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Effects of temperature changes on soil hydraulic properties

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ABSTRACT

Accurate simulation of the effects of temperature on soil water movement processes is lacking in the study of hydrothermal interactions in soil systems. Previous research has proposed some likely mechanisms (e.g., surface tension-viscous flow) to explain soil hydraulic properties in relation to temperature, but little research has focused on the temperature dependence of soil particles (e.g., thermal expansion). Using simulation analyses and experimental data, the effect of temperature on soil hydraulic properties was explored focusing on the thermal effect of water surficial properties and soil particle characteristics. Two temperature coefficients, λ, representing the thermal effect of water surficial properties and c, representing the thermal effect of soil particle characteristics are introduced into soil hydraulics formulae to represent temperature dependence. Results show that temperature-dependent changes in water surficial properties including kinematics viscosity, surface tension and water density effects on soil hydraulic properties. Changes in temperature also affect soil particles, soil porosity and the interactive surface between liquid and solid, especially in heavy loam with high clay content. Expected soil hydraulic properties were calculated at three temperatures in two soil types and then compared to corresponding experimental results. Comparison of predicted and experimental soil hydraulic properties revealed overall similarities with a few exceptions. This study represents an initial simulation study of the effects of temperature on soil hydraulic properties.

1. Introduction

The effects of temperature on soil hydraulic properties have long been recognized but the mechanisms are far from fully understood. Temperature gradients are not only a driving force of capillary liquid flow but also significantly affect soil hydraulic properties (Hopmans and Dane, 1985; Grant and Bachmann, 2002). A widely accepted mechanism explaining this thermal effect is the surface tension-viscous flow theory (STVF). In the STVF model, the effect of temperature changes on soil hydraulic properties attributes to the thermal response of fluid viscosity and surface tension of liquids in the soil. However, some studies have shown that the STVF imperfectly interprets temperature-dependent changes in soil–water movement (Nimmo and Miller, 1986).

The derivation of the mathematical formula representing the Soil Water Characteristic Curve (SWCC) by Philip and de Vries (1957) was important in furthering understanding of temperature-dependent effects on soil hydraulic properties. In this model, the effect of temperature changes on the SWCC is attributed solely to the temperature dependence of water surface tension. Wilkinson and Klute (1962) proposed a thermally driven relationship between soil water pressure head and soil water content and concluded that changes in water surface tension are driven by temperature. These findings have been widely used by researchers to explain experimental results showing increasing soil water pressure head with increasing temperature (Haridasan and Jensen, 1972; Constantz and Murphy, 1991; Bachmann et al., 2002; Grant and Bachmann, 2002). Although this progress has advanced understanding of temperature-dependent effects on soil hydraulic properties, observed results still deviate from predicted results. Some explanations for this gap are the effect of temperature on entrapped air and the presence of contaminants affecting surface tension at the air–water interface.

Saturated and unsaturated hydraulic conductivity and soil–water diffusivity are the basic properties to describe the soil water movement process. Observed increases in hydraulic conductivity at a given water content under increasing temperature are attributed to a decrease in the viscosity of water (Haridasan and Jensen, 1972). However, with increasing temperature there are two conflicting effects of temperature on hydraulic conductivity: an increase in matric potential, and a decrease in viscosity of water

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(Hopmans and Dane, 1985). At a given matric potential, hydraulic conductivity decreases as the amount of water held in soil decreases with increasing temperature. Conversely, a decrease in water viscosity increases soil hydraulic conductivity. Many studies have shown that experimental temperature dependence of hydraulic conductivity is greater than results predicted by models (Flocker et al., 1968; Hopmans and Dane, 1986a; Constantz and Murphy, 1991).

There are four proposed mechanisms to explain the greater temperature dependence of soil water potential and hydraulic conductivity observed in experimental results (Grant and Bachmann, 2002). The first mechanism proposed is an increase in the volume of entrapped air with increasing temperature. This mechanisms increases temperature sensitivity of soil water pressure head. However recent research has questioned this mechanism (Hopmans and Dane, 1986b). The second mechanism is the temperature dependence of water expansion. However, the predictions of this model are not credible at the lowest and highest extremes of capillary pressure (She and Sleep, 1998). The third proposed mechanism is the effect of solutes on the surface tension of water (Chen and Schnitzer, 1978). The last proposed mechanism are temperature-sensitive contact angles (King, 1981). Though these mechanisms shed light on the temperature dependence of soil hydraulic properties, none fully describes the existing results from experiments. Bachmann et al. (2002) suggest that the most likely mechanisms for the considerably greater temperature dependence of capillary pressure are solute effects on surface tension and temperature-induced changes in contact angles.

The temperature dependence of soil structure is a relevant factor influencing hydraulic properties. Increases in temperatures can reduce inter-particle bond strength, which, when coupled with the differential thermal expansion between mineral particles and water can result in a reduction in the void ratio. The expansion of particles also causes a reduction in specific surface area further implying that water holding capacity of particles decreases. However, no reports give a detailed description of this theory (Constantz, 1982; Romero et al., 2001). The objectives of this study are as follows: (1) to determine the effect of temperature on the soil hydraulic properties, and (2) to conduct a preliminary investigation of the mechanisms driving temperature dependence of soil structural changes and hydraulic properties.

2. Theory

2.1. Soil water characteristic curve

The SWCC describes the relationship between pressure head (water potential) and water content, but almost all SWCC models ignore temperature effects on this relationship. Of the empirical and semi-empirical formulae quantifying this curve, the van Genuchten model derived with a closed-form analytical expression is one of the most flexible (van Genuchten, 1980; van Genuchten and Nielsen, 1985). Saturated volumetric water content (θ_s), residual volumetric water content (θ_r) and pressure head (h), were introduced into this model as the initial condition parameters and boundary condition parameters. The other three independent parameters, α, m and n, were obtained by fitting the experimental data from given soil samples. To obtain a closed-form expression for hydraulic conductivity, a relationship ($m = 1 - 1/n$) was determined artificially in this model. The van Genuchten model for SWCC is more flexible than many others and is widely applied. The model can also be used to estimate hydraulic conductivity parameters through statistical analysis of the pore size distribution. The expression of this model is as follows:

$$Se = \frac{1}{[1 + (\alpha|h|)^n]^m} \tag{1}$$

where Se is the effective degree of saturation, $0 < S < 1$; α is an empirical parameter with a reciprocal value of h_d, viz., $\alpha = 1/h_d$, h_d is the air-entry value; m and n are the empirical constants for pore size distribution parameters affecting the slope of the retention curve of a given soil.

Assuming any temperature T and a reference temperature T_o, the Van Genutchen model represents temperature dependence effects as follows:

$$Se_T = \frac{[1 + (\alpha h_{To})^n]^m}{[1 + (\alpha h_T)^n]^m} \times Se_{To} \tag{2}$$

If the water content is close to the saturated water content, the soil-water suction is very low. Under such conditions, the values of $h \approx 0$ and $Se \approx 1$. Conversely, if the water content is low, then the value of $(\alpha h)^n >> 1$ (Shao and Horton, 1998). The number “1” in Eq. (2) can be ignored. A relationship can be derived as follows:

$$Se_T = \frac{(\alpha h_{To})^{n-1}}{(\alpha h_T)^{n-1}} \times Se_{To} \tag{3}$$

According to Hopmans and Dane (1985), the knowledge of a reference soil–water pressure head (h_{To}) at a reference temperature allows the soil water pressure head value at any other temperature to be approximated by:

$$h_T = \delta h_{To} \tag{4}$$

where δ is a parameter associated with the effect of temperature on surface tension, $\delta = \sigma_T/\sigma_{To}$. σ_T and σ_{To} represents the surface tension of water at any temperature and a reference temperature, respectively. Application of capillary pressure theory and Eq. (4) allows the temperature dependence of SWCC to be determined from Eq. (3):

$$Se_T = \lambda Se_{To} \tag{5}$$

where:

$$\lambda = \left(\frac{\sigma_{To}}{\rho_{To}} / \frac{\sigma_T}{\rho_T}\right)^{n-1} \tag{6}$$

where λ is determined as a temperature dependent sensitivity parameter, ρ is the density of water, g cm^{-3}. According to Eqs. (5) and (6), the temperature dependence of the SWCC based on the van Genuchten model accounts for the temperature dependence of

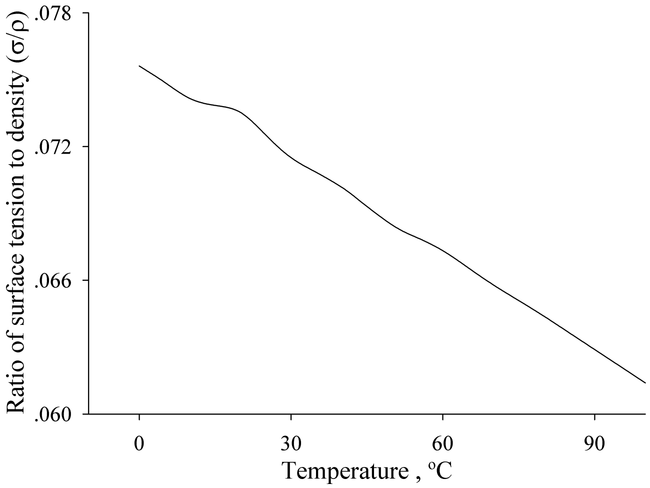

Fig. 1. Changes in the ratio of water surface tension to density (σ/ρ) *vs* temperature (T). σ water surface tension; ρ: water density.