COUPLED THERMAL- HYDRO ANALYSIS FOR UNSATURATED FROZEN SOILS

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1. INTRODUCTION

The occurrence of frost heave in cold regions is accompanied by a complicated process of heat and water transfer, which is closely related to the temperature gradient, water potential, latent heat, overburden pressure, and so on. Based on thermodynamics and continuum mechanics, a coupled thermal-hydro model combined with the unknown parameters obtained from the soil freezing characteristic curve is proposed to describe the temperature variation and liquid water/vapor redistribution in unsaturated frozen soil. The proposed model was validated through a unidirectional freezing test on a soil column. The results reveal that the temperature variation and total water content distribution obtained by the proposed model are consistent with the test results.

2. COUPLED THERMAL-HYDRO MODEL

2.1 Basic assumptions

A unidirectional freezing soil column can be broadly divided into three layers along the soil height: unfroze area, frozen area (including ice lens), and freezing fringe, as shown in Fig. 1. Clearly, the liquid water, dry air, and heat migrate from the warm end to the cold end under the corresponding driving force. However, the vapor moves from the warm end toward the freezing front (position of the freezing point), condenses into water at this location due to the low temperature, and further migrates toward the cold end as portion of the liquid water. The other basic assumptions for simplifying the numerical analysis of the thermal-hydro coupled analysis are included in the model:

(1) Both the soil particles and formed ice lens are incompressible and non-transportable.
(2) All the gas phases (vapor, dry air) can be considered ideal gases.
(3) The hysteretic behavior in unsaturated soil can be ignored.
(4) Only liquid water and dry air can be transferred into the frozen zone.
(5) The heat losses through insulated walls can be ignored in the numerical simulation.

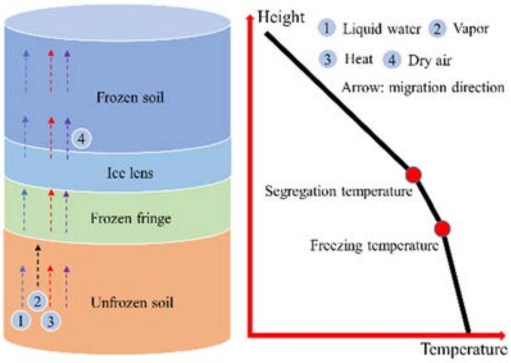

Fig. 1 Schematic of soil column during freezing

2.2 Equation governing heat transfer

The heat is primarily transferred in unsaturated frozen soil through conduction and convection. Equation governing heat transfer can be expressed as (Li et al. 2021):

$$C_f\frac{\partial T}{\partial t}+L_w\rho_l\frac{\partial \theta_v}{\partial t}-L_i\rho_i\frac{\partial \theta_i}{\partial t}=\frac{\partial}{\partial y}\left(\lambda_f\frac{\partial T}{\partial y}\right)-C_l\frac{\partial q_lT}{\partial y}-C_v\frac{\partial q_vT}{\partial y}-C_a\frac{\partial q_aT}{\partial y}-L_w\rho_l\frac{\partial q_v}{\partial y} \qquad (1)$$

where C_f, C_l, C_v, and C_a are the volumetric heat capacities of the porous media, liquid water, vapor, and air, respectively. L_w and L_i are the latent heats of vapor condensation and ice-to-water transformation, respectively. λ_f is the heat conductivity of the soil.

2.3 Equation governing water and vapor transfer

The total moisture in the frozen soil exists in three forms: unfrozen water, ice, and vapor. Based on the Reynolds transport theorem, the conservation equation of the water for the 1D problem can be expressed as:

$$\frac{\partial}{\partial t}(\theta_l\rho_l)+\frac{\partial}{\partial t}(\theta_i\rho_i)+\frac{\partial}{\partial t}(\theta_v\rho_v)=-\frac{\partial}{\partial y}q_v-\frac{\partial}{\partial y}q_l \qquad (2)$$

where θ_l, θ_i, and θ_v are the volumetric contents of the unfrozen water content, ice, and vapor, respectively; ρ_l, ρ_i, and ρ_v denote the densities of the unfrozen water content, ice, and vapor, respectively; q_v and q_l are the vapor flux and liquid water flux, respectively; t represents the time; y is the spatial coordinate with the upward direction being positive.

2.4 Equation governing dry air transfer

The dry air in the frozen soil exists in two forms: direct transfer in the pores and dissolution in the liquid water. Considering these two mechanisms, the conservation equation of the dry air can be expressed as (Thomas and Sansom 1995):

$$\frac{\partial}{\partial t}\left[\rho_d\left(\theta_a+H_c\theta_l\right)\right]=-\frac{\partial}{\partial y}q_a \qquad (3)$$

where θ_a and ρ_d are the volumetric content of moist air and density of the dry air, respectively; q_a is the dry air flux; H_c represents Henry's constant.

3. NUMERICAL SIMULATION OF SOIL-COLUMN TEST

3.1 Unidirectional freezing test

A unidirectional freezing soil-column test without a water supply on a cylindrical silty clay sample with a height of 10 cm and radius of 5 cm was carried out to obtain the temperature variation, total water content. The liquid and plastic limits of

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the clay were 32.8% and 19%, respectively. Test samples with a dry density of 1640 kg/m3 and an initial mass water content of 20% were fabricated from this silty clay.

The experiment was conducted in the freezing test chamber with temperature programming capability, wherein the variation range of the freezing test chamber can be adjusted from -35 °C to 40 °C. A schematic of the test apparatus can be shown in Fig. 2. Five thermistors with an accuracy of ± 0.1 °C were installed on one side (at 1, 3, 5, 7, 9 cm from the warm end) to measure the soil temperatures. During the one-side freezing test, the temperature of the soil column was initially controlled at 1 °C. Subsequently, the sample was thermally insulated at the side surface, but its top and bottom surfaces were always exposed to a constant temperature of -3 °C and 1 °C, respectively. After 100 h of freezing, the soil column was sliced into several small soil columns with a height of 1 cm to measure its total water content (unfrozen water content plus ice content) using a thermostat drying box.

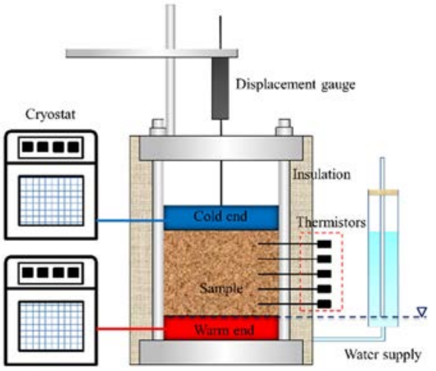

Fig. 2 Schematic of freezing test apparatus

3.2 Numerical simulation of thermal field

Fig. 3. presents the calculated and experimental results for the dynamic temperature at different positions. The calculated results are in well agreement with previously obtained experimental results. The temperature variation at different positions can be divided into two stages. During the first 10 h, the temperature rapidly declined, and the gradient and amplitude of the temperature decrease became larger as the position approached the cold end of the soil column. In the second stage, the temperature remained approximately constant at different heights in the soil column owing to the energy equilibrium.

3.3 Numerical simulation of hydro field

The volumetric contents of total water at 100 h are compared in Fig. 4. As can be seen, the experimental and predicted results approximately overlap in the unfrozen zone. Moreover, the ice lens position and amount can also be accurately predicted by the proposed model, which demonstrates the effectiveness of the model in the water migration simulation.

Fig. 5 shows the calculated liquid, vapor, and total flux profiles in the soil column at 20 h and 100 h; a positive value indicates upward movement. It can be observed that the liquid flux dominated the total flux at the beginning of freezing. As time passed, the vapor flux played a dominant role in the total flux, which may be attributed to the fact that the amount of liquid water for migration kept on decreasing. This phenomenon also indicated that the vapor flux cannot be ignored when the initial water content of the soil is extremely low.

4. CONCLUSIONS

In this study, a coupled model was established based on continuum mechanics and thermodynamics theory to quantify the variation in the temperature and liquid/vapor transfer in unsaturated frozen soil. The proposed numerical model was experimentally validated by performing a unidirectional freezing test of the soil column in a closed system. The main findings of the study are summarized as follows:

(1) The proposed model can accurately predict the variation of temperature, liquid, and air in unsaturated frozen soil under both heat flux and fixed temperature boundary conditions.

(2) The vapor flux plays an important role in a closed system during soil freezing, particularly when the initial water content is low.

In this study, soil freezing was regarded as a unidirectional thermal-hydro coupled problem. The driving force during freezing process in horizontal direction will be studied further.

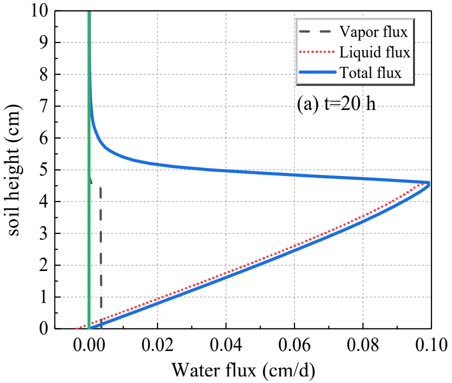

Fig. 5(a) Water flux at 20 h

REFERENCES

Zhiming Li, Jian Chen, Aiping Tang, Mitsutaka Sugimoto (2021). A novel model of heat-water-air-stress coupling in unsaturated frozen soil. International Journal of Heat and Mass Transfer, 175: 121375.

H.R. Thomas, M.R. Sansom (1995). Fully coupled analysis of heat, moisture, and air transfer in unsaturated soil. Journal of Engineering Mechanics, 121(3): 392–405.

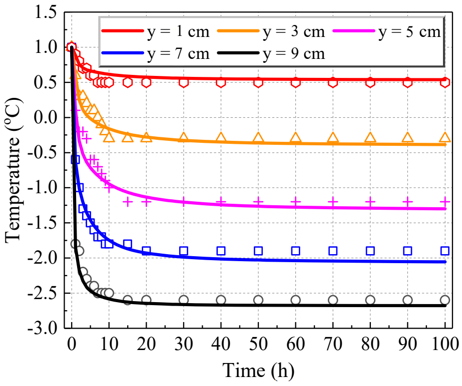

Fig. 3 Temperature distribution

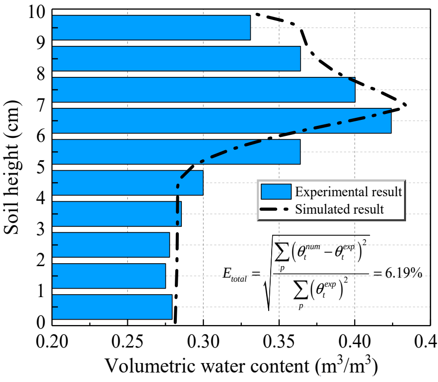

Fig. 4 Water contents at 100 h

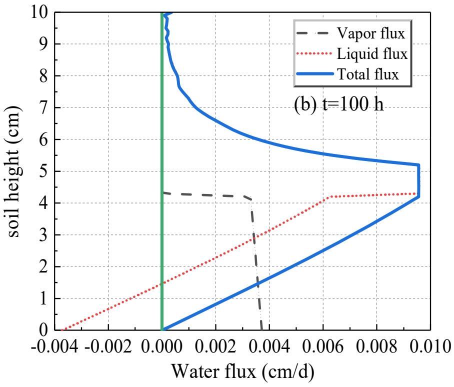

Fig. 5(b) Water flux at 100 h