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Unsaturated Soil Mechanics in Geothermal Energy Applications

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ABSTRACT: This paper focuses on the role of unsaturated soil mechanics in different thermal energy applications in geotechnical engineering. These applications include ground-source heat exchangers in geotechnical engineering infrastructure (drilled shafts, diaphragm walls, etc.), injection of spurious heat into near-surface thermally active geotechnical systems involving unsaturated soils (embankments, retaining walls with poorly draining backfill), and soil-borehole thermal energy storage systems. In addition to discussing the effects of temperature on soil properties, results from different physical modeling experiments on thermally active geotechnical systems are presented. The results indicate that consideration of inter-relationships between heat transfer, water flow, and mechanical effects leads to opportunities for improving heat transfer in unsaturated soils, as well as for improving the performance of geotechnical systems involving unsaturated soils.

1 INTRODUCTION

There are a number of new applications at the intersection between geotechnical engineering and near-surface geothermal energy, in which a heat pump is used to transfer heat stored in the subsurface to or from a building. One of the primary applications involves the incorporation of closed-loop heat exchanger tubing within drilled shaft foundations to form “energy piles” (Brandl 2006). Although it is possible for unsaturated conditions to affect the performance of energy piles (Stewart and McCartney 2013), there are other opportunities for heat exchange applications which are designed to operate in unsaturated soils, including heat storage and thermal soil improvement using spurious heat generated by industry (McCartney 2012). In these applications, it is important to consider coupling between heat and water flow in unsaturated soils, which may cause a corresponding change in effective stress. Further, the effects of temperature on the volume change response, preconsolidation stress, and shear strength of unsaturated soils should be carefully considered.

This paper presents a review of recent studies on the effects of temperature on the behavior of unsaturated Bonny silt. The geotechnical properties of this soil have been reported by Coccia and McCartney (2013) and Traore (2013), amongst others. Further, two geothermal energy applications involving unsaturated soils will be reviewed, the first involving prediction the face deflections in a thermally active retaining wall and the second an evaluation of heat storage in a borehole array.

2 ROLE OF NONISOTHERMAL CONDITIONS IN UNSATURATED SOIL MECHANICS

2.1 *Effects of Temperature on the SWRC and Effective Stress*

Changes in the shape of the SWRC may occur with temperature due to changes in porosity as well as due to changes in the interface tension and soil-fluid contact angle (Grant & Salehzadeh 1996). These effects typically lead to a reduction in the degree of saturation for a given matric suction. The reduction in degree of saturation is typically the greatest at large suction magnitudes (Grant & Salehzadeh 1996; Romero et al. 2003). SWRC data for Bonny silt defined under room temperature at low and high suctions and T = 65 °C at high suctions are shown in Fig. 1. The role of decreased porosity in the shape of the SWRC cannot be observed when plotted in terms of degree of saturation, although a change in the pore size distribution may affect the slope of the SWRC for intermediate degrees of saturation. Several studies have shown that the effective stress in unsaturated soils is closely linked with the SWRC (e.g., Lu et al. 2010). The implication of the shift of the SWRC with temperature is that the effective stress change may be smaller at higher temperatures (as the degree of saturation is linked with the effective stress parameter). However, this may not always be true in unsaturated soils, as thermally induced water flow under a temperature gradient will lead to drying of the soil in the region of the heat source, increasing the effective stress.

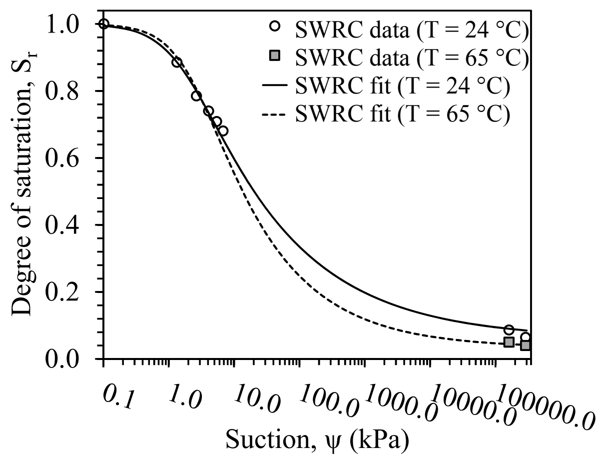

Figure 1. Impact of temperature on the SWRC of Bonny silt at high suctions (after Alsherif 2013).

2.2 *Coupled Heat Transfer and Water Flow in Unsaturated Soils*

Thermally induced water flow in unsaturated soils is an important mechanism in thermally active geotechnical systems, as it can be used to drive water from soils to cause an increase in effective stress (Coccia et al. 2013) or to create a convective cycle to enhance heat transfer into the soil layer (McCartney et al. 2013). Early research in soil physics led to the development of theories for nonisothermal flow of water in liquid and vapor forms (Philip & de Vries 1957), which generally assume that water evaporates and condenses upon discrete liquid islands at particle contacts to cause flow of water from high to low temperature zones in soils. Thermally induced water flow is most effective in soils under intermediate to low degrees of saturation. A greater zone of influence and faster response is expected for silts or low plasticity clays due to their greater permeability over a wide range of water content (Yong & Mohammed 1996). Thermally induced water flow may lead to a coupled change in the heat transfer processes in unsaturated soils. Although it is well known that thermal conductivity of soils decreases with degree of saturation under room temperature, Smits et al. (2012) observed that the apparent thermal conductivity of soils under elevated temperatures will increase with degree of saturation up to a certain point before dropping off to the value of dry soils. This occurs due to the transfer of latent heat during phase change of the pore water under higher temperatures. The phase change and associated convection processes due to movement of water vapor will enhance the heat transfer process.

Coccia & McCartney (2013) performed a numerical investigation using VADOSE/W to understand the influence of heat exchange on the thermo-hydro-mechanical response of compacted Bonny silt at different initial degrees of saturation. They simulated the impact of thermally induced water flow away from a heat exchanger installed at mid-height of a 2 m-thick soil layer. A constant thermal conductivity with temperature and water content was used for this example for simplicity, which implies that less heat and water flow likely occurred away from the heat exchanger due to the lack of consideration of coupling in the analysis. The predicted change in the degree of saturation at different depths in a soil layer having an initial degree of saturation of 0.3 during application of a change in temperature of 40 °C to the heat exchanger for a total of 50 days is shown in Fig. 2. The porosity (θ_s) van Genuchten (1980) SWRC parameters (θ_r, α_{vG}, n_{vG}), hydraulic conductivity (k_s), specific heat capacity (C), and thermal conductivity (λ) for Bonny silt are shown in this figure. This temperature was selected as being representative of a lower bound on the temperature of water in cooling operations. A maximum decrease in degree of saturation of 0.12 was observed at the heat exchanger location. A relatively narrow zone of influence of about 0.3 m was formed above and below the heat exchanger, while a smaller zone of wetting was observed further away from the heat exchanger. Similar observations were made experimentally for Bonny silt by Coccia et al. (2013).

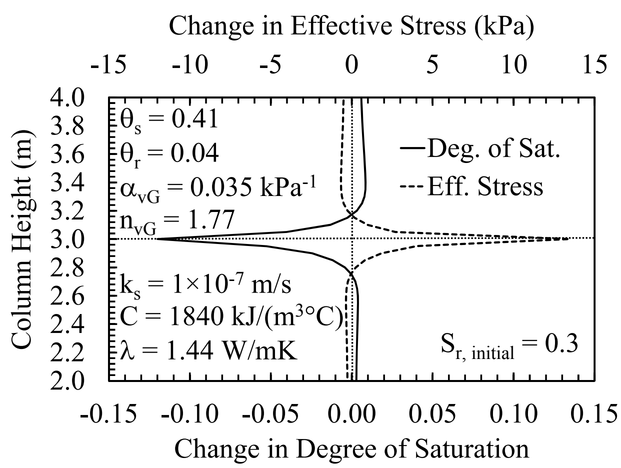

Figure 2. Modeled impact of heating on the degree of saturation and effective stress in unsaturated layer of Bonny silt (after Coccia & McCartney 2013)

The predicted changes in degree of saturation in Fig. 2 were used to predict the changes in effective stress in the soil layer with depth using the definition of effective stress of Lu et al. (2010). An increase in effective stress of about 13 kPa was observed at the location of the heat exchanger. These results can be used to understand the effects of locations of heat exchangers, geosynthetic reinforcements, and internal drainage layers in thermally active retaining walls (Stewart et al. 2014).

2.3 *Thermal Volume Change of Unsaturated Soils*

An important side effect of the heating of saturated soils is the possibility for excess pore water pressure generation and volume change during subsequent drainage. Campanella & Mitchell (1968) observed an increase in pore water pressures in normally consolidated, saturated soils due to differences in the relative coefficients of thermal expansion of the water and soil particles. Despite the decrease in volume due to heating, no change in the coefficient of compression was observed during subsequent compression. Hueckel & Baldi (1990) observed that the overconsolidation ratio plays an important role in the volume change of saturated soils. Heating of heavily overconsolidated soils leads to expansion, followed by elastic contraction upon cooling. Similar to the results of Campanella & Mitchell (1968), heating of normally consolidated soils leads to contraction, followed by additional elastic contraction during cooling. Another issue observed in saturated soils is that temperature leads to a decrease in the apparent preconsolidation stress for overconsolidated soils (Hueckel & Baldi 1990). The change in preconsolidation stress is usually inferred by measuring the load-settlement curve of a specimen after heating. The decrease in preconsolidation stress observed for most soils is attributed as the cause of the decrease in peak shear strength of soils tested under elevated temperatures. Evaluation of the change in preconsolidation stress after a heating-cooling cycle is not thoroughly understood, but the subsequent cooling process may lead to an increase in preconsolidation stress (Plum & Esrig 1969).

Vega (2013) performed cyclic heating and cooling tests on compacted specimens of Bonny silt having an initial void ratio of 0.51 tested in a thermal oedometer. The results are shown as a function of OCR in Fig. 3 in terms of the slope of the volumetric strain versus temperature curve. The data of Uchaipichat and Khalili (2009) for saturated silt is shown for comparison. Consistent behavior between the two soils is observed, with a decreasing trend in volume change with temperature with OCR. Vega (2013) observed a slight decrease in volume change with further thermal cycles.

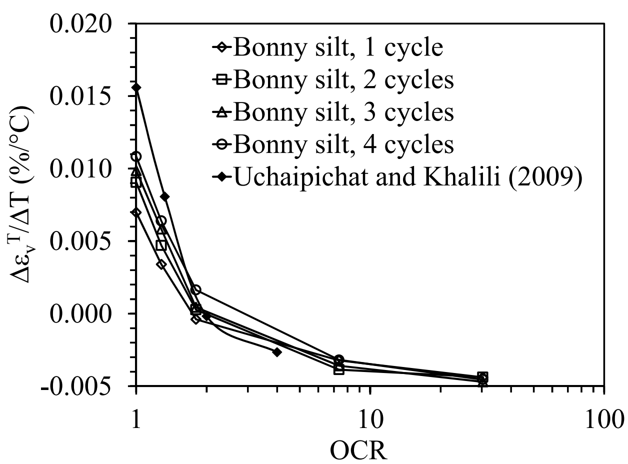

Figure 3. Impact of temperature on the thermal volume change of saturated Bonny silt (after Vega 2013, along with data modified from Uchaipichat and Khalili 2009).

The mechanisms of thermal volume change in unsaturated soils differ from those in saturated soils, as the differential expansion of the solids and pore water will not lead to excess pore water pressures that cause volume change upon subsequent drainage. However, changes in temperature will still cause an expansion of the pore water, which may result in an increase in the degree of saturation and a decrease in suction. Uchaipichat & Khalili (2009) performed constant water content (undrained) heating tests on compacted silt at suctions up to 300 kPa, and measured a decrease in matric suction of 50% during heating from 25 to 60 °C. Undrained heating of the specimen also led to expansion, but the volume and suction changes were reversible after cooling.

A decrease in suction would normally lead to expansion, but unsaturated soils often show contraction during drained heating (Uchaipichat & Khalili 2009). The reasons for this discrepancy are currently being investigated, but changes in preconsolidation stress with suction and temperature may play a role. During drying, suction will lead to a hardening effect and an increase in preconsolidation stress. However, similar to saturated, overconsolidated soils, heating leads to a decrease in the preconsolidation stress for unsaturated soil. If the unsaturated soil is under a relatively high effective stress, the specimen may be relatively close to the yield surface. If the decrease in preconsolidation stress is significant enough, the soil be in an unstable state. This may cause plastic collapse and contraction during heating. In this case, the effects of heating may be similar to that observed in saturated silt.

The results from drained heating tests on compacted Bonny silt are shown in Fig. 4 in terms of OCR. The OCR was defined using the effective stress definition of Lu et al. (2010), along with the preconsolidation stress values obtained from shear strength measurements of Alsherif (2013).

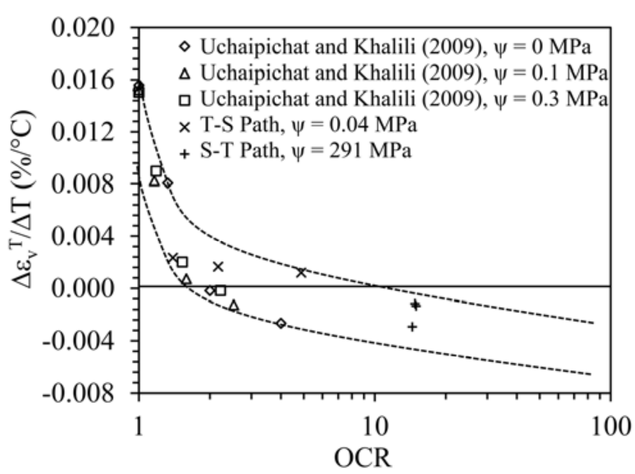

Figure 4. Impact of temperature on the thermal volume change of compacted Bonny silt under different suction magnitudes (along with data modified from Uchaipichat and Khalili 2009).

Results from tests specimens heated at a suction of 0.04 MPa (T-S Path) and from tests on specimens heated after application of a suction of 291 MPa (S-T Path) are reported in Fig. 4. Data reported by Uchaipichat & Khalili (2009) were also re-interpreted and are shown in this figure using a similar definition of effective stress, along with their reported effective preconsolidation stress values. During drained heating, the specimens expanded under low mean effective stresses (high OCR), and contracted under higher mean effective stresses (low OCR). The decreasing trend with OCR for the specimens having a wide range of suction values is similar to that observed for saturated silt.

2.4 *Effects of Temperature on Peak Shear Strength and Critical State in Unsaturated Soils*

Temperature may have an effect on the shear strength and stiffness of unsaturated soils through suction changes associated with thermally driven water flow, thermal volume change, and changes in the shape of the plastic yield surface. Uchaipichat & Khalili (2009) observed that the peak shear strength of unsaturated specimens at suction magnitudes less than 300 kPa decreases with increasing temperature. However, the shear strength at critical state conditions was unaffected by temperature. These observations confirm the hypothesis that the preconsolidation stress decreases with temperature, leading to a reduction in the size of yield surface. However, an important observation for thermally active geotechnical systems drawn from the results of Uchaipichat & Khalili (2009) is that increasing suction leads to a greater increase in shear strength than the decrease in peak shear strength due to temperature.

Alsherif (2014) investigated the nonisothermal behavior of Bonny silt under a suction of 162 MPa using a new triaxial cell that uses the vapor flow technique to control the suction magnitude. The change in shear strength with temperature was observed to depend on the testing path, as observed in Fig. 5. In all of the tests shown in Fig. 5, the specimens were consolidated under as-compacted conditions (initial degree of saturation of 0.41 and suction of approximately 40 kPa) to different net confining stresses. A set of baseline tests involved application of a suction of 162 MPa at room temperature. Another set of tests were heated by 42 °C under as-compacted conditions, a suction of 162 MPa was applied after reaching equilibrium (T-S path). A third set of tests involved application of a suction of 162 MPa was applied, then the specimen was heated by 42 °C (S-T path). In all three sets of tests, application of a high suction magnitude led to a significant hardening effect that led to very brittle stress-strain curves. The results indicate that the S-T path led to an increase in peak shear strength, while the T-S path led to a decrease in shear strength. A possible reason for the difference in behavior for the two testing paths is that the degree of saturation at the time of heating may affect whether changes in temperature leads to a hardening or softening effect. Another possibility is that the changes in preconsolidation stress with suction and temperature are nonlinear for high suction magnitudes, leading to a path-dependent response.

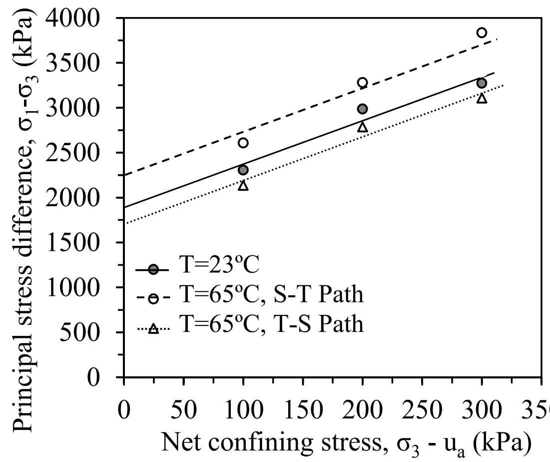

Figure 5. Impact of temperature on the peak shear strength of Bonny silt under a suction of 162 MPa (after Alsherif 2013).

3 THERMALLY ACTIVE RETAINING WALLS

Fill-type retaining structures are typically constructed with free-draining backfill to minimize the chance for deformations associated with suction changes during water infiltration. Poorly draining backfills may be used if thermally induced water flow is used to maintain unsaturated conditions. Heat exchangers can either be attached to geosynthetic reinforcements or placed at lifts between reinforcements. The latter case may have certain advantages, as woven geotextile reinforcements may also act as a drain for water vapor. An example of a thermally active retaining wall is shown in Figure 6.

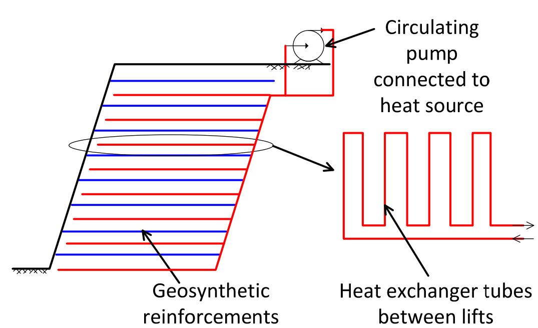

Figure 6. Thermally active retaining wall.

Stewart et al. (2014) developed a modified Jewell-Milligan model to predict the face deflections of mechanically stabilized earth (MSE) walls reinforced with woven geotextiles. In the modified model, the face deflections depend on the stiffness of the geosynthetic, as well as the active earth pressure coefficient. The effects of temperature on the stiffness of a polyethylene geosynthetic were interpreted from creep curves obtained using the time-temperature superposition method. Although temperature was observed to reduce the stiffness of woven geosynthetics, the effects of confinement are observed to increase the stiffness by preventing necking of the geosynthetic (i.e., restraining the geometry) during tensile loading. Accordingly, the effects on confinement on the geosynthetic stiffness were assessed using the results from confined creep tests. Finally, the model incorporated the change in effective stress at the location of the geosynthetic obtained from the analysis in Fig. 2 on the active earth pressure, assuming Bonny silt is the backfill. The results from three of the cases evaluated by Stewart et al. (2014) are shown in Fig. 7 in terms of the face deflection normalized by the maximum face deflection in the case where the effects of temperature and confinement are not considered (Case A). Case B considers only the effect of self-weight confinement, without the effects of temperature, and the deflection profile indicates that less deflection is expected due to confining effects. Case C considers the effect of self-weight confinement, but also the effects of temperature on the stiffness of the geosynthetic and the effective stress change due to thermally induced water flow. These predictions are currently being confirmed through a series of temperature-controlled pullout and confined creep tests.

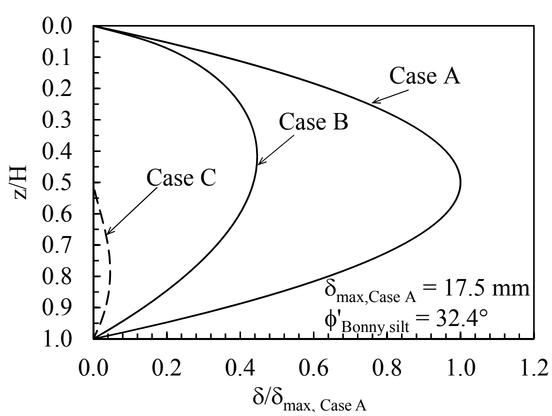

Figure 7. Face deflections for thermally active retaining walls with polyethylene geosynthetics (after Stewart et al. 2014).

4 SOIL-BOREHOLE THERMAL ENERGY STORAGE SYSTEMS

Soil-borehole thermal energy storage (SBTES) systems are an approach to store heat collected from renewable resources such as solar thermal panels in an array of boreholes. Most of the systems developed to date, such as the Drake Landing Solar Community (DLSC) in Okotoks, Alberta, incorporate boreholes installed beneath the water table. Although the efficiency of heat recovery at the Drake Landing solar community is only approximately 25% (Zhang et al. 2012), it still provides 90% of the annual heating for 52 homes. Nonetheless, the heat transfer efficiency of SBTES systems may be improved if they are installed within the vadose zone above the water table (McCartney et al. 2013). In this case, heat transfer is expected to lead to coupled water flow, potentially causing the development of a convective cell similar to that of a heat pipe.

The basic concept and flow processes in the borehole array are shown in Fig. 8. By incorporating a surficial insulation and hydraulic barrier, water vapor evaporating from the drying front will rise through dry soil layers. If the water vapor cannot escape into the atmosphere due to surficial insulation, it will condense near the surface, forming a saturated layer that will sink back toward the water table in the cooler soil between the boreholes. The rate of heat transfer may be 10 times faster when accounting for the coupled heat-mass transfer than when assuming that conduction is the only means of heat transfer (Zhang et al. 2012).

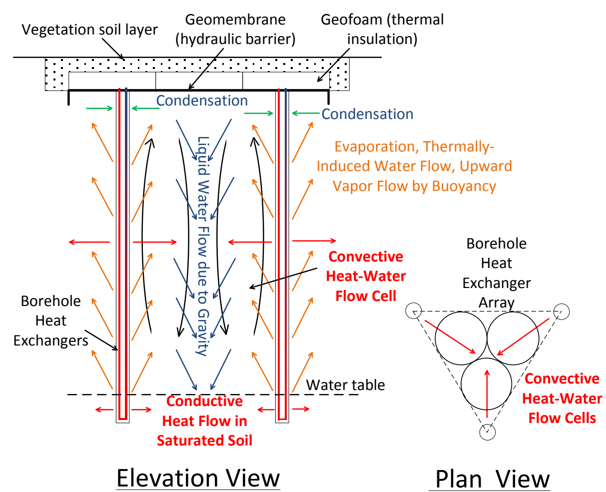

Figure 8. Illustration of coupled heat and mass transfer processes in SBTES systems in the vadose zone.

A physical modeling test was performed to evaluate the coupled heat and water flow processes within a borehole array in unsaturated Bonny silt using the setup shown in Fig. 9. A triangular array of heat exchanger loops were placed at the edge of a 603-mm diameter, insulated cylindrical tank filled with silt compacted to a dry density of 1400 kg/m^3 at a compaction water content of 24% ($S_{r,initial}$ = 0.5) atop a layer of saturated sand. Dielectric sensors were used to measure temperature and water content changes along the centerline with depth, and a KD2Pro probe was used to measure changes in thermal conductivity. Water from a heated reservoir was circulated through the heat exchangers at a rate of 37 ml/s. The inlet and outlet water temperatures were consistently 85 and 79 °C, reflecting steady heat injection.

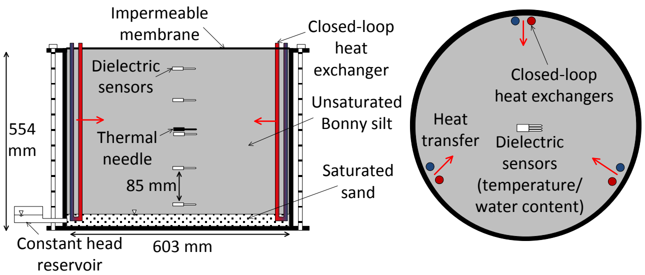

Figure 9. Physical model of an SBTES system.

The data from this test is shown in Fig. 10. The soil at the center of the array reached a steady increase in temperature of 16 °C after about 100 hours, during which time the degree of saturation increased by 23%. A linear increase in thermal conductivity and specific heat capacity was also observed, reflecting an increase in heat transfer and the possible formation of a convective cell.

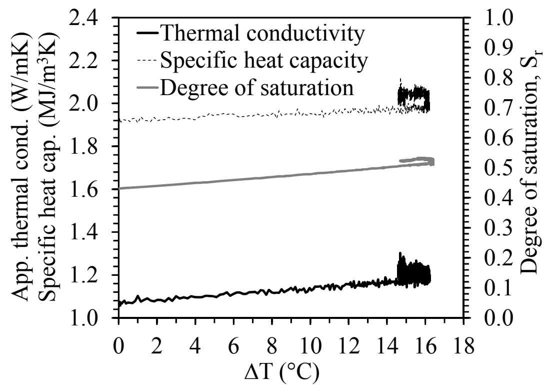

Figure 10. Observed increase in thermal properties in the center of the soil layer during heat injection process.

5 CONCLUSIONS

The thermo-hydro-mechanical behavior of unsaturated Bonny silt in thermal energy applications was discussed in this paper. Coupling between heat transfer and water flow in unsaturated soil layers was observed to lead to an increase in heat transfer, but also played a role in the improvement of the mechanical behavior of unsaturated silt.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

Alsherif, N. (2014). *Nonisothermal Shear Strength of Unsaturated Silt under High Suction Magnitudes*. PhD Thesis. U. of Colorado.

Brandl, H. (2006). Energy foundations and other thermo-active ground structures. *Géotechnique*. 56(2): 81-122.

Campanella, R.G. & Mitchell, J.K. (1968). Influence of temperature variations on soil behavior. *JSMFED*. 94(SM3): 709–734.

Coccia, C.J.R. & McCartney, J.S. (2013). Impact of heat exchange on the thermo-hydro-mechanical response of reinforced embankments. *ASCE GeoCongress 2013*. San Diego, CA. 343-352.

Coccia, C.J.R., Casady, A., & McCartney, J.S. (2013). Thermo-hydro-mechanical response of unsaturated soils during cyclic heating and cooling. *1st PanAm Conf. on Unsat. Soils*. 6 pg.

Grant, S. & Salehzadeh, A. (1996). Calculations of temperature effects on wetting coefficients of porous solids and their capillary pressure functions. *WRR*. 32: 261-279.

Hueckel, T. & Baldi, M. (1990). "Thermoplasticity of saturated clays: experimental constitutive study." *Journal of Geotechnical Engineering*. 116(12): 1778–1796.

Jewell, R.A. & Milligan, G.W.E. (1989). Deformation calculations for reinforced soil walls. *12th ICSMFE*. Rio de Janeiro. 2: 1257-1262.

Lu, N., Godt, J. & Wu, D. (2010). A closed-form equation for effective stress in unsaturated soil. *WRR*. 46, W05515.

McCartney, J.S., Ge, S., Reed, A., Lu, N., & Smits, K. (2013). Soil-borehole thermal energy storage systems for district heating. *European Geothermal Congress*. Pisa, Jun. 3-7. 10 pg.

Philip, J.R. & de Vries, D.A. (1957). Moisture movement in porous materials under temperature gradients. *Transactions of the American Geophysical Union*. 38(2): 222-232.

Plum, R.L. & Esrig, M.I. (1969). Some temperature effects on soil compressibility and pore water pressure. *Highway Research Board*. Washington, DC. Report 103: 231–242.

Romero, E., Gens, A., & Lloret, A. (2003). Suction effects on a compacted clay under non-isothermal conditions. *Géotechnique*. 53(1): 65-81.

Saix, C., Devillers, P., & El Youssoufi, M.S. (2000). Element de couplage thermomechanique dans la consolidation de sols non satures. *Canadian Geotechnical Journal*. 37: 308-317.

Smits, K.M., Sakaki, T., Howington, S.E., Peters, J.F. & Illangasekare, T.H. (2012). Temperature dependence of thermal properties of sands over a wide range of temperatures [30-70ºC]. *Vadose Zone J.* DOI10.2136/vzj2012.0033.

Stewart, M.A., Coccia, C.J.R., & McCartney, J.S. (2014). Issues in the implementation of sustainable heat exchange technologies in reinforced, unsaturated soil structures. *GeoCongress 2014*. 10 pg.

Stewart, M.A. & McCartney, J.S. (2013). Centrifuge modeling of soil-structure interaction in energy foundations. *ASCE JGGE*. DOI: 10.1061/(ASCE)GT.1943-5606.0001061.

Traore, T. (2013). *Physical Modeling of Coupled Water and Heat Flow within a Borehole Heat Exchanger Array in the Vadose Zone*. MS Thesis. U. of Colorado. 147 pg.

Uchaipichat, A. & Khalili, N. (2009). Experimental investigation of thermo-hydro-mechanical behaviour of an unsaturated silt." *Géotechnique*. 59(4): 339–353.

van Genuchten, M. (1980). A closed form equation for predicting the hydraulic conductivity of unsaturated soils. *SSSAJ*. 44: 892-898.

Vega, A. (2013). *Impact of Temperature Cycles on the Thermal Consolidation of Saturated Silt under Different Stress States*. 97 pg.

Yong, R.N., & Mohamed, A.-M. (1996). Evaluation of coupled heat and moisture flow patterns in a bentonite-sand buffer material. *Engineering Geology*. 41: 269-286.

Zhang, R., Lu, N., and Wu, Y-S. (2012). Efficiency of a community-scale borehole thermal energy storage technique for solar thermal energy. GeoCongress 2012. 4386-4395.