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Research Paper

Experimental and numerical simulations on heat-water-mechanics interaction mechanism in a freezing soil

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ABSTRACT

In cold regions, the annual ground freezing is responsible for many distinct and widespread terrain features, such as ice wedges, frost mound and ground ice. In particular, the frost action caused by the soil freezing is a prevailing and heavy damage to engineering structures. The frost heave process of a freezing soil involves complicated coupled heat and water transfers as well as mechanical variation. To explore this multi-physical interaction, first, we built a numerical heat-water-mechanics model based on energy, mass and momentum conservation principles. In this model, several critical important characteristics of the freezing soil are taken into account. Then, we carried out a one-side freezing experiment of silty clay column in an open system with non-pressure water supply. Meanwhile, we used the experiment to simulate the water, temperature and deformation variations of the freezing soil column. The simulated temperatures and displacement well agree with those measured data, which implies the numerical model is valid and can describe the heat-water-mechanics process in the freezing soil. Finally, the heat-water-mechanics interaction mechanism of the freezing soil is explained and analyzed by combining the experimental investigation and numerical simulation. This study is helpful to better understand the interaction between water, temperature, deformation and the frost heave mechanism of the freezing soil. Furthermore, the model and results in the study can serve as references for further investigation, too.

1. Introduction

Ground temperature is a generally accepted criterion for defining cold regions of the world, and an area in which the ground temperature during the coldest month of the year is below 0 °C is often defined as cold region [1,2]. According to this criterion, the cold region is extensively distributed on the earth and its areas account for 50% of the land area (see Fig. 1) [1,3].

In cold regions, the annual ground freezing is responsible for many distinct and widespread terrain features, such as ice wedges, frost mound and ground ice as shown in Fig. 2. Under continuous cooling of air temperature during the coldest month of the year, a freezing surface appears and moves downward in the ground. At the same time, in-situ pore water is partially converted into ice and increases in volume by about 9% in shallow freezing ground and a portion of pore water in unfrozen zone mitigates through the soil pores toward the freezing surface by temperature gradient, causing the frost heave occurring in the freezing ground. The frost heave cannot get back completely and residual deformation may exist and accumulate year by year, resulting in the distinct terrain features form in cold regions [1,2].

Up to now, many researchers have been using different laboratory, analytical and numerical methods to investigate the frost heave mechanism in a freezing ground. Early studies were mainly carried out by experimental method. For instance, Taber explained the frost heave and rhythmic banding due to alternating layers of ice and clay in an open freezing system [4]. Sill and Skapski analyzed the water transfer and driving force on the basis of the capillary theory [5]. Kemper found the pore water moved in thin liquid films existing between adjacent soil particles [6]. Hoekstra measured moisture movement in Fairbanks silt under temperature gradients with a cold-side temperature below freezing [7]. Dirksen and Miller investigated water transfer was changed by pore ice lens [8]. Miller found an ice-water relationship in a freezing soil [9]. Subsequent studies began to simulate the physical process of the frost heave in the freezing soil. Harlan proposed a coupled heat-fluid transport in porous media by a Darcian approach [10]. Guymon and Luthin developed a one-dimensional model of heat-moisture interaction based on an equivalent quasilinear variational function for the Richards equation [11]. Jame and Norum used Harlan's model with some modifications of the hydraulic conductivity

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Nomenclature

A	area
a	experimental constant
$a_1 \sim a_9$	experimental constants
b	experimental constant
$b_1 \sim b_9$	experimental constants
c	specific heat capacity
C^*	equivalent heat capacity
c_4, c_6, c_7	experimental constants
D_{θ_w}	water diffusion coefficient
d_4, d_6, d_7	experimental constants
E_T	elastic modulus
e_4, e_6, e_7	experimental constants
f	body force
f_6, f_7	experimental constants
F	yield function
h	convection coefficient
k_{θ_w}	hydraulic conductivity
L	latent heat of phase change between water and ice
$\mathbf{n}$	outward unit vector
n_s	porosity
Q	plastic flow rule potential
q_T	heat flux
q_θ	water flux
T	temperature
t	time
T_a	ambient temperature
T_f	freezing point
$\bar{T}_0$	temperature boundary
u	displacement
$[A] \sim [M]$	coefficients of heat-water model
$[N]$	shape functions matrix
∇	Hamilton operator
Δ	increment sign
ρ	soil density
λ	thermal conductivity
ρ_i	ice density
θ_i	volumetric ice content
Γ	finite element boundary
θ_w	volumetric content of liquid water
$\bar{\theta}_{w0}$	water boundary
ρ_w	water density
λ^*	equivalent thermal conductivity
χ	weight factor
σ	stress
ε	strain
$[\partial]$	differential operator matrix
ε_{vp}	viscoplastic strain
ε_{fh}	frost heave strain
ν_T	Poisson's ratio
γ_T	viscosity parameter
Φ	arbitrary function

to successfully simulate the coupled heat and mass transfers in a horizontal porous medium [12,13]. Gilpin built a theoretical model for predicting ice lensing and frost heave in soils [14]. Konrad and Morgenstern presented a theory of ice lens formation and frost heave in fine-grained soils [15]. O'Neill and Miller explored a rigid ice model of the frost heave in a saturated, granular, air-free and solute-free soil from fundamental thermo-mechanical considerations [16]. Nixon modified the Gilpin's model and gave a discrete ice lens theory for frost heave in soils [17]. Konrad and Duquennoi proposed a one-dimensional model for water transport and ice lensing in saturated and solute-free soil specimens to simulate small-scale frost heave tests [18]. All of these models mentioned above have attempted to address the frost heave process from the standpoint of temperature and moisture interaction in the freezing soil. However, the frost heave in the freezing soil actually involves not only water and heat transfers but also mechanical process, so the mechanical term must be taken into account when the frost heave in the freezing soil is analyzed, and some relevant researches have been carried out. For instance, Shen and Ladanyi built a numerical model of coupled heat, water and stress process in freezing soil [19]. Based on the Harlan's model and Clausius-Clapeyron equation, Selvadurai et al. proposed a computational model of differential frost heave to analyze the interaction between a buried pipeline and a soil region [20,21]. Similarly, Li et al. applied the Clausius-Clapeyron equation and the energy and mass conservation principles to establish a heat-moisture-deformation coupling model for a frozen soil foundation [22,23]. In recent years, Nishimura et al. presented a coupled thermo-hydro-mechanical finite element formulation to consider the freezing and thawing in water-saturated soils [24]. Zhou, Li and Pei proposed a mathematical model for the frost heave with variables of temperature, porosity and displacement, in which the Clausius-Clapeyron equation was employed as a phase equilibrium condition of water and ice in the freezing soil [25,26]. The above studies all adopted the Clausius-Clapeyron equation to describe the phase change process between ice and water. However, some questions on applicability of the Clausius-Clapeyron equation during soil freezing have been raised as the soil freezing tends to be a non-equilibrium thermodynamic process [27–29]. Moreover, based on plenty of experiments, Ma et al. found the changes in pore water pressure are ascribed to a superposition of multiple factors and thus cannot be described by the Clausius-Clapeyron equation [29]. Although the existing studies have these limitations, they can provide important theoretical bases and references for further study in future.

From the point view of the science of materials, the freezing soil is a natural particulate composite and composed of four different constituents: soil skeleton, unfrozen water, ice and air. The most important characteristic by which it differs from other soils is that under natural conditions its matrix, mostly consisting of ice and water, changes continuously with variational temperature and applied stress [2,30,31]. In other words, the freezing soil has the temperature-related and rheological characteristics. Therefore, it is significant to take these characteristics into account when a theoretical analysis of the frost heave in the freezing soil is done. Only by doing so can the frost damage mechanisms of the freezing soil in cold regions be disclosed to the maximum extent.

The objective of this study is to explore the frost heave mechanism of the freezing soil. First, a numerical heat-water-mechanics model is derived on the basis of energy, mass and momentum conservation principles, in which the temperature-related and rheological characteristics of the freezing soil are considered [10,13,30]. Second, a one-side freezing experiment of silty clay column is done in an open system with non-pressure water supply [26,32]. Third, the experiment is taken as an example, and the water, temperature and deformation variations of the freezing soil column are simulated. Lastly, the heat-water-mechanics interaction mechanism of the freezing soil is explained and clarified by combining the experimental investigation and numerical simulation. This study is helpful to better understand the interaction between water, temperature, deformation and the frost heave mechanism of the freezing soil.