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Numerical studies on the effect of temperature on the unsaturated hydraulic response of geotextiles

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ABSTRACT

A series of coupled thermo-hydraulic simulations were performed on a soil–geotextile column to understand the effect of temperature on suction distribution throughout the soil column and on the hydraulic performance of the geotextile as a drainage/capillary barrier layer. Two different constant temperatures of 0 °C and 38 °C and a temperature gradient of 4 °C along the column were modeled. Changing the temperature from 0 °C to 38 °C did not have a significant effect on the suction head distribution in the soil–geotextile column. The temperature gradient resulted in appreciable thermal vapor flow and changes in suction head and hydraulic conductivity of the geotextile. During drainage, the temperature gradient and lower temperature at the top of the column increased suction in the geotextile and its ability to function as a capillary barrier. During capillary rise, the temperature gradient and lower temperature at the top of the column decreased the suction in the geotextile and its ability to function as a capillary barrier. Changing the direction of the thermal gradient reversed the water vapor flow direction and its effect on the suction in the geotextile. A temperature gradient did not have a noticeable effect on the suction head of the geotextile when positive pore pressure was developed in the geotextile and adjacent soil during drainage.

1. Introduction

Nonwoven geotextiles are often used for drainage, filtration, separation, and/or reinforcement in the design of geotechnical systems. During construction, geotextiles are emplaced in soils that are not fully saturated. The soils with which a given geotextile are in contact are expected remain unsaturated for much of the design life of the system – periods of saturation will likely be brief and intermittent. In addition to varying degrees of saturation, geotextiles will typically be subjected to thermal gradients, such as those caused by solar heating or exothermic waste decomposition. In this work, we will focus on the hydraulic behavior of geotextiles in contact with unsaturated soils and how that behavior varies with applied thermal gradients.

Due to their specific hydraulic properties [26], nonwoven geotextiles can function both as drainage layers and capillary barriers [31]. When saturated (or very nearly so) geotextiles have a high hydraulic conductivity and will act as a drainage layer. However, hydraulic conductivity decreases rapidly with increasing suction and geotextiles will begin to function as a capillary barrier due to the discontinuity in conductivity across the soil–geotextile interface. Consequently, geotextiles have been proposed for use both as drainage and capillary barrier layers in landfills and pavement sections [12,27]. Clough and French [5] performed an early study on geotextiles as capillary barriers in pavement sections. They showed that geotextiles can reduce capillary rise in soil. Henry [10] proposed the use of geotextiles as capillary barriers in pavement sections to reduce frost heave. McCartney et al. [18] compared the performance of the geotextile capillary barriers with that of soil-only capillary barriers in landfill covers. They showed that a geotextile capillary barrier provides higher water storage in the overlying fine soil compared to a soil-only capillary barrier. In addition to causing a capillary break, geotextiles have been used to drain water from unsaturated soil in pavement sections [4,30].

The hydraulic properties of geotextiles constitute a key design parameter. The specific properties of interest are the moisture characteristic curve (MCC) and the saturated conductivity. These properties have been the subject of several studies found in the literature [26,29,22]. Soil column [18,28] and capillary rise [12] studies have been conducted to evaluate the behavior of geotextiles as

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Nomenclature

D	vapor diffusivity (m^2/s)	T	temperature (K)
g	acceleration due to gravity (m/s^2)	t	time (s)
h	suction head (negative-valued pressure head) (m)	z	vertical spatial coordinate, positive downward (m)
H	total hydraulic head (pressure head plus elevation head) (m)	θ	volumetric water content (m^3/m^3)
H_R	relative humidity ( )	θ_s	saturated volumetric water content (m^3/m^3)
K_h	thermal conductivity (J/m s K)	μ	empirical factor to account for increased microscale temperatures in the pore air (relative to the macroscale temperature) and vapor diffusion through pore water [21]
K_L	hydraulic conductivity for liquid water (m/s)	ρ_v	vapor density (kg/m^3)
M	molecular weight of water (kg/mol)	ρ_{vs}	saturated vapor density (kg/m^3)
q_h	heat flux density (J/m^2 s)	ρ_w	density of water (kg/m^3)
q_v	vapor flux density (m/s)		
R	universal gas constant (J/mol K)		

a capillary barrier. These studies have shown that the geotextile increased water storage in the overlying soil during infiltration (see Stormont and Anderson [25] for a thorough discussion of water storage in capillary barriers).

To better understand the behavior of geotextiles emplaced in unsaturated soils, the effects of temperature and thermal gradients must also be considered. In unsaturated porous materials (particularly those that are quite dry), water vapor flow may be the predominant mechanism for moisture movement. Philip and de Vries [21] studied thermal effects in unsaturated soils. They developed an approximate analytical procedure to predict the general behavior and to describe moisture and heat transfer in porous media under suction and temperature gradients. Later, Milly [16] extended that work to a heterogeneous and hysteretic medium. These approaches assumed that air flow can be neglected, which is adequate in many situations. Faust and Mercer [6] developed a basic formulation for modeling geothermal reservoirs and handled the problem of phase change induced by heating. However, in this approach, capillary effects and the possible presence of air are neglected. Philip and de Vries [21] approach uses suction head and temperature as state variables. Temperature gradients result in thermal water vapor flow and consequently, changing suction in the medium [24]. Mohamed and Shooshpasha [19] performed a series of one dimensional coupled heat and moisture tests on a capillary barrier consisting of three soil layers. The capillary barrier was subjected to thermal and suction gradients in opposite directions to simulate arid lands with sub-irrigation systems. They showed that both thermal and suction gradients resulted in moisture movement. Suction gradients caused upward moisture flow from the water source to the middle of the barrier and temperature gradients resulted in moisture flow from a higher temperature at the top of the profile toward the lower temperature at the middle of the barrier.

The effect of temperature and thermal gradients on matric suction distributions in soil–geotextile systems have not previously been considered. In the current work, we study the effects of matric suction and thermal gradients on the infiltration and drainage properties of a vertical soil–geotextile column using UNSAT-H [8,7]. Two soil types and four temperature conditions were considered, and the behavior of the geotextile under drainage and capillary rise were evaluated. Matric suction profiles along the column under different temperature conditions are presented and the performance of the geotextile as a drainage layer/capillary barrier is evaluated in terms of variations in suction head and associated change in the hydraulic conductivity.

2. Overview of the numerical model

UNSAT-H [8,7] is a finite difference program for simulating coupled air, water, and heat flow in one dimension without considering gravity-driven consolidation or coupled mechanical effects. It has been previously shown to reasonably reproduce field measurements for infiltration, storage, and drainage in soil profiles [9,14,15]. UNSAT-H simulates water flow using a modified form of Richards' equation [23]:

$$\frac{\partial\theta}{\partial h}\frac{\partial h}{\partial t} = \frac{\partial}{\partial z}\left[K_L(h)\frac{\partial H}{\partial z}\right] - S(z,t) \tag{1}$$

where θ is volumetric water content, h is suction head, t is time, K_L is the conductivity for liquid water, z is depth below the surface, H is total hydraulic head, and S is a sink term used to capture transpiration (zero in the current work). Note that suction is equal to positive-valued negative pore water pressure.

Richards' equation does not include the vapor flow, so Fick's law is used to capture thermal and isothermal vapor flow:

$$q_v = \left[\frac{D}{\rho w}\rho_{vs}\frac{Mg}{RT}H_R\frac{\rho h}{\rho z}\right] - \left[\frac{D}{\rho w}\mu H_R\frac{d\rho_{vs}}{dT}\frac{\partial T}{\partial z}\right] \tag{2}$$

where q_v is flux density of water vapor, D is vapor diffusivity in soil, ρ_w is density of water, ρ_{vs} is saturated vapor density, M is molecular weight of water, g is gravitational constant, R is the gas constant, T is temperature, H_R is relative humidity, h is suction head, z is depth below the surface, and μ is an enhancement factor to consider increased cross section area and decreased path length for vapor diffusion.

The first term in the right hand side of Eq. (2) is isothermal vapor flow and the second term describes thermal vapor flow. Heat flow is calculated using Fourier's law of heat conduction:

$$q_h = -l_h\frac{\partial T}{\partial z} \tag{3}$$

where q_h is heat flux density, k_h is thermal conductivity, T is temperature, and z is depth below the surface.

Thermal conductivity may be approximated as a function of volumetric water content as follows [3]:

$$k_h = a + b\left(\frac{\theta}{\theta_s}\right) + (a-d)exp\left[-c\left(\frac{\theta}{\theta_s}\right)^e\right] \tag{4}$$

where θ is water content, θ_s is saturated water content, and a, b, c, d, and e are constants.

The heat flux, vapor flow, and liquid flow equations are solved using a modified Picard iteration scheme [8]. The user specifies the spatial discretization of the profile (an example profile with the geotextile on the bottom is presented in Fig. 1) and the time step is adjusted to a value necessary to provide a stable solution. UNSAT-H does not simulate the freeze/thaw process.