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A model of migration potential for moisture migration during soil freezing

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A B S T R A C T

Frost heave is attributed to water migration to the freezing front and the ice lens develops. Therefore, evaluation of frost heave requires the determination of the water migration in the freezing process. In order to predict the water migration in freezing soil, a water migration model which introduced the concept of migration potential (*MP*) was presented. This model presents a new approach for describing the water migration in freezing soils, in which the determination of the permeability coefficient in the frozen fringe and unfrozen zone was avoided. To verify the correctness of the proposed model, a series of unidirectional freezing experiments were conducted. Results show that small amount of water is intake to the soil due to the fast freezing rate, and that once the freezing rate becomes slow, the total amount of water intake is approximately increased with elapsed time. The water intake flux always changing with the elapsed time. As a result, the migration potential is a function of elapsed time. Finally, it is demonstrated that the predicted water intake flux is similar to the measured ones.

1. Introduction

In cold regions, constructions have encountered many problems, such as cracking of constructions pavements and bump at bridge-head (Wu and Liu, 2005; Yu et al., 2013), stabilization of construction excavations by artificial freezing (Xiao and Cheng, 2002), and periglacial solifluction on slopes (Harris et al., 2007). Most of these problems are related to the freezing or freezing–thawing cycles (Taber, 1930).

Studies have shown that water migration performs a core role in the process of soil freezing (Hoekstra, 1966). Thus, to discover the water migration characteristics in freezing soil has an important bearing on the engineering stability.

When a frost-susceptible soil is subjected to freezing, heave occurs as a result of the development of ice lenses formed from water supplied from an external source. This phenomenon has been known for a long time and has been the subject of numerous studies, and much research activities were carried out in many countries, such as Russia, America and Canada (Burt and Williams, 1976; Cary, 1965; Konrad and Morgenstern, 1980; Wu and Liu, 2005). Before the introduction of personal computers, water migration processes were primarily studied by conducting laboratory experiments (Cary, 1965; Hoekstra, 1966; Taber, 1930; Xu, 1982). From these experimental results, the basic rule of water migration was revealed. Harlan (1973) is generally credited with developing the first numerical model for coupled water flow and heat transport for unsaturated freezing soils. Later, Harlan's model has been referred and further developed by Taylor and Luthin (1978). Harlan's strategy as well as the modified version has been called the hydrodynamic model. The hydrodynamic model can explain some basic concepts of the water and heat transfer in freezing soil, but it was considered to be too coarse to describe the process of water migration (O'Neill and Miller, 1985).

In the application of water transfer equations to a freezing soil, the most difficult and also important is to determine the value of parameters. Due to the limited data on parameters of frozen soils, various assumptions have been introduced in the frost heave model (Guymon et al., 1980; Nixon, 1991; Sheng et al., 1995; Shoop and Bigl, 1997; Hansson, et al., 2004). Such as, the soil physical properties were treated as constant in time although they are strongly influenced by the frost itself (Harlan, 1973). Furthermore, the unsuitable parameters in many current models of heat and water flow in frozen soils result in overestimating the redistribution of water (Lundin, 1990; O'Neill and Miller, 1985). In the application of hydrodynamic model to predict the moisture migration, it can be seen that parameters, such as hydraulic conductivity and driving force, performed a core role in the water migration model but are not easy to measure in the laboratory. Thus, it is very hard to talk about the usefulness of the model, if the parameters could not get through the indoor test directly. Therefore, in the past few decades, many models have been proposed to describe the water migration process, but none of them has been widely accepted as a reliable tool in engineering applications.

An engineering theory of frost heave is required to predict the frost heave in a simple way (Konrad and Morgenstern, 1981; Wu and Liu, 2005). In a different approach from the hydrodynamic model, which is expressed by a system of equations describing the quasi-steady state process of freezing of moisture soil, Konrad and Morgenstern (1980,

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1981) proposed a simple theory of frost heave, called the segregation potential theory, based on the experimental result. At the formation of the final ice lens, the water intake flux is proportional to the temperature gradient across the frozen fringe, and the proportionality was called segregation potential. The theory of segregation potential has been adopted to estimate the frost heave for engineering problems (Konrad and Morgenstern, 1984; Nixon, 1987). The use of the concept of segregated potential has resolved the moisture migration problem in a stable state during the process of ice lens formation. However, some limitations of the segregation potential model have become apparent. Such as, when the continuous freeze happens, it is incorrect to assume the SP as a constant (Xu et al., 2010). Due to the change of the freezing rate, any moisture field changes could cause the change of SP, as a consequence, the concept of potential can no longer be used. If the SP was still treated as a constant, there is a large difference between the predicted value and the measured value (Chen et al., 2006). Furthermore, the model did not explicitly predict the relationship between frost heave rate, temperature gradient and other fundamental soil properties (Nixon, 1991). In addition, the segregation potential model is intended for pseudo-steady state water migration using a temperature gradient, but the phenomenon of water migration happened before the final ice lens appeared.

The above mentioned requires a simple and precise model to predict the water migration during soil freezing. Based on a literature review and our current laboratory tests, this paper presents a new approach to predict the one dimensional water migration in freezing soils. Firstly, based on the essence of water intake flux, the migration potential model, which could provide a simple method to describe the water migration in freezing soil, was presented. Second, to characterize the rule of the water migration, ten unidirectional freezing tests were carried out in the laboratory. Finally, the migration potential was obtained from the experimental result. In the discussion, to give a further understanding of water migration in freezing soil, a detailed analysis on the migration potential model was presented.

2. Migration potential model

To obtain the analytical solution some assumptions were made:

(1) suppose the Darcy's law is still valid for the unstable flow;
(2) water flow is continuous through the unfrozen area and frozen fringe;
(3) water and heat transfers are one-dimensional.

Based on the assumptions mentioned above, the water intake flux through the unfrozen section can be described as:

$$v_{uf} = -k_{uf}\frac{\partial Pw}{\partial x} \tag{1}$$

where *vuf* is the water intake flux to the warmest ice lens; *Pw* is the pore water pressure, and k_{uf} is the overall hydraulic conductivity in unfrozen zone and frozen fringe.

Background studies illustrate that there exists a certain amount of unfrozen water in the vicinity between the surfaces of soil grains and ice grains (Dash et al., 2006; Rempel, 2011). The relationship among ice pressure, water pressure, and temperature coexisting in phase equilibrium can be expressed by the Clapeyron Equation (Black, 1995):

$$P_w = \frac{\rho_w}{\rho_i}P_i + L\rho_w \ln\left(\frac{T}{T_0}\right) \tag{2}$$

where P_w and P_i are the pore water pressures and pore ice pressures, respectively;ρ_w and ρ_i are the densities of pore water and pore ice, respectively; L, T, and T_0 are the latent heat of fusion, the current temperature and the freezing point of bulk water, respectively.

Since the generalized Clapeyron equation was applied to describe the phase equilibrium condition of water and ice in soil (Edlefson and Anderson, 1943), the effectiveness of using the generalized Clapeyron equation to describe the driving force of water migration has been very controversial (Black, 1995; Bronfenbrener and Bronfenbrener, 2010). Actually, the Clapeyron equation is used here, only to link the water pressure in the frozen fringe to the temperature at the ice–water interface. In the meantime, the generalized Clapeyron equation is valid to describe the relationship among ice pressure, water pressure and temperature, only in the case that unfrozen pore water and pore ice coexist in equilibrium. Actually, in any transient process, this equilibrium condition cannot be strictly achieved. In this paper, it is assumed that the temperature change and the water migration are slow enough, compared to the phase change. Therefore, Eq. (2) is valid under the transient condition.

According to previous study (Hopke, 1980), the ice pressure in frozen soil can be expressed as,

$$P_i = P - \frac{P}{l}z \tag{3}$$

where P is overburden pressure; l is depth of frozen layer; and z is the distance of any point to the upper of frozen layer.

Substituting Eq. (3) into Eq. (2),

$$P_w = \frac{\rho_w}{\rho_i}P\left(1-\frac{z}{l}\right) + L\rho_w \ln\left(\frac{T}{T_0}\right). \tag{4}$$

Substituting Eq. (4) into Eq. (1), the water intake flux can be written as,

$$v_{uf} = -k_{uf}P\frac{\partial}{\partial x}\left(\frac{\rho_w}{\rho_i}P\left(1-\frac{z}{l}\right) + L\rho_w \ln\left(\frac{T}{T_0}\right)\right). \tag{5}$$

Rearranging Eq. (5),

$$v_{uf} = -k_{uf}P\frac{\rho_w}{\rho_i}\frac{\partial}{\partial x}\left(1-\frac{z}{l}\right) - k_{uf}L\rho_w\frac{\partial}{\partial x}\left(\ln\left(\frac{T}{T_0}\right)\right). \tag{6}$$

Numerous experimental results indicate that the driving force of water migration has a close relationship with pressure and temperature (Konrad and Lemieux, 2005). Thus, the derived formula of the driving force of water migration is more applicable in this paper.

Rearranging Eq. (6),

$$v_{uf} = -k_{uf}P\frac{\rho_w}{\rho_i}\frac{\partial}{\partial x}\left(1-\frac{z}{l}\right) - k_{uf}L\rho_w\frac{\partial}{\partial x}\left(\ln\left(\frac{T}{T_0}\right)\right). \tag{7}$$

Here, η is a coefficient, only related with temperature, and can be expressed as $\eta = \frac{l-z}{l}$.

$$v_{uf} = -k_{uf}P\frac{\rho_w}{\rho_i}\frac{\partial\eta}{\partial T}\frac{\partial T}{\partial x} - k_{uf}L\rho_w\frac{\partial}{\partial x}\left(\ln\left(\frac{T}{T_0}\right)\right) \tag{8}$$

If the temperature changes in a small range, such as −20–10 °C, the curve of $\ln\left(\frac{T+273}{273}\right)$ is similar to a straight line, therefore Eq. (8) can be expressed as:

$$v_{uf} = -k_{uf}P\frac{\rho_w}{\rho_i}\frac{\partial\eta}{\partial T}\frac{\partial T}{\partial x} - k_{uf}L\rho_w\gamma\frac{\partial T}{\partial x}. \tag{9}$$

Here, γ is a coefficient, only related with temperature.

Rearranging Eq. (9),

$$v_{uf} = -k_{uf}\left(P\frac{\rho_w}{\rho_i}\frac{\partial\eta}{\partial T} + L\rho_w\gamma\right)\frac{\partial T}{\partial x}. \tag{10}$$