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A unified model for frost heave pressure in the rock with a penny-shaped fracture during freezing

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ABSTRACT

In order to investigate the mechanisms of rock deterioration at low temperature, a unified model for frost heave pressure in the rock with a penny-shaped fracture during freezing was proposed, in which the main influencing factors can be classified into four groups: 1) the mechanical properties of ice and rock (E_i, υ_i, E_s and υ_s); 2) the external loading conditions (q and λ); 3) shape characteristic of the fracture (η); and 4) effective volume expansion coefficient (β_e). The model attempts to unify the volume expansion theory, water immigration theory and combination theory. Validation was carried out, and the comparisons indicated that the proposed model can accurately reflect the variation of the frost heave pressure. Parametric sensitivity analyses were performed to examine the effect of various parameters and to improve the understanding of the damage of fractured rock mass subjected to frost heave. The results showed that β_e is the most important parameter that affects the magnitude of frost heave pressure, apart from it, the mechanical properties of ice (E_i and υ_i) are also crucial, and then is the parameters of E_s, q and η. Relatively speaking, υ_s and λ have little influence. Besides, some discussions were given to the newly defined variableβ_e, which is a crucial parameter that can unite the three existing frost heave mechanics of rock.

1. Introduction

Rock or stone, as a natural substance formed in a geological process, is one of the most common substances on the earth's surface. With the development of human economic activities, more and more geotechnical engineering structures are being constructed in cold regions. The deterioration of rock under frost heave and freezing-thawing (FT) cycles has become an unavoidable concern in engineerings such as road, railroad, bridge, tunneling, pipeline, and building constructions (Matsuoka and Murton, 2008; Harris et al., 2009; Krautblatter et al., 2013; Tan et al., 2011a,b). Since 1916, scientists have been actively working in this field for a century (Taber, 1916; Arosio Bayram, 2012; Al-Omari et al., 2015; Feuer and Ince, 2015; Jamshidi et al., 2016; Ni et al., 2017). Nevertheless, the mechanisms of rock deterioration at low temperature and freeze-thaw cycle environment are still not well understood. Fortunately, one main factor is clear now, that is, frost heave pressure causing by water/ice phase change or water flux in the pores/fractures of rock during freezing are considered as the main reason of rock deterioration (Ondrášik and Kopecký, 2014; Mu et al., 2017; Jia et al., 2017; Wang and Zhou, 2018). Therefore, to prevent the structures from being damaged or destroyed by the low-temperature disasters, it is of great significance to study the characteristics of frost heave pressure in the pores/fractures of rock during freezing.

In order to obtain the magnitude of the frost heave pressure, the frost heave mechanisms of rock during freezing must be understood. Therefore, studies in this field are briefly introduced first. Generally speaking, the frost heave mechanisms of rock can be divided into three categories. The first one considered is that frost heave in freezing rocks is directly or indirectly related to the volume expansion during the water-ice phase change process when a saturated rock is placed in an environment of $< 0^\circ$C, the water in it will expand by approximately 9%. The expansion process either lead to a direct crystalline pressure developing through a hydraulic pressure generated by the expansion accompanying freezing water (Power, 1945), or the growth of bodies of ice crystals pressure (Davidson and Nye, 1985; Hori and Morihiro, 1998; Chen et al., 2004). The second one suggests that the damage of rock during freezing does not depend on this feature of water/ice phase change, but caused by the water immigration into the freezing front,

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although the researchers have not reached an agreement for the driving pressure due to water migration (Walder and Hallet, 1985; Murton et al., 2000, 2006; Tan et al., 2011a,b; Kang et al., 2013, 2014). Apart from these, advanced considerations were also made by assuming that a combination of both processes, i.e. volume expansion and water migration, could occur simultaneously, depending on the properties of the rock, cooling velocity, boundary conditions and so on (Tharp, 1987; Matsuoka, 1990; Vlahou and Worster, 2010; Vlahou, 2012). Based on these frost heave mechanisms, the frost heave pressure was widely studied., Power (1945) firstly proposed the expression of the maximum hydraulic pressure acted on rock *during freezing* according to hydraulic pressure theory. Mellor (1970) illustrated a potential linear freezing strain expression based on the theory that 9% volume increase will produce during the process of water completely freezes in a saturated closed system. As the frost heave damage of rock normally leads a tensional failure (e.g. Everett, 1961; Winkler, 1968; Mellor, 1970), the frost heave pressure originating from the volume expansion was given by Matsuoka (1990). Everett (1961) firstly proposed that water will migrate into the freezing fringe by the action of capillary suction during the process of temperature decreasing according to equilibrium thermodynamics, the expression of the capillary suction was given which produced by the pressure difference between ice and water. After that, researchers found that considerable water remains unfrozen at subfreezing temperatures in rocks (for example, Mellor, 1970; Dunn and Hudec, 1972; Fukuda, 1983). Correspondingly, several suction force models that cause water migration were proposed (Murton et al., 2006). Walder and Hallet (1985) presented a mathematical model for the breakdown of porous rock by the growth of ice within cracks, which quantitatively explored the effects of water migration in rocks at subfreezing temperatures. Recently, Kang et al. (2014) also proposed an equation to calculate the frost heave pressure according to the water immigration theory. Furthermore, an idealized problem of a sphere of ice growing symmetrically in a spherical cavity within a porous rock was studied by Vlahou and Worster (2010), they divided the freezing process into two stages. At the first stage, the water just begins to freeze in the pore, the ice radius is small compared with the size of the pores. Under this situation, the pressure inside the rock is mainly caused by the volume expansion, and the magnitude of the pressure depends mainly on the permeability of the rock. When the size of ice body is very close to the pore, the freezing moves into the second stage. They considered that there is a disjoining pressure existed to balance the pressure difference between the ice and the water, which was presented as the main reason for the damage the structure of rock, and a very complicated model based on van der Waals forces was deduced according to pre-melting dynamics (Vlahou, 2012).

In summary, the importance of frost heave pressure has been widely recognized, and many expressions or models were proposed. Besides, as Matsuoka and Murton (2008) noted that the migration of water towards the freezing interface is recognized as an important feature of frost heave in rock. However, most of existing literature focused on how and how much water freezes into ice in the pores/fracture, and its influence on frost heave pressure (for example: Mellor, 1970; Walder and Hallet, 1985; Matsuoka, 1990; Vlahou, 2012; Jia et al., 2017) with less attention paid to the other factors that affects the frost heave pressure such as the strength parameters of the rock and ice (Kang et al., 2014). Huang et al. (2018a,b) established an analytical frost heave pressure model for a single fracture, which took into account the moisture migration flux, the mechanical properties of the rock and ice. While their work neither took into account the effects of external loading conditions nor examined the effect of various parameters, therefore, further studies should be carried out.

In this paper, the idea of Huang et al. (2018a,b) was further explored. A preliminary model for frost heave pressure in the rock with a penny-shaped fracture during freezing will be presented first in Section 2. Then, validation was carried out by fitting the model with the results of Walder and Hallet (1985) (in Section 3). After that, a parametric sensitivity analysis of the factors is analyzed in detail in Section 4. Finally. Some discussions and conclusions were presented in Sections 5 and 6.

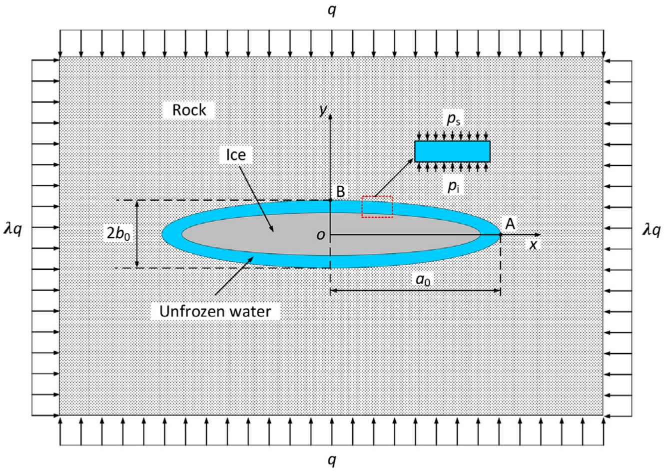

Fig. 1. Geometry and boundary conditions of the calculated model.
Note: a_0 and b_0 are the semi-major and semi-minor axes of the penny-shaped fracture, respectively; q is external pressure; λ is lateral pressure coefficient; $p_i$is frost heave pressure; p_s is the reaction pressure of the rock.

2. Frost heave pressure in the rock with a penny-shaped fracture

2.1. Basic assumptions

The geometry and boundary conditions of the theoretical model can be seen in Fig. 1, the following simplification and assumptions are introduced to facilitate the theoretical development:

(1) The frost heave was calculated within the within the scope of plain strain problem, and the rock mass is considered as an isotropic elastic medium.
(2) The fracture is water-saturated and the water supply in unfrozen zone is unlimited, and the compressibility of the water is ignored.
(3) The shape of fracture is maintained during freezing.
(4) Strain of the rock caused by gradient of the environmental temperature during freezing is ignored.

2.2. Model for frost heave pressure

2.2.1. Volume variation of the fracture under the action of water/ice phase change and p_s

It can be seen from the analysis of frost heave mechanism in Section 1 that, during the freezing process, a certain amount of water may flow into or out of the fracture, while a little part of the water will not freeze even at subzero temperature. Assuming the amount of water flowing into the fracture is Q, and the unfrozen water content isχ, the volume variation of the fracture in the process of water/ice phase change under unconstrained condition can be written as:

$$\Delta V = \beta (V_0 + Q)(1 - \chi) \tag{1}$$

where, ΔV the volume variation; β is the volume expansion coefficient of water/ice phase change under unconstrained condition; $\chi$is unfrozen freezing water content (%); Q is the volume of water flowing into the fracture which is affected by many factors, including freezing duration, freezing rate, freezing temperature, permeability of the rock, etc. V_0 is the initial volume of the fracture. For plane strain condition, V_0 can be rewritten as:

$$V_0 = \pi a_0 b_0 \tag{2}$$