Frost heaving damage mechanism of fractured rock masses: Main research progress and prospects for international frontiers

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Abstract. The frost heaving damage mechanism of fractured rock masses (FRM) is the basis of theoretical research related to rock mechanics in cold regions, and it is also an important factor that must be considered in the investigation, design, construction, and operation and maintenance stages of cold-region rock engineering projects. Despite the great achievements made by scholars worldwide regarding this aspect, it still faces many difficulties and challenges. This paper firstly briefly reviews the development history of research on low-temperature FRM, and clarifies the differences and connections between them and soil and porous media rocks in terms of frost heaving damage mechanism. The progress of research on the frost heaving damage mechanism of FRM is introduced from four aspects of theoretical studies, laboratory experiments, field tests, and numerical simulations. The hotspots and difficulties in the study of FRM under conditions of low temperature and freeze-thaw cycle are summarized, including theoretical solution method of frost heaving force, migration law of water in the fracture and matrix, and crack expansion law, and numerical simulation method, etc. Finally, an outlook on the future development directions of this field is provided, with emphasis on the importance of the investigation on ice-rock properties, water migration, etc., to improve the existing research results and further expand future research directions.

Keywords: Cold regions; Fractured rock masses; Water migration; Water-ice phase transition; Frost heaving force.

1. Introduction

Geology defines frozen soil as a variety of rocks and soils containing ice below 0°C, which can be classified as short-term (hours to half a month), seasonal (half a month to several months), and permafrost frozen soils (lasts for two or more years). According to statistics, the area of frozen soil on Earth accounts for about 50% of the land area (about 74.45 million km^2), of which the area of permafrost frozen soil accounts for about 20 to 25% (about 35 million km^2), and it is mainly distributed in the northern part of Europe and Asia, the North America, the shallow continental shelves of the Arctic Ocean, and so on. China ranks third in the world in terms of the area of frozen soil. The area of permafrost frozen soil accounts for about 22.83% of the country's land area (about 2.19 million km^2), which is mainly distributed in the Qinghai-Tibetan Plateau, the Daxing'anling and Xiaoxing'anling regions, the Altai Mountains, the Tianshan Mountains, the Qilian Mountains, the Himalayas, and other mountainous regions. The area of seasonal frozen soil accounts for about 49.6% (about 4.76 million km^2) of the country's land area. The area of transient frozen soil is about 1.86×10^6 km^2, accounting for 19.33% of the country's land area. In other words, about 96.2% of the country's land is covered by different types of frozen soils[1].

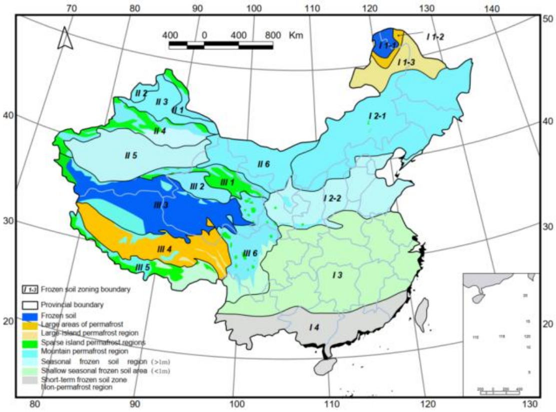

Fig. 1 1:10 million frozen soil regionalization and type distribution map of China

Human activities in the early period were mainly concentrated in warm areas or low-altitude plains, so there was less awareness of frozen soils. However, with the enhancement of human's ability to transform nature and the increase in demands for natural resources, people have gradually turned their attention to high-altitude mountainous areas and cold polar regions. Accordingly, researchers have gradually shifted from an early focus on the physical and mechanical properties, disaster mechanisms, and prevention and control measures of soils under freezing and freeze-thaw cycle environments, to an emphasis on the problem of frost heaving damage of cold-region rock masses in high-altitude mountainous areas.

This paper firstly briefly reviews the development history of research on low-temperature FRM, and clarifies the differences and connections between them and soil and porous media rocks in terms of frost heaving damage mechanism. The progress of research on the frost heaving damage mechanism of FRM is introduced from four aspects of theoretical studies, laboratory experiments, field tests, and numerical simulations. The hotspots and difficulties in the study of FRM under the conditions of low temperature and freeze-thaw cycle are further summarized. Finally, the future development directions of this field are outlined.

2. Development history of research on FRM in cold regions

The study of frost heaving of rock and soil masses in cold regions originated from the research of soils. First of all, the research history of cold-region soil mediums is briefly summarized. In the 19th century, the UK and the Soviet Union began to study the deep artificial ground freezing technique, which marked the beginning of the research on soil freezing. In the following 30 years, in-situ frost heaving theory[2], adsorption-film theory, capillary theory[3], and hydrodynamic model have been successively put forward[4]. The research on the soil frost heaving theory reached the climax around 1980, during which the rigid ice theory[5], the segregation potential theory[6], the Takashi model[7], the porosity model[8], and the thermo-hydro-mechanical coupled model were proposed[9]. The rigid ice theory and the segregation potential theory have been given special attention and greatly developed. Although Loch and Kay verified the rigid ice theory proposed by Miller, it was still questioned. A group of scholars, such as Gilpin[10], proposed an improved rigid ice theory by making simplifications, whose correctness was verified by designed experiments. Also, they developed an analysis software that can predict the actual frost heaving[11]. Numerical computation has been greatly developed after 2000, and some complex models such as the thermo-hydro migration coupled model[12], the thermo-hydro-mechanical coupled model[13], the elasto-plasticity model[14], and separation ice model were proposed[15].

The study of frozen rocks often follows the theories related to frozen soils. For example, the segregation potential theory was borrowed from the soil theory to explain the frost heaving behavior of limestone, and its application in rocks was formally completed until 1970. During the same period, there were also the capillary theory[16] and the osmotic pressure theory[17]. More complex ones such as the crystallization pressure theory[18], the micro ice crystal theory[19], and the pore medium mechanics theory[20] have been developed and verified by numerical means after 2000.

Before the 21st century, the influence of pore features of rocks on the frost heaving behavior of rocks was not recognized. Therefore, the early theories of rock frost heaving did not distinguish their applicability in terms of rock types. The study of rocks in the 21st century revealed that rocks could be classified into two categories according to their pore features. One is the rock with high porosity and good connectivity, which is called "porous medium rock" (e.g., sandstone, shale). The other one is the rock with low porosity and poor connectivity, but the interior of the rock is often cut by the developed joints and fractures, which is called "fractured rock mass" (e.g., marble, granite). In the early period, the distinction of the applicability of the various theories was not sufficiently established, leading to the misapplication of many of them.

After 2000, it is recognized that FRM were different from porous medium rocks, and there has been a great explosion of research on the frost heaving theory of FRM. For example, the early volume expansion theory was confirmed by scholars in field observations of frost heaving damage of FRM. Observations[21-22] of frost heaving in Alps and in high and steep cliffs of Japan confirmed the segregation mechanism as the main driving force for the fracture expansion of rock masses and the bedrock erosion. The theoretical study of FRM has benefited from the improvement of numerical computation capability, and a large number of numerical validations on the newly developed hybrid frost heaving theory have been conducted. According to the different assumed shapes of fractures, the hybrid frost heaving theory can be categorized as the spherical fracture model[23], the elliptical fracture model[24], the cylindrical fracture model[25], and the ice wedge model[26]. There is also the fatigue stress theory which equates the freeze-thaw cycle to fatigue stress and the uniform frost heaving theory[27]. It should be noted that the hybrid frost heaving theory has many difficulties in numerical computations due to the relatively large number of factors to be considered. At present, the current applications of the theory are based on simplified computations, and the development of the theory still needs to move forward over time and with the enhancement of the computational power.

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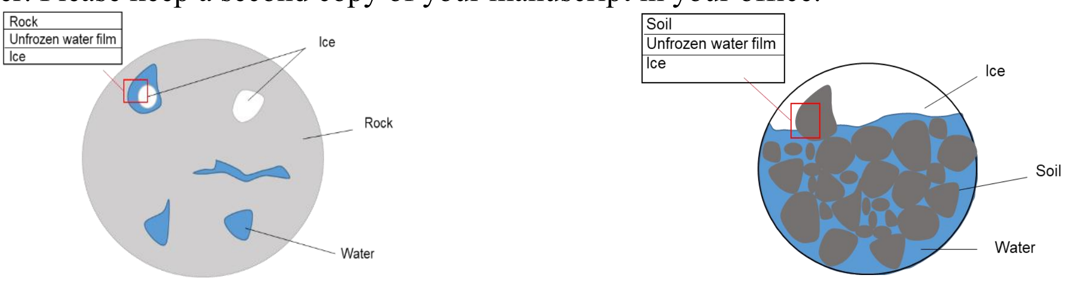


Fig. 2 Water-ice-soil matrix and water-ice-rock matrix

3. Progress of research on frost heaving damage mechanism of FRM

3.1 Frost heaving damage theories of FRM

Different from porous medium rocks, the frost heaving damage of FRM has a large spatial scale, which is manifested as the expansion of fractures driven by the frost heaving force. Currently, the damage theories for FRM mainly include the volume expansion theory and the segregation potential theory related to the space of fracture, the hybrid frost heaving theory related to the assumption of pore shape, and the non-uniform frost heaving theory.

3.1.1 Volume expansion theory

In the 20th century, scholars[2] found that water expands by 9% in volume during freezing, which generates a large force in a confined space. Later, it was used to explain the frost heaving damage of rocks, based on which the theory of frost heaving force was deduced[28]. Everett[16] and Mellor[29] deduced the frost heaving strain of saturated rocks under different elastic constraints of rock to ice. Winkler[30] et al. considered that the essence of frost heaving damage was tensile damage, and deduced the frost heaving force Fv as[31]:

$$F_v = \varepsilon_{pl} E_t = 0.03 n E_t \qquad (3)$$

where E_t is the elastic modulus.

Two conditions are required for the generation of frost heaving force: ①a confined space that provides sufficient constraints, and ②the saturation of the space should be greater than 91%[26]. It is difficult to satisfy these two conditions under natural conditions, so the measured value of frost heaving force is usually lower than the theoretical value[32]. According to the above conditions, there is a contradiction between the provision of confined space inside the rock and the saturation degree of the space greater than 91%, i.e., if the pore space inside the rock is confined, the water absorption is poor, and the saturation degree cannot be very high.

3.1.2 Volume expansion theory

The conditions that need to be satisfied for the application of the segregation potential theory[33]are: ①low freezing rate and long freezing time; ②sufficient migration of unfrozen water to the ice lens during the freezing process; and ③easy freezing of rocks[26]. Walder[34] et al. established a theoretical model of ice segregation of rock masses based on the research results of soil frost heaving by Gilpin[10], as illustrated in Fig. 3. It was assumed that the strength and stiffness of rock was infinite and finite, respectively, and the evolution law of the frost heaving force was obtained as[35]:

$$p_i(t) = \frac{L(-T_c)}{v_S T_a}\left(1 - e^{-\frac{t}{\tau}}\right) + p_0 e^{-\frac{t}{\tau}} \qquad (4)$$

where p_0 is the initial ice pressure in the fracture; τ is the characteristic time, which can be expressed as:

$$\tau = \left(\frac{8}{3\pi}\right)\left(\frac{1-\nu}{\mu}\right)\left(\frac{g c v_L}{v_s}\right) R_f \qquad (5)$$

where p_i is the ice pressure; v_L is the specific volume of water; v_S is the specific volume of ice; R_f is the resistance to flow of water; ν and μ are the Poisson's ratio and shear modulus of rock, respectively; c is the geometric dimension of fracture; g is the gravitational acceleration; L is the latent heat of ice; T_a is the absolute temperature; and T_c is the temperature of fracture wall relative to the freezing temperature of ice.

The calculation results of Walder demonstrated that frost heaving damage was most intense when rock temperature was maintained at -4°C to -15°C. It could be inferred from this theory that frost heaving damage did not depend on the volume expansion of initial water freezing. Hallet[35] et al. verified the correctness of Walder's theory by detecting the freezing process in FRM via the acoustic emission technique. FRM are generally surrounded by porous rocks, while the fractures provide good water conveyance channels. Increasing the saturation of porous rocks before frost heaving favors the occurrence of the segregation potential mechanism.

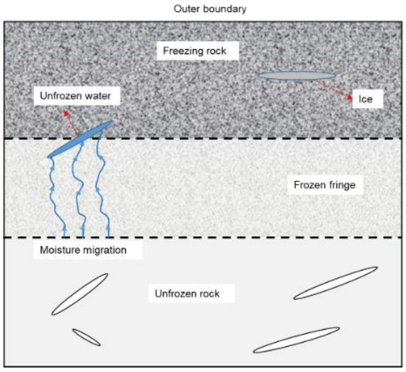


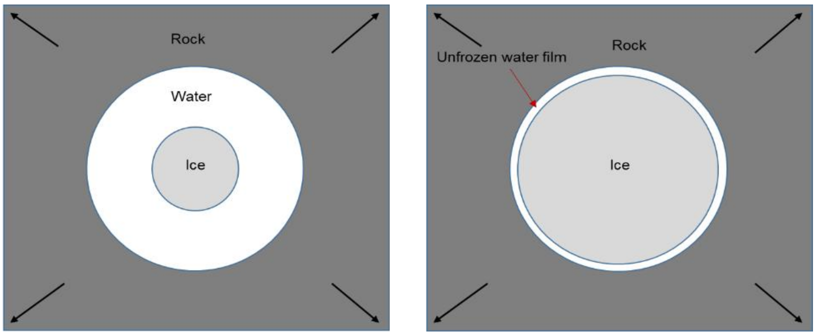
Fig. 3 Walder Segregation potential theory

3.1.3 Volume expansion theory

The hybrid frost heaving theory points out that the frost heaving of rocks depends on the freezing rate of fracture water and the boundary conditions of rocks, etc., and that the frost heaving mechanism cannot be scientifically explained by a single frost heaving theory. The hybrid frost heaving theory mainly assumes that the shape of fracture is spherical, elliptical, cylindrical, and wedge-shaped.

(1) Spherical fracture model

Vlahou[23] et al. assumed the rock fracture as a sphere, and analyzed the evolution mechanism of frost heaving force in different freezing stages by dividing the freezing damage into two stages. Based on the circular fracture assumption, the theoretical solution of frost heaving force for low-permeability rock masses was derived[36].



Schematic diagram of the initial freezing period Schematic diagram of late freezing

Fig. 4 Vlahou 's theoretical diagram of segregation potential

The solution of frost heaving force at the early stage of freezing is:

$$p_l = \begin{cases} \frac{\mu\Delta\rho}{\Pi\rho_l}\frac{a^2\dot{a}}{r}(r > R) \\ \frac{\mu\Delta\rho}{\Pi\rho_l}\frac{a^2\dot{a}}{R}(r < R) \end{cases} \tag{6}$$

where p_l is the water pressure in the pore; μ is the dynamic viscosity of water; a is the radius of ice body; $\dot{a}$ is the growth rate of ice body; Π is the permeability of rock.

The expansion mechanism produces a relatively large frost heaving force only when $R \geq 1cm$ and $\Pi=10^{-14}\text{-}10^{-15}cm^2$. To balance the pressure difference between water, ice, and rock in the late stage of freezing, the unfrozen water film generates a separation pressure. The maximum frost heaving force in the second stage is obtained as:

$$p\frac{\rho_s\rho_l L\Delta T}{\Delta\rho T_m}\frac{R}{1+K_{max}} \tag{7}$$

The analytical solution of frost heaving force in circular fracture under water migration condition is derived as[24]:

$$P_f = \frac{L(T_c - T_a)}{(\frac{1}{\rho_i} - \frac{1}{\rho_w})T_a}\frac{R_h}{1+k_r} \tag{8}$$

(2) Elliptical fracture heaving force theory

Afterwards, scholars proposed the elliptical fracture model to analyze the effect of water-filled fracture on the frost heaving damage of rock masses. The expression for frost heaving force of the elliptical fracture is derived by combining the volume expansion theory and the water migration theory[36]:

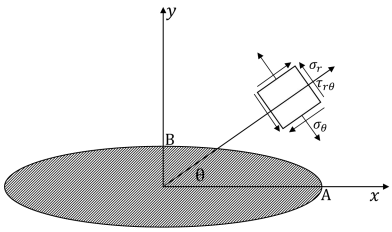


Fig. 5 Calculation model of crack cross-section tip stress field

$$p_f = \frac{k_i - 1}{\frac{k_i}{K_i^T} + \left(\frac{a}{b} - \frac{1 - \nu_s^T}{2}\right)\frac{1}{G_s^T\left(1 + \nu_s^T\right)}} \tag{9}$$

where $k_i = (1 + \beta u^T)(1 - \xi)$ is the volume expansion coefficient of fracture water considering water migration; $K_i^T = \frac{E_i^T}{3(1 - 2\nu_i^T)}$ is the volume modulus of ice; *a* and *b* are the geometric parameters of elliptical fracture; ξ is the water migration flux; β is the volume expansion coefficient of water-ice phase transition in free state; G_s^T is the shear modulus of rock; ν_s^T is the Poisson's ratio of rock.

Eq. (9) confirms that the frost heaving force is related to the geometrical parameters of the fracture, the water migration flux, the mechanical properties of rock and ice, the freezing temperature, and the freezing rate[36]. Based on the above study, Kang[37] concluded that the frost heaving force could only form an ice plug and limit the unfrozen water migration in the fast-closing fracture, and derived the maximum frost heaving force in the tip of the fracture at this moment:

$$P = \frac{V_{wi}}{V_{wi}^0}{}_{i_{imax}} \tag{10}$$

Also, the effect of temperature stress on the deformation of the elliptical fracture was considered, and the analytical equation of frost heaving force under low-temperature thermo-mechanical coupling was deduced[38]:

$$p_f = \frac{1}{\frac{1}{E_e} + \frac{k_i}{K_i}}\left(k_i - 1 + \frac{\sigma_\beta^T}{E_e}\right) \tag{11}$$

where $k_i = \frac{\rho_w}{\rho_i}(1 - \xi)$ is the effective volume expansion coefficient considering water migration; E_e is the equivalent elastic modulus considering mechanical properties and pore geometric parameters of rock, $E_e = \frac{E_s}{\left[2\left(\chi + \frac{1}{\chi + v_s - 1}\right)\right]}$, where $\chi = \frac{b}{a}$; σ_β^T is the temperature stress acting on the surface of fracture, $\sigma_\beta^T = \frac{2G_s}{2G_s + \lambda_s}\frac{\alpha_s^T E_s \Delta T}{1 - 2v_s} sin^2\beta$, where α_s^T is the linear thermal expansion coefficient and β is the dip angle of fracture.

Huang[38] proposed the solution of frost heaving force by using the experimental parameters of Bost and Pouya, which was then verified by Tao.

$$p_f = \frac{13.32\left(1 - e^{-1.0824t}\right)}{2.1312 + 0.0133\left(1 - e^{-1.10824t}\right)} \tag{12}$$

(3) Cylindrical fracture model

Liu[25] et al. assumed that the fracture was cylindrical and deduced the frost heaving forces with and without considering water migration. The equation of frost heaving force without considering water migration was expressed as:

$$\lambda_s^2 p_i^2 + [2\lambda_s + (1 + \alpha)\beta\gamma\lambda_i]p_i - (1 + \alpha\beta)\gamma + 1 = 0 \tag{13}$$

where $\lambda_s = (1 + \mu_s)/E_s$、$\lambda_i = 2(1 + \mu_i)(2\mu_i - 1)/E_i$; μ_s and μ_i are the Poisson's ratios of rock and ice; E_s and E_i are the elastic moduli of rock and ice; p_i is the frost heaving force; α is the volume expansion coefficient of water-ice phase transition at one atmosphere; β is the freezing rate of fracture water; γ is the saturation degree of fracture.

When $p_i > 0$, then $\gamma > 91.7\%$, which is essentially to derive the frost heaving force of cylindrical fracture rock using the volume expansion theory. When considering water migration, the theoretical expression for the frost heaving force of cylindrical fracture cracking at the hydraulic pressure driven stage is obtained as:

$$\bar{p}_1 = -\frac{\mu}{k}\left\{\frac{\Delta\rho}{\rho_1\rho_i}\frac{\lambda_T^1}{\vartheta}\left[-\Delta T + \frac{\Delta\rho}{\rho_1\rho_i\vartheta}p_1 T_m\right] - (1-\phi)RR\ln\frac{R}{R_1}\right\} \quad (14)$$

where,

$$R = \left(\frac{1}{2G}p_1 + 1\right)R_0 \quad (15)$$

It can be seen from Eq. (14) that the frost heaving force is linearly inversely correlated with the permeability, indicating that the formation of frost heaving force in the FRM requires a low permeability condition.

After the completion of phase transition, the ice-rock interface still exists nanoscale unfrozen water film. The unfrozen water film is simultaneously subject to the curvature and interfacial melting, and the interfacial separation pressure at interfacial prethawing stage is[39]:

$$\rho_i\vartheta\frac{T_m - T^1}{T_m} = (p_1 - p_m)\frac{\Delta\rho}{\rho_1} + \rho_T(h) + \gamma_{i1}k \quad (16)$$

Separation pressure is a function of unfrozen water film[40]:

$$P_T = -\frac{A}{6\pi h^3} \quad (17)$$

where $\bar{P}_1$ is the freezing water pressure; μ is the fluid viscosity coefficient; k is the rock permeability; ρ_1 and ρ_i are the densities of water and ice, $\Delta\rho = \rho_1 - \rho_i$; ϑ is the phase transition; λ_T^1 is the thermal conductivity of unfrozen water; $\Delta T = T_m - T_f$ is the difference between the freezing temperature of volumetric water and the freezing temperature at far field; Tm is the freezing temperature of water at the hydrostatic pressure; φ is the permeability of rock; R is the pore radius after expansion; R_1 is the location of boundary far away from the center of the fracture ; G is the shear modulus of rock; R_0 is the initial radius of the pore; p_T is the separation pressure; γ_{i1} is the free energy at the ice-water interface; K is the curvature of the water-ice interface; h is the thickness of the unfrozen water film; and T^1 is the temperature at the water-ice interface.

(4) Ice wedge frost heaving theory

Jia[26] et al. considered that the frost heaving problem of FRM under freeze-thaw action was essentially the ice wedge damage under volume expansion, and that the mechanism was stress corrosion cracking[36]. With use of the ice wedge model, the theoretical solution of frost heaving force of open fractures in low-permeability rocks was deduced by combining the volume expansion theory and the cantilever beam theory[41]:

$$p_f = \frac{24E_s I \times W_A}{b^3(4l-b)} \quad (18)$$

where E_s is the elastic modulus of rock; I is the moment of inertia of rock beam; W_A is the deflection at the point, which is equal to the opening of the fracture; b is the length of ice-rock contact surface; and l is the length of the fracture.

(5) Other theories

At present, there are fewer studies on the frost heaving theory under freeze-thaw cycles. Scholars considered that the magnitude of frost heaving force was independent of the number of freeze-thaw cycles, The single frost heaving theory or the number of freeze-thaw cycles as fatigue stress was still employed in the research. Some other scholars believed that the frost heaving force was related to the number of freeze-thaw cycles, and they derived the equation for the frost heaving force[27]:

$$P_i = \frac{k_i - 1}{\frac{k_i}{k_i^T} + \left(\frac{a_i c}{b_i^2} - \frac{1-v_j^T}{2}\right)\frac{1}{E_j^T(1+v_j^T)}} \quad (19)$$

where $k_i = (1+\lambda)(1-\eta)^i$ is the volume expansion coefficient; $k_i^T = \frac{3E_i^T}{(1-2\nu_i^T)}$ is the bulk modulus when the ice temperature is T; ν_i^T is the Poisson's ratio when the temperature is T.

This theory is essentially based on the volume expansion theory and the elastic mechanics, in which the effects of freeze-thaw cycles are converted into ice-rock material deterioration.

The current frost heaving theories of FRM are mainly developed from the frost heaving theory of soils and porous media. They mainly include the frost heaving evolution model based on water-ice phase transition, the segregation potential model based on fracture, and hybrid model based on different fracture shapes. The authors believe that the generation of frost heaving force is highly related to the freezing mode. Under natural condition, the temperature on the rock surface is low and the temperature inside the fracture is high in winter. The direction of freezing is from outside to inside, which is conducive to the formation of an ice cap on the fracture surface. The frost heaving force is generated mainly by the water-ice phase transition and the volume expansion. During the freezing process, the internal water of rock masses migrates to the fracture ice, the frost heaving force increases, and the segregation potential mechanism further increases the frost heaving force. The high surface temperature of the fracture in spring prevents the formation of an ice cap, and it is difficult to fulfil the conditions of volume expansion mechanism. The content of unfrozen water increases after the ice in the upper fracture melts, and the upper meltwater migrates towards the ice crystals along the unfrozen layer between the ice and the fracture. At this time, the ice in the upper part of the fracture is melting, the ice crystals in the lower part are growing, and the frost heaving force at the tip of the fracture increases. This phenomenon has been observed in the field and experiments, and rock fractures have been indicated to expand instead during the melting stage.

3.2 Laboratory experiments on frost heaving damage of FRM

Field experiments conclude that the frost heaving force generated by water-ice phase transition tends to cause fracture expansion, but the physical details of fracture expansion are not understood, and the basic frost heaving process has not been comprehensively analyzed theoretically. There are a large number of laboratory experiments on frost heaving damage of FRM worldwide, mainly including the frost heaving and freeze-thaw cycle experiments on rock masses.

The difficulty of experiments on FRM lies in the real-time stress measurement and the observation of fracture damage process. To address the above issues, Davison and Nye[42] used plexiglass instead of rock mass, and it was revealed that the measured frost heaving force generated during the freezing process of the fracture water could reached 1 MPa with the help of photoelastic stress measurement technique. Uneven strains were observed in the experiments during freezing, which was an important cause of fracture cracking. Temperature gradient and water content were responsible for the generation of uneven strains, and the expansion of macroscopic fractures was closely related to the water-ice phase transition. The ice plug extrusion occurred in the experiment, which was of great significance in revealing the frost heaving mechanism of FRM.

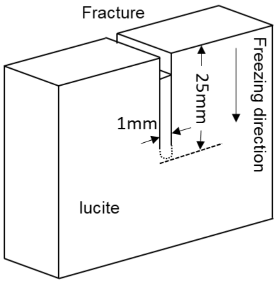


Fig. 6 Photoelastic test model

Thrap[43] designed comparative experiments for conical and streamer-like fractures in the same period. The results showed that the length-to-diameter ratio of the fracture had a great influence on the ice wedge action. Vertical fractures with the length-to-diameter ratio greater than 10^{-2} were most susceptible to cracking under ice wedge action, whereas plastic flow in wide fractures caused ice pressure relaxation. The effect of fracture geometry on frost heaving was stronger than that of freezing time and temperature. The experiments also found that the frost heaving force generated by 9% volume expansion was not sufficient to crack the fractures with small length-to-diameter ratios. This also proved the frost heaving model proposed by Walder and Hallet[35].

In addition to the geometrical features of the fractures, scholars have revealed that fracture freezing is related to the freezing temperature. Matsuoka[44] designed a frost heaving damage experiment on granite and suggested for the first time that the fastest fracture expansion occurred during the temperature dropped from 0°C to -1°C. This experiment also found that the maximum frost heaving rate for hard rock was 0.1%, which was much lower than the commonly accepted rate of 9%. This suggested that hard rock walls would cause frost heaving to develop upwards or sideways, reducing lateral expansion. Inspired by this, Jia[41] classified the freezing and thawing of FRM in natural state into three modes, i.e., from top to bottom, from bottom to top, and bidirectional freezing, and then investigated the changes of frost heaving force of fractures under the action of ice wedge and the deformation of the fractures after freeze-thaw cycles. It was also pointed out that the freezing direction was an important factor in fracture wedge damage.

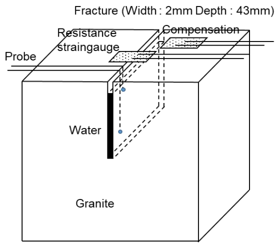


Fig. 7 Matsuoka frozen fractured rock mass test

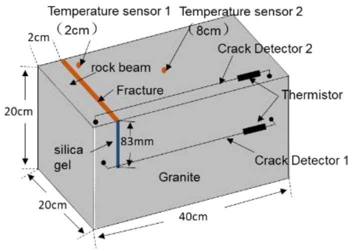


Fig. 8 Frost heave test of Jia fractured rock mass

To more accurately explore the occurrence laws of frost heaving of the fractures in the field, it is necessary to approach the natural environment more closely. Bost[43] et al. simulated the actual conditions of frost heaving weathering of FRM in cold regions, and obtained the same results as those of Davison and Nye. The distribution of the frost heaving force within the fracture during frost heaving was not uniform, while the extrusion of ice and the non-uniform temperature field of the freezing front had a significant effect on the evolution of frost heaving force within the fracture, which validated Matsuoka's[44] proposal that the ice separation had an important effect on frost heaving. In response to Thrap's[45] conjecture on the relationship between the fracture geometry and the frost heaving, the existence of a critical depth and a critical frost heaving force was explicitly pointed out, and the specific solutions were given.

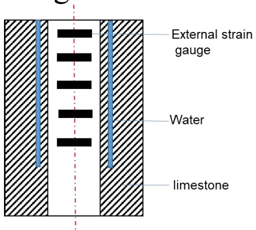


Fig. 9 Frost heave test of Bost fractured rock mass

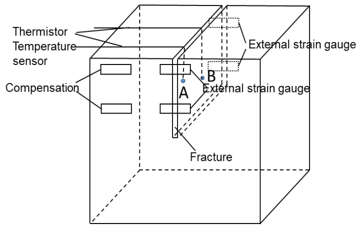


Fig. 10 Frost heave test of Lv fractured rock mass

A theoretical calculation model closer to actual situation of the cold-region projects can only be proposed by comprehensively considering the ice extrusion and non-uniform distribution of the temperature field in the FRM during freezing process. Lv[46] conducted freezing experiments on FRM with different permeabilities under uniform and unidirectional freezing modes, and concluded that uniform freezing was more common and the two freezing modes were very different, and that freezing mode and permeability of rocks determined water migration in the fractures.

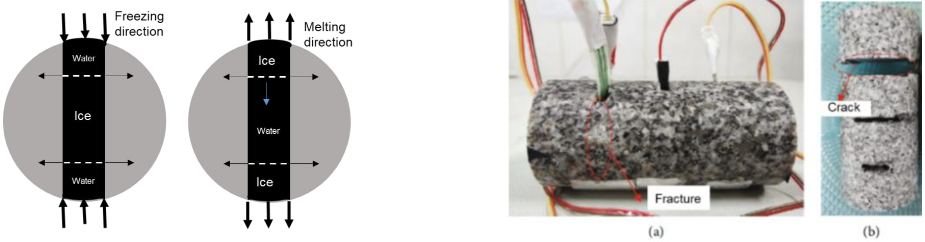


Fig. 11 Frost heave test of cracked cylindrical rock mass

In the early period, the large, fractured, square-shaped rock masses were primarily used to observe the frost heaving process. With the further investigations, it is necessary to not only observe the process but also conduct mechanical experiments on the rock masses after frost heaving or freeze-thaw cycles. To investigate the effect of fracture size, Luani designed freeze-thaw cycling experiments on single-fractured rock masses. It was found that the frost heaving fractures on the surface of specimens with large fracture lengths expanded significantly along the prefabricated direction. In addition, the melting water migrated to the interior of the fractures and froze again when it encountered the frozen rock, which caused new damage and led to eventual fracture of rock, i.e., the occurrence of secondary frost heaving[47]. Scholars have also studied the effects of fracture width, dip angle, and the number of fractures on the frost heaving force. Huang[48] theoretically and experimentally revealed the contribution of unfrozen water film to frost heaving force. When the temperature dropped to about 0°C, the rock matrix contracted and nearly 90% of pore water froze at -5°C. The thickness of unfrozen water film decreased and the frost heaving force increased. Huang experimentally demonstrated that FRM could achieve appreciable frost heaving force without considering the unfrozen water film, which explained why satisfactory results were also obtained with previous models.

In addition to external factors, the lithology, structure, and cement of FRM have a very significant influence on frost heaving weathering. The lithology determines the water migration capacity, affects the water-ice phase transition, and is a decisive factor affecting the frost heaving force[49]. Frost heaving force causes the weaker cemented particles in rock to dislodge, resulting in more pores and storage of more water. Wang[49] pointed out that the order of influence on the frost heaving deterioration of FRM was: rock lithology > fracture width > cement > fracture length.

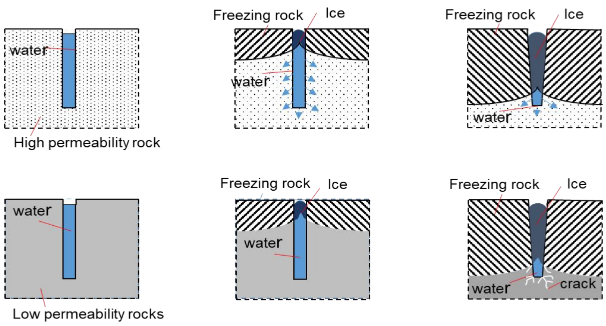


Fig. 12 Schematic diagram of frost heave failure process of fractured rock mass

Tests have revealed that in highly permeable FRM, an ice cap forms on the outside of rock as temperature decreases. In unidirectional freezing, the temperature continues to decrease and the thickness of ice cap increases. The volume expansion of water-ice phase transition causes an increase in the frost heaving force in rock masses. The water storage zone in the more permeable rock mass is not completely closed, and the frost heaving force does not increase after it reaches a threshold. The frost heaving force becomes the driving force for the water to flow into the rock masses, in which case the fractures do not crack. Whereas an ice cap forms on the outside of the low-temperature, highly permeable rock masses, the temperature continues to decrease with the volume expansion of water-ice phase transition. This process is accompanied by a very small amount of water penetration inside the fracture and a sharp increase in the frost heaving force. Suitable width and length of the fractures and sufficient duration of frost heaving make it easy for new fractures to appear at the tip of rock masses to release the frost heaving force, and frost heaving damage happens. In the actual freezing process, there are often multi-directional and non-uniform freezing. The lithology of rock masses determines the water migration within the fractures. Water migration leads to differences in physical variables such as water-ice expansion coefficient, which directly lead to differences in the magnitude of frost heaving force. With regard to the experiments on FRM, there is a preliminary consensus on the generation, development, and dissipation of frost heaving. If laboratory experiment is to be developed to the microscopic level, it is a priority to achieve accurate measurement of frost heaving force, and to clarify water-ice-rock connection and separation at the microscopic level, especially how the water changes in the unfrozen water film and migrates in the fracture pores due to the thermal effect during the frost heaving process. The underlying reason for the ability of frost heaving to produce damage in FRM is still the interaction between rock and water under the influence of temperature.

3.3 Field observation experiments of FRM

In Northern Europe and Canada, the frost heaving hazards were recognized during the construction of cold-region geotechnical engineering, and a group of scholars have carried out long-term field observation experiments on the frost heaving of FRM. Christiansen[50] performed one-year on-site monitoring of the ice wedge FRM in Svalbard island, Norway, and found that the FRM started to expand slowly only at -15°C. Fahey and Lefebure[51] carried out an observation study on the FRM in Ontario, Canada, and confirmed that the number of freeze-thaw cycles in air was different from that in fractures. This suggested that the FRM did not melt immediately in the presence of an internal cold source, and that the number of cycles inside rock masses did not coincide with that outside. In addition to investigations of cracking temperature and number of cycles, researchers identified the significant effect of freezing rate on the cracking of rock masses. Wegmann and Gudmundsson made observations of rock masses in Switzerland and measured the freezing rate in the field. Matsuoka[44] found that freeze-thaw in different seasons had different effects on damages of FRM, with spring and autumn being the high seasons for fracture expansion. Ishikawa[22] pointed out that the in-situ frost heaving forces ranged from 0 to 7 MPa through the observations of frost heaving in alpine fractures in Japan, which indicated that the actual frost heaving forces were sufficient to cause geological hazards.

With the in-depth research, scholars have been committed to exploring the frost heaving mechanism of FRM. Field observations of frost heaving of alpine rock cliffs found that the frost heaving weathering damage of rock masses had a great influence on fracture expansion. Frost heaving weathering damage of FRM was a result of the chemical and thermodynamic coupling effect, which was related to the ice-rock interaction. After thawing of fracture ice, the structural plane of the fracture was weakened, the shear strength of the FRM was reduced, and the structural plane of FRM was prone to shear damage when the strength of the structural plane was reduced by multiple freeze-thaw cycles. This process was confirmed by Hasler's[53] observation that FRM were more prone to shear expansion in the thawing season. The widening of fractures in autumn was mainly related to freeze-thaw cycles, whereas the expansion width of the fracture was related to the water content and freezing strength of the fracture. The fracture expansion in spring was caused by the melting snow and ice on the fracture surface entering the fissure, resulting in increased development of frost heaving at the bottom of the fracture. Matsuoka[44], a Japanese scholar, conducted long-term field monitoring of widths and temperatures of fractures on Alps Mountain, Japan, to investigate the frost heaving weathering of FRM. The results showed that spring and autumn were the peak seasons for fracture widening, and were also the critical window periods for frost heaving.

The field observations on external factors affecting the frost heaving of FRM mainly include magnitude of in-situ frost heaving force, fracture initiation temperature, freezing rate, difference between freeze-thaw cycles, and two window periods of frost heaving cracking. Subsequent field observations should focus on different temperature gradients, freezing time, freezing direction, influencing depth, different freezing medium, different water environments, different ion contents, different frozen rock materials, and different fracture sizes under natural environment.

3.4 Numerical studies of frost heaving damage of FRM

Frost heaving damage of FRM is a typical thermo-hydro-mechanical (T-H-M) coupling process. When the stress intensity factor at the tip of the fracture is greater than the fracture toughness of the rock under THM coupling, the fracture will expand. Current research on THM coupling process of frost heaving in FRM mainly focuses on intact rocks, and therefore it is necessary to gradually consider the influence of the fracture.

Liu's team conducted systematic studies on frost heaving damage of FRM by using numerical analyses. Firstly, the model was built using ANSYS by using the THM coupling as controlling equation, and then it was imported into FLAC3D for calculation[48]. The method performed a large number of simplifications, for example, the permeability coefficient was simply assumed to be linearly related to temperature. The equivalent thermal expansion coefficient method was used to simulate and analyze the thermo-mechanical coupled stress field under the water-ice phase transition of low-temperature FRM. To avoid the stress at the tip of the fracture from tending to infinity, the fracture tip singular units and the direct thermo-mechanical coupling unit property in ANSYS were used for thermo-mechanical coupling analysis[24]. The numerical analysis results showed that there was a significant tensile stress concentration at the fracture tip under the frost heaving force, and that the process involved the problem of non-flat fracture inclusions, and there was a certain error in the calculation. In particular, the adjustment of the stress field in the ice body by the flow of water in the fractures was not considered in the model, resulting in a stress distribution in the fracture field not being idealized as isotropically uniform and equal. There was a water-ice medium in the fracture that cannot be amenable to the direct solution command of the fracture tip stress intensity factor in ANSYS, resulting in a loss of realism[24]. To address the problems of previous numerical studies, the team numerically analyzed the frost heaving forces of FRM and the fracture tip stress field using an improved equivalent thermal expansion coefficient method.

In addition to elasticity[53], the plastic characteristics of rocks should also be considered. The stress-strain relation of the rock under two-dimensional compression conditions after different numbers of freeze-thaw cycles was established by using a semi-implicit graphical return algorithm. With regard to the freezing phenomenon of surface fractured hard rock under low temperature, Shen[54] et al. explored the evolution process of internal temperature field and frost heaving load of fractured hard rock with development of freezing depth from multiple perspectives, and introduced the multi-field coupled numerical program Comsol-Multiphysics for simulation. Ma[55] et al. derived the evolution law of frost heaving force considering water migration during frost heaving by a combination of effective volume expansion coefficient method, MATLAB platform programming, and XFEM calculation method. Li[27] established a three-dimensional model considering the loss of water migration during frost heaving, and numerically simulated water-filled fractures by using the equivalent volume expansion coefficient and particle flow calculation method. A numerical model considering the latent heat of pore water and the migration of fracture water was developed by Lv[46]. Tao[43] established a thermo-hydro-mechanical coupled model in the framework of the TOUGH-FEMM simulator that considers the complex coupling processes of water-ice phase transition and non-planar cracking, with special emphasis on the simulation of the double fractures, and obtained the effects of stress anisotropy and stress interference on fracture expansion.

Numerical analyses of FRM have made great progress after many years of development, and computational results provide corroboration of experimental results and theoretical analyses. However, due to the influence of temperature field - seepage field - stress field involved in the frost heaving process of FRM, the irregular shape of actual fracture, and the non-flat face fracture entrapment, the tip of the fracture generally experiences the stress concentration. The ice-rock contact connection mechanism has not been fully clarified, whereas simple contacts are often used for analysis.

4. Conclusions and Prospects

This paper reviews the development process of the research on low-temperature FRM, and introduces the main progress of the research on frost heaving damage mechanism of FRM in recent years from four aspects, namely, theoretical studies, laboratory experiments, field tests, and numerical simulations. The following conclusions can be drawn:

(1) Due to large differences in composition, structure, and mechanical properties of frozen soils, porous media, and fractured rocks, frost heaving damage modes they experience also differ greatly. Which theory is applicable to specific engineering needs to be rationally selected according to the different media.

(2) There are many factors affecting frost heaving force of FRM, and the key factors are water migration and phase transition. The magnitude of frost heaving force of FRM is closely related to angle, length, width, number, freezing temperature, and temperature gradient of fractures. In the future, the investigation of frost heaving force should start from the micro scale, and combine the interface mechanics, phase transition theory, and seepage mechanics to investigate the water migration mechanism.

(3) Water-ice phase transition process in FRM involves the intersection of rock mechanics and condensed matter physics. The function relationship between unfrozen water film and temperature is affected by air humidity, contact material, and solute content. Future research should concentrate on the microscopic studies of the interaction mechanism of ice particles with rock particles and water film, and thermodynamic properties and microfluidic mechanism of the unfrozen water film.

Scholars all over the world have recognized that frost heaving damage of FRM is a complex scientific problem that needs to be followed up and continued to be explored. For the difficulties and focus of the subsequent research on FRM, the authors make the following recommendations.

(1) The mechanism of fracture expansion evolution in rocks is a current research hotspot, and introduction of seepage, temperature loading, and frost heaving force undoubtedly makes the study extremely challenging. The investigation needs to extend frost heaving of single-fractured rock masses to those of multiple-fractured rock masses and fracture network.

(2) Water is the fundamental material source of frost heaving, which makes the physical description of water behavior in FRM a major challenge and a research hotspot. The study of the main driving force of water migration, the role of water in the formation process of frost heaving, and the unfrozen water film is crucial for the enhancement of frost heaving force.

(3) Quantification of frost heaving force is challenging. There are many factors affecting frost heaving force, but the frost heaving force is the result of water-ice phase transition that is coupled with the fracture expansion. The focus should capture the process of interaction between the fracture water migration and the mechanical strength of the rock masses, i.e., the fracture and water.

(4) With regard to field tests, it is necessary to develop a water detection system for geotechnical engineering in cold regions and an observation system for frost heaving force and displacement. Long-term observation of water distribution around FRM is essential to clarify the role of groundwater in the frost heaving in the field.

(5) In terms of laboratory experiments, similar transparent material experiments should be performed. Given the significance of water migration in the frost heaving process of FRM, the design of transparent materials to observe water migration direction and migration fluxes can provide experimental support for theoretically determining the driving force of water migration and the migration mechanism.

(6) The study of frost heaving of FRM serves the engineering construction. After systematic field monitoring and laboratory experiments, different rock geological and natural freeze-thaw conditions can be graded by combining artificial intelligence and big data analysis. The computer can derive frost heaving prediction functions from obtained data, which provides convenience to the field construction.

(7) With respect to numerical calculations, it is difficult for existing calculation modules to be compatible with various problems such as the water-ice phase transition, the non-planar cracking of fractures, the non-convergence of computation due to the sudden generation of frost heaving force, the stress concentration at the tip of the fracture, and the coupling of seepage-temperature-mechanical-chemical fields. It is not possible for existing commercial software to satisfy such conditions at the same time, and therefore it is necessary to develop a set of modules applicable to the frost heaving damage of FRM on a commercial platform.

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