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Importance of vapor flow in unsaturated freezing soil: a numerical study

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ABSTRACT

The role of vapor flow in unsaturated freezing soils is unclear, and usually ignored when analyzing water migration. Indeed, vapor flow is seldom considered in geotechnical design. On the other hand, frost heave damages were recently observed in a cold and arid region in China, where the groundwater table is about 20 m deep, and cannot be explained using the classical frost heave theory which focuses on the coupled flow of heat and liquid water. This paper presents a new approach for modeling moisture and heat movement in unsaturated freezing soils, in which the phase change of evaporation, condensation of vapor flow are taken into account. The method enables numerically stable solutions with energy and mass conservation. The performance of the proposed model was evaluated by a series of laboratory freezing experiments, which involve a 60 cm long soil column subjected to different initial conditions and boundary temperatures. It is shown that the proposed model is capable of effectively simulating the freezing process of an unsaturated soil. The vapor flux is shown to be significant, especially at the end stage where the freezing process is stabilized. Parametric analysis was carried out to clarify the role of vapor in moisture migration. The results show that vapor flow apparently contributes to ice formation and generally accounts for more than 10% of total water flux. The percentage of vapor flux in total flux (vapor flux ratio) positively relates to temperature gradient and freezing depth, but negatively relates to initial water content. Relations between vapor flux ratio and hydraulic parameters are less clear.

1. Introduction

Soil freezing is a coupled process of heat and water transfer. When a temperature gradient forms in a freezing soil, heat flows from the higher temperature to the lower one, and drives pore water migration in the same direction. Water–ice phase change causes the variation of soil hydraulic and thermal properties. Meanwhile, pore water flow influences the heat transfer through convection and latent heat of phase change (Harlan, 1973; O'Neill and Miller., 1985; Teng et al., 2016). Thus the heat and water transfer in freezing soils is a complicated process which conjugates heat conduction with water migration, supplemented with phase changes of evaporation, condensation and congelation.

Vapor flow is usually assumed to make negligible contribution to the overall moisture transfer in a freezing soil (Harlan, 1973; Hu et al., 1992; Kung and Steenhuis, 1986; O'Neill and Miller., 1985; Zhang et al., 2016; Zhou et al., 2014). However, when the groundwater table is sufficiently deep, such as in cold and arid regions of northwestern China, moisture transfer in unsaturated soils takes place usually in the form of vapor flow, especially in the case where the temperature gradient is relatively large. Recent experimental evidence also proves that vapor flow in freezing soils could lead to a large amount of ice formation, being the dominant mechanism of moisture migration (Eigenbrod and Kennepohl, 1996; Guthrie et al., 2006; Wang et al., 2012). Eigenbrod and Kennepohl (1996) is perhaps the first who noted the importance of vapor flow to frost heave under pavements where the groundwater table is relatively deep. Recent observation of significant frost heave damage to an airport in northwestern China, where the groundwater table is about 20 m deep and the annual rainfall is very limited, also reveals the importance of vapor flow to frost heave in relatively dry soils (Li et al., 2014). Vapor flow can accumulate a large amount of moisture in soils under impermeable surface covers. Road or airport pavements are typical such covers that prevent evaporation. Vapor flow also significantly affects the movement of heat, since it carries a substantial amount of energy as the latent heat of vaporization (Sakai et al., 2009). Therefore, it is important to clarify the role of vapor transfer in unsaturated freezing soils.

The theory of coupled moisture and heat transfer in unsaturated soils was pioneered by Philip and de Vries (1957), who developed a mathematical model to describe the coupled movement of liquid water and water vapor under non-isothermal conditions. Milly (1984) adopted the matric head instead of the total volumetric water content in the Philip and de Vries model. Nassar and Horton (1989) further extended Milly's work by including osmotic effects on liquid and water vapor movement. Sakai et al. (2009) presented a coupled model for water and vapor movement which considers condensation and evaporation effects under non-isothermal and low water content conditions. Although these models of simultaneous movement of liquid water,

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vapor, and heat in unsaturated soils have been proposed, few of them have been used for freezing soils where ice formation and frost heave may take place. In other words, existing theories mainly apply to the limiting situation of super-freezing soil temperatures, and a model for coupled liquid water, vapor, and heat movement in unsaturated soils subjected to both sub- and super-freezing temperatures is not available in the literature.

In this paper, a mathematical model is presented to simulate the one-dimensional coupled heat and mass transfer in an unsaturated freezing soil where the processes of evaporation, condensation, and congelation may take place. The numerical model is then calibrated against experimental results from the literature. The relative contribution of vapor flow in the overall moisture movement in the freezing unsaturated soil is elucidated by performing parametric studies.

2. Mathematical model for liquid water, vapor, and heat flow in unsaturated freezing soil

The movement of water and heat in unsaturated freezing soils is schematically illustrated in Fig. 1. Liquid water and heat move along the direction of potential energy gradient (water head and temperature), and vapor diffuses from the warmer and more humid end to the colder and dryer end and subsequently condenses there. If the soil temperature at a certain depth is lower than 0 °C (freezing front of water, as shown in Fig. 1), the migrating water starts to solidify into ice. In the frozen zone, close to solid particles and more tightly bound to them, a film of unfrozen water remains, this adsorbed water film has lower free energy at a lower negative temperature, which can drive the liquid water from the warmer part to feed the accumulation of pore ice. Meanwhile, the gradient in the vapor density remains, in accordance with the temperature gradient. This process facilitates the liquid water and vapor flow in the unfrozen zone (Sheng et al., 2014). The aforementioned movement of liquid water, vapor, and heat in unsaturated freezing soil is a closely coupled process.

In order to simplify the quantitative description of liquid water, vapor and heat transfer with phase change, some assumptions are made as follows:

(a) The deformation of the soil matrix due to variations of temperature and pore water pressure or ice formation can be neglected.
(b) The freezing front is always located at the depth where the soil temperature is 0 °C.
(c) The specific vapor density is tiny for a subzero temperature, its gradient in frozen zone can be neglected (Tetens, 1930). Therefore, the vapor flux at the freezing front is assumed to condense into liquid water, and that only liquid water and ice exist in the frozen zone. This assumption is in accordance with the concept of frozen fringe of Miller (1980).
(d) Hysteresis in the water retention behavior of the unsaturated soil is neglected.
(e) Pore air pressure in the soil remains atmospheric.

2.1. Liquid water and vapor flow

The flow of liquid water and vapor in an unsaturated soil is usually driven by a temperature gradient or a matric head gradient, as proposed by Philip and de Vries (1957):

$$q_{\mathrm{L}} = q_{\mathrm{L}h} + q_{\mathrm{L}T} = -K_{\mathrm{L}h}\left(\frac{\partial h}{\partial z}+1\right) - K_{\mathrm{L}T}\frac{\partial T}{\partial z} \tag{1a}$$

$$q_{\mathrm{v}} = q_{\mathrm{v}h} + q_{\mathrm{v}T} = -K_{\mathrm{v}h}\frac{\partial h}{\partial z} - K_{\mathrm{v}T}\frac{\partial T}{\partial z} \tag{1b}$$

where $q_{\mathrm{L}h}$ and $q_{\mathrm{L}T}$ are isothermal and thermal liquid water fluxes (m s^{-1}), respectively; $q_{\mathrm{v}h}$ and $q_{\mathrm{v}T}$ are isothermal and thermal vapor fluxes (m s^{-1}), respectively, h is the water pressure head or the negative matric head (m), T is the temperature (K), and z is the spatial coordinate positive upward (m). $K_{\mathrm{L}h}$ (m s^{-1}) and $K_{\mathrm{L}T}$ (m^2 K^{-1} s^{-1}) are the isothermal and thermal hydraulic conductivities for liquid water fluxes due to gradients in h and T, respectively; $K_{\mathrm{v}h}$ (m s^{-1}) and $K_{\mathrm{v}T}$ (m^2 K^{-1} s^{-1}) are the isothermal and thermal vapor hydraulic conductivities, respectively.

The volumetric water content in an unsaturated soil can be divided into three components: liquid water, ice and vapor content. In the unfrozen zone, liquid water flow mainly results in the change of liquid water content, while vapor flow leads to the variation of vapor content. In the frozen zone, however, only the liquid water flows, generating the changes of unfrozen liquid water content and ice content. The following expressions can be derived from mass conservation:

$$\text{Unfrozen zone} \quad \frac{\partial \theta_{\mathrm{L}}}{\partial t} = -\frac{\partial q_{\mathrm{L}}}{\partial z} - E \tag{2a}$$

$$\frac{\partial \theta_{\mathrm{v}}}{\partial t} = -\frac{\partial q_{\mathrm{v}}}{\partial z} + E \tag{2b}$$

$$\text{Frozen zone} \quad \frac{\partial \theta_{\mathrm{L}}}{\partial t} + \frac{\rho_{\mathrm{i}}}{\rho_{\mathrm{w}}}\frac{\partial \theta_{\mathrm{i}}}{\partial t} = -\frac{\partial q_{\mathrm{L}}}{\partial z} \tag{2c}$$

where θ_{L}, θ_{i} and θ_{v} are the liquid water content, pore ice content, and vapor content (all in form of an equivalent water content, m^3 m^{-3} or %), respectively, and E represents the evaporation or condensation rate (s^{-1}), ρ_{i} and ρ_{w} are the densities of ice and liquid water (Kg m^{-3}), respectively. t is time (s).

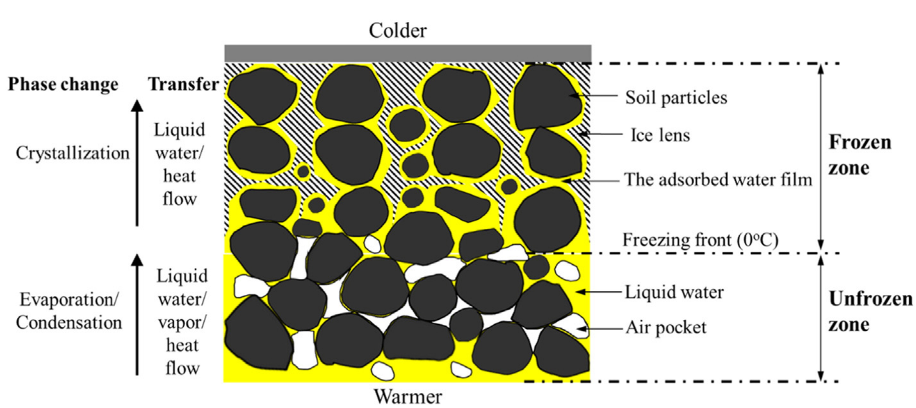

Fig. 1. Schematic diagram of liquid water, vapor, and heat flow in unsaturated freezing soil.