric strain to temperature change for unsaturated low PI soils: [1] Uchaipichat & Khalili (2009); [2] Tang et al. (2008)

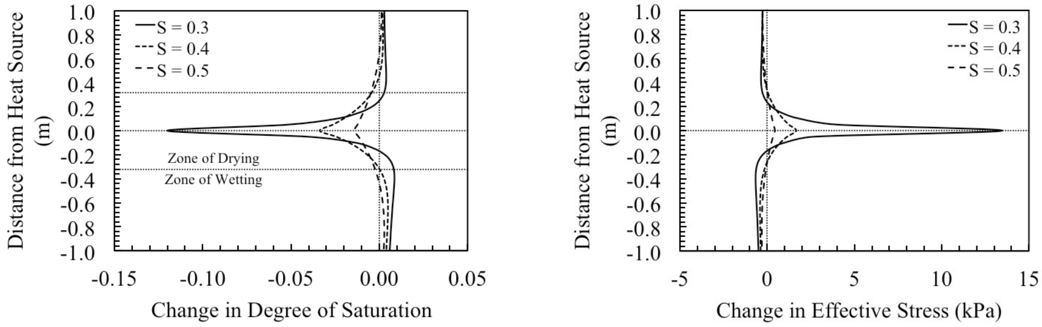
As the preconsolidation stress induced through compaction of poorly draining backfill will generally be higher than the overburden stress from soil self-weight, the results in FIG. 2 indicate that the unsaturated backfill will likely expand during heating. For a change in temperature of 40 °C, soils having OCRs ranging from 2 to 4 should experience thermal volumetric expansions ranging from 0 to 0.12% according to the results shown in FIG. 2. Further, for soils under active earth pressure conditions (K<1) where K is the ratio of the horizontal effective stress to vertical effective stress, the soil is expected to thermally expand at a larger magnitude in the horizontal direction than in the vertical direction (Coccia and McCartney 2012), potentially causing increased horizontal wall deflections.

In addition to thermal expansion, water will move from regions of high temperature to regions of lower temperature in both the liquid and vapor phases within the unsaturated zone. The zone of influence of this liquid and vapor movement will vary as a function of initial saturation, hydraulic conductivity, thermal conductivity, and porosity. 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 poorly draining backfill at different initial degrees of saturation. Specifically, they simulated the impact of thermally induced water flow on the effective stress state in an unsaturated soil layer with a heat exchanger installed at mid-height. The soil-water retention curve (SWRC) and thermal properties of Bonny silt were utilized for the investigation. Profiles of the change in degree of saturation with height in the backfill lifts above and below a heat exchanger are shown in FIG. 3(a). The results shown in FIG. 3(a) indicate a significant decrease in degree of saturation near the heat exchanger, with a greater decrease occurring for soil with a lower initial degree of saturation. For an applied temperature change of 40 °C, decreases in degree of saturation of 0.12, 0.034, and 0.014 were observed for soil layers having initial degrees of saturation of 0.3, 0.4, and 0.5, respectively. A discrete zone of drying of about 0.3 m was formed above and below the location of heat exchanger, while a less predominant zone of wetting was observed away from the heat exchanger [FIG. 3(a)].

The decrease in degree of saturation (or increase in suction) near a heat exchanger is expected to result in an increase in effective stress, which can be defined using the model of Lu et al. (2010):

$$\sigma' = \sigma - u_a + (u_a - u_w)/\left[1+\left(\frac{u_a-u_w}{a}\right)^{n}\right]^{1-\frac{1}{n}} \qquad \textbf{(1)}$$

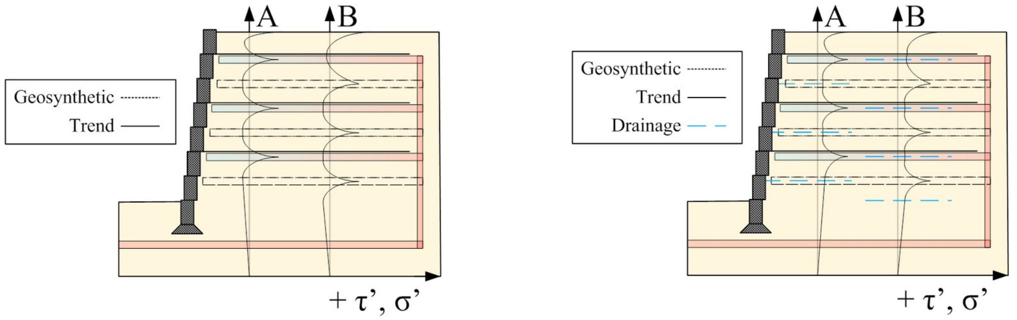
where σ' is effective stress, σ is total stress, u_a and u_w are the pore air and water pressures, respectively, and a and n are parameters used characterize the shape of the SWRC. Profiles of effective stress were defined from the modeled degree of saturation profiles, as shown in FIG. 3(b). Increases in effective vertical stress of 13.4, 1.7, and 0.4 kPa were observed near the heat exchanger for soil layers with initial degrees of saturation of 0.3, 0.4, and 0.5, respectively. These changes in effective stress are expected to lead to increases in the shear strength and stiffness of the soil. Decreases in effective stress of less than 1 kPa were found at the zones of wetting.



(a) **(b)**

FIG. 3. Impact of heating on unsaturated silt surrounding a heat exchanger: (a) Degree of saturation; (b) Effective stress (after Coccia and McCartney 2013)

A negative result of thermally induced water flow is the potential for weaker soil zones (i.e. decreased effective stress and shear strength) at the location of wetting. Depending on the placement of the heat exchange loops, this may negatively impact the mechanical response of the MSE wall. The expected effective stress and shear strength behaviors along the depth of a MSE wall for two loop configurations is shown in FIG. 4(a) where configurations A and B correspond to placement of the heat exchange loops at and between the geosynthetics, respectively.



(a)	**(b)**

FIG. 4. Trends in shear strength and effective stress for an MSE wall for two different configurations: (a) without vapor drainage; (b) with vapor drainage

A potential approach to address the formation of zones of increased saturation is to install drainage blankets between each heat source, allowing water vapor to drain from the MSE wall as it is driven from the heat exchange lines. These drainage blankets may be permeable geosynthetic reinforcements as well. The effective stress in between each heat source would be expected to be greater if drainage is provided within the backfill, resulting in an increase in shear strength from heating throughout the MSE wall [FIG. 4(b)]. This behavior may lead to a reduction in the horizontal deflection of the MSE wall.

Behavior of Geosynthetics

The tensile stiffness (J) of a geosynthetic, defined as the slope of the force-displacement curve ($P:\delta$ curve) in the elastic region, may also be negatively impacted by increases in temperature. The sensitivity of a geosynthetic to thermal changes is largely a function of the polymer itself. Each polymer has an associated glass transition temperature (T_g) designated as the temperature which the polymer transitions from a stiff to softened mechanical response, indicated by a decrease in J. Polypropylene (PP) and polyethylene terephthalate (PET) have glass transition temperatures of -20 and 69 °C, respectively (Oswald and Menges 2003). Accordingly, PP will exhibit a softened response to loading even at ambient temperatures, as compared with PET which will remain stiff up to temperatures of around 69 °C.

Existing unconfined tensile test data from the literature on PP geosynthetics (Zornberg et al. 2004, Bueno et al. 2005) and PP single filaments (Karademir 2011) was analyzed to quantify the effects of heating on PP geosynthetic stiffness (FIG. 5). For PP geosynthetics and polymers exposed to temperatures above the glass transition temperature, a decreasing logarithmic trend was observed for the tensile stiffness with increasing temperature. A similar behavior may exist for PET geosynthetics exposed to temperatures greater than 69 °C. However, limited experimental results exist.

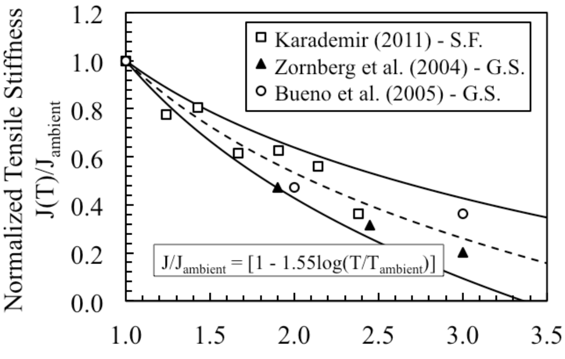


FIG. 5. Decrease in stiffness due to elevated temperatures for: PP geosynthetic reinforcement (G.S.) and PP single filament (S.F.)

Geosynthetics are often tested in unconfined (in-isolation) conditions. Although this is an adequate method for determining the properties of the geosynthetic itself, it may not accurately describe the behavior of the geosynthetic in-situ. Comparison of in-isolation tests with in-situ tests suggests an apparent increase in stiffness as a function of confining pressure. This increase in stiffness is commonly attributed to an increased resistance to necking due to increases in confining pressure (McGown et al. 1982, Bueno and Zornberg 2005) and is typically observed only for non-woven geosynthetics (França and Bueno 2011), as the structure of woven materials is not susceptible to the necking phenomenon. The impact of confining pressure on the apparent tensile stiffness of non-woven geosynthetics is shown in FIG. 6. The data suggests a non-linear relationship between confining pressure and tensile stiffness. The relationship in FIG. 6 indicates that the performance of MSE walls incorporating non-woven geosynthetics could potentially benefit from thermally induced water flow due to the resulting increases in effective stress.

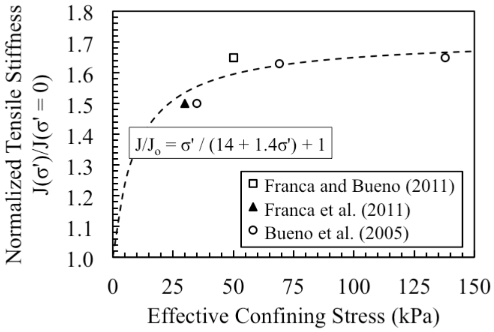


FIG. 6. Increase in geosynthetic tensile stiffness with confining pressure

IMPACT OF ELEVATED TEMPERATURES ON THE MECHANICAL RESPONSE OF MSE WALLS

The Jewell-Milligan (JM) model is a simple analytical approach to estimate the horizontal wall deflections of an MSE wall (Jewell and Milligan 1989), as follows:

$$\delta_{total} = \left[\frac{H \cdot P_{max}}{J} \right] \cdot m \qquad \textbf{(2)}$$

where H is the wall height, P_{max} is the maximum horizontal force in the geosynthetic, J is the stiffness of the geosynthetic, and m is a function of the soil properties (i.e. friction angle and active earth pressure coefficient) and wall geometry, given by:

$$m = \left(1 - \frac{z}{H}\right) \cdot \tan\left(45 - \psi/2\right) + \frac{1}{K_a} \cdot \left(1 - \frac{z}{H}\right) \cdot \text{¿¿¿¿} \qquad \textbf{(3)}$$

¿

where ϕ_{ds} is the friction angle obtained from direct shear testing, z is the height from the base, and K_a is the Rankine active earth pressure coefficient, which can be modified to account for the impact of suction on the effective stress:

$$K_a(\sigma_v')=\frac{1-\sin\phi}{1+\sin\phi}-\frac{2\cdot\psi\tan\phi}{\sigma_v'}\cdot\sqrt{\frac{1-\sin\phi}{1+\sin\phi}} \tag{4}$$

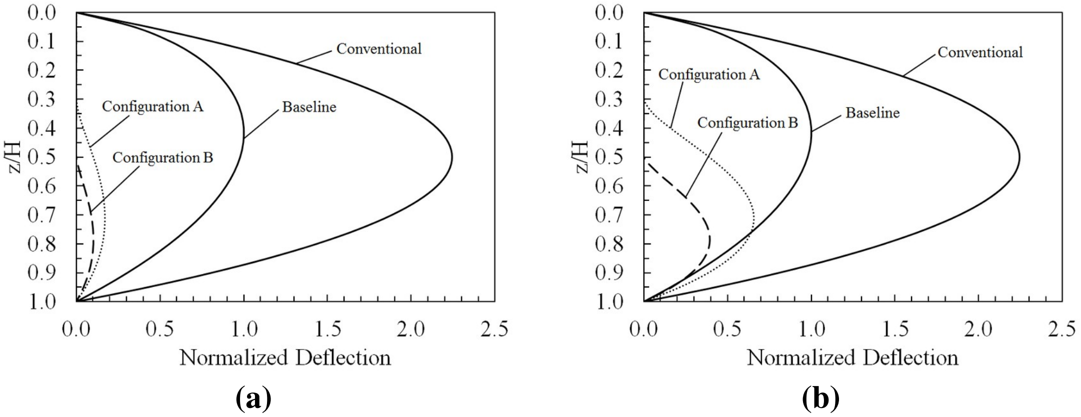
where ϕ is the friction angle, σ_v' is the effective vertical stress, and ψ is the suction present in the reinforced soil mass. The suction can be calculated from the degree of saturation using the SWRC of the backfill, and the effective stress can be calculated using Eq. (1).

Stewart and McCartney (2013) modified the value of J in the JM model to account for the impacts of temperature and confining stress on the tensile stiffness of the geosynthetic reinforcements using the relationships summarized in FIGs. 4 and 5, respectively:

$$J(T,\sigma_v')=J_o\left[1-1.55\log(T/T_o)\right]\left[1+\frac{\sigma_v'}{14+1.4\sigma_v'}\right] \tag{5}$$

Wall deflections can be calculated with the modified JM model by inserting the value of $J(T,\sigma_v')$ from Eq. (5) and $K_a(\sigma_v')$ from Eq. (4), into Eq. (2). Although the modified JM model provides a convenient closed-form estimate of wall deflection, the modified geosynthetic stiffness does not capture the complete thermo-hydro-mechanical behavior of the soil-geosynthetic system. Further, the modified JM model assumes no slippage along the soil-geosynthetic interface, which may not be realistic.

The potential impacts of thermally induced water flow and thermal softening of the geosynthetic reinforcements on the horizontal wall deflections of a MSE wall were assessed using the modified JM model. Two thermally active MSE wall configurations (A and B), corresponding to the heat exchanger/reinforcement layouts shown in FIG. 4(a), were analyzed. Configurations A and B reflect the cases where the geosynthetic is co-located with the heat exchanger or where it is used as a drainage layer between heat exchangers, respectively. The analyses were performed by first calculating the effective stress at the depth of each geosynthetic from Eq. (1), using the profiles of degree of saturation determined by Coccia and McCartney (2013) for the case of an initial degree of saturation of 0.3 and an increase in temperature of 40 °C from an initial temperature of 20 °C. The changes in degree of saturation with depth were found to correspond to changes in effective stress of +13.4 and -0.66 kPa at the locations of the geosynthetic reinforcements in Configurations A and B, respectively. These values were used to account for the impact of confinement on the geosynthetic stiffness in Eq. (5). In order to estimate K_a with depth, the weighted average of the change in matric suction with depth was determined from the profile of degree of saturation shown in FIG. 3(a). The average change in matric suction throughout the depth of the wall was 16 kPa. The results of the analyses for Configurations A and B for PET and PP geosynthetics are shown in FIGs. 7(a) and 7(b), respectively. Analyses were also performed using the conventional JM model (no consideration of temperature or confining effects), and the modified JM model considering self-weight confining effects but without consideration of temperature or thermally induced water flow (which serves as the baseline case).



(a) **(b)**

FIG. 7. Normalized deflection versus depth for backfill with an initial saturation of 0.3: (a) Non-woven PET geosynthetics; (b) Non-woven PP geosynthetics

Comparison of the "baseline" and "conventional" cases indicates a significant decrease in the expected horizontal wall deflection through incorporation of self-weight confining stress effects in the conventional JM model. It should be noted that the self-weight confining effects are due to restraint of the geometry of nonwoven geotextiles, and effects of this magnitude are not expected for woven geotextiles or geogrids. Comparison of the baseline case with the results for the thermally active MSE walls in Configurations A and B indicates heating to lead to a reduction in normalized wall deflection. Although temperature may cause a reduction in the stiffness of the geosynthetic reinforcement resulting in an increase in wall face deflection, it also leads to thermally induced water flow that dominates the reduction in expected wall face deflection. The lack of face deflections in the top half of the wall for Configurations A and B implies that the formation of an active wedge is largely suppressed by the matric suction. Comparison of the magnitude of the face deflections in FIGs. 7(a) and 7(b) suggests the geosynthetic polymer (PET vs. PP) to have a significant impact on the thermo-mechanical response of the MSE wall. For Configurations A and B, maximum normalized wall deflections of 0.171 and 0.102 were calculated for the PET geosynthetic and 0.657 and 0.385 were calculated for the PP geosynthetic, indicating PET geosynthetics to be more suitable for thermally active MSE walls due to their resistance to thermal softening within the temperature range expected (T < 70 °C).

CONCLUSIONS

The Jewell-Milligan model was modified to investigate the deformation behavior of thermally active MSE walls. The stiffness of the geosynthetic reinforcing elements was found to decrease due to the effects of thermal softening, but was overcome by greater increases due to confining effects. Thermally induced water flow was found to cause an increase in effective stress in the wall, leading to a greater confining effect. The results indicate that geosynthetics with a high glass transition temperature should be considered for these applications. The conclusions drawn from this model should be confirmed in future studies using confined creep tests with temperature control.

ACKNOWLEDGEMENTS

Support from NSF grant CMMI-1054190 is gratefully acknowledged. The views in this paper are those of the authors alone.

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