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Transversely isotropic frost heave of saturated rock under unidirectional freezing condition and induced frost heaving force in cold region tunnels

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ABSTRACT

A series of freezing experiments has been conducted to investigate the frost heaving property of saturated rock under unidirectional freezing condition. Results show that the frost heave parallel to the freezing direction is considerably larger than that perpendicular to the freezing direction, and the frost heave is isotropic on the plane perpendicular to the freezing direction. Thus, the transversely isotropic frost heaving property of saturated rocks under unidirectional freezing condition is proposed, in which the plane perpendicular to the freezing direction is the plane of transverse isotropy and the line parallel to the freezing direction is the axis of transverse isotropy. In cold region tunnels, the inflow of cold air leads to the unidirectional freezing of the surrounding rock along the radial direction of tunnels. Hence, the frost heave of the surrounding rock is transversely isotropic during the freezing process. The cylindrical surface constituted by the circumferential and axial directions is the surface of transverse isotropy and the line along the radial direction is the axis of transverse isotropy. Furthermore, an analytical solution for frost heaving force in cold region tunnels is derived, in which an anisotropic frost heave coefficient k is used to consider the transversely isotropic frost heave of the surrounding rock. The calculated results of the solution are compared with in situ measured data to prove the reasonability of the solution. Finally, the solution is used to optimize the design of the thermal insulation layer of a cold region tunnel.

1. Introduction

In cold region tunnels, frost heaving force is one of the most critical challenges because it is a common cause of lining damage. Surveys conducted on cold region tunnels in northeastern Japan in the 1970s and 1980s indicates that frost heaving force is the main external force inducing the lining damage (Lai et al., 2000). In China, severe frost damage occurs in more than 70% of the cold region tunnels (Wu et al., 2003), and even some tunnels are closed for traffic for 8 to 9 months each year. Hence, frost heaving force calculation is a problem to be solved urgently. Two steps are required to solve the problem: (1) investigate the frost heaving property of the surrounding rock and (2) derive a practical solution for frost heaving force that considers the corresponding frost heaving property.

In cold region tunnels, the inflow of cold air results in the unidirectional freezing of the surrounding rock along the radial direction of the tunnels. Studies on the frost heaving property of soil under unidirectional freezing condition began much earlier than those on the frost heaving property of rock. Considerable experiments have shown that the frost heave of soil is anisotropic under unidirectional freezing condition in an open system. For example, Taber (1929, 1930) observed that the formation of ice lenses predominantly occurred in the direction of heat flow in unidirectional freezing experiments on saturated soil. Kanie et al. (2012) measured the frost heave rate of Fujinomori clay parallel and perpendicular to heat flow direction, respectively, and the results showed that frost heave rate in the freezing direction was larger. At present, a consensus for soil holds that ice lenses grow predominantly in the freezing direction, thereby resulting in anisotropic frost heave with a major frost heaving strain along the freezing direction under unidirectional freezing condition (Lai et al., 2014; Zhou et al., 2014).

Moreover, the anisotropic frost heave of the surrounding rock should be considered in calculating frost heaving force; however, this factor has been ignored in most current studies. Lai et al. (2000) proposed an analytical viscoelastic solution, whereas Gao et al. (2012) proposed an analytical elastoplastic solution for frost heaving force in cold region tunnels. Nonetheless, both solutions simplified frost heave as isotropic expansion. Only a few studies have considered the anisotropic frost heave of soil in analyzing the interaction between structures and freezing soil in numerical simulations. Parameters α_n and α_τ, which

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List of symbols

ε^{f}	Frost heaving strain
ε_{u}	Strain collected during the experiments
α_{c}	Thermal expansion coefficient of quartz
ΔT	Temperature variation in the quartz slice
$\varepsilon_{//}^{f}$, $\varepsilon_{\perp}^{f}$	Frost heaving strain parallel and perpendicular to the freezing direction
ε_{1}^{f}, ε_{2}^{f}, ε_{3}^{f}	Frost heaving strain components along coordinate axes 1, 2 and 3
ε_{V}^{f}	Volumetric strain caused by frost heave
ε_{r}^{f}, ε_{θ}^{f}	Frost heaving strain components in the radial and circumferential directions
k	Anisotropic frost heave coefficient defined in Eq. (4)
P_{b}, P_{c}	Frost heaving forces on the lining and the unfrozen surrounding rock
E	Elastic modulus
μ	Poisson's ratio
σ_{r}, σ_{θ}	Radial and circumferential stresses
ε_{r},ε_{θ}	Radial and circumferential strain
u_{r}	Radial displacement
r	Radius in radial direction
a	Inner radius of the lining (zone I)
b	Inner radius of the frozen surrounding rock (zone II)
c	Inner radius of the unfrozen surrounding rock (zone III)
C_{1}, C_{2}	Integral constants in Eq. (12)
Δ_{b}, Δ_{c}	Radial frost heaving displacement on the inner edge ($r = b$) and outer edge ($r = c$) of zone II
h_{f}	Freezing depth
Superscripts or subscripts I, II, III	Variables or properties associated with zones I, II, III, respectively

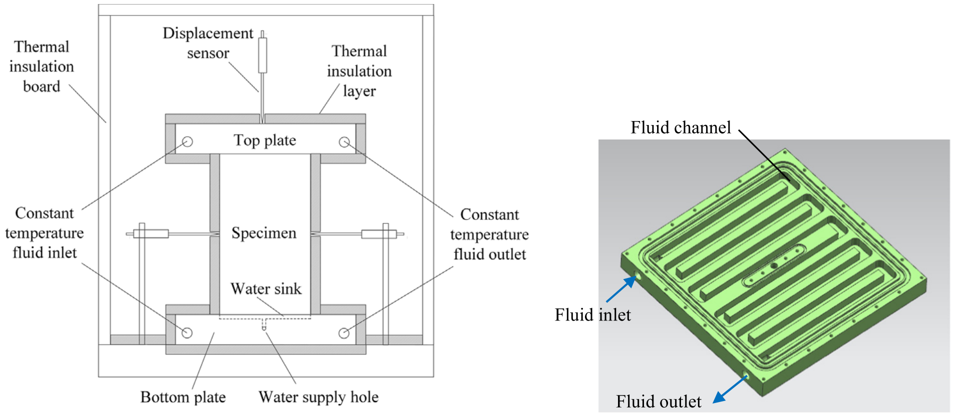
refer to the expansion coefficients in the directions parallel and perpendicular to the freezing direction, respectively, were used to denote anisotropic expansion strain under unidirectional freezing condition in solving 2D frost heave problems of soil (Konrad, 1994; Konrad and Shen, 1996). A dimensionless quantity ξ was used to distribute volume growth in an anisotropic manner in the frost heave model based on the porosity rate function (Michalowski, 1993; Michalowski and Zhu, 2006). A similar parameter was also used by Kim (2011), Kanie et al. (2012), Zheng and Kanie (2015), and Zheng et al. (2015) to consider the anisotropic characteristic in analyzing the frost heave of soil. Furthermore, Kanie et al. (2012) proposed equations to estimate the parameter.

The frost heaving properties of rock and soil are similar in certain aspects. Akagawa et al. (1988) observed ice lens growth in rocks during unidirectional freezing experiments in open systems and suggested that the segregation ice concept would be generally applicable to common rocks (Akagawa and Fukuda, 1991). Thus, the frost heaving property of rock is frequently analogized to soil for the lack of literatures on rock. However, the tensile strength of rocks, which prevents frost heave on itself, makes rock different from soil. For example, the initiation temperature of ice lens depends on the strength of rock (Nakamura et al., 2012). Therefore, in the present study, the anisotropic frost heave of rock under unidirectional freezing condition in closed and open systems is investigated by conducting systematic experiments on rock. Additionally, the anisotropic behavior in the frost heave of rock is proved to be transverse isotropy, which is a particular case of anisotropy. Then, an analytical solution for frost heaving force in cold region tunnels is derived. In the solution, an anisotropic frost heave coefficient k is used to consider the transversely isotropic frost heave of the surrounding rock. The solution is proved to be reasonable because the results of the solution are close to the in situ measured data. Finally, the analytical solution is used to optimize the design of a cold region tunnel.

2. Experiment design

Unidirectional freezing experiments in closed and open systems are performed using the self-designed equipment shown in Fig. 1. Antifreeze fluid with a constant temperature circulates separately through the top and bottom plates, and the temperature of the plates are controlled via cryostats, which can be set from −50 °C to 90 °C with an accuracy of ± 0.1 °C. The controlled temperatures of the top and bottom plates are maintained unchanged during one experiment. The manner in which the fluid circulates in the top plate, which is similar to that in the bottom plate, is shown in Fig. 1(b). Moreover, the top and bottom plates are made of aluminum alloy with excellent thermal conductivity, which ensures the evenly distributed heat on the plates. Besides, the thermal insulation board is made of tempered glasses.

Ten experiment conditions are listed in Table 1, in which the experiments under conditions VII to X are comparative experiments. Experiments are conducted on mortar in conditions VII to IX and on sandstone in other conditions. The temperature of the bottom plate is +1 °C. The physical and mechanical properties of sandstone and mortar are listed in Table 2. The designed strength grade of mortar is M5, and the mix ratio of cement, river sand and water is 1.0:6.9:1.5 according to the Chinese Specification for Mix Proportion Design of Masonry Mortar (JGJT 98-2010). The dimensions of the sandstone and mortar



(a) Schematic of the experiment equipment (b) Design of the top plate

Fig. 1. Equipment used in the unidirectional freezing experiments.