Title
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Permalink
https://escholarship.org/uc/item/9hp4p5q6

ISBN
9783030062484

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Publication Date
2019

DOI
10.1007/978-3-030-06249-1_10

Peer reviewed

Emerging thermal issues in geotechnical engineering

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Abstract. Application of changes in temperature to soils may lead to a wide range of flow processes and physical phenomena. This chapter focuses on the fundamental aspects of coupled heat transfer and water flow in saturated and unsaturated soils, thermal pressurization of pore fluids, thermal volume change, thermal softening of the preconsolidation stress, thermal hydro-shearing, and desiccation cracking. Established applications are also presented, including energy piles, barriers for radioactive waste repositories, and thermal energy storage. Future research areas including the role of thermal processes in climate change and elevated temperature landfills are also discussed.

Keywords: geothermal · coupled thermo-hydro-mechanical processes · thermal softening · thermal pressurization · thermal volume change · energy piles · heat storage · climate change · elevated temperature landfills

1 Introduction

In the last few years, geotechnical engineering has expanded its domain into the field of energy geotechnics, which is associated with the extraction, transfer, storage, and management of energy, energy waste, or energy infrastructure in the subsurface soil or rock. The development of energy geotechnics has led to the identification of new problem classes that require an understanding of the behavior of soils and rocks under complex and potentially extreme pressure and temperature regimes in both water-saturated and unsaturated (multi-phase) conditions, often involving coupled thermo-hydro-mechanical (THM) processes (McCartney et al. 2016; Sanchez et al. 2016).

A schematic illustration of the basic physics and their mutual interactions anticipated in soils and rocks subjected to simultaneous THM boundary conditions is shown in Figure 1. Heat transfer in soils due to conduction is closely tied with the amount of water in the soil and the porosity. Temperature affects the properties of the pore fluids, including their density and viscosity among others, resulting in water and gas flow in the soil. This flow will lead to additional heat transfer due to convection, which may be enhanced in unsaturated soils due vapor diffusion and phase change.

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Further, in the case of unsaturated soils, changes in degree of saturation will lead to changes in thermal conductivity and specific heat, altering the heat transfer process. The changes in temperature and water flow processes will also lead to changes in effective stress and soil volume, which in turn are coupled with the heat transfer and water flow processes as the thermal and hydraulic properties of soils are dependent on the porosity. The thermal volume changes may be recoverable (thermo-elastic) or irrecoverable (thermo-plastic) depending on the type of soil and drainage conditions.

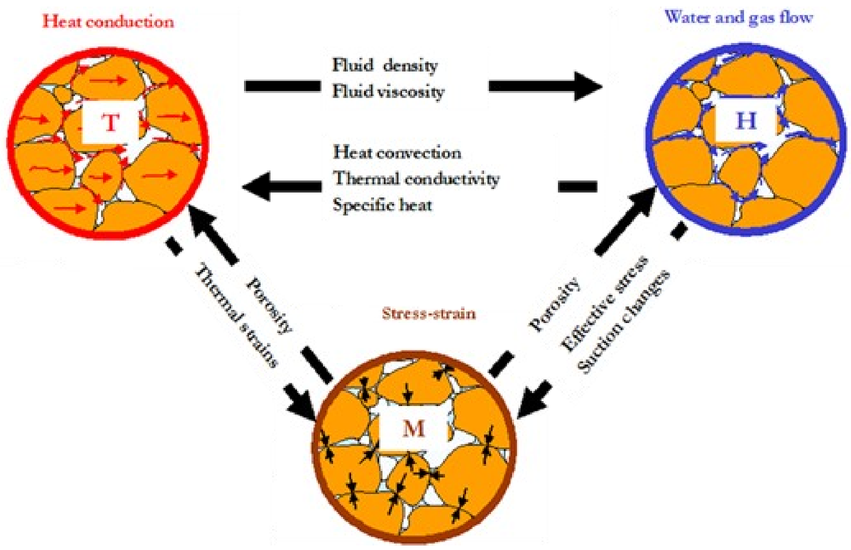

Fig. 1. Inter-relationships between thermal, hydraulic, and mechanical processes in soils

Although the range of problems in energy geotechnics requiring an understanding of THM processes is evolving, it is well known in geotechnical engineering that the processes of heat transfer and water flow are closely linked with the mechanical behavior of soils, with potentially different effects depending on the thermo-hydro-mechanical paths followed. There has been a long history of research and interest in nonisothermal problems in soil physics and agronomy going back to the early 1900's, with focus primarily on coupled heat transfer and water flow in nondeformable soils. Interest in nonisothermal problems in geotechnical engineering started in the 1950's and 1960's, involving the effects of temperature on soil sampling, engineering properties, thermal pressurization of saturated soils, and design of roads in permafrost regions (Highway Research Board 1969). In the 1970's and 1980's, the topics of interest to geotechnical engineers expanded to offshore storage of nuclear waste, buried high voltage electrical cables, thermal failure, geothermal heat exchangers, and aquifer thermal energy storage systems. Due to the need to provide a long-term management solution for nuclear waste (an idea started in 1956), significant research focused on the development of advanced thermo-hydro-mechanical constitutive models and experimental efforts in the 1980's and 1990's.

Renewed interest in geothermal heat exchange in the 2000's and 2010's led to interest in energy piles, desiccation of clays, high temperature thermal remediation of contaminated sites, enhanced geothermal systems, and massive hydraulic fracturing. Most recently, energy geotechnics problems have evolved, including borehole thermal energy storage, compressed air energy storage, energy extraction from landfills, methane hydrate behavior, and CO_2 sequestration. Consideration of the effects of climate change on geotechnical infrastructure also requires a deep understanding of the thermo-hydro-mechanical behavior of soils. Although a strong body of knowledge has been assembled on the non-isothermal problems, additional efforts are still required before the necessary level of technological maturity is reached to be used in geotechnical engineering practice.

The purpose of this chapter is to provide a general overview of the important phenomena and fundamental mechanisms encountered in studying the thermo-hydro-mechanical behavior of soils and rocks, and to point to practical applications and evolving areas of research involving thermal issues. This includes a discussion on the coupling between the effects of temperature on the soil pore fluids (e.g., fluid-solid contact angle, fluid viscosity, surface tension, etc.), the generalized governing equations for heat transfer and water flow in unsaturated soils (in either liquid or vapor forms), as well as coupling between the fundamental properties governing these processes. These properties are in the form of function relationships that describe the changes in the parameters with the degree of water saturation, and include the soil-water retention curve (SWRC), hydraulic conductivity function (HCF), thermal conductivity function (TCF), and volumetric heat capacity function (VHCF). Interesting challenges can be encountered when coupling flow processes with mechanical effects. This includes the effects of temperature on the relative expansion and contraction of soil constituents (air, water, solids) and associated volume changes during drained conditions or pore fluid pressurization during undrained conditions. Although temperature does not have a major effect on macroscopic mechanical properties of soils, such as the friction angle and compressibility indices, changes in the yield stress associated with thermal softening may lead to contractile volume changes during heating. Although this has led to the use of elasto-plastic models to simulate thermal volume changes, the actual mechanisms of thermal volume change are not fully understood.

2 Thermo-hydro-mechanical behavior of soils

This section is arranged to first focus on the fundamental aspects governing coupled heat transfer and water flow in both saturated and unsaturated soils, as this flow mechanism will be present in any thermal energy application in geotechnical engineering. Next, this section focuses on the mechanical implications of this heat transfer and water flow process, starting with thermal softening of the preconsolidation stress, thermal pressurization during undrained heating, thermal volume change during drained heating, thermal hydro-shearing of brittle soils or

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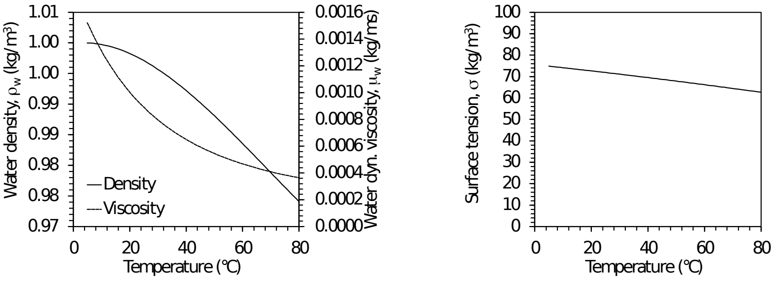
rocks, and thermal desiccation cracking. This section concludes with a summary of codes available that integrate the fundamental concepts discussed in this section that can be applied in numerical simulations of different energy geotechnics applications.

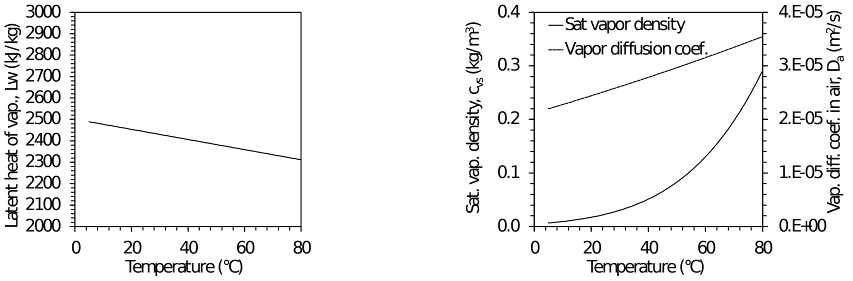
2.1 Coupled heat transfer and water flow in porous media

Coupled heat transfer and water flow in soils has been shown to be relevant to the understanding of many energy geotechnics topics. These topics include radioactive waste disposal (e.g., Zhang et al. 1994), ground-source heat pumps (Preene and Powrie 2009), energy piles (e.g., Brandl 2006; Laloui et al. 2011; Olgun and McCartney 2014; Murphy et al. 2014), thermally-active embankments (Coccia and McCartney 2013), heat storage in soils (Zhang et al. 2012; McCartney et al. 2013), geological carbon dioxide sequestration (e.g., Ebigbo 2005), and recovery of unconventional hydrocarbon resources (e.g., Cortes et al. 2009).

As the properties of water in liquid and gas phases are dependent on temperature, heat transfer may lead to coupled flow of water through soils. Specifically, temperature dependency of the density of liquid water (Hillel 1980) and the viscosity of liquid water (Lide 2001) may lead to thermally-induced water flow through saturated soils, with a magnitude depending on the hydraulic properties of the soil (Savvidou 1988; Catolico et al. 2016). Further, the temperature dependency of other properties such as the surface tension of soil water (Saito et al. 2006), relative humidity at equilibrium (Philip and de Vries 1957), saturated vapor concentration in the gas phase (Campbell 1985), vapor diffusion coefficient in air (Campbell 1985), and latent heat of vaporization of water (Monteith and Unsworth 1990) may lead to thermally-induced water flow in both liquid and vapor forms through unsaturated soils. Examples of the effects of temperature on the properties of air and water are shown in Figure 1.



(a) (b)



(c) (d)

Fig. 1. Effects of temperature on properties of air and water: (a) Water density and viscosity, (b) Air-water surface tension; (c) Latent heat of vaporization of water; (d) Saturated water vapor density in gas phase and water vapor diffusion coefficient in air

Because of temperature effects on the water-air surface tension σ(T), Grant and Salehzadeh (1996) proposed a correction for the capillary pressure, equal to the difference in pore air and pore water pressures ($P_c = u_a - u_w$), as follows:

$$P_c(T)=P_c(T_{ref})\left[\sigma(T)/\sigma(T_{ref})\right] \tag{1}$$

where P_c is the capillary pressure at a given temperature T (K) and T_{ref} is a reference temperature (K). The relative humidity of the pore air at equilibrium R_{he} is related to the capillary pressure and water density through Kelvin's equation, which also incorporates effects of temperature, as follows:

$$R_{he}=\exp\left[P_c M_w/(\rho_w RT)\right] \tag{2}$$

where R is the universal gas constant and M_w is the molecular weight of water. The product of R_{he} and the saturated vapor density in the gas phase c_{vs} in Figure 1(d) is equal to the equilibrium vapor density $\rho_{v,eq}$.

The governing equations for coupled heat transfer and water flow are well-established in the literature for deformable, water-saturated porous media (Biot 1941; Schiffmann 1971; Booker and Savvidou 1984, 1985; Senevirante et al. 1994). Although the predictions from these studies match well with observed distributions in pore water pressure and temperature in soils with variable hydraulic conductivities, the mechanisms of thermal volume change in these models is still evolving, as will be discussed in the next section of this chapter. The governing equations for coupled heat transfer and flow of water in liquid and vapor forms have also been investigated for unsaturated porous media in nondeformable conditions (Philip and DeVries 1957; Taylor and Cary 1964; Cary 1965; Thomas et al. 1996; Luikov 1966; Milly 1982; Pandey et al. 1999; Smits et al. 2011), deformable conditions (Thomas and He 1996; Thomas et al. 1996), and in the presence of pore fluids containing chemicals (Cleall et al. 2007; Guimaraes et al. 2007, 2013). There are perhaps more opportunities for advancing the state of the art on the simulation of heat transfer and water flow in unsaturated soils, including: (1) consideration of nonequilibrium water vapor diffusion (i.e., considering water vaporization in unsaturated soils as a time-dependent process), (2) consideration of elasto-plastic volume change mechanisms for unsaturated soils using the single-valued effective stress principle (Lu and Likos 2006; Lu et al. 2010), and (3) consideration of coupled, nonisothermal constitutive relationships for deformable and nondeformable soils. Some of these issues have received attention in recent studies (e.g., Cleall et al. 2011; Smits et al. 2011; Moradi et al. 2015, 2016; Başer et al. 2016b). Other challenges include consideration of desiccation cracks on the heat transfer and water flow processes in unsaturated soils (Peron et al. 2009a, 2009b).

Several general observations may be made regarding coupled heat transfer and water flow in unsaturated porous media: (1) heat transfer occurs by a combination of conduction, convection in both liquid and gas phases, and latent heat transfer associated with water phase change; (2) water movement due to a temperature gradient is controlled by both vaporization/condensation processes as well as the development of a suction gradient caused by changes in water properties with temperature (i.e., density, viscosity, solid-liquid contact angle); (3) the magnitude of thermally induced liquid water flow depends on the initial degree of saturation; and (4) the times required to reach steady-state distributions in degree of saturation and temperature may be different depending on the coupling between the thermal and hydraulic properties of a given soil. Fluid movement in soils due to temperature gradients is caused by buoyancy forces that form due to thermally-induced variations in the fluid density and viscosity. When an unsaturated soil is subjected to thermal gradients, the water in liquid and vapor forms in the pores will decrease in density and viscosity, resulting in flow upward and away from a heat source toward colder regions. In unsaturated soils, thermal gradients also create vapor density gradients that cause the pore water to evaporate from hot regions and flow toward colder regions. When the water vapor eventually condenses, latent heat transfer will occur due to the energy release associated with phase change. Non-uniform distributions in degree of saturation in unsaturated soils will also cause a decrease in the vapor density gradient as well as the development of a matric suction gradient in the direction opposite to the vapor density gradient. The development of a matric suction gradient causes liquid water to flow from the colder and relatively wetter locations back toward hotter and drier regions.

Philip and de Vries (1957) and de Vries (1958), derived a widely-used theory for liquid water and water vapor transport building upon the vapor flow theory of Penman (1940) under non-isothermal flow conditions as an extension to Richards' equation (Richards 1931). In this approach, liquid water and water vapor transport is driven by both pressure head and temperature gradients. The model of Philip and de Vries (1957) has since become the underlying theory employed in many other studies (e.g., Sophocleous 1979; Baladi et al. 1981; Milly 1982; Cass et al. 1984; Thomas and King 1991; Shepherd and Wiltshire 1995; Thomas and Sansom 1995; Cahill and Parlange 1998; Saito et al. 2006; Bittelli et al. 2008; Sakai et al., 2009). However, the model of Philip and de Vries (1957) includes a number of simplifications and assumptions to reduce complexity that may not represent the mechanisms of heat transfer and water flow on a pore scale (Smits et al. 2011). Specifically, the approach of Philip and de Vries (1957) proposed two effects occurring at the pore scale that contributed to enhancement of water vapor diffusion through partially saturated soils. First, because of the different thermal conductivities of the soil, air, and water, they hypothesized that a microscopic temperature gradient across air-filled pores would be higher than a macroscopic temperature gradient measured across the soil sample. Second, they hypothesized that water vapor diffusion is enhanced due to condensation and evaporation from liquid islands between the particles, in effect causing an increase in the area available for vapor diffusion. Because vapor flux predictions by Fick's law of diffusion did not match experimental data, Philip and de Vries (1957) implemented an enhancement factor to account for the greater diffusion of vapor under nonisothermal conditions. Several studies have measured values of the vapor enhancement factor for different soils (e.g., Cary and Taylor 1962; Cass et al. 1984).

Although the approach of Philip and de Vries (1957) has been used in many coupled heat and water flow transfer problems, an issue with their model is that the vapor enhancement factor was explained at the pore scale following the hypotheses mentioned in the previous paragraph, while the vapor diffusion process was formulated macroscopically (Smits et al. 2011). Further, their hypotheses of the physical mechanisms leading the enhancement in vapor diffusion have been drawn into question (Ho and Webb 1998; Shokri et al. 2009; Sakai et al. 2009). For example, Ho and Webb (1998) used a pore-scale model to estimate the steady state mass flow of water vapor in two different pore-scale transport paths including vapor mass transfer through the liquid islands and around the liquid island. They found that the net water vapor mass transfer through the liquid islands may be only an order of magnitude higher than water vapor transport around the liquid island by Fickian diffusion. More recently, Shokri et al. (2009) found that the vapor enhancement factor may not be needed if capillary flow is included, meaning that Fick's law of diffusion may be sufficient. Consideration of capillary flow requires a careful assessment of tortuosity effects for water flow in unsaturated soils (Millington and Quirk 1961).

An alternate approach to solving coupled heat transfer and water flow problems is through the theory of irreversible thermodynamics, summarized in detail by Luikov (1966) and further investigated by Pandey et al. (1999). A similar approach was used in the model of Taylor and Cary (1964) specifically for unsaturated soils. Although Thomas et al. (2001) notes that this approach may be more fundamentally correct than the mechanistic approach of Philip and de Vries (1957), it is difficult to calibrate some of the parameters used in the Luikov (1966).

Another issue is the choice between coupled heat transfer and water flow models that include equilibrium or nonequilibrium phase change. In the case of equilibrium phase change, the pore water is assumed to volatalize instantaneously. This is a common assumption in many coupled heat transfer and water flow models (e.g., Philips and de Vries 1957; Milly 1982; Cahill and Parlange 1998; Saito et al. 2006; Bittelli et al. 2008; Sakai et al., 2009). However, experimental studies have identified that time is required for liquid water to volatilize in response to a change in vapor pressure in a pore that may be caused by gas phase vapor diffusion caused by gradients in vapor pressure and/or temperature (Benet and Jouanna 1982; Armstrong et al. 1994; Chammari et al. 2008, Benet et al. 2009). To account for this in a model of coupled heat transfer and water flow, a source term for the liquid/gas phase change rate is typically added to the mass balance equations of liquid and vapor. This is the case in the formulations of Bénet and Jouanna (1982), Bixler (1985), Zhang and Datta (2004), Smits et al. (2011), Moradi et al. (2016), and McCartney and Baser (2017). The phase change rates used in these formulations are based on irreversible thermodynamics, first order reaction kinetics, or the kinetic theory of gases which all contain a phenomenological coefficient that is physics-based or defined as a fitting parameter during modeling efforts. Smits et al. (2011) adopted the approach of Bixler (1985), who derived a phase change equation from the kinetic theory of gases so it inherently temperature dependent. In the model of Bixler (1985), the vaporization rate is proportional to (a) the difference between local equilibrium vapor pressure and local partial vapor pressure and (b) the difference between local moisture content and residual moisture content. Smits et al. (2011) compared the predictions from equilibrium and nonequilibrium models for coupled heat transfer and water flow, and found major differences in the initial stages of evaporation and for soils with initially low degrees of saturation.

McCartney and Baser (2017) used a form of the model of Smits et al. (2011) extended by Moradi et al. (2016), but incorporated a new set of coupled thermo-hydraulic constitutive relationships (described in the next section), and presented an experimental approach to define the parameters governing the vapor enhancement factor and the vapor phase change rate. In their model, the governing equation for nonisothermal flow of water in unsaturated soils is given as follows:

$$nS_{rw}\frac{\partial \rho_w}{\partial t}+n\,\rho_w\frac{dS_{rw}}{dP_c}\frac{\partial P_c}{\partial t}+\nabla\cdot\left[\rho_w\left(-\frac{k_{rw}\kappa}{\mu_w}\right)\nabla\left(P_w+\rho_w g z\right)\right]=\text{¿}-R_{gw}\text{¿} \tag{3}$$

where n=porosity (m^3/m^3), S_{rw}=degree of water saturation (m^3/m^3), ρ_w=temperature-dependent density of water (kg/m^3) (Hillel 1980), t=time(s), P_c=P_w-P_g=capillary pressure (Pa), P_w=pore water pressure (Pa), P_g=pore gas pressure (Pa), k_{rw}=relative permeability function for water (m/s); κ=intrinsic permeability (m^2); μ_w=temperature-dependent water dynamic viscosity (kg/(ms)) (Lide 2001), g=acceleration due to gravity (m/s^2) R_{gw}=Phase change rate (kg/m^3s). Similarly, the governing equation for nonisothermal flow of air in unsaturated soils is given as follows:

$$nS_{rg}\frac{\partial \rho_g}{\partial t}+n\,\rho_g\frac{dS_{rg}}{dP_c}\frac{\partial P_c}{\partial t}+\nabla\cdot\left[\rho_g\left(-\frac{k_{rg}\kappa}{\mu_g}\right)\nabla\left(P_g+\rho_g g z\right)\right]=\text{¿}R_{gw}\text{¿} \tag{4}$$

where S_{rg}=degree of gas saturation (m^3/m^3), ρ_g=temperature-dependent density of gas (kg/m^3) (Smits et al. 2011), k_{rg}=relative permeability function for gas (m/s); μ_g=temperature-dependent gas dynamic viscosity (kg/(ms)). The water vapor mass balance needed to consider the balance of liquid and water vapor is given as follows:

$$n\frac{\partial\left(\rho_g S_{rg} w_v\right)}{\partial t}+\nabla\cdot\left(\rho_g u_g w_v-D_e\rho_g\nabla w_v\right)=R_{gw}\tag{5}$$

where $D_e=D_v\tau$=effective diffusion coefficient (m^2/s), D_v=diffusion coefficient of water vapor in air (m^2/s) (Campbell 1985), w_v=mass fraction of water vapor in the gas phase (kg/kg), $\tau=n^{1/3}S_{rg}^{7/3}\eta$=tortuosity (Millington and Quirk 1961). The enhancement factor for vapor diffusion, η following the approach of Cass et al. (1984) is:

$$\eta=a+3S_{rw}-(a-1)\exp\left\{-\left[\left(1+\frac{2.6}{\sqrt{f_c}}\right)S_{rw}\right]^3\right\}\tag{6}$$

where a=fitting parameter, f_c=clay fraction. The nonequilibrium gas phase change rate R_{gw} in Eqs. (3), (4), and (5) is given as follows (Bixler 1985; Moradi et al. 2016):

$$R_{gw}=\left(\frac{bS_{rw}RT}{M_w}\right)\left(\rho_{veq}-\rho_v\right)\tag{7}$$

where b=empirical fitting parameter (s/m^2), R=universal gas constant (J/molK), $\rho_{veq}=R_{he}c_{vs}$=equilibrium vapor density (kg/m^3) (Campbell 1985), T=Temperature (K), ρ_v=vapor density (kg/m^3), M_w=molecular weight of water (kg/mol). Finally, the heat transfer energy balance that considers both conduction, convection, and phase change is given as follows (Whitaker 1977; Moradi et al. 2016):

$$\left(\rho C_p\right)\frac{\partial T}{\partial t}+\nabla\cdot\left(\left(\rho_w C_{pw}\right)u_w T+\left(\rho_g C_{pg}\right)u_g T-\left(\lambda\nabla T\right)\right)=\text{¿}-LR_{gw}+Q\,\text{¿}\tag{8}$$

where ρ=total density of soil (kg/m^3), C_p=specific heat of soil (J/kgK), C_{pw}=specific heat capacity of water (J/kgK), C_{pg}=specific heat capacity of gas (J/kgK), λ=thermal conductivity (W/mK), L=latent heat due to phase change (J/kg), u_w=water velocity (m/s), u_g=gas velocity (m/s), Q=heat source (W/m^3).

A major challenge in applying the coupled set of equations described above is the determination of the material parameters. In particular, the parameters *a* and *b* depend on the soil type (Baser et al. 2017) and must be determined using physical modeling tests involving inverse analysis of temperature and degree of saturation measurements during heating (McCartney and Baser 2017). The other thermo-hydraulic parameters are more established, but linkages between the individual parameters need to be further explored. In unsaturated soils, the soil-water retention curve (SWRC) is the fundamental relationship governing the amount of water in the soil and the energy state in the water. A commonly-used SWRC is that of van Genuchten (1980), as follows:

$$S_{rw} = S_{rw,res} + \left(1 - S_{rw,res}\right)\left[\frac{1}{1 + \left(\alpha_{vG} P_c(T)\right)^{N_{vG}}}\right]^{1-1/N_{vG}} \tag{9}$$

where $S_{rw,res}$ is the residual degree of saturation to water, α_{vG} and NvG are parameters representing the air entry pressure and the pore size distribution, respectively, and $P_c(T)$ is the temperature-corrected capillary pressure according to the model of Grant and Salehzadeh (1996). Although most studies use the van Genuchten (1980) SWRC model to fit a smooth function to experimental SWRC data, recent advances indicate that there may be other forms that better capture the mechanisms of water retention. For example, the SWRC of Lu (2016) can represent both the capillary regime at low suctions and the adsorbed regime at higher suctions. Another advance is the consideration of volume change on the shape of the SWRC (Romero and Vanaut 2000; Nuth and Laloui 2008; Tarantino 2009; Salager et al. 2013; Tsiampousi et al. 2013; Zhou and Ng 2014; Pasha et al. 2015) and ways to consider hysteresis (Pasha et al. 2017).

It is well established that the hydraulic conductivity of unsaturated soils depends on the available pathways for water flow through the soil that change with the degree of saturation (Mualem 1976). The hydraulic conductivity function (HCF) describes the relationship between hydraulic conductivity and degree of saturation (or suction), and can be predicted by incorporating the van Genuchten (1980) SWRC, as follows:

$$k_{rw} = \sqrt{\left(\frac{S_{rw} - S_{rw,res}}{1 - S_{rw,res}}\right)}\left[1 - \left(1 - \left(\frac{S_{rw} - S_{rw,res}}{1 - S_{rw,res}}\right)^{1/\left(1-1/N_{vG}\right)}\right)^{1-1/N_{vG}}\right]^2 \tag{10}$$

where α_{vG} and NvG are the same parameters as in Eq. (9). Although the SWRC is temperature dependent (Grant and Salehzadeh 1996; She and Sleep 1998), the temperature dependency of the HCF has not been well evaluated. It would be expected that the temperature dependency of the SWRC and the change in viscosity of the pore fluid would both have important effects on the magnitude and shape of the HCF.

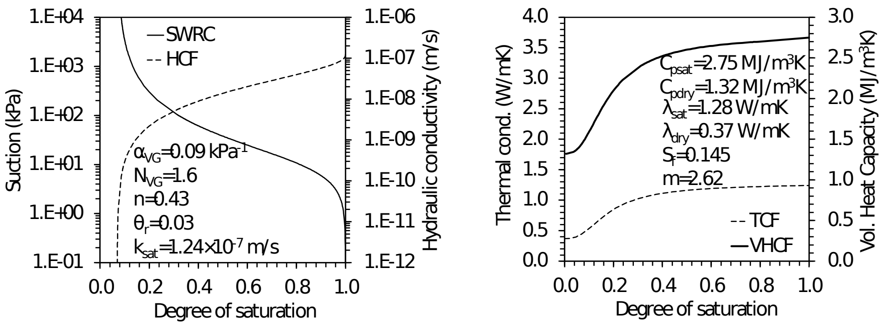
As the transfer and storage of heat in unsaturated soils are both dependent on the amount of water in the pores, a logical extension is that the thermal properties are linked to the shape of the SWRC (Dong et al. 2015). Several studies have evaluated the degree of saturation on the thermal conductivity (Farouki 1981; Brandon and Mitchell 1989; Smits et al. 2013; Likos 2014a, 2014b). Dong et al. (2015) summarized several of the constitutive modeling approaches that have been used to capture the trends in the thermal conductivity with degree of saturation, including multi-phase mixing models that involve series and parallel combinations of solid, air, and water, mathematical models that build upon analogous relationships for other physical properties (electrical conductivity, hydraulic conductivity) and involve volume factions of the different components, and empirical models developed based on curve fitting. Unfortunately, only the empirical models have been shown to have a good match to the experimental data, so several models have been widely used in practice (e.g., Johansen 1975; Campbell et al. 1994; Côté and Konrad 2005; Lu et al. 2007). However, because of the empirical nature of these models, the thermal and hydraulic properties are uncoupled if they are used in coupled heat transfer and water flow models. To address this shortcoming, Lu and Dong (2015) developed a new thermal conductivity function (TCF) that builds upon the shape of the SWRC, and using a large database of experiments performed in an extended version of the transient-release and imbibition method (TRIM) of Wayllace and Lu (2012) defined empirical relationships between the parameters and those of the SWRC. Their TCF is given as follow:

$$\frac{\lambda-\lambda_{\mathrm{dry}}}{\lambda_{\mathrm{sat}}-\lambda_{\mathrm{dry}}}=1-\left[1+\left(\frac{S_e}{S_f}\right)^m\right]^{1/m-1} \tag{11}$$

where λ_{dry} and λ_{sat} are the thermal conductivities of dry and saturated soil specimens, respectively, S_e is the effective saturation, S_f is the effective saturation at which the funicular regime is onset, and m is defined as the pore fluid network connectivity parameter for thermal conductivity. The TCF does not approach λ_{sat} at Se=1, so this should be considered as an additional fitting parameter. Baser et al. (2016) extended the TCF of Lu and Dong (2015) to define a relationship for the volumetric heat capacity function (VCHF) that employs the same parameters as the TCF, as follows:

$$\frac{C_v-C_{v_{\mathrm{dry}}}}{C_{v_{\mathrm{sat}}}-C_{v_{\mathrm{dry}}}}=1-\left[1+\left(\frac{S_e}{S_f}\right)^m\right]^{1/m-1} \tag{12}$$

where $C_{v\mathrm{dry}}$ and $C_{v\mathrm{sat}}$ are the volumetric heat capacities of dry and saturated soil, respectively, and are similarly treated as fitting parameters, and S_f and m are the same parameters as in Eq. (9). Examples of the SWRC and HCF for a silt are shown in Figure 3(a), while examples of the TCF and VHCF for a silt are shown in Figure 3(b). The shapes of these coupled thermo-hydraulic relationships are highly nonlinear, with the hydraulic relationships varying over several orders of magnitude and the thermal relationships varying over a single order of magnitude. The VCHF can be defined concurrently with the TCF if a dual-thermal needle is used in the nonisothermal TRIM test. However, the VCHF has only been measured for unsaturated silt, so further research is needed to confirm the shape of the VCHF for other soils.



(a) (b)

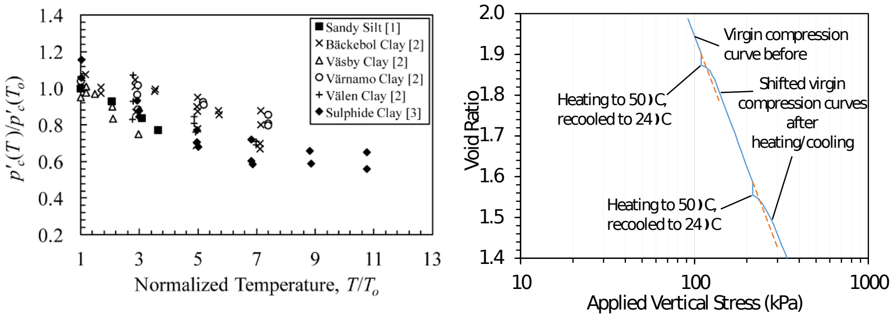
Fig. 3. Coupled properties of unsaturated Bonny silt obtained using the thermal TRIM analysis of Lu and Dong (2015): (a) Hydraulic properties; (b) Thermal properties

In summary, there are many challenges needed when evaluating the coupled heat transfer and water flow in soils, especially when the soil is unsaturated. Applications of the governing equations discussed in this section have been presented for surface evaporation from unsaturated soils by Smits et al. (2011) and for thermal energy storage systems by Moradi et al. (2016) and for geothermal heat exchangers by McCartney and Baser (2017). Future fundamental studies may focus on further linkages between the thermal and hydraulic properties of saturated and unsaturated soils together with the parameters governing phase change and enhanced vapor diffusion. The applicability and validation of the nonequilibrium approach for considering phase change in unsaturated soils could also be further explored for different soil types, such as high plasticity, expansive clays. The role of the liquid island assumption in explaining the concept of enhanced vapor diffusion is another issue that deserves further experimental and pore-scale evaluations, as it has only been investigated for sandy soils that can be approximated as an assembly of bulky particles.

2.2 Thermal softening of the preconsolidation stress

As heat transfer and water flow occur through saturated and unsaturated soils, changes in mechanical behavior are expected. Although most mechanical properties of soils have been found to be temperature independent, like the friction angle (Laloui 2001) and compression indices (Campanella and Mitchell 1968), the preconsolidation stress has been found to be dependent on temperature for both saturated soils (e.g., Baldi et al. 1988; Laloui and Cekeravac 2003) and unsaturated soils (Salager et al. 2008; Uchaipichat and Khalili 2009; Alsherif and McCartney 2016). One source of these changes in mechanical behavior is due to changes in effective stress with changes in suction or degree of saturation (Lu and Likos 2006; Lu et al. 2010), but this may not fully explain some of the changes in volume observed in the literature. Instead, the preconsolidation stress, which reflects the stress history in the soil, may have a more significant role. Observations of the role of stress history in the literature encouraged the development of thermo-elasto-plastic models, where temperature is expected to cause changes in the preconsolidation stress (Hueckel and Borsetto 1990; Cui et al. 2000; Laloui and Francois 2009). Although these models have been used successfully to capture the observations from element-scale tests, they unfortunately may cover up the underlying mechanisms of temperature effects on soils. In particular, two important challenges are the prediction of the role of temperature variations in changes in the preconsolidation stress of soils and in the volume change of soils. Further, the role of unsaturated conditions in both challenges leads to other concerns (Alsherif and McCartney 2016). An improved understanding of the underlying mechanisms that govern these phenomena along with development of modeling strategies will help better predict the behavior of soils in nonisothermal conditions. Further study of these topics may help to better understand the impacts of cyclic heating and cooling that have been observed in some studies (Burghignoli et al. 2000; Vega and McCartney 2015) and on the role of anisotropic stress states (Coccia and McCartney 2012). Specifically, both topics have important effects on the performance of geothermal heat pumps incorporated into civil engineering infrastructure.

An underlying feature of the thermo-elasto-plastic models mentioned above is the impact of temperature on the preconsolidation stress in soils. A summary of the trends in normalized preconsolidation stress after heating several saturated soils is shown in Figure 4(a). A decreasing trend is observed, indicating softening. Although the slope of the compression curve is not affected by temperature, the trends indicate that plastic strains initiate at an earlier stress. The softening effect on the preconsolidation stress due to heating may not be permanent, and limited sets of data show that drained cooling after a drained heating stage may lead to an increase in preconsolidation stress from before the temperature cycle was applied, as shown in Figure 4(b). Despite these observations, the underlying cause behind the change in preconsolidation stress with temperature is not understood.

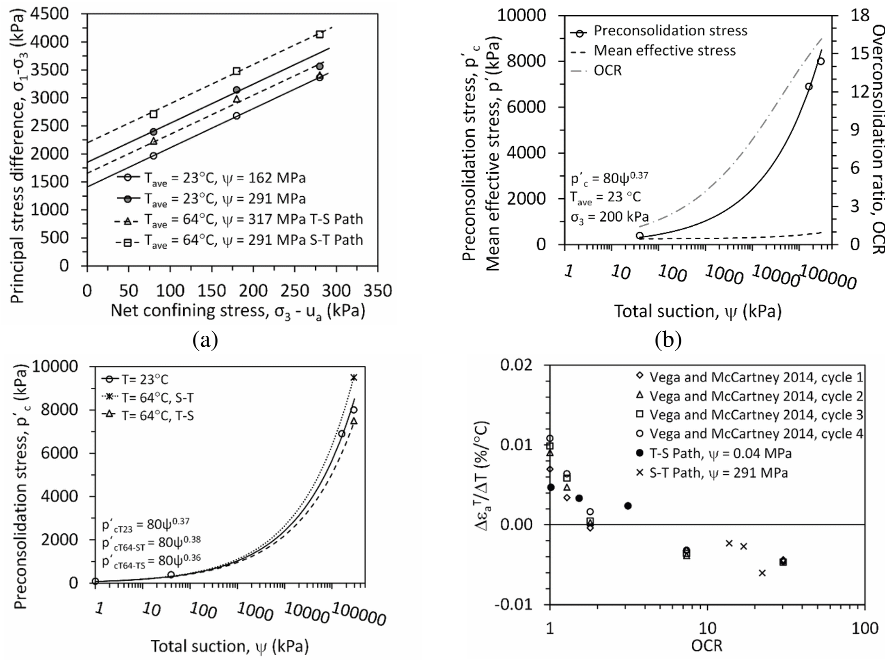


(a) (b)

Fig. 4. (a) Change in preconsolidation stress of normally consolidated clays after a change in temperature (Coccia and McCartney 2016a); (b) Change in compression response of normally consolidated soils after heating and cooling (Plum and Esrig 1969)

The interaction between softening mechanisms due to the heating of soils with hardening effects due to changes in suction have been observed to lead to interesting soil behavior, as observed in the shear strength results of Alsherif and McCartney (2015) shown in Figure 5(a). These results show that the path of heating and suction application can lead to changes in the apparent cohesion. The role of temperature and suction on the effective stress in unsaturated soils is another important issue to consider. The interplay between the effective stress and preconsolidation stress during application of high suction magnitudes for a specimen at room temperature is shown in Figure 5(b). Some soils exhibit different rates of increase in effective stress and preconsolidation stress with suction, which may lead to metastable structures that are susceptible to collapse (Khalili et al. 2004). The model of Grant and Salehzadeh (1996) indicates that the SWRC will shift downward to reflect lower water retention at higher temperatures due to a decrease in surface tension and soil-particle contact angle, which is expected to affect the effective stress state. Changes in the shape of the SWRC with temperature are expected to lead to changes in the effective stress in unsaturated soils (Lu et al. 2010). Further advances may be obtained in effective stress analyses using the new SWRC of Lu (2016), which considers the independent roles of capillarity and adsorption in water retention. These two mechanisms of water retention may be affected differently by temperature. The results in Figure 5(c) indicate that different path-dependent (i.e., drying first then heating, or heating first then drying) lead to different increases in the preconsolidation stress for unsaturated soils under high suctions and temperatures. Although the underlying mechanism behind the changes in preconsolidation stress and the path effects is not fully understood, empirical models for the preconsolidation stress such as those shown in Figure 5(c) are useful to determine trends in the overconsolidation ratio. An understanding of the effective stress permits trends in the thermal volume change of unsaturated silt measured by Alsherif and McCartney (2016) to be reconciled with the thermal volume change of saturated silt measured by Vega and McCartney (2015), as shown in Figure 5(d). The results in this figure show promise in the use of the effective stress principle to unify the thermo-hydro-mechanical behavior of unsaturated soils.

The results in Figure 5(d) also reflect the role of cyclic heating and cooling on the volume change behavior of soils. Vega and McCartney (2015) found that cyclic thermal loads may affect the behavior of soils as well, which could lead to seasonal changes in the performance of energy geostructures. When considering the behavior of unsaturated soils, it is important that constitutive models to capture the volume change response consider the role of changes in degree of saturation during changes in void ratio. Mun and McCartney (2016) found that the model of Zhou et al. (2012) can provide a good means of considering the role of changes in degree of saturation on the compression curve in terms of effective stresses. Models like this that use bounding surface plasticity concepts to consider nonlinearity in the compression curve may lead to better stress-strain predictions than elasto-plastic models.



(a) (b)

(c) (d)

Fig. 5. Thermo-mechanical behavior of compacted silt (Alsherif and McCartney 2015; 2016): (a) Changes in shear strength due to changes in suction and temperature; (b) Changes in preconsolidation stress, effective stress, and OCR with suction; (c) Path dependent changes in preconsolidation stress of unsaturated soils; (d) Thermal volume change trends with OCR

2.3 Thermal pressurization

It is well established that during undrained heating of soils, positive pore water pressures will be generated (Campanella and Mitchell 1968; Houston et al. 1985; Baldi et al. 1988; Ghaaowd et al. 2015). Since the early model of Campanella and Mitchell (1968) was developed, several studies have continued the development of thermo-poro-mechanical theories assuming thermo-elasticity to predict thermal pressurization (McTigue 1986; Aversa and Evangelista 1993; Rice 2006; Ghabezloo and Sulem 2009; Mahajerani et al. 2012; Ghaaowd et al. 2015) and thermo-elasto-plasticity (Veveakis et al. 2013). In the thermo-elastic models for thermal pressurization, the compatibility of strains during undrained heating is given as follows:

$$\alpha_w V_w \Delta T + \alpha_s V_w \Delta T - (\Delta V_{st})_{\Delta T} = - m_v V_m \Delta u - m_w V_w \Delta u \qquad (13)$$

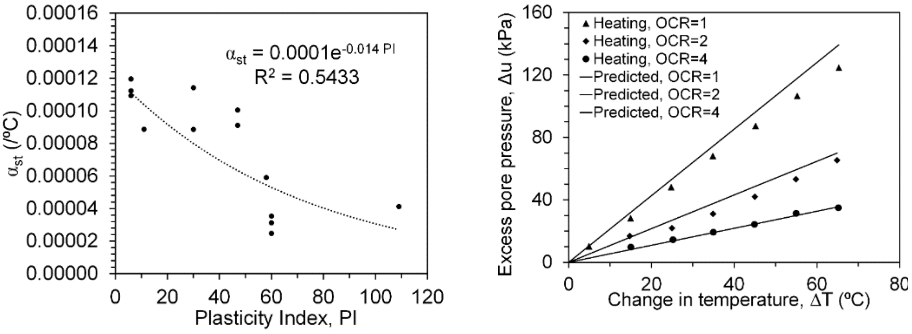
where α_w is the cubical coefficient of thermal expansion of the pore water, α_s is the cubical coefficient of thermal expansion of the mineral solids, V_w is the initial volume of pore water before heating, V_m is the total volume of the soil mass equal to the sum of V_w and V_s, ΔT is the change in temperature of the soil, Δu is the change in pore water pressure, $(\Delta V_{st})_{\Delta T}$ is the volume change of the soil due to the reorientation and relative movement of the soil particles during undrained heating, m_w is the coefficient of volume compressibility of water and m_v is the coefficient of volume compressibility of soil skeleton. This equation can be reorganized to estimate the change in pore water pressure during undrained heating (Campanella and Mitchell 1968):

$$\Delta u = \frac{n\,\Delta T\left(\alpha_s - \alpha_w\right) + \alpha_{st}\,\Delta T}{m_v} \tag{14}$$

where α_{st} is the physico-chemical coefficient equal to $(\Delta V_{st})_{\Delta T}/V_m$. As it may be challenging to define the value of mv, which depends on the effective stress increment, it is possible to incorporate the bi-log-linear compression indices for isotropic loading conditions to define the change in pore water pressure during undrained heating normalized by the initial mean effective stress (Ghaaowd et al. 2015):

$$\frac{\Delta u}{p'_0} = \frac{\left[n\left(\alpha_s - \alpha_w\right) + \alpha_{st}\right]\left(1 + e_o\right)\Delta T}{\left(1 - \Lambda\right)\lambda} \tag{15}$$

where p_0' is the initial mean effective stress, e_0 is the initial void ratio, $\Lambda=\kappa/\lambda$, λ is the slope of the virgin compression in isotropic conditions, κ is the slope of the recompression line in isotropic conditions. The main challenge of applying Eq. (15) is the appropriate definition of material properties governing thermal pressurization (Ghabezloo and Sulem 2009), in particular the physico-chemical coefficient. Eq. (15) was used by Ghaaowd et al. (2015) to evaluate the physico-chemical coefficient for different soils in the literature, as shown in Figure 6(a). The correlation for the physico-chemical coefficient shown in Figure 6(a) is still very approximate, but was also used to successfully predict the excess pore water pressure in saturated clays having different overconsolidation ratios (quantified using different initial void ratios and mean effective stresses) in Figure 6(b). Future research is needed to evaluate thermal pressurization in other soil types, especially sands and unsaturated soils.



(a) (b)

Fig. 6. Thermal pressurization of saturated clays (Ghaaowd et al. 2016): (a) Physico-chemical coefficient as a function of plasticity index; (b) Impact of temperature change on the change in pore water pressure in Bangkok clay having different OCRs

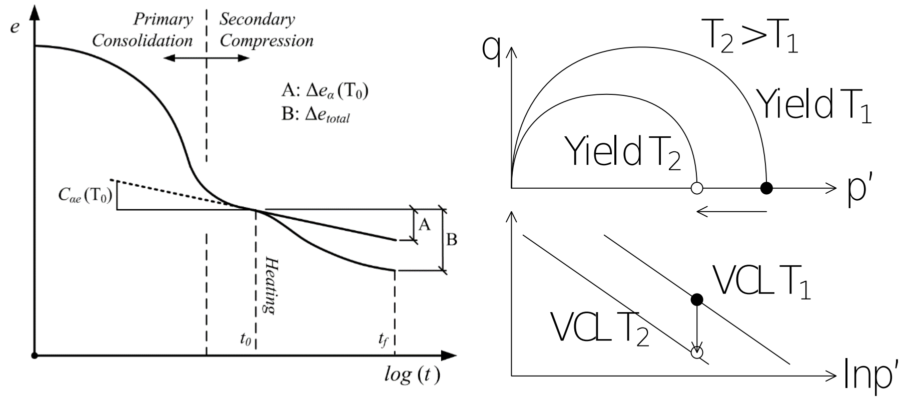
2.4 Thermal volume change

Another relevant issue is that volume changes may arise in soils due to coupled heat transfer and water flow, potentially occurring due to changes in effective stress, changes in the preconsolidation stress, or thermally-induced creep. Efforts in the characterization of thermal volume changes have been divided between the development of constitutive models that couple temperature changes with volume change, focusing on equilibrium conditions, and models that consider the impact of volume change on the heat transfer and water flow processes in soils. The motivations of many of these studies have varied, with a few including consideration of temperature effects on soil sampling, thermal stability of buried electrical cables, earthen barriers for radioactive waste disposal, and soil-structure interaction in energy piles.

The conventional explanation of thermal volume change for normally consolidated soils is the dissipation of these excess pore water pressures, which has been incorporated into numerical simulations (Britto et al. 1989). However, several sets of data have shown that this explanation may not work in all cases. First, the magnitude of excess pore water pressures during undrained heating has not been linked to a volumetric strain expected after drainage, even though Delage et al. (2000) showed that the process still follows a time dependent process similar to consolidation. Further, Burghighnoli et al. (2000) and Towhata et al. (1993) found that preparation of overconsolidated specimens by unloading will lead to thermal expansion upon heating, while preparation by reloading from a very high OCR leads to contraction. As the thermally-induced excess pore water pressures during undrained heating are expected to be positive in all soils, the dissipation of pore water pressures is not a sufficient explanation. Also, the changes in pore water pressure will lead to a change in effective stress during undrained heating, but the effective stress will not change after cooling, making this explanation difficult to apply.

The possibility for thermal volume changes to be due to thermally-accelerated creep has been proposed in several previous studies (Campanella and Mitchell 1968; Houston et al. 1985; Burghignoli et al. 2000). Following these studies, Coccia and McCartney (2016a; 2016b) proposed a new model using a testing methodology developed by Coccia and McCartney (2016c) that assumed the coefficient of secondary compression C_α is sensitive to the temperature and dependent on the change in viscosity of the pore water with temperature. This means that the secondary compression expected under the increment of effective stress applied before a temperature change may be enhanced by an amount equal to $\Delta e_\alpha(T_0)$ defined by Coccia and McCartney (2016b), as shown in Figure 7(a). This mechanism may reflect the ease of clay particles to rearrange into the direction of shear at elevated temperatures, or potentially a time-dependent change in the diffuse double layer due to temperature changes.

The thermal volume change of unsaturated soils also presents a complex scenario to explain if using the dissipation of thermally-induced excess pore water pressures as the cause of thermal volume changes. Specifically, heating is expected to lead to expansion of the pore water, which should lead to an increase in degree of saturation, decrease in suction, and decrease in effective stress, all of which should lead to thermal expansion. However, in many unsaturated soils a contractive behavior is noted. This permanent contraction has been satisfactorily explained by Coccia and McCartney (2016b) using the thermal creep mechanism. However, a collapse mechanism related to the decrease in preconsolidation (yield) stress with temperature may be an alternate mechanism, as shown in Figure 7(b). Heating of a normally consolidated soil will lead to a decrease in the preconsolidation stress, which will mean that the soil is in an unstable state requiring permanent collapse to a stable preconsolidation stress, causing a downward shift from one virgin compression line (VCL) to another.



(a) (b)

Fig. 7. Alternate mechanisms of thermal volume change: (b) Thermally-accelerated creep (Coccia and McCartney 2016b); (a) Thermal collapse

Regarding constitutive model development, some efforts focused on poromechanical models to predict thermal pressurization of pore fluids during undrained heating (Campanella and Mitchell 1968; Ghaaowd et al. 2016) and thermo-elasto-plastic models to predict thermal volume changes of saturated and unsaturated soils (Hueckel and Borsetto 1992; Cui et al. 2000; Laloui and Cekeravac 2003; Abuel-Naga et al. 2009; Laloui and Francois 2009). Thomas and He (1995) and Thomas et al. (1996) developed coupled thermo-hydro-mechanical models that can consider both heat transfer and water flow processes as well as deformations, which have been validated by subsequent experimental studies (e.g., Cleal et al. 2011). An issue with this topic is that some of the advances in the constitutive model development have not been incorporated into the coupled thermo-hydro-mechanical models to better capture the response of some soils (i.e., soft clays, unsaturated compacted soils). Another issue is the incorporation of the single-value effective stress definition into the deformation models. Alsherif and McCartney (2015) found that the effective stress principle is valid even under elevated temperatures and high suctions in unsaturated soils (where the soil would be expected to behave in a brittle fashion), and Alsherif and McCartney (2016) used trends in the preconsolidation stress defined in terms of the effective stress using the approach of Lu et al. (2010) or Khalili and Khabbaz (1998) to unify the thermal volume change behavior of saturated soils tested by Vega and McCartney (2015) with unsaturated soils tested by Alsherif and McCartney (2015).

As mentioned, changes in volume of saturated soils may occur during heating, typically with elastic expansion observed for overconsolidated soils and elasto-plastic contraction observed for normally consolidated soils (Baldi et al. 1988, 1991; Towhata et al. 1993; Hueckel et al. 1998; Burghignoli et al. 2000; Graham et al. 2001; Sultan et al. 2003; Celervak and Laloui 2004; Laloui and Cekerevac 2008; Abuel-Naga et al. 2007). These volume changes will have important effects on the thermal and hydraulic properties of saturated soils, in particular the hydraulic conductivity is expected to decrease with decreasing void ratio and the thermal conductivity is expected to increase with decreasing void ratio. The changes in these two parameters may lead to changes in the heat transfer pattern in saturated soils, especially those with substantial thermally-induced water flow (e.g., Savvidou 1988).

The main fundamental topics where further developments may be investigated for water-saturated porous media include the consideration of coupling effects associated with large strain thermal consolidation of very soft clays, the role of fluid pressurization during undrained heating leading to thermal failure, and the underlying mechanisms of thermal volume change. On the last topic, Coccia and McCartney (2016a; 2016b) evaluated different mechanisms for thermal volume change including thermo-poro-elastic evaluations (e.g., Campanella and Mitchell 1968; Ghaaowd et al. 2016; Takai et al. 2016) and thermo-elasto-plastic models (Hueckel and Borsetto 1992; Cui et al. 2000; Laloui and Cekeravac 2003; Abuel-Naga et al. 2009; Laloui and Francois 2009), and found that both have shortcomings in predicting thermal volume change of overconsolidated soils prepared by re-loading (instead of unloading) evaluated by Towhata et al. (1993) and Burghignoli et al. (2000). The thermo-visco-elastic behavior of soils is another topic that deserves further study (Boudali et al. 1994; Coccia and McCartney 2016b).

2.5 Thermal hydro-shearing

Thermal hydro-shearing is the process of pressurization of rock fluid leading to a reduction in effective stress, which in the presence of an initial shear stress may lead to possible shear failure or fracturing. The magnitude of fluid pressurization can be estimated using approaches similar to that described in Section 2.3 on thermal pressurization. The problem was first identified in practice during so-called "thermal failure" of clays and shales, arising around heat sources, such as buried cables

(Brandon et al. 1989) or nuclear waste canisters (Hueckel and Pellegrini 1991, 1992; Hueckel et al. 2009). Saturated natural clay samples loaded to a total in-situ stress, heated slowly, may develop undrained shear failure when the pore pressure grows at a constant principal stress difference and the effective stress path reaches the critical state at about 74 °C. An example of thermal failure of Boom clay are shown in Figure 8, showing the changes in pore water pressure normalized by the initial effective confining stress during both a room-temperature shearing test and a test where the specimen was sheared to point B and then the temperature was raised in stages. Similar behavior has also been noted in several other clays and rocks by Hueckel and Pellegrini (1991, 1992), such as high porosity plastic Boom clay (Belgium), highly fractured stiff Pasquasia shale (Sicily), Sasamon clayey shale responded similarly. The strains observed in Figure 8 cannot be simulated using thermo-elastic models, and must be considered using thermo-elasto-plastic models such as those of Hueckel and Borsetto (1990) or Hueckel et al. (2009) for clays and Hueckel et al. (1994) for rocks.

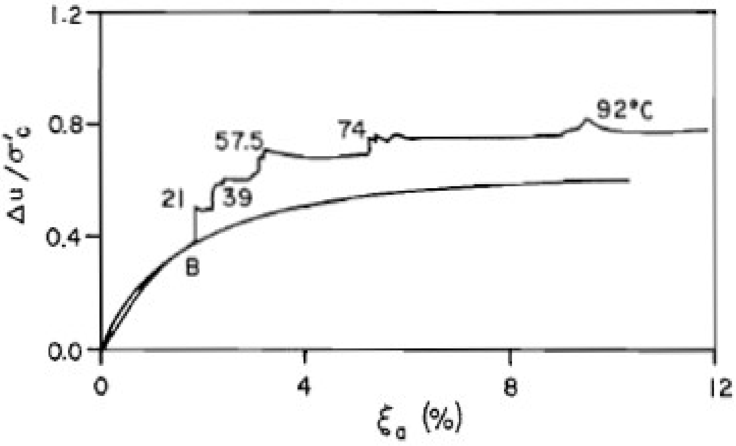


Fig. 8. Pore pressure vs. axial strain during undrained heating (Hueckel and Pellegrini 1991)

There are visible differences between the thermal failure and hydro-shearing encountered during hydraulic fracturing processes in energy reservoirs. During hydraulic fracturing, only a part of the pore pressure boost comes from the constrained heating of the cooler injected pore water, while a comparable boost comes from the injection pressure (Chaborra et al. 2011). Further, there is also a difference in heat exchange between rock and water. During hydro-shearing, the rock is cooling as the hydraulic fracturing process proceeds, which means that the rock shrinks and induces further stresses. Hence, the pore pressure increase is magnified by the collusion of two thermally driven processes: water expansion and rock shrinkage. It is thus clear that the assessment of the amount of pressure boost and activation of the critical shear depends on our understanding of water expansion (highly non-linear with temperature) and thermo-plastic deformation of rock.

In enhanced geothermal systems (EGS), hot water is retrieved through extraction boreholes when it reaches a required temperature, while a corresponding volume of cold water is supplied via an injection well. The cooled rock after the extraction process undergoes subsequent re-heating by the adjacent rock mass, and a corresponding reduction of pore pressure, while the new cooler water is being mixed with the departing hot water. At this stage, the heated rock is thermally expanding. Notably, cyclic heating/cooling most likely creates dilatancy associated with a progressive damage (Hueckel and Pellegrini 1992). This suggests also that the pressure required to inject water at an n^{th} cycle of operation in an EGS system should be considered based on the estimated amount of accumulated damage.

2.6 Thermal desiccation cracking

The discussion to this point in the chapter assumes that the soil remains as a continuum during a coupled heat transfer and water flow process. However, near a free surface changes in temperature and water content may lead to desiccation cracking, which may lead to a change in the boundary condition for heat transfer and water flow. Specifically, the thermo-hydraulic surface boundary condition may extend deeper into the soil layer than in the case that the soil layer was intact. Thermal desiccation cracking is a superposition of several parallel and coupled processes: thermal expansion or contraction (depending on the stress history), drying shrinkage or straining, depending on kinematic constraints, air entry connected with water, vapor and air mass transport, heat transport, and the driving phenomenon of evaporation. Cracking is highly undesirable in soil from both the mechanical and hydraulic points of view, usually degrading engineering soil quality. Cracking may adversely affect integrity of soil in energy production/storage related projects, such as nuclear waste container barriers, storage/retrieval of heat from energy piles.

Desiccation cracks arise in an absence of external forces. Hence, either self-equilibrated stresses resulting from kinematic incompatibilities, or reaction forces at the constraints appear as a cracking cause, when reaching tensile strength. At a meso-scale tubular drying pores are modeled (Hu and Hueckel 2013) near a random imperfection, inducing a stress concentration, in the presence of significant suction. This model uses the effective stress analysis, which away from the stress concentration point yields a criterion paradox: compressive effective stress in the field, a physically incompatible criterion for tensile crack. Experiments on clusters of grains suggest that an imperfection of an air entry deep into the medium penetrates over 4 to 8 radii of a typical pore that yields a tensile effective stress concentration at the air entry finger-tip, sufficient for crack propagation (Hueckel et al. 2014).

Subcritical crack propagation resulting from a spontaneous or engineered change in the rock chemical environment is of relevance in several energy technologies, among which are unconventional oil and gas recovery, and enhanced geothermal systems. The enhancement consists of a combination of fluid pressure and injection of acids. Acid chemically softens the material, which occurs relatively quickly, especially in carbonate rocks. The main question is to correlate the chemical flux to the rate of crack propagation. Hu and Hueckel (2013, 2014) addressed the effect of mineral mass removal on the material strength, via coupled chemo-plasticity approach. The chemical part of the processes being explicitly rate dependent, requires plasticity to be treated incrementally and iteratively. Simplified calculations with Extended Johnson approximation (all fields are axially symmetric round crack tip point) allow following the stress evolution as minerals are dissolved. The effect of coupling of chemicals on elasticity near a crack subject to acidizing under isothermal conditions is another topic of importance. The release of mineral mass into liquid phase affects solute diffusion, while the rate of mass release is dependent on local acidity. Most importantly, when a fraction of mass is removed from a stressed solid, a further strain is induced. This induced strain is assumed to be proportional to the mass removal, with the proportionality (chemical deformation) coefficient, likely dependent on the material damage. In the deviatorically-coupled solution obtained using an adapted Airy function, a dramatic increase in hoop stress is observed in front of the crack tip which can be associated with the shrinkage of the chemically affected zone. Other scenarios and their possible combinations still await suitable solutions.

2.7 Simulations of thermo-hydro-mechanical effects

A theoretical formulation is an appropriate way to integrate the relevant THMG phenomena discussed in the previous sections via a consistent and unified framework. In a coupled formulation, the roles of the various physical phenomena and their mutual relationships are clearly expressed with no ambiguity. Once implemented numerically, the mathematical formulation can be used to achieve a better understanding about the interaction between the different physics (e.g., Olivella et al. 1996; Rutqvist et al. 2011). There are several topics that have received significant attention and are at the point that a good understanding is available for the topics although they could still benefit from further study. These include the development of thermo-hydraulic flow models (TOUGH2, COMSOL), thermo-elasto-plastic models (models from the groups of Hueckel, Laloui, Cui, Gens, etc.), validated research codes (CODE_BRIGHT, COMPASS, LAGAMINE, COMSOL), experimental and theoretical soil structure interaction analyses for energy piles, development of advanced laboratory tests for thermo-hydro-mechanical behavior (thermal triaxial, thermal oedometer, thermal needle, etc.), and field tests (e.g., the thermal response tests on geothermal heat exchangers, FEBEX test on bentonite barriers). Many of these codes are currently only suitable for research purposes, and may need further refinement for use in energy geotechnics practice.

3 Thermal energy applications in geotechnical engineering

This section describes three emerging applications of thermal energy in geotechnical engineering that have reached a reasonable stage of maturity but still require varying amounts of research to be fully implemented into engineering practice. The first application involves barrier systems for radioactive waste repositories. Although barriers involving compacted bentonite have been implemented into practice in several situations, the complex behavior of these clays under unsaturated conditions and elevated temperatures. The second application is that of energy piles, which are perhaps the most established energy geotechnics technology that integrates the concept of ground-source heat exchangers into deep foundations. These systems require an understanding of the heat transfer performance of these systems, as well as the thermally induced stresses and strains in the energy pile. The third application involves storage of thermal energy in the subsurface. Although types of thermal energy storage systems have been evaluated and implemented into practice, an emerging application is the storage of thermal energy in unsaturated soils or rocks, transferred using ground-source heat exchangers. Unsaturated geomaterials have lower thermal conductivity than when saturated, so they are expected to have lower heat losses. However, the mechanisms of heat transfer in unsaturated soils and rocks are much more complex and must be considered as part of the design of these systems.

3.1 Barrier systems for radioactive waste repositories

The storage of high level radioactive waste (HLW) is an important topic that involves coupled heat transfer and water flow (Pollock 1986). Deep geological disposal of HLW is a preferred option for the isolation of high level nuclear waste, and requires significant input from geotechnical engineers (Gens 2003, 2010). Most repositories involve an unsaturated rock deposit that serves as a natural barrier in which tunnels are formed for placing waste canisters, which are encapsulated by a highly densified buffer material (e.g., pure bentonite or a sand-bentonite mixture). The natural and engineered barriers are expected to be subjected to simultaneous thermal, hydraulic, mechanical and chemical (THMC) phenomena triggered by the heat-emitting nature of the nuclear waste, the swelling character of the unsaturated clay barrier, the highly confined conditions of the isolation system, and the chemical interactions between the barriers material and the pore fluid. Many of the fundamental studies on the thermo-hydro-mechanical behavior of saturated and unsaturated soils discussed in Section 2 were developed as part of the design of barrier systems for radioactive waste repositories. The FEBEX test on bentonite barriers was a major step forward in providing useful validation data for the different numerical simulations used to design these barrier systems, and further efforts will be necessary as different evolutions in modified bentonite materials are developed (e.g., polymer bentonites).

3.2 Energy piles

In recent years, reinforced concrete geostructures like piles, walls and slabs have been used as geothermal heat exchangers to access the relatively constant temperature of the ground for efficient heating and cooling of buildings. Full-scale energy piles have been successfully implemented in buildings and experimental tests in Europe (Brandl 2006; Laloui et al. 2006; Adam and Markiewicz 2009), Japan (Hamada et al. 2007), the United Kingdom (Bourne-Webb et al. 2009; Amatya et al. 2012), China (Gao et al. 2008), Australia (Bouazza et al. 2011; Wang et al. 2014), and the US (Sutman et al. 2014; Akrouch et al. 2014; Murphy and McCartney 2015; Murphy et al. 2015; McCartney and Murphy 2017). The soil-structure interaction response and heat exchange capabilities characterized in these studies have generally indicated that energy piles can serve as sustainable geothermal heat exchangers. The main advantage of energy piles is that they help improve the energy efficiency of building heat without needing additional infrastructure or materials beyond that needed for building support.

Several researchers have evaluated the thermo-mechanical response of energy piles in soils subjected to monotonic or cyclic heating or cooling (Amatya et al. 2012; Murphy et al. 2015; Goode and McCartney 2015). Based on findings from previous studies on energy piles in soils, different approaches or guidelines have been developed to analyze the complex interaction between temperature changes and induced thermo-mechanical stresses and deformations in sands and clays, like numerical methods based on the axial load transfer (T-z) approach (Knellwolf et al. 2011; Suryatriyastuti et al. 2014; Chen and McCartney 2016) and finite element or finite difference methods (Laloui et al. 2006; Ouyang et al. 2011; Gao et al. 2008; Olgun et al. 2014a; Wang et al. 2015; Batini et al. 2015). Of these methods, axial load transfer is most commonly used in the design of piles (Mimouni and Laloui 2014;) or to study the behavior of piles under cyclic thermo-mechanical loading (Suryatriyastuti et al. 2014). Some design recommendations have been made using finite element analyses via parametric analyses (Batini et al. 2015). Future challenges for energy piles involve an assessment of the behavior of energy piles in deformable soils where changes in soil volume may lead to dragdown effects on energy piles (McCartney and Murphy 2017), as well as the development of design codes that incorporate both structure and geotechnical aspects of energy piles.

3.3 Thermal energy storage

An important challenge facing society is the storage of energy collected from renewable sources. One such application is the storage of heat collected from solar thermal panels in the subsurface during summer, so it can be harvested in winter (Sibbitt et al. 2012; McCartney et al. 2013). A practical mode of heat injection into the subsurface involves the circulation of a heated carrier fluid through a closely-spaced array of closed-loop geothermal heat exchangers in boreholes or shallow trenches (Claesson and Hellström 1981; Cirrielo et al. 2015; Başer et al. 2016a). Unsaturated soils in the vadose zone are an ideal storage medium for heat because the storage volume is abundant and lower heat losses can be expected in unsaturated soils due to lower thermal conductivity (Başer et al. 2016a). However, the mode of heat transfer during injection of heat into the ground in the vadose zone is complex as it may be coupled with thermally-induced water flow in either liquid or vapor forms.

Most models of heat transfer from geothermal heat exchangers employ analytical solutions to the heat equation assuming conduction is the primary mechanism of heat transfer, with constant thermal properties for the soil (e.g., Kavanaugh 1985). These include analyses of heat transfer for an infinite line source (Ingersoll and Plass 1948; Beier et al. 2014), a finite line source (Lamarche and Beauchamp 2007), a hollow cylinder source (Ingersoll et al. 1954; Gehlin 2002), a finite plate source (Ciriello et al. 2015), and one- and two-dimensional solid cylinder sources (Tarn and Wang 2004). Numerical simulations of geothermal heat exchangers have also been performed, although most also consider conduction as the primary mechanism of heat transfer in soils (Ozudogru et al. 2015; Başer et al. 2016a). While these conduction-based numerical simulations may be practical for the design of heat exchangers in dry or saturated low permeability soils, they may not be practical for those in unsaturated soils due to the potential for convective heat transfer associated with thermally-induced liquid water or water vapor flow (e.g., Philip and de Vries 1957; Başer et al. 2015; Smits et al. 2011; Moradi et al. 2015). Further, the thermal properties of unsaturated soils are highly dependent on the degree of saturation even if conduction is assumed to be the primary mode of heat transfer (e.g., Farouki 1981; Smits et al. 2013; Dong et al. 2015; Lu and Dong 2015). In addition, the analytical solutions for heat transfer from geothermal heat exchangers may not be practical due to convective heat transfer in saturated soils with high permeability due to buoyancy-driven thermally-driven water flow (Catolico et al. 2016).

Most studies on the behavior of geothermal heat storage systems focus on their overall performance during heating and do not consider coupled heat transfer and water transport (Claesson and Hellström 1981; Eskilson 1987). However, some recent studies highlighted the importance of considering coupled heat transfer and water flow in unsaturated soils in the vadose zone to better understand heat transfer mechanisms when the soils are subjected to relatively higher temperature gradients as in borehole heat storage systems (Catolico et al. 2016; Moradi et al. 2016). Further, the impact of vapor flow during heating and cooling has been investigated by McCartney and Baser (2017), who found that permanent drying during heat injection leads to a longer period of heat storage when the system cools ambiently. Further studies on the impact of this mechanism on the efficiency of heat extraction are still needed.

4 Emerging thermal problems in geotechnical engineering

This section includes some recent developments involving thermal effects in geotechnical engineering associated with climate change and elevated temperature landfills. Climate change effects have only been simulated due to the large scale of the problem, while the setting of elevated temperature landfills has only been characterized experimentally due to the complex material properties. Both problems are challenging and require application of the fundamental concepts discussed in this chapter.

4.1 Effects of climate change on geotechnical infrastructure

While several large-scale studies have been conducted to evaluate various aspects of climate change, there is a clear gap in the state of our knowledge in terms of assessing the resilience of critical geotechnical infrastructure (natural and engineered) to extreme events (e.g., drought, extreme precipitation, etc.) under a changing climate. Climate change may affect both the shear strength and compressibility of near-surface soils through changes in degree of saturation and desiccation, but may also affect the loading on geostructures due to changes in the water table and infiltration (CACC 2015; Vahedifard et al. 2016a; Robinson and Vahedifard 2016).

While progress has been made in understanding the unsaturated soil behavior, the impacts of concurrent changes in degree of saturation and temperature, especially for relatively dry soils, remain uncertain. Robinson et al. (2016) developed a framework referred to as the Non-Isothermal Soil Strength Analysis (NISSA) to quantify changes in soil shear strength resulting from concurrent changes in degree of saturation and temperature on a regional scale. The underlying physics associated with the NISSA framework are summarized in Figure 9. The framework considers conductive, convective, and latent heat transfer to characterize soil-atmosphere interactions and the suction stress concept of Lu et al. (2010) to evaluate their impacts on shear strength. The water balance model (a) demonstrates the components that are controlled by atmospheric interaction, including condensation, evaporation, infiltration, precipitation, radiative exchange, and surface runoff. The physical soil models (b) are used to generalize the physics associated with drought-stricken (residual saturation) soils and wetter soils. Drought-stricken representative elementary volumes (REVs) are assumed to have water films surrounding the particles so heat transfer is limited in the soil. The dry conditions also lead to low suction stress and the effective stress is equal to the total stress. In contrast, wetter REVs have more paths for heat transfer and suction stresses greater than zero. The outcome is a greater effective stress and shear strength.

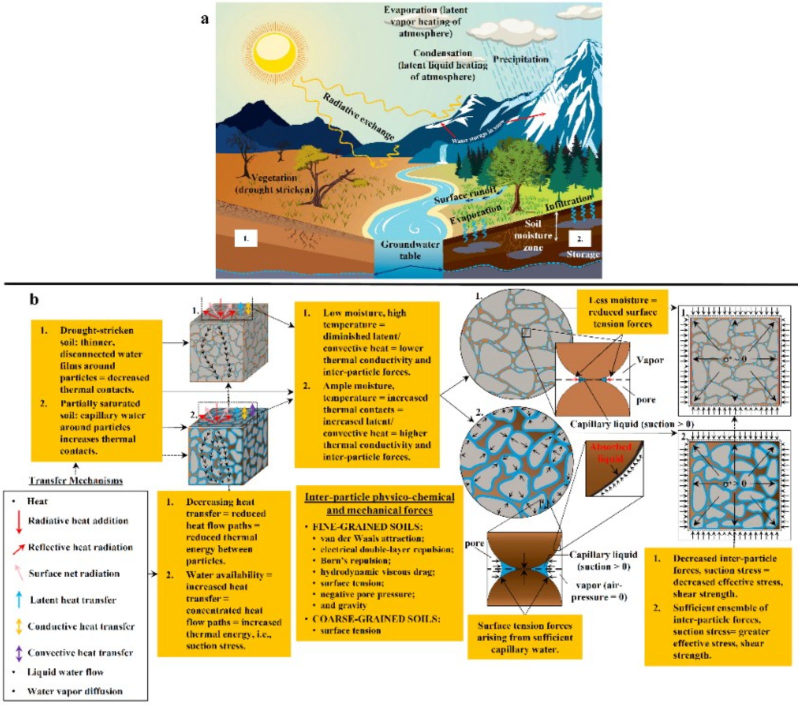


Fig. 9. Underlying physics associated with the NISSA framework (Robinson et al. 2016).

A comparison between the surface soil shear strength predictions from the NISSA framework in the Sacramento-San Joaquin Delta of California during a wet and cool year (2011) and a period of dry and hot years (2012-2015) is shown in Figure 10. NISSA integrates degree of saturation and temperature data, soil hydraulic and mechanical properties, as well as surface energy fluxes, from the NOAA land-surface model available through the NASA's North American Land Data Assimilation System project phase 2 (NLDAS-2) (Kumar et al. 2006). Spatial distributions in soil data were obtained from the National Resource Conservation Service (NRCS), representing a wide range of soil types within the region. The shear strengths in Figure 10 were computed at a depth of 100 centimeters (z = 1 m), and the distributions of shear strength through the region show that low degrees of saturation and high temperatures during 2015 contributed to the substantial changes in shear strength. Evaporation at the surface contributes to higher matric suction and suction stress and, thus higher shear strength, but the elevated temperatures may lead to a reduction in shear strength (Shukla et al. 2015; AghaKouchak et al., 2015). Low degrees of saturation and high temperatures hamper water flow, thus dampening evaporation rates. The shear strength throughout parts of the Delta were estimated to decrease as much as 95 and 76% during the spring and summer seasons, respectively.

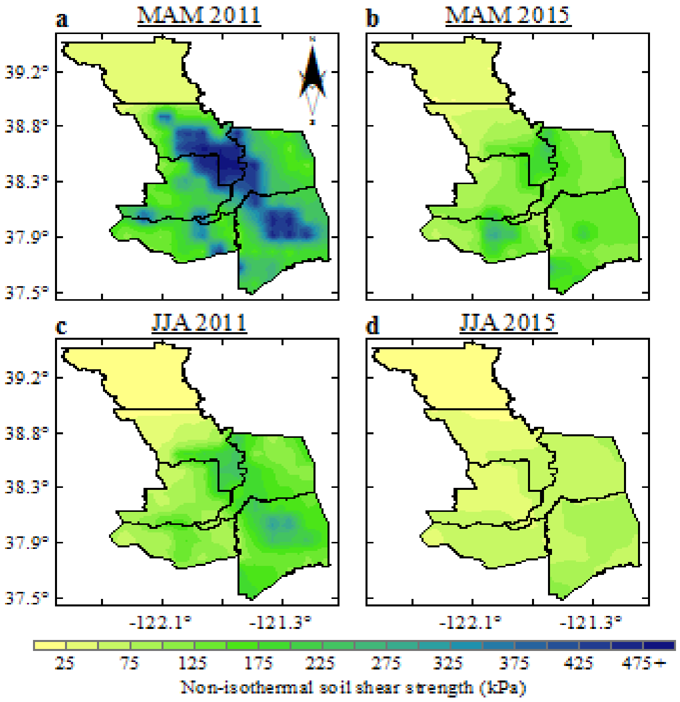


Fig. 10. Spatio-temporal distributions in the non-isothermal soil shear strength in 2011 (wet and cool year) and 2015 (warm and dry year). The spatio-temporal distributions are presented for the spring (a – b; March, April, May (MAM)), and summer (c – d; June, July, August (JJA)) seasons (Robinson et al. 2016).

California's Delta region has been historically undergoing major land subsidence due to microbial oxidation and compaction of organic-rich soils resulting from extreme temperatures and groundwater extraction (Mount and Twiss 2005; Brooks et al. 2012; Vahedifard et al. 2016a). Recent results from a long-term remote sensing study showed that land subsidence in parts of the Delta reached historical rates of around 5 centimeters per month in 2014 and 2015 (Farr et al. 2015). Shear strength variations govern soil stability (Vahedifard et al. 2015, 2016b, 2016c) and settlement (Lu and Likos 2004), so the changes in shear strength observed in Figure 10 could lead to changes in behavior of geotechnical engineering systems.

4.2 Elevated temperatures in landfills

Leachate, gas, and heat are the three most common byproducts of organic waste decomposition in landfills. Landfill monitoring has shown that temperatures in MSW landfills are usually within the mesophilic range of 38 to 54°C (Yesiller et al. 2005). As a result, most research on landfills, e.g., desiccation of geosynthetic clay liners and cover systems, service life of geomembranes, thermal-chemical-biological modeling, waste mechanics and shear strength, contaminant transport, and in situ monitoring, are focused primarily on temperatures below 65ºC. Recent landfill case studies indicate that extremely high temperatures (above 100 ºC) can develop and negatively impact the behavior and performance of waste containment systems. This section provides a summary of current research in elevated temperature landfill engineering and identifies pressing challenges for future research in thermal energy geotechnics.

Elevated temperatures have been documented in municipal solid waste (MSW) landfills, construction demolition debris landfills, industrial waste fills, and sanitary dumps. Several factors can lead to elevated landfill temperatures (i.e., exceeding 65°C), including aerobic decomposition, partially extinguished surface fires, exothermic chemical reactions, spontaneous combustion, and smoldering combustion. For example, the amphoteric reaction of aluminum dross with water produces hydrogen gas and heat (Calder and Stark 2010). Observed temperatures of MSW landfills undergoing aluminum reactions range from 88 to 110°C (Stark et al. 2012; Jafari et al. 2014a). However, the most common mechanism causing elevated temperatures is the introduction of ambient air into a landfill during gas collection and control operations, thus increasing waste temperatures to 80°C. The introduction of oxygen in the waste mass and accumulation of heat via aerobic biodegradation or another exothermic process, provides the necessary conditions to initiate and sustain subsurface combustion of MSW (Martin et al. 2013). Smoldering combustion has been documented to persist within a solid waste landfill between 100°C and 120°C (Ettala et al. 1996). In other cases, smoldering combustion temperatures observed in MSW landfills have ranged from 200 to 300°C and as high as 700°C (Ruokojarvi et al. 1995).

Techniques, such as gas wellhead monitoring, geophysical methods, infrared imagery, and surface elevations, are used to detect elevated temperatures (Martin et al. 2013). Jafari (2015) shows the initiation and expansion of elevated temperature results in a sequence of indicators that delineates the location, boundary, and movement. These indicators follow the systematic progression: (1) changes in landfill gas composition (decreasing ratio of CH_4 to CO_2 and elevated carbon monoxide and hydrogen levels; (2) increased odors; (3) elevated waste and gas temperatures, e.g., wellhead temperatures greater than 55 to 90°C; (4) elevated gas and leachate pressures that cause leachate outbreaks; (5) increased leachate volume and migration; (6) slope movement; and (7) unusual and rapid settlement. Although the global behavior and indicators of elevated temperature events have been defined, fundamental research questions relating to thermal geotechnics remain. The pressing challenges are developing numerical models that can capture the progression of indicators (specifically, landfill slope instability and settlement), evaluating the efficacy of heat extraction for renewable energy and containment of elevated temperatures, and development and performance of novel engineered barriers.

Slope instability and movement have occurred at landfills with elevated temperatures, gas, and leachate pressures (Stark et al. 2012; Jafari et al. 2013; Hendron et al. 1999). The failure described by Stark et al. (2012) resulted in over 6 m of displacement and waste being located outside of the permitted landfill boundary. In general, slope movement is preceded and accompanied by forceful gas and leachate outbreaks. Mechanisms for slope instability usually include elevated gas pressures, perched leachate surfaces, and/or reduced MSW shear strength (Stark et al. 2010). For example, the interconnecting plastics and other reinforcing materials that contribute to the high shear strength of fresh MSW are mostly consumed, degraded, burnt, and/or decomposed at elevated temperatures.

The energy balance inside a landfill subjected to elevated temperatures, slope movement, and settlement is shown in Figure 11. In this schematic, heat is generated by three processes: (1) aerobic decomposition caused by air intrusion into the waste mass from cracks in the soil cover or damaged wellheads; (2) anaerobic decomposition of organic matter by methanogenesis; and (3) smoldering combustion of MSW. Several mechanisms are shown to result in heat loss in the system, but the gas collection and leachate removal systems are likely the most influential. The schematic also shows the possible thermal energy transfer due to elevated temperatures. Heat generated in the smoldering front can induce a thermal gradient inside the landfill. This heat also drives moisture away from MSW (see blue arrows in gas and heating fronts in Fig. 11) and thermally degrades the waste via pyrolysis/combustion, which produces large quantities of gas (CO_2, H_2, and CO) and results in excessive and rapid settlement beneath the smoldering front and combustion/pyrolysis zones. Due to the elevated leachate and gas pressures, the propagation of smoldering combustion and other heat generating processes is leading to slope instability and settlement via heat transfer (conduction, phase change, and convection), movement of leachate and gas from hotter regions to cooler areas near the side slopes and surface, and changes in biological and chemical nature of waste.

Some studies, such as Nastev et al. (2001) and El-Fadel et al. (1996), have developed numerical models to capture generation and transport of gas and heat in landfills. To date, numerical models that capture the heat and gas generation of smoldering combustion, settlement and slope movement, fluid (gas, steam, leachate) flow, and gas-leachate contaminant transport at elevated temperatures has not been investigated, and hence is a pressing challenge for future research. Another challenge is measuring the properties of waste required for input in the numerical models. These inputs include thermal, compressibility and permeability relationships, shear strength, gas production potential, and leachate generation.

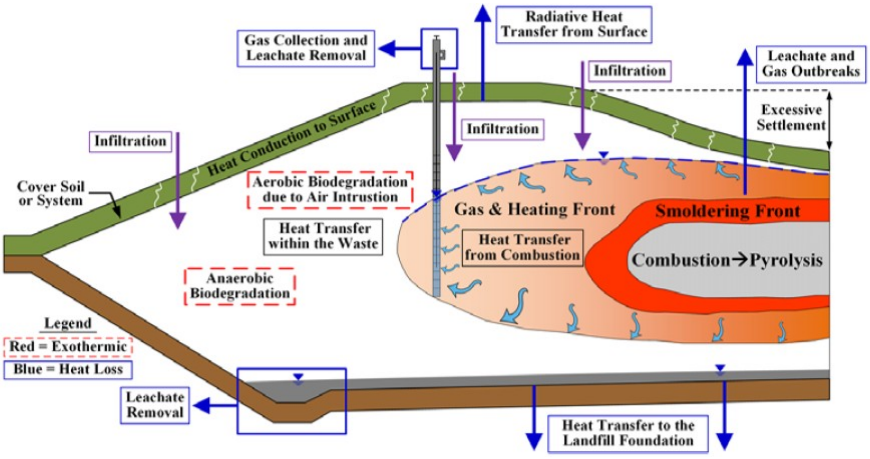


Fig. 11. Schematic of an elevated temperature landfill showing heat transfer mechanisms

Another challenge is isolating and containing elevated temperatures from normal operating areas. In recent cases, landfill owners, design engineers, and environmental regulators have lacked proven containment alternatives, such as vertical barrier walls, ground source heat pumps, and injection of coolants, to isolate and contain heating events. For example, a U-tube heat exchanger system has been installed at a facility to isolate/contain an elevated temperature event. Future research should investigate the design of ground source heat pumps to extract heat from elevated temperature landfills, which otherwise escapes from the gas collection system, for energy applications (Coccia et al. 2013).

Sustained elevated temperatures can degrade and compromise gas extraction, leachate collection, and barrier systems. For example, Jafari et al. (2014b) evaluate the time-dependent antioxidant depletion and stress cracking to predict high-density polyethylene (HDPE) geomembrane service life. Using time-temperature history of a liner system, they conclude that HDPE geomembrane service life can decrease from several hundred years to less than a decade. As a result, there is a need to develop novel barrier systems for industrial waste leachates, elevated temperatures, and hazardous air pollutants. In particular, future research on novel barriers should investigate the mechanisms of contaminant migration, changes in mechanical properties, bentonite desiccation, polymer chemistry, and degradation.

5 Conclusions

This chapter summarizes the fundamental issues related to the thermal behavior of saturated and unsaturated soils and rocks that may be encountered in energy geotechnics applications. A major emphasis of this chapter is on the need to consider coupled processes that occur in nonisothermal conditions in soils. Heat transfer and water flow processes in soils are closely coupled with changes in degree of saturation and stress state, which may lead to changes in volume which further alter the properties that govern heat transfer and water flow. Changes in the preconsolidation stress and effective stress in saturated and unsaturated soils may have significant effects on the mechanical response of soils, and the interplay between softening mechanisms associated with heating of soils that lead to reductions in preconsolidation stress with other hardening mechanisms associated with unsaturated soil conditions and mechanical loading that lead to increases in preconsolidation stress need to be carefully considered in future studies. The underlying mechanisms behind changes in preconsolidation stress with temperature and suction may help better explain thermal volume change, and may help identify if creep or collapse mechanisms should be used to simulate thermal volume change behavior.

There are also other key issues that have not received significant attention and need collaborative research efforts to solve. These include physical modeling or field observation for model validation, evaluation of cyclic heating and cooling or wetting and drying effects, including consideration of creep phenomena and underlying mechanisms of thermal volume change, evaluation of coupled chemical effects with both flow and mechanical processes, understanding of scale effects, including application of pore scale processes to element scale to hydrological scales, study of climate change phenomena that incorporate soil behavior, identification of appropriate hydrogeological siting of energy storage systems and their effects on efficiency, evaluation of soil/rock behavior under low temperatures and freeze/thaw cycles, and thermal remediation of contaminated soils using elevated temperatures of 35 to 70 °C associated with geothermal heat exchanger operation (e.g., enhanced soil vapor extraction, enhanced bioremediation with bio-augmentation). Future fundamental challenges may be encountered when including biological and chemical effects in the coupling relationships between heat transfer, water flow, and the mechanical response of soils. Big-risk and big-payoff ideas in thermal energy geotechnics include solving key issues with enhanced geothermal systems, such as thermal shock, drilling costs, sampling and field investigations. Others include mega-landfill issues that may be encountered due to the fewer number of large landfills, environmental problems associated with the recovery of gas hydrates, and issues with CO_2 sequestration such as cap rock integrity, cost limited conditions, and induced seismicity.

Acknowledgement

JM would like to acknowledge financial support of this work from NSF grants CMMI-0928159 and CMMI-1054190.

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