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Numerical simulation of soil freezing and associated pipe deformation in ground heat exchangers

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ABSTRACT

In cold regions, the soil freezing always restricts the application of ground source heat pump. The aim of this study is to develop a numerical model to simulate the soil freezing course and investigate the characteristics of soil freezing and associated pipe deformation. Meanwhile, the influence of initial pipes center distance on pipe-soil structure is discussed. It can be found that the ice content and soil compressive stress show asymmetric distributions near the U-pipe. The soil freezing can lead to the pipe deformation and displacement. Smaller initial pipe center distance can lead to more asymmetric and larger soil compressive action on the pipes.

1. Introduction

In recent years, the ground source heat pump (GSHP) system was applied in the fields of building (Hesaraki et al., 2015; Kharseh et al., 2015), transportation (Balbay and Esen, 2010; Balbay and Esen, 2013) and agriculture (Esen and Yuksel, 2013), etc. Actually, the demand for energy sources is more prominently in these fields of cold regions. However, the soil freezing in cold regions always restricts the application of GSHP for a long time. Because the buried heat exchange pipe can be squeezed by the volume expansion in freezing soil, which could not only shorten the pipe's service life but also influence the system efficiency and safety (Lenarduzzi et al., 2000). Actually, many studies about the freezing phenomenon in pipe-soil structure have been conducted in other industry fields (Zhao et al., 2014; Yu et al., 2017; Li et al., 2017; Liu et al., 2015), such as petroleum, chemistry, foundation and tunnel. These studies included in-situ test, model experiment, as well as numerical simulation.

In the in-situ study, there are four famous large-scale tests (the Calgary test, the Caen test, the Fairbanks test and the UAF test). The Calgary pipeline frost heave test facility was constructed in Canada, which measured the deformation of soil and pipeline (Carlson and Nixon, 1988). The Caen frost heave test was conducted by France and Canada in Caen, France. In this test, half of the pipe was buried in non-frost susceptible sand and the other half in highly frost susceptible silt, four freeze/thaw cycles were operated to study the frost heave force (White, 2006) and the pipe deformation (Williams et al., 1993). The Fairbanks test facility was constructed by Northern Engineering Services Co. Ltd. By virtue of this test, many factors which could influence the frost heave, such as the soil type, pipe heat insulation (Nixon, 1975), pipe temperature and pipe buried depth (Nixon, 1991), were investigated. The UAF test was conducted by University of Alaska Fairbanks and Hokkaido University to study the differential frost heave and the pipeline upheaval (Huang et al., 2004; Kim et al., 2008). The pipes in the four in-situ tests were made of steel, and showed considerable deformation and displacement during the soil freezing. However, the heat exchange pipe in GSHP is made of high density polyethylene (HDPE) normally, the structural strength of which is much less than the steel pipe. So the heat exchange pipe in GSHP is faced with more noticeable deformation and displacement during low temperature mode and should be given more attention.

In the study of model experiment, researchers could conduct with more controllable conditions. In order to alleviate the soil freezing around chilled gas pipeline, O.J. Svec (Svec, 1981) proposed a method of heating soils by cables under pipe's thermal insulation slab, and verified this idea through an experiment. M. Christ (Christ et al., 2010) added rubber particles to silty-sand, it can be found from the experiment, rubber-soil mixture could decrease the freezing soil pressure on the buried pipe. F.J. Lenarduzzi (Lenarduzzi et al., 2000) studied the severe performance problems in a GSHP project during the heating season in Canada, and then implemented a model experiment, which indicated that the pipe deformation due to soil freezing was the source of performance problems. The authors of this paper also conducted a model experiment (Wang et al., 2013) on the basis of pipe-soil structure in GSHP, to investigate the movement of freezing front, the pipe

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Nomenclature

C	Volumetric heat capacity, J/(m3 °C)
E, G	Young's modulus and shear modulus, Pa
L	Latent heat of ice, J/kg
N	Porosity rate, s^{-1}
N_m	Maximum porosity rate, s^{-1}
T	Temperature, °C
T_m	Temperature at N_m occurs, °C
T_0	Freezing point of water, °C
a	Decay rate of unfrozen water, $°C^{-1}$
c	Mass heat capacity, J/(kg °C)
p	Soil porosity
t	Time, s
w	Unfrozen water content

Subscripts

i	Ice
p	Compression
s	Soil grain
w'	Unfrozen water content at a low reference temperature
w_0	Unfrozen water content at freezing point
α	Thermal coefficient of expansion, $°C^{-1}$
γ	Shear strain
ε	Strain
θ	Volumetric fraction
λ	Thermal conductivity, W/(m °C)
μ	Poisson's ratio
ξ	Coefficient of anisotropy
ρ	Mass density, kg/m3
σ	Stress, Pa
τ	Shear stress, Pa
w	Unfrozen water
1,2,3	Directions determined by rectangular coordinate system 1-2-3

deformation and the freezing soil pressure on pipe.

However, limited by the measuring technology and the high operating cost, the model experiment is hard to get more detailed information about freezing soil and buried pipe. Hence, more and more numerical models were put forward to describe and predict the variation of pipe-soil structure during soil freezing. Overall, there are four types of basic models (hydrodynamic model, rigid ice model, segregation potential model and thermo-mechanic model), which are well known by theorists and engineers.

The hydrodynamic model was put forward by R.L. Harlan (Harlan, 1973), who assumed that mass transportation across the freezing front is water flux only in this model. The freezing front is determined by the soil-water characteristic curve and the empirical relationship between hydraulic conductivity and pore-water pressure. Some efforts have been made to extend the hydrodynamic approach to a thermo-hydrodynamic model by adding the stress in the soil (Li et al., 2000; Li et al., 2002). The rigid ice model was developed by R.D. Miller (Miller, 1978) and K.O. Neill (Neill and Miller, 1980). The description of soil freezing in this model is based on the soil particle travelling through the ice block (Fowler and Krantz, 1994; Bronfenbrener and Bronfenbrener, 2010; Rajaei and Baladi, 2015). J.M. Konrad and N.R. Morgenstern (Konrad and Morgenstern, 1980; Konrad and Morgenstern, 1981) introduced the segregation potential model, which relates the water flux to the temperature gradient in the freezing front and regards the course of soil freezing as water migration towards growing ice lens. The thermo-mechanic model was introduced by R.L. Michalowski (Michalowski, 1993; Michalowski and Zhu, 2006), this model did not predict the growth of individual ice lens, but the distribution of ice growth. Evaluation and comparison of the thermo-mechanic model with two other models (hydrodynamic model and rigid ice model) was carried out by K.S. Henry (Henry et al., 2005). It was found that the thermo-mechanic model showed better simulation accuracy. As a matter of fact, the soil freezing model in this paper is on the basis of the thermo-mechanic model.

At present, the studies of pipe-soil structure in GSHP are focused on the heat transfer (Esen et al., 2007) and the analysis of system efficiency (Esen et al., 2017). Compared to other fields, the study of pipe-soil structure variation due to soil freezing is fewer. In order to get more detailed information about heat exchange pipe and freezing soil in GSHP during soil freezing, a numerical model is set up in this paper. Based on the experimental validation, the numerical model is applied to simulate the soil freezing course. Meanwhile, the freezing temperature field, the ice content and compressive stress in freezing soil, the U-pipe deformation and displacement are analyzed. Besides, the influence of initial pipes center distance on pipe-soil structure is investigated. This study is beneficial to GSHP technology promotion in cold regions.

2. Numerical model description

2.1. Assumptions

To conduct the numerical calculation in a convenient way, the following assumptions are made:

(1) The initial soil is fully saturated and isotropic.
(2) The difference of soils inside and outside borehole is neglected.
(3) The temperature change is the result of heat conduction, the heat convection and heat radiation are nonexistent.
(4) The freezing soil and heat exchange pipe are regarded as elastic.
(5) There is no pressure difference inside and outside the heat exchange pipe.
(6) The circulating fluid temperature is constant and temperature difference between inlet pipe and outlet pipe is 1 °C.

2.2. Governing equation

The course of soil freezing mainly includes the soil porosity change, the pipe-soil structure deformation and the phase change heat transfer.

2.2.1. Soil porosity function

In this numerical model, the increase in ice content is determined by the porosity rate function. This function is introduced as a material function that determines the ability of the soil to increase in volume due to growth of ice. The effectiveness of this function to calculate the soil volume expansion has been verified by experiment (Michalowski and Zhu, 2006). The function can be expressed as follows:

$$N = N_m\left(\frac{T - T_0}{T_m}\right)^2 e^{1-(T-T_0/T_m)^2} \tag{1}$$

2.2.2. Pipe-soil structure deformation

(1) Pipe deformation

During the course of soil freezing, the heat exchange pipe is not only squeezed by the deformed soil, but also affected by the expansion and contraction itself due to temperature change. According to the linear thermal stress theory, the total strain of pipe is determined by the stress and the temperature. Therefore, the Hooke law can be modified as a function which includes thermal strain: