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Experimental and numerical investigations on frost damage mechanism of a canal in cold regions

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ABSTRACT

Frost action is a prevailing and heavy damage to canals in cold regions, and it involves complicated heat and mass transfer as well as frost deformation in the seasonal freeze–thaw ground. To explore the frost damage mechanisms of canals in cold regions, firstly, a numerical water-heat-mechanics model is set up and corresponding computer program is developed. Secondly, a model test on a canal is carried out in one freezing–thawing cycle. Then, the canal model is simulated to analyze its temperature, water and mechanical states during the freezing–thawing process. The results show that under the drive of temperature, the total water contents in freezing–thawing fronts are very high and even a part of the freezing front is filled with ice and unfrozen water, which causes high tensile stress and heavy frost heave. In particular, the deformations at the toe of the canal slope are much larger than those in other zones. Therefore, this zone should be monitored closely to ensure safe operation. As a preliminary study, the experimental and numerical model and results in this study may be a reference for design, maintenance and research on other canals in cold regions.

1. Introduction

In the world, cold region areas account for about 50% of the total land area. In cold regions, ground temperature remains below 0 °C continuously from year to year or involves below 0 °C during the coldest month of the year (Zhou et al., 2000). The annual ground freezing is responsible for the frost heave that occurs with downward movement of the freezing surface because in-situ pore water becomes ice and increases in volume by about by 9% on freezing. Meanwhile, additional heave results from the formation of ice lenses normal to the direction of heat flow as water migrates by capillary through the soil pores toward the freezing surface (Andersland and Landanyi, 2004). As a result, many engineering constructions suffer frost damage if they are built in seasonal frozen ground (Chen, 2004; Cheng and Shen, 2003; Feng, 2003; Jia and Cheng, 2007; Liao et al., 2008). In particular, as far as canals in cold regions are concerned, the freezing action usually causes serious damage, such as surface heaving and cracking in winter due to sufficient soil water leaking from the canal (See Fig. 1(a)). If water is not drained and remains in the canal, the water that migrates is fully replenished and ice lenses grow continually during the freezing period, hence frost heaves up to 15 cm are by no means uncommon in regions with a moderate winter climate (Zhang and Wang, 2007). In addition, with the approach of spring and warmer temperatures, thawing occurs. The thaw of ice leads to high water content in the soil, which directly decreases soil strength, causing larger deformations, instability and even collapse of the canal slope (See Fig. 1(b)).

There are many canals in cold regions, and most of them have been damaged by frost action. For example, in Northeastern China, 83% of an irrigation canal has been damaged by freezing–thawing cycles in Heilongjiang Province (Ge, 2004), and a damage investigation of 216 canals in Jilin Province showed that 39.4% of engineering problems were caused by frost heave (Chen, 2004). In Northern China, there were many cracks along some canal slopes in 10 Irrigation Districts including Shijin and Tanghe, and the maximum width of crack was even greater than 15 cm. so some parts of the canals had to be repaired and even reconstructed (Li, 2009). In addition, in Northwestern China, of the canals more than 500 m in length surveyed in Qinghai Province, 50%–60% had been damaged by frost action (Li, 2009). Similarly, due to frost heave cracks, some canals in the Shuluhe Irrigation District could not convey water and had to be repaired after only two years of service (Zhang and Wang, 2007). Therefore, in order to maintain normal water conveyance and lower the cost of engineering, it is necessary and urgent to study the frost damage mechanisms of cold region canals.

To decrease frost damage and increase the service life of canals in cold region, some temperatures and deformation states of canals were measured and analyzed in seasonally frozen ground regions (Cheng and Shen, 2003; Feng, 2003; Li, 1989; Wu et al., 2005). According to actual freezing–thawing variations and freezing depths of ground, frost heave prevention methods and measures, such as thermal insulation,

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(a) Frost heave damage

(b) Collapse of canal slope

Fig. 1. Frost heave and collapse of canals in cold regions.

foundation replacement, and anti-seepage and drainage, have been proposed and applied to canal engineering (He et al., 2003; Huo et al., 2004; Jia and Cheng, 2007; Li, 2005; Liao et al., 2008; Na and Yuan, 2007; Pan, 2004; Sun et al., 2007; Wang and Lu, 2007; Zhou et al., 2005). Meanwhile, some new anti-frost heave canal structures were also developed to decrease or delay frost damages (Chen, 2004; Chen et al., 2006; Han et al., 2002; Li, 2008; Li et al., 2000, 2009). In the course of designing the new canal structures and in the application of new measures, the concrete lining of canals was considered as continuous beam or plate and its internal forces were calculated by structural mechanics methods (Chen, 2004; Li, 2009; Shen et al., 2012; Wang et al., 2008; Xin, 2008; Yu et al., 2002). Although some design parameters could be determined by this method, it is unreasonable to simplify frost heaving forces as point load or uniform pressure because the interaction between the canal lining and soil is a compatible and continuous change during the freezing process. To solve this problem, some numerical methods, such as the finite element method (FEM) and finite difference method (FDM), were used to analyze the temperature and stress changes in the canal lining and ground (Li, 2008, 2009; Li et al., 2013a; Liu, 2010; Liu et al., 2011; Wang, 2005; Xin, 2008). These numerical methods and results relatively conform to actual continuous compatible deformation conditions. But several important characteristics and phenomena in freezing ground, such as temperature-related physical and mechanical parameters, water migration, frost heave displacement and rheology, are neglected in these studies.

In fact, from the point view of the science of materials, frozen soil is a natural particulate composite and composed of four different constituents: solid grains, unfrozen water, ice and gases. The most important characteristic by which it differs from common unfrozen soils is that under natural conditions its matrix, mostly consisting of ice and water, changes continuously with varying temperature and applied stress (Andersland and Landanyi, 2004; Li et al., 2009, 2013b; Ma et al., 1999; Qi et al., 2008). Moreover, as mentioned above, water migrates through the soil pores toward the freezing surface during the freezing process (Gilpin, 1980; Guymon et al., 1984; Harlan, 1973; Jame and Norum, 1980; Shoop and Bigl, 1997; Taylor and Luthin, 1978). Consequently, the water contents in the freezing–thawing fronts increase rapidly and meanwhile some pore water become ice, which directly lead to frost damage happening (Bluhm et al., 2014; Kruschwitz and Bluhm, 2005; Shen and Landanyi, 1987). Therefore, it is significant to take these characteristics and phenomena that occurred in the frozen soil into account when a theoretical analysis of cold region canal is done. And only by doing so can the frost damage mechanisms of canals in cold regions be disclosed to the maximum extent.

The objective of this study is to explore frost damage mechanisms of a canal in cold region. Firstly, a numerical water-heat-mechanics model is set up based on the balance equations of energy and mass as well as momentum equation (Harlan, 1973; Jame and Norum, 1980; Li et al., 2014a; Taylor and Luthin, 1978). At the same time, a model test on the canal is done in one freezing–thawing cycle. Then, the test is taken as an example, and the water, temperature and mechanical states of the canal during the freezing–thawing process are simulated. At last, the frost damage mechanisms of the canal is explained and clarified by combining the model test and numerical simulation. From this study, the freezing–thawing process of the canal is clarified, and the easily frost damaged zone of the canal is also pointed out, which may provide a theoretical basis and reference for the design, maintenance and research of canals in cold regions.

2. Mathematical model and equations

The canal belongs to the thin–long engineering structure, and is a classical plane strain example (Davis and Selvadurai, 2002; Potts and Zdravkovic, 1999; Zienkiewicz and Taylor, 2009), so the mathematical model is established under a plane coordinate system.

2.1. Coupled water–heat transport model

During the process of heat transfer, the heat convection could be neglected (Jame and Norum, 1980), but water migration and ice–water phase change should be included in heat transport equation, which can be expressed as.

$$c\rho\frac{\partial T}{\partial t} = \mathbf{div}(\lambda \cdot \mathbf{grad}\,T) + L\rho_i\frac{\partial \theta_i}{\partial t} \tag{1}$$

where **div** and **grad** are divergence and gradient operators, respectively; T is temperature; c represents specific heat capacity; λ denotes thermal conductivity; ρ and ρ_i are soil and ice densities, respectively; t represents time; L is the specific latent heat; and θ_i denotes volumetric ice content. The last term, $L\rho_i\frac{\partial\theta_i}{\partial t}$, is equal to 0 in the unfrozen zone.

The boundary conditions are as the follows:

1)

$$S_1 : T = \overline{T} \tag{2}$$

2)

$$S_2 : \lambda\mathbf{grad}T \cdot \mathbf{n} = q_T \tag{3}$$

3)

$$S_3 : \lambda\mathbf{grad}T \cdot \mathbf{n} = h(T_a - T) \tag{4}$$

where $\mathbf{n}$ is outward normal to the surface, $\mathbf{n} = n_x i + n_y j$; q_T denotes heat flux; h is convection coefficient; and T_a represents ambient temperature.