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A separate-ice based solution for frost heaving-induced pressure during coupled thermal-hydro-mechanical processes in freezing soils

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ABSTRACT

A frost heaving-induced pressure (FHIP) solution is developed in this paper based on the proposed separate-ice frost heave model. A coupled thermal-hydro-mechanical (THM) model, describing the growth of a single ice lens under the restraint, is firstly constructed by considering the relationship between soil porosity and effective stress. The new ice lens formation criterion indicates that the formation of a new ice lens occurs when the disjoining pressure at the ice-water interface exceeds the summation of the external pressure and the critical pressure of soil strength. With consideration of the influence of the external pressure on the deformation of unfrozen soil, equivalent water pressure and critical separation pressure for ice segregation, the FHIP model is established by combining the growth model of a single ice lens and the formation criterion of new ice lenses. The freezing tests of Xuzhou (China) silty clay under different restraints were conducted to verify our numerical results, and the observed consistency thus validates the FHIP model. Our numerical results demonstrate the stress induced deformation of the soil column and indicate that the FHIP increases with the restrained stiffness. Particularly, with the decrease of the restrained stiffness, the FHIP decreases following an exponential function. The prediction of the FHIP using the proposed method improves our understanding of the characterized behavior of the FHIP under various restraints, and thus contributes to the analysis of the coupled thermal-hydro-mechanical processes in freezing soils.

1. Introduction

Owing to the physical characteristics of soil, freezing leads to the frost heave of strata, which results in frost heaving-induced pressure (FHIP) and thus the occurrence of many geotechnical hazards in cold regions (Ma et al., 2000; Palmer and Williams, 2003). The phenomenon of frost heaving is mainly caused by moisture migration under both a hydraulic gradient and a thermal gradient, and the FHIP is derived from the restrained structure when frost heave occurs (Yong and Osler, 1971; Wang et al., 2009). From the view of engineering applications, the prediction of the FHIP is of potential significance for the stability assessment of artificial freezing and cold regions engineering. In the literature, scholars have applied the intermittent freezing method to reduce frost heave, and corresponding mechanisms and theories have been revealed by analyzing the growth of the ice lens (Zhou et al., 2012; Zhou and Zhou, 2012). However, the research on frost heave, the growth of ice lenses, and the FHIP during freezing under various restrained stiffness is insufficient (Lai et al., 2000). Konrad and Morgenstern (1982) have conducted experimental and theoretical research on frost heave under the constant applied pressure. However, the interaction between the frost heave and the FHIP under a restraint is a more common scenario in freezing engineering. Fig. 1 shows the schematic of a typical artificial freezing engineering profile and the FHIP on the shaft lining. The FHIP is induced at the soil-structure interface due to the inhibiting effect of the shaft lining on frost heave, i.e. restraint. It can be found that the different restrained stiffness of the shaft lining will cause different results of the FHIP during freezing. Therefore, it is important to predict the FHIP and to conduct sensitivity analysis of the FHIP under different restrained stiffnesses. This paper attempts to study the interaction between frost heave and the FHIP, and to explore the possibility of a new FHIP mechanism that was not considered during the design and construction of freezing engineering.

Freezing of a moist soil is a process that couples thermal-hydro transfer (Sheng et al., 1995a, 1995b; Lai et al., 2017). Studies on the frost heave model are the theoretical basis for the prediction of the FHIP. Generally, mathematical models for dealing with the freezing process can be classified into three categories: the physical field model, the growth model of a single ice lens, and the mechanistic frost heave

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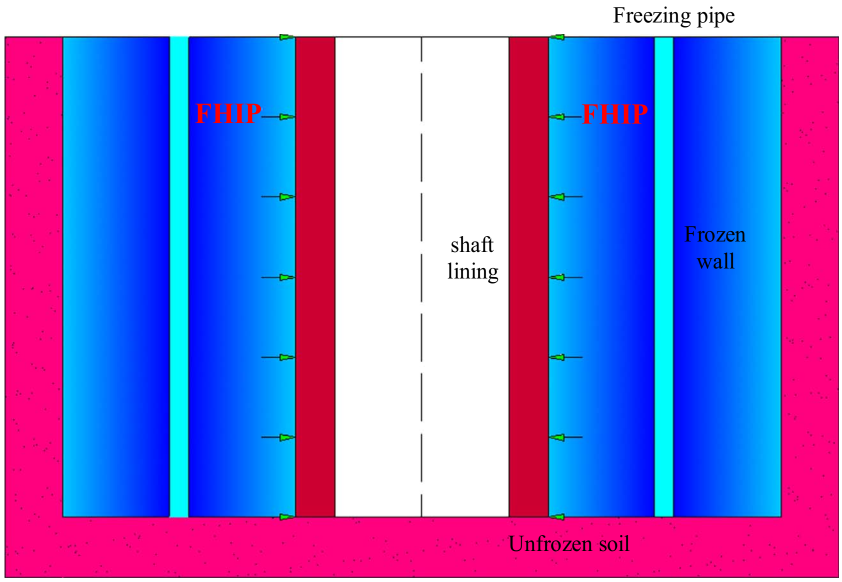

Fig. 1. Schematic of artificial freezing engineering and the mechanism of the FHIP under restrained conditions.

model. The physical models focus on the description of temperature field, moisture field, and stress field during soil freezing. However the development of the ice lens is usually not considered (Harlan, 1973; Shen and Branko, 1987; Fremond and Mikkola, 1991; Zhang et al., 2016). The growth model of a single ice lens can be mathematically described; however, the new ice lens forming in the frozen fringe cannot (Woster and Wettlaufer, 1999). The typical models include the segregation potential model (Konrad and Morgenstern, 1982; Konrad, 2005; Tiedje and Guo, 2012) and the coupled thermal-hydro model describing the growth of a single ice lens (Zhou and Zhou, 2012). The mechanistic frost heave model can describe the repeated process for growth of the active ice lens and the formation of new ice lenses (Gilpin, 1980; O'Neil and Miller, 1985; Nixon, 1991; Bronfenbrener and Bronfenbrener, 2010; Sheng et al., 2013; Wu et al., 2015). Although many models have been developed in recent decades, the study concerning the mechanism for the movement of unfrozen water is insufficient, and the definition for driving force that governs the movement of unfrozen water is not strict. Zhou and Zhou (2012) introduced a new concept of equivalent water pressure, which dominates the movement of the unfrozen water. In this paper, the prediction of the FHIP and the sensitivity analysis of the FHIP based on the separate-ice frost heave model are carried out. The separate ice model consists of two parts: one part is the coupled THM model describing the growth of a single ice lens, and it can be seen as an extension of the thermal-hydro model reported by Zhou and Zhou (2012). The other part is the segregation criterion for the formation of new ice lenses in the frozen fringe.

As the ice lenses grow, the FHIP increases with the frost heaving under the constraint. Although frost heaving and the FHIP are both well-known and well documented in geotechnical literature, their interaction has not previously been considered. The influence of the FHIP on frost heave governing equations is investigated in this paper to reflect their interactions, and in an attempt to find a solution for the FHIP. Firstly, the moisture flow velocity is dominated by the equivalent water pressure, and the FHIP has an inevitable effect on the equivalent water pressure at the warm end of the ice lens, which results in variation of the moisture flow velocity. The FHIP on soil column can lead to the consolidation of the unfrozen soil. The FHIP can also prevent frost heave by impeding formation of the ice lenses, it is a key aspect to determine where and when new ice lens emerges under the FHIP. Therefore, the new ice lens formation criterion indicates that the formation of a new ice lens occurs when the disjoining pressure at the ice-water interface exceeds the summation of the FHIP and the critical pressure of soil strength. By taking the above effects of FHIP have on the frost heave governing equations, the FHIP model is then established.

In this paper, a one-dimensional FHIP apparatus is developed, and freezing tests of silty clay in an open system with water supply (no-pressure) are implemented. An elastic restraint is employed at the top of the soil column. The elastic restraint is deformed with frost heaving, resulting in the FHIP at the soil-restraint interface. The authors investigate the interaction of these two phenomena of frost heave and the FHIP, and in an attempt to make a prediction of the FHIP under various restraints. The FHIP model also provides an insight into the development mechanism of the FHIP. Additionally, the numerical research on frost heave and the FHIP under a free boundary and restraints with different restrained stiffnesses are carried out. Following the presented results, the relationship between the FHIP and the frost heave ratio has been explored by the numerical method.

2. Frost heaving-induced pressure model

2.1. Equivalent water pressure

Gilpin (1979) proposed a theory for the characterized behavior of water at a solid-liquid interface, and it provided a physical understanding of frost heaving. The theory was applied to calculate the frost heave by some researchers, which led to good agreement with the observations (Zhou and Zhou, 2012; Cao et al., 2007). The most important assumption of the theory is that the water near the solid-liquid interface experiences a force of attraction acting toward the solid. Many of the phenomena that occur when ice is in contact with a substrate follow directly from this assumption. Zhou and Zhou (2012) adopted Gilpin's theory and defined a new concept of equivalent water pressure:

$$P = P_0 + P_{Lh} - P_{atm} - \frac{g(h)}{v_w} \tag{1}$$

where P_{Lh} is the disjoining pressure at the ice-water interface, $g(\cdot)$ is the effect of the solid surface, h is the thickness of the liquid layer, v_w is specific volume of the liquid. In Gilpin's theory, the reference pressure P_0 applied for frozen zone is 1 atm, while for the unfrozen zone, the reference pressure is pressure of the local bulk water. P_{atm} = 1atm is chosen for both the unfrozen zone and the frozen zone. From Eq. (1), it can be seen the equivalent water pressure is the relative pressure of local bulk water in the unfrozen zone, while the equivalent water pressure in the frozen zone is determined by P_{Lh} and h. It can be pointed out that the water flow can be seen as the Darcy flow in the active zone