## Title
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## Chapter 8

# Energy GeoStructures in Unsaturated Soils

### 8.1. Introduction

Because the performance of near-surface geotechnical systems is closely related to water flow arising from environmental interactions, most geotechnical design guides for fill-type systems attempt to minimize the impact of water by using free-draining backfill soils [SAB 97; ELI 01]. However, this can lead to high construction costs, especially in areas where such backfills are not available. In addition to poor drainage, compacted backfills with high clay content are avoided in geotechnical systems because their strength and stiffness tend to decrease with increasing water content (or decreasing suction) during environmental interactions[ZOR 94; MIT 95; ZOR 95]. Silts are avoided for similar reasons and because of their susceptibility to frost heave. However, if these soils remain in unsaturated conditions, these detrimental impacts on the performance of fill-type geotechnical systems with poorly draining backfills may be minimized. It is well known in unsaturated soil mechanics that suction plays an important role in the effective stress state [KHA 98; LU 06; NUT 08]. An increase in effective stress in unsaturated soils can lead to significant improvements in their engineering properties including shear strength and stiffness. A novel way of maintaining unsaturated conditions in poorly draining backfills is to engineer the mechanically stabilized earth (MSE) wall so that thermally induced water flow away from embedded heat exchangers causes drying of the backfill.

An example of a thermally active geotechnical system in unsaturated soil involves placement of heat exchangers into the compacted backfill of a MSE wall.

The heat exchangers can be placed at intermediate lifts between the reinforcements, so that the geosynthetics may serve as permeable pathways for thermally induced water flow. To serve this purpose, the geosynthetic reinforcements may be either permeable woven geogrids or nonwoven geotextiles. In this case, the geosynthetics will not only serve their conventional, passive roles (reinforcement, separation, drainage), but will also serve an active role by providing a boundary condition for thermally induced water flow. A schematic of a thermally active MSE wall is shown in Fig. 8.1(a). The spacing and location of heat exchangers is not only important for uniform soil-geosynthetic composite improvement, but also to create a thermal gradient between the backfill and atmosphere, which will in turn drive water from the system. A strategy for routing of heat exchange tubing is shown in Fig. 8.1(b).

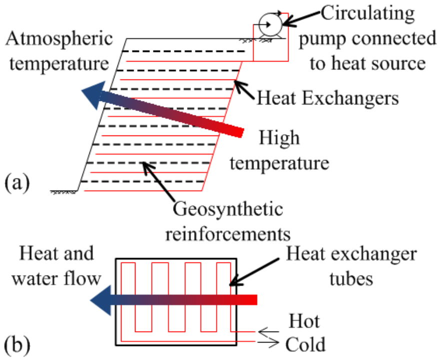


**Figure 8.1.**Thermally active MSE wall: (a) Elevation section; (B) Plan view

Thermally active geotechnical systems have the added benefit of enhancing the energy efficiency of heat pump systems for cooling of buildings or in rejection of excess heat from power plants or industrial facilities. Cooling needs are typically defined in terms of equivalent tons of cooling, defined as the heat rejection in cooling 12 liters/minute by 5 °C [DRB 96]. Buildings typically require 0.82 tons of cooling (4396 W) per 100 $m^2$of floor area [NRE97] while a 700 MW power plant can require as much as 100,000 tons of cooling [DRB 96]. As heat is rejected through conduction, the inlet fluid temperatures, heat exchanger lengths/spacing, and fluid circulation rates are the important design variables that can be varied to reach a heat rejection goal. The entering water temperature typically ranges from 50 to 80 °C in typical cooling applications [OME 08].

This chapter includes a critical review and synthesis of data presented in the literature on the different impacts of temperature on the thermo-hydro-mechanical behavior of unsaturated soils, as well as a discussion on the implications of temperature on the behavior of geosynthetic reinforcements.

## 8.2.Thermally Induced Water Flow

Thermally induced water flow in soils is the main driver for maintaining unsaturated conditions in the backfill of thermally active geotechnical systems. A significant body of work has been assembled on this topic in the area of vadose zone hydrology, including definition of governing equations for water flow in liquid and vapor forms [PHI 57], analytical and numerical solutions [CAR 62A; CAR 62B, TAY 64; MIL 82], and field experiments [MIL 96]. The governing equations have been incorporated into commercial finite element programs, such as VADOSE/W [WIL 94], while the impact of volume change has been evaluated in advanced models [THO 95A, 95B, 96]. Although analysis of thermally induced water flow under a heat exchanger boundary condition is important, the role of atmospheric boundary conditions on the flow of heat and water into and out of the system must be considered. The prediction of atmospheric interaction in soil layers has been investigated in landfill cover analyses [MCC 04; ZOR 05; SCA 02; OGO 08].

Two experimental studies of thermally induced flow away from an axisymmetric line heat source in unsaturated soils are shown in Fig. 8.2. For a temperature of 90 °C applied to a sand-bentonite mixture, Yong and Mohammed [YON 96] noted a decrease in degree of saturation of 0.5 near the heat source after 3 days, with a drying zone of influence of about 40 mm. For a temperature of 70 °C applied to sand, Ewen and Thomas [EWE 89] observed a drying over a zone of influence of 20 mm. Although the zones of influence observed in these two examples are small, a greater zone of influence and faster response is expected for silts or low plasticity clays due to their greater hydraulic conductivity over a range of water content.

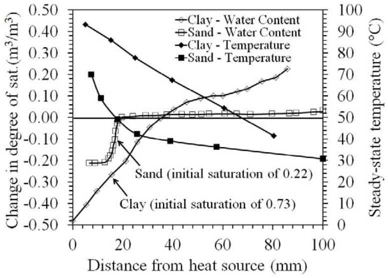
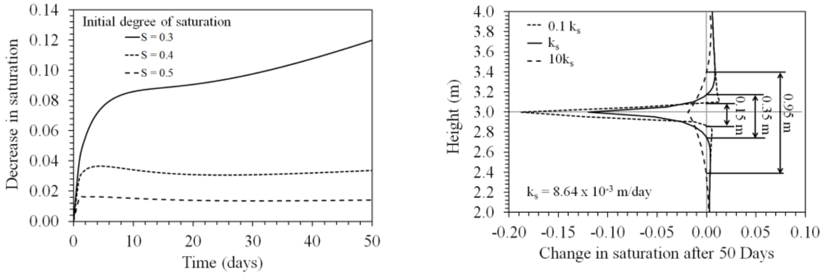


**Figure 8.2.**Thermally-induced water flow in clay [YON 96] and sand [EWE 89]

The affected zone and magnitude of thermally induced water flow are functions of the initial degree of saturation (S), hydraulic conductivity for saturated conditions ($k_s$), thermal conductivity ($\lambda$), and porosity (n). Coccia and McCartney [COC 13] observed a greater decrease in saturation at the location of a heat exchanger for silt with lower initial S [Figure 8.3(a)]. Further, soils with lower $k_s$ tended to have a smaller zone of drying [Figure 8.3(b)]. Thermally induced water flow is also affected by coupled changes in the thermal conductivity of soil, which may decrease by a factor of about 10 as S approaches zero, with a lower limit of 0.25 to 0.5 W/m°C depending on density and mineralogy [FAR 81].However, Smits et al. [SMI 13] observed nonlinear changes in thermal conductivity for sands during drying under temperatures above 55 °C, with a peak value at a saturation of 0.1.



(a) (b)

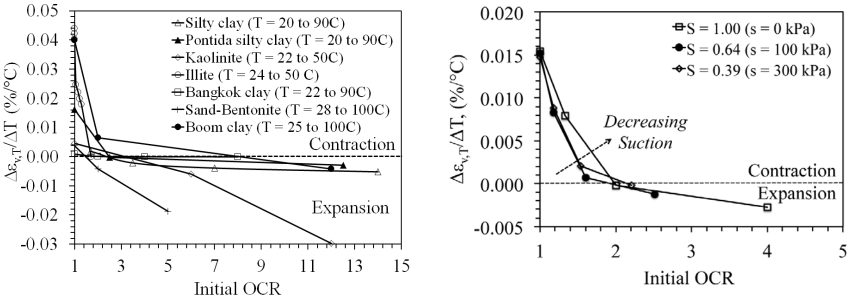
**Figure 8.3.**(a) Decrease in saturation at the location of heat exchange with time; (b) Thermal saturation profile as influenced by hydraulic conductivity

## 8.3. Thermal Volume Change in Unsaturated Soils

An important side effect of soil heating is the possibility for excess pore water pressure generation that may lead to additional flow of water away or toward the heat exchanger, as well as a decrease in undrained shear strength. Campanella and Mitchell [CAM 68] found that positive excess pore water pressures are induced in saturated normally consolidated soils due to differences in the relative expansion of the water and soil skeleton during heating. Specifically, the coefficient of thermal expansion of pore water is approximately 7-10 times that of most soil particles [MCK 65; MIT 05]. If these excess pore water pressures are permitted to drain, time dependent, irrecoverable (elasto-plastic) contraction or expansion will occur depending on the soil structure and stress history. Saturated normally consolidated soils tend to contract plastically during drained heating, then contract elastically during cooling. Saturated soils with overconsolidation ratios (OCRs) greater than 1.5 to 3 tend to expand and contract elastically during drained heating and cooling, respectively. This behavior is summarized in Figure 8.4(a) for different soils. Soils with a greater plasticity index show more volume change during heating [SUL 02]. This behavior has been incorporated into constitutive models based on the Cam-Clay model [HUE 90A; HUE 90B; CUI 00; LAL 03; FRA 08; CUI 09].

Different from saturated soils, fewer studies have focused on the thermal volume change behavior of unsaturated soils [SAI 90; SAI 91; SAI 00; ROM 03; ROM 05;

FRA 05; TAN 08; TAN 09; UCH09]. Of these studies, all but two were performed on expansive clays, which would be unsuitable as backfills. Saix et al. [SAI 00] performed drained heating tests on clayey silt specimens at a constant suction of 4.5 kPa, and observed plastic contraction during heating. Uchaipichat and Khalili [UCH 09] performed constant water content (undrained) heating tests on compacted silt, and measured a decrease in matric suction of 50% during heating from 25 to 60 °C. The pore water likely expanded and filled more voids, leading to the decrease in suction. A re-evaluation of drained thermal volume change data for unsaturated silt from Uchaipichat and Khalili [UCH 09] as a function of the OCR calculated using the effective stress definition of Khalili and Khabbaz [KHA 98] is shown in Figure 8.4(b). The trends are similar to those for saturated soils, confirming the importance of stress state. However, the reasons for this behavior are different from saturated soils. For the low OCR specimens, it is possible that the change in temperature led to a decrease in the preconsolidation stress and the associated yield function, which may lead to a tendency for an unsaturated soil having a stress state near the yield function to collapse during heating. The trends for unsaturated silt are also confirmed by studies on compacted bentonite [ROM 03; TAN 08].



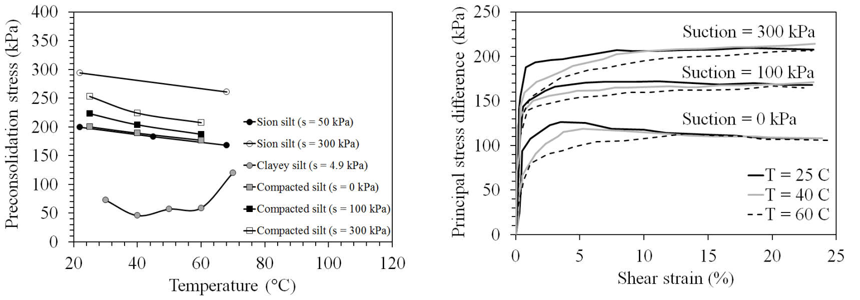
(a) (b)

**Figure 8.4.**Gradient of drained thermal volumetric strain ($\Delta\varepsilon_{v,T}$) with temperature changes (ΔT) for: (a) Saturated soils (Silty clay [TOW 93], Pontida clay [BAL 88], Kaolinite [CEK 04], Illite[PLU 69], Bangkok clay [ABU 07A], Sand-Bentonite [GRA 01], Boom clay [SUL 02]; (b) Unsaturated compacted silt[UCH 09]

### 8.4. Thermal Effects on Soil Strength and Stiffness

Temperature generally does not have a significant effect on the engineering properties of most saturated and unsaturated soils. Campanella and Mitchell [CAM 68] studied the compression behavior of saturated soils under different temperatures, and found that the compression index was independent of temperature. This has been confirmed by other studies on saturated soils [DEM 82; GRA 01] and unsaturated soils [SAI 00; UCH 09]. Soils which do show temperature-dependent compression indices are typically expansive clays [DEL 00; ROM 03], which are not suitable for use as backfills. Cekeravac and Laloui [CEK 04] summarized data from the literature indicating that temperature does not have a significant impact on the friction angle. This is supported by studies that found that the critical state line is independent of temperature for saturated soils [FIN 51; KUN 95; GRA 01; ABU 07B; ABU 09] and unsaturated soils [UCH 09]. However, Hueckel et al. [HUE 09] hypothesized that the critical state line may be sensitive to the stress history and drainage conditions during heating for some soils, and proposed alternative explanations for data presented in the literature.

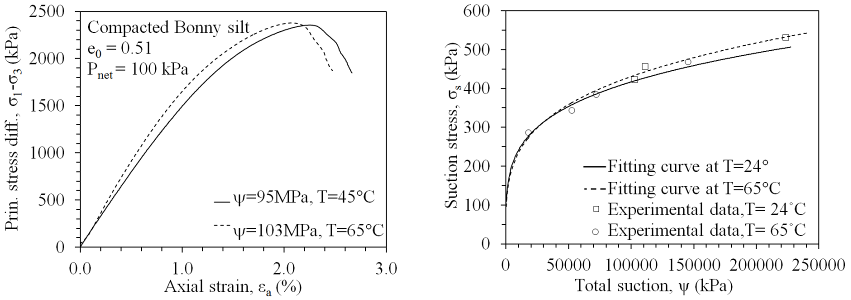
Temperature primarily affects the shear strength and stiffness of soils through volume change and changes in the shape of the plastic yield surface. For saturated normally consolidated (NC) clays, the volumetric contraction after dissipation of thermally induced positive excess pore water pressure has been found to correspond to an increase in strength and stiffness [HOU 85; HUE 92; ABU 07B; ABU 09]. Saturated overconsolidated (OC) soils show a decrease in strength after heating due to volumetric expansion [PAA 67; PLU 69]. During mechanical loading of saturated soils after heating, a lower preconsolidation stress is observed for OC clays. For unsaturated soils, suction causes a hardening effect and an increase in the apparent preconsolidation stress [ALO 90]. Similar to saturated OC soils [ERI 89; TID 89], mechanical loading of soils after heating indicates that the soil has a lower preconsolidation stress [UCH 09]. The data in Figure 8.5(a) from different studies confirm this trend. Saix et al. [SAI 00] observed that this decreasing trend may not be general for all temperatures. The effect of a lower preconsolidation stress is typically a more ductile stress-strain curve, as shown in the data from Uchaipichat and Khalili [UCH 09] in Figure 8.5(b). Comparison of the relative impacts of temperature and suction on the shear strength of unsaturated soils indicates that suction has a more significant effect.



(a) (b)

**Figure 8.5.**Impact of heating on the:(a) preconsolidation stress of silts [SAI 00; FRA 05; UCH 09]; (b) stress-strain curves of unsaturated silt [UCH 09]

The trends observed in Figure 8.5 may not hold for the high suction magnitudes that may be encountered in thermally active geotechnical systems. Preliminary work by Alsherif and McCartney [ALS 12] indicates that temperature does not have a significant impact on the shear strength of compacted silts under high suction magnitudes. The stress-strain curves in Figure 8.6(a) for specimens having an initial suction of approximately 100 MPa under the same net mean normal stress but different temperatures were similar, with a relatively brittle shape. The suction-stress characteristic curves derived from failure envelopes for specimens at different initial suctions and different temperatures in Figure 8.6(b) indicate similar behavior.



(a) (b)

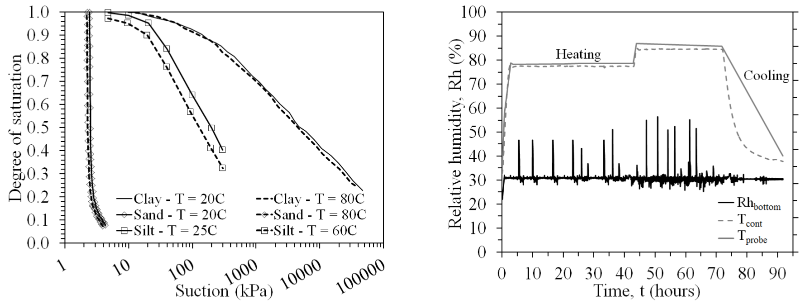
**Figure 8.6.**Shear strength of compacted silt under high suctions and high temperatures: (a) Stress-strain curves ($e_0$ = initial void ratio, $P_{net}$ = net normal stress, ψ = suction, T = temperature); (b) Suction-stress characteristic curves

### 8.5. Thermal Effects on Hydraulic Properties of Unsaturated Soils

A linkage between the effective stress in unsaturated soils and the soil-water retention curve (SWRC) has been observed in many studies[VAN 96; NUT 08; KHA 98]. Khalili and Khabbaz [KHA 98] found that the role of suction in the effective stress is strongly dependent on the ratio of the suction to the air entry suction. The air entry suction is an important point on the SWRC. Lu et al. [LU 10] derived an equation that integrates the SWRC directly into the effective stress:

$$\sigma' = (\sigma - u_a) + (u_a - u_w) \Big/ \left(1 + \alpha (u_a - u_w)^n\right)^{(n-1)/n} \qquad [8.1]$$

where σ′ and σ are the effective and total stresses, $u_a$ and $u_w$ are the pore air and water pressures, and n and α are the parameters of the van Genuchten [VAN 80] SWRC model. Eq. 8.1can be used to interpret the shear strength of both unsaturated and saturated soils, as this equation reduces to the classic definition of effective stress for saturated conditions. The impact of temperature on the effective stress in unsaturated soils can be evaluated through the SWRC, as the water retention of unsaturated soils decreases with temperature [NIM 86; HOP 86; GRA 96; ROM 01; BAC 02; SAL 07; UCH 09]. Specifically, the interface tension and soil-fluid contact angle, variables important in the Kelvin model for suction, are temperature dependent. The interface tension of pure water decreases at a rate of 0.2%/°C [GRA 96], and the fluid-solid contact angle can decrease by as much as 0.26°/°C [BAC 02]. SWRCs for soils defined under constant temperatures are shown in Figure 8.7(a). Temperature has a greater impact on the suction magnitude with decreasing degrees of saturation [GRA 96]. The reduction in suction of 100 kPa observed for the compacted silt at a degree of saturation of 0.4 is substantial, indicating that temperature may affect the effective stress. Grant and Salehzadeh [GRA 96] and Salager et al. [SAL 07] developed incremental-form models for temperature effects on the SWRC that use Kelvin's equation for suction and consider the relative thermal expansion of soil and water, but do not incorporate common SWRC equations. An area of continued research is the impact of temperature on the SWRC at high suction magnitudes. Alsherif and McCartney [ALS 13] developed a new thermal triaxial cell with suction control using the vapor circulation technique [LIK 03]. The relatively constant relative humidity (Rh) for different temperatures (T) in Figure 8.7(b) reflects the feasibility of maintaining constant high suctions during elevated temperatures with this device.

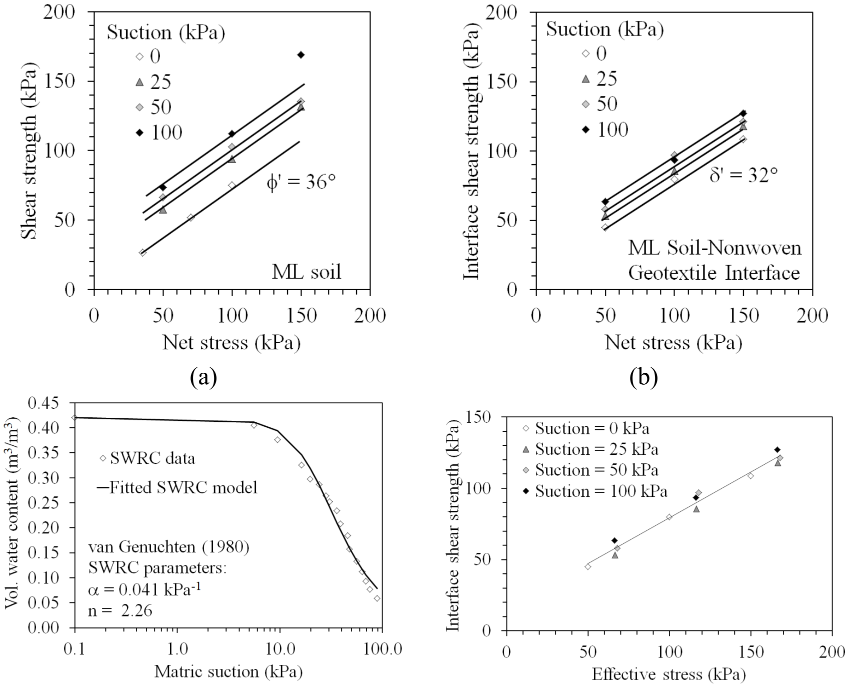


(a) (b)

**Figure 8.7.**(a) Thermal effects on SWRCs of clay [ROM 03], silt [UCH 09], and sand [EWE 89]; (b) Thermal effects at high suctions on compacted silt [ALS 12]

## 8.6. Thermal Effects on Soil-Geosynthetic Interaction

Woven geotextiles or geogrids and nonwoven geotextiles are primarily used for reinforcement of poorly draining backfills because extruded geogrids do not interact well with fine-grained soils. Recent studies on reinforcement of poorly draining backfills have focused on measurement of the effects of suction on soil-geosynthetic interface shear strength [HAT 08; SHA 98; HAM 09; KHO 10]. These studies used a two stress-state variable approach to interpret the effects of suction on shear strength [Figs. 8.8(a) and 8.8(b)]. However, the results from the previous section indicate that the impact of temperature may be easier to interpret when the shear strength is interpreted using effective stress. The SWRC of this soil [Fig. 8.8(c)] indicates that the interface shear strength can be interpreted well using a single-value effective stress [Fig. 8.8(d)]. This confirms that the shear strength of unsaturated soil-geosynthetic interfaces is strongly dependent on the matric suction in the soil.

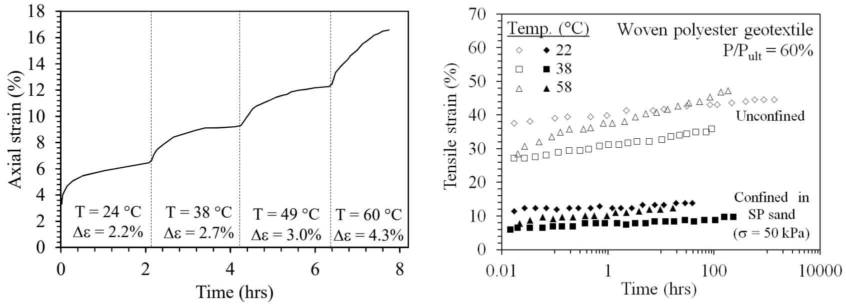


(a) (b)

(c) (d)

**Figure 8.8.**Unsaturated interface shear strength of soil-geosynthetic interfaces [KHO 10]: (a) Impact of suction on soil (ϕ′ is soil friction angle); (b) Impact of suction on soil-geosynthetic interface (δ′ is soil-geosynthetic interface friction angle); (c) SWRC; (d) Interface shear strength using effective stress

An added complexity in thermally active geotechnical systems is that the tensile stress-strain behavior of geosynthetics is sensitive to temperature, a feature that has been exploited to accelerate the creep process using the stepped isothermal method [THO 98; ZOR 04; BUE 05]. The results from unconfined thermal creep tests in Fig. 8.9(a) indicate a linear increase in creep strain with temperature, which reflects the potential impacts of temperature on the stress-strain behavior. Despite this observed behavior, confinement of the geosynthetic in soil may reduce the impact of thermally induced creep by preventing geometric distortion of the geosynthetic structure [MCG 82]. The data in figure 8.9(b) show that confinement not only leads to a lower initial tensile strain during application of a relatively high fraction of the ultimate tensile strength $P_{ult}$, but a lower rate of creep strain over time [FRA 11].



(a) (b)

**Figure 8.9.** (a) Thermally induced creep strain (Δε) of a geotextile [ZOR 04]; (b) Impact of confining stress on creep of a nonwoven geotextile ($\sigma$ = confining stress, P = tensile stress, $P_{ult}$ = ultimate tensile strength) [FRA 11]

## 8.6. Conclusions

Some of the key issues involved in the development of thermally active geotechnical systems in unsaturated soils are summarized in this chapter. Additional research is required to synthesize the thermo-hydro-mechanical processes in the unsaturated soils, and to understand the interaction between unsaturated conditions and thermally induced creep deformations of confined geosynthetics. Nonetheless, the results from the literature indicate that the strategy to maintain unsaturated conditions in soil systems using thermally induced water flow will enable, under the right conditions, use of a broader class of backfills than currently permitted in fill-type geotechnical applications. Further, although temperature may have some negative impacts from the perspective of thermal soil improvement, the positive effects of increased suction due to thermally induced water flow may be sufficient to compensate for these effects. An added benefit of thermally active geotechnical systems is that they can dissipate spurious heat generated by buildings or industry.

## 8.7. Acknowledgements

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