The research of frost heaving damage caused by fracture extension length under the freezing conditions

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Abstract

The cold regions tunnel area is widely distributed in our country. The water inside the tunnel surrounding rock fracture will freeze in the cold environment. Fissure volume will expand after freezing. Treated water ice phase change as the research object, considering moisture migration effects, combined with the rock internal characteristics and external environment factors, the differences of water under the free state of frost heave and its constraint conditions to determine the crack frost heaving rate of frost heave. Relying on elastic mechanics theory, under the condition of plane strain, calculation of frost heave volume increases a lot and the size of the frost heaving force, crack extension length is deduced with the relationship between the frost heaving force. Freezing and thawing damage of tunnel rock should be fully considered the influence of freezing and thawing and crack extension, and the elastic modulus change caused by crack extension. The meso damage mechanics in the Mori Tanaka method and establish damage coefficient and freeze-thaw cycles, the crack propagation relationship between the length and provide a theoretical basis for the future of cold regions engineering construction, so as to solve the problem of engineering rock mass freezing thawing damage of engineering problems.

Keywords

Fracture, Frost heaving ratio, Frost heaving force, Crack extension length, Damage coefficient.

1. Introduction

Most parts of china are in cold region, and the northwest area exist a large seasonal temperature difference. In cold regions engineering construction will encounter frost heave damage instability which poses a serious threat to safety of rock engineering. With the continuous improvement of the technology and the product development, China will construct a large number of tunnels, which has very important significance on the tunnel in cold region. The rocks are rich in joints and fissures and these joints and fissures become the important factors threatening the stability of rock mass. A water ice phase changes happen during Joint water due to a lower temperature in the winter. The water in the free state condense into ice, and the expansion coefficient is 9%. However, due to the constraint of the rock itself, the volume expansion value should be smaller than that of the value. Constraint of surrounding rock and the expansion of the volume of surrounding rock to produce frost heaving force is a pair of acting force and counterforce which are equal and opposite in direction. By analyzing the theory of elastic mechanics, a consistent model is established, the frost heaving force and crack propagation length are calculated, the mechanism of frost heaving and the damage on the stability of surrounding rock are summarized.

Many domestic and foreign scholars have done a lot of research on frost heave fracture. Through the analysis of rock frost heave test data, the calculation formula of rock frost heaving ratio is modified by Xia Caichu [1]. The frost heave of crack freezing is analysed and frost heave value of corresponding line rate is given out. From the perspective of elastic-plastic mechanics, fracture mechanics, Yan Xidong [2] studied the frost heaving force on single crack propagation characteristics, and the relationship between the crack propagation length and Frost heaving force was deduced. The equation of rock macroscopic damage and the amount of frost heave force was established by using Mori-

Tanaka method. It discussed the change rule between rock elastic modulus, the number of freeze-thaw, frost stress and permeability coefficient of variation, and the test results were compared and analyzed. Considering moisture transfer conditions and taking the phase transition of water ice as the breakthrough point, Liu Quansheng [3] analysis the frost heave load saturated fractured rock mass stress field distribution combining with fracture mechanics and elastic plasticity theory. The damage failure mechanism and mechanical characteristics of the jointed rock mass under freezing and thawing conditions was studied by Liu Hongyan [4] through cyclic freeze-thaw and similar material test. The research results have important reference value for the construction and safe operation of rock in cold region. For freezing and thawing by the rock mass under the cold joint rock engineering structures, Li Xinping [5], jointed rock mass was simulated using the prefabricated crack method in rock-like material. Through freeze-thaw cycle test and uniaxial compression test, the impact of fractured rock sample geometric characteristics (fissure length, fissure angle) on rock mass strength was studied. Liu Quansheng [6] describes the engineering rock freeze-thaw damage as a common problem in cold region, and the main cause is the frost heave rock moisture and shrinkage effect. To truly reveal the frozen rock damage mechanism, It should take the phase change from water to ice as the breakthrough point, basing on mesoscopic scale, giving full consideration to the mutual influence between frost heaving-thaw collapse and fracture extension, and Expanding it to the effects of freeze-thaw action on the development of rock mass fracture network.

At present, domestic and foreign scholars on the main research contents of frozen rock can be roughly summarized as the physical and mechanical properties of frozen rock, phase change process, freeze-thaw damage model and numerical analysis. For decades, in many ways, domestic and foreign scholars through theoretical analysis, numerical simulation, field and laboratory tests on frozen rock launches the research, has achieved fruitful results, but the research on frozen rock is far from mature, many studies still remain in the test stage of exploration. The rock of frost heaving rate for basic from the starting point in fracture mechanics, damage mechanics, elastic mechanics theory based on established the calculation formula under plane strain condition. With the help of frost heaving ratio and strain size, find the relationship between frost heaving force with crack length and crack volume value. Finally, deduced crack propagation length and damage coefficient between the relationship, from the theoretical analysis of crack under the condition of frost heave extended length of damage effect and hope that can provide a theoretical basis for the frost heaving zone project construction technical problems to solve.

2. Fracture of frost heaving and frost heaving ratio

Frost heaving ratio is the description of a physical quantity of rock frost heaving, which is the foundation of rock mass. Rock mass is composed of rock and jointed, winter cold regions tunnel water due to the low temperature will freeze, the water turns into ice is a volume increase, the free volume will increase 9%. However, due to the restriction of rock, fracture water ice phase transition increases the value to be less than 9%. Frost heave of rock mass is influenced by many factors: temperature, rock frost susceptibility, the grade of surrounding rock, porosity, outside water supply conditions. Freezing can affect the physical and mechanical properties of rocks, and the freezing and thawing cycles can cause the deformation of the rock, which is caused by the damage of the rock mass.

Assuming the rock is homogeneous medium, the ratio of rock volume increment and the volume of the original rock called frost heaving ratio. The process of volume phase transition is 9%, rate of frost heave:

$$\eta = \frac{\Delta V}{V} \tag{1}$$

M.Mellor [7] derived a closed under the condition of frost heaving ratio calculation formula of saturated rock:

$$\eta = 9\% n \tag{2}$$

Rock on the frost heave of ice can produce an external force is ignored by the above formula in the process of frost heave on the constraints of the rock. Xia Caichu [1] fitted the relationship between the frost heaving ratio and rock porosity and got He got saturated rock frost heaving ratio formula under the closed condition, the rock self-confinement effect is considered, namely in situ pore water freezing expansion effect of saturated rock frost heaving rate calculation formula:

$$\eta = 2.17\% n \quad (3)$$

Frost susceptibility rocks need to consider the effects of water and heat transfer. Water heat transfer is the flow of the water in the nonfreezing zone to the freezing zone, which is a process of accumulating ice. With the accumulation of ice, it will cause the change of rock shape. Modification of formula (3) by considering the effect of hydrothermal migration [1], we can get the frost heaving ratio calculation formula under the open condition of saturated rock.

$$\eta = 2.17\% \zeta n \quad (4)$$

In the Calculation formula: ζ is the influence coefficient of water heat transfer. The rock frost susceptibility value is 158.46% and the non-frost susceptibility value is 100%.

3. The relationship between crack length and frost heaving force

According to the energy theory of Griffith, the crack propagation needs two stages: 1) With the decrease of temperature, the water is frozen, and the crack will be stored in the surrounding of the crack due to the constraint of the rock to the crack surface. When the stress intensity factor at the crack tip K_I and the fracture toughness value K_{IC} are satisfied $K_I > K_{IC}$, the crack growth begins. The stored elastic energy can be released to provide energy for the crack propagation. Then there is the following relationship:

$$W = E - U \quad (5)$$

In the Calculation formula: W is the work of frost heaving force; E is the elastic strain energy of crack storage; U is the total potential energy of the whole system. It is assumed that the elastic strain energy can be fully released during the crack propagation. Then there is the following relationship:

$$W = -U \quad (6)$$

After the crack begins to expand, the classical elliptical crack model is established, and the crack growth state is analyzed. The assumption is that there is a flat elliptical crack in the finite geometry of B width and length is 2L. The length of the crack is 2a, the opening degree is 2b. As shown in Figure 1, when the frost heaving and micro crack wall effects have uniform distribution of frost heaving force, in the study of crack propagation length to make the following assumptions: ①The crack is a flat elliptical crack in plane state. ②Free water can not be compressed. ③Ice bodies and rocks are regarded as isotropic homogeneous elastic media. ④The crack is always in a state of saturation. ⑤Uniform crack extension.

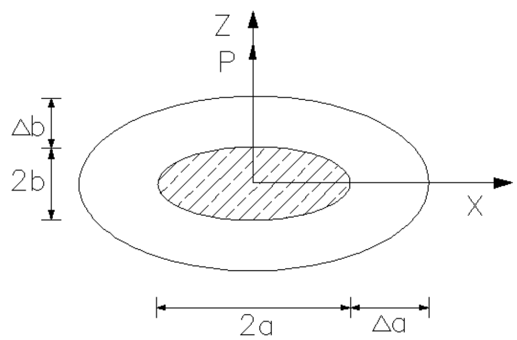

Fig.1 Schematic of a crack extension under frost heaving

Considering the effect of water and heat transfer, under the plane strain condition, through the calculation of crack length value, relying on line frost heaving ratio to solve the crack open the opening, seeking a method to calculate the crack expands value with the relationship between frost heaving force method. Crack after frost crack opening degree increments and frost crack opening ratio of rate of frost heaving of line α_f , to describe the frost heave in fracture.

$$\alpha_f = \frac{\Delta b}{b} \tag{7}$$

In the hydrothermal migration [1], fracture line of frost heave rate was $\alpha_f = 4\%$. According to the fissure water before and after water ice phase change, list the relation between the volume increment is:

$$\pi ab + \Delta S'_i = \pi(a+\Delta a)(b+\Delta b) \tag{8}$$

In the Calculation formula: $\Delta S'_i$ is the actual amount of volume per unit width.

If the fracture surface is not considered, under the condition of free expansion of the ice body, it is assumed that the volume of the ice volume expansion is ΔS_i. But in the actual case, fracture surface of ice will exert a body size of P reaction, with the size of the frost heave force of equal size. Ice mass produce elastic strain, according to the elastic theory, under the condition of plane strain, normal strain size is

$$\varepsilon = \frac{(1-\nu_i)(1+2\nu_i)}{E} P \tag{9}$$

In the Calculation formula: ν_i is Poisson's ratio,E is elastic modulus.

As a result, the volume of the ice on the volume of the volume of the actual increase is

$$\Delta S'_i = \Delta S_i - S_i \varepsilon \tag{10}$$

In the Calculation formula: S_i is the non-frost heaving total volume of water.

$$\Delta V = \Delta S_i \cdot \Delta h \tag{11}$$

By (1), (7), (11)

$$\Delta S_i = \frac{S_i \cdot \eta}{\alpha_f} \tag{12}$$

By (11), (12) we can draw in the plane strain condition, the relationship between the volume change quantity and frost force is:

$$\Delta S'_i = \frac{S_i \cdot \eta}{\alpha_f} - S_i \frac{(1-\nu_i)(1+2\nu_i)}{E} P \tag{13}$$

By (1), (7), (8), (9), (10), (12) we get the relationship with the crack length of frost heaving force:

$$\Delta a = a\left(1 - \frac{1 + \frac{\eta}{\alpha_f} - \frac{(1-\nu_i)(1+2\nu_i)}{E} P}{1+\alpha_f}\right) \tag{14}$$

4. Relationship between crack growth length and freeze-thaw damage

Method of using meso damage mechanics [2], the micro mechanical effects of micro holes and micro cracks are neglected, and the results of micro damage mechanics are used to reflect the macroscopic mechanical properties of materials. According to the Mori-Tanaka method, the effective elastic modulus is obtained by considering the interaction between the micro cracks under two-dimensional conditions expressed as

$$\frac{E_n}{E_0} = \frac{1}{1+\pi\alpha} \tag{15}$$

In the Calculation formula: E is the initial elastic modulus of rock mass (MPa): E_n is the equivalent elastic modulus after freezing and thawing several times (MPa). α is the crack density parameter, expressed as $\alpha = Na^2, N$ is the number of cracks in the unit area on average for a half-length of a(stripe/m^2).

According to the previous hypothesis that the crack is always saturated, therefore, frost heave stress depends only on the temperature, namely each freezing and thawing cycles crack extension length are equal, after n times of freeze-thaw cycle, crack density parameter expressed as

$$\alpha = N(a + n(\Delta a))^2 \tag{16}$$

Combination formula (14) and formula (15) can get the relationship between the elastic modulus of rock mass and the elastic modulus of rock mass.

The modulus of elasticity can be changed during the freezing and thawing cycles, and there is a certain relationship between the change of elastic modulus and the damage. The relationship between damage variable and elastic modulus was established to calculate the change of damage under the condition of freezing and thawing cycles.

Damage variable D_n can be expressed as

$$D_n = 1 - \frac{E_n}{E_0} \tag{17}$$

In the Calculation formula: E_n is the elastic modulus of intact rock after n times freezing and thawing cycles, E_0 is elastic modulus of intact rock before freezing and thawing.

By (15), (16), (17)

$$D_n = 1 - \frac{1}{1 + \pi N(\alpha + n(\Delta a))^2} \tag{18}$$

According to the formula (14) and (18), the relationship between the crack growth length and the damage variable can be obtained under the condition of freeze-thaw cycles.

5. Conclusion

(1)Under the condition of frost heave rate which is closed related to the porosity and rock constraints. Frost susceptibility rocks need to consider the effects of water and heat transfer. Frost heaving ratio is in addition to related to porosity and rock constraints, also related to the water heat transfer coefficient. Considering the effects of water and heat transfer, the line of frost heaving ratio value is 4%. Line rate of frost heave and frost heave rate is proportional to the relationship.

(2) Establishing a typical elliptical crack geometry model, under the condition of plane strain, relying on the theory of elastic mechanics knowledge to push the relationship between derived strain and frost heaving force. Volume increase value and derived the relationship between the rate of frost heave and frost heaving force under plane strain condition. Finally to solve the relationship between crack extension length and frost line rate, frost heaving ratio, frost heaving force.

(3) Through the relationship between damage coefficient and modulus of elasticity, Mori Tanaka method in elastic modulus and density parameters, the relations between the density parameters and the length of crack propagation. At last, the establishment of a damage coefficient and crack propagation length of relationship, it is concluded that the damage coefficient increases with crack length increases.

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