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Fracture mechanism of rock collapse in the freeze-thaw zone of eastern Sichuan-Tibet Mountains under seasonal fluctuating combinations of water and heat

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Abstract:

In the freeze-thaw zone of eastern Sichuan-Tibet Mountains, the phases of water in cracks show strong seasonal variations, which significantly affect the stability of perilous rocks in mountains. However, few works have clearly addressed the role of water/ice in crack development from a fracture mechanics viewpoint to explain the seasonality of rock collapse. In this study, we built physical models from a fracture mechanics viewpoint to calculate water-freezing stress, hydrostatic pressure, and their combinations induced by water/ice in cracks, and show the crack propagation mechanism under temperature fluctuations in different seasons in mountainous regions. Based on the models, we calculate fracture conditions, simulate the crack process, and illustrate the rock collapse mechanism in different seasons by the extended finite element method. The results indicate that different phases of water, which induce stress under spatiotemporal fluctuations of temperature, determine the various propagation styles and influence what kind and when a collapse will occur. The collapse of fractured rocks in different seasons generally results from rock damage accumulation owing to the initiation, propagation, and connection of primary cracks under freezing stress or hydrostatic pressure or their different combinations.

Keywords: rock collapse, fracture mechanics, seasonal temperature fluctuation, eastern Sichuan-Tibet, combination of water and heat

1 Introduction

Rock collapse widely occurs in the mountains of the eastern Tibetan Plateau owing to the

27 geomorphic features of active crustal stress and large elevation differences. Especially in recent 50
 28 years, the occurrence of rock collapse and avalanche disasters increase drastically (Hore et al. 2018).
 29 These collapses and their secondary disasters pose danger to towns, roads, other inhabited regions.
 30 Outstanding examples include the Yigong rock avalanche blocked the Yigong River for 2 months and
 31 killed 94 people, the Baga collapse in Tibet dammed the Chayu River, and the Xinmo collapse-rock
 32 slide in Sichuan buried 64 houses, caused dozens of people missing (Hu et al. 2018; Xu et al. 2012).

Fig. 1 Collapse bodies, perilous rock, and cracks in the mountains

35 Rock collapse is a process in which a relatively intact mass on a well-defined rupture surface
 36 rapidly detaches and undergoes extensive internal disaggregation, which directly leads to a rockslide
 37 or avalanche disaster (Eisbacher 1979). Many studies mainly focused on the dynamical mechanism of
 38 rockfalls or avalanches after collapses (Locat et al. 2006). Relatively few studies have clearly
 39 addressed the rock collapse mechanism, although the character, distribution law, and induced factors
 40 of collapse have been well studied in a qualitative or semi-quantitative manner (Ez Eldin et al. 2013).
 41 Nevertheless, these results cannot be used to explain how a collapse develops.

42 Field surveys in eastern Sichuan-Tibet Mountains have shown that the perilous rocks situated on

43 steep scarps or cliffs are cut into crushes by various cracks ([Chen et al. 2012](#)) (Fig. 1a), and many
44 collapses occur along dominant cracks and mainly distribute at freeze-thaw zone. As shown in Fig.
45 1(b), these deep and controlled cracks are often filled by ice or water in different seasons and bear
46 complicated loads with the seasonal fluctuations of combined water and heat. This effect causes large
47 collapses in the late spring or early summer with increasing precipitation and temperature, and small
48 but frequent collapses when the temperature decreases in late autumn.

49 Many studies have shown that **cracks** influence rock stability. [PANEK et al. \(2009\)](#) pointed out the
50 gradual propagation of cut surfaces weakens the rock mass and leads to collapse. [Alippi et al. \(2010\)](#)
51 suggested that rock collapse results from crack development in rocks. However, few studies have
52 elucidated how the cracks in perilous rocks **develop** and cause collapse.

53 Other studies have studied the effects of **freeze-thaw action** on rock-soil mass. [Neaupane and](#)
54 [Yamabe \(2001\)](#) researched the coupled thermo-hydro-mechanical model of frozen rock according to
55 continuum mechanics. [Nicholson and Nicholson \(2000\)](#) analyzed the freeze-thaw damage evolution
56 of rocks. Unfortunately, these studies did not involve the mechanism of collapses with **deep cracks** in
57 freeze-thaw mountainous settings (Fig. 1b).

58 Cracks and seasonal freeze-thaw actions are two sides of the same issue regarding rock collapse in
59 mountains. Primary cracks decrease the rock-soil mass strength, provide water channels, and facilitate
60 weathering. The freezing and thawing of water/ice in different seasons, in turn, extend the crack and
61 further reduces the rock stability. **The effects of water and temperature on cracks in perilous rocks**
62 **hence take a significant role in collapse within the freeze-thaw zone.** However, the environmental
63 conditions considering the seasonal effects of temperature and moisture on rock collapse remains an
64 open question in the eastern Sichuan-Tibet Mountains. Aside from preliminary studies regarding
65 collapse mechanism on different altitudes ([Wu et al. 2020](#)), few investigations have addressed the role
66 of water/ice in different seasons in crack development clearly from the viewpoint of fracture mechanics
67 and explained the seasonality of rock collapse.

Hence, the major objective in our paper is to clearly study the rock collapse mechanism in the freeze-thaw zone of eastern Sichuan-Tibet Mountains from a fracture mechanics standpoint with consideration of phase change of water under seasonal fluctuations of surrounding temperatures. We analyzed the various water-heat combinations in different seasons and develop four models to characterize the driving forces of crack growth, including ice gravity, friction, water hydrostatic pressure, ice-induced stress, and their combinations. Based on these models, we calculated SIFs (the stress intensity factors), and analyzed the stability of crack by the fracture mechanics. We gave the way to solve crack extension and studied quantitatively the effects of crack characteristics under the seasonal combination of water-heat on rock collapse patterns. Aided by XFEM (extended finite element method), we simulated the entire crack propagation eventually.

We first determined the research area and then built models of crack driving forces in perilous rocks under different water-heat environments based on the field survey. We calculated the crack initiation and propagation using XFEM and studied different variations on the crack models to explain the rock collapse mechanism under seasonal fluctuations of water and heat. We apply the results to practical examples to demonstrate the new theory of rock collapse.

2 Background

Various hazards including landslides and debris flow are widely distributed in the eastern Sichuan-Tibet Mountains owing to complicated geology, neotectonic movement, geomorphology, and climate. Among them, rock collapse poses a serious threat to local inhabitants and usually results in rock avalanches/debris flows, which can block rivers and induce floods.

2.1 Characteristics of nature environment

The study area, Maojiagou gully, is located approximately 11.2 km southwest of Kangding town in Sichuan, China. As shown in Fig. 2, many important transport lines, such as the G318 national road and Sichuan-Tibet railway (under construction), pass across near this area. The mountain slopes in the

study area are very steep and thus numerous potential rock detachment zones develop on both sides of the valley. Maojiagou gully has a subtropical mountain monsoon climate. The local meteorological data show that the maximum and minimum values of average monthly air temperatures are 8.3 °C and −14.1 °C at the gully mouth respectively (3220 m altitude). The precipitation is about 810 mm a year and nearly 80% occurs in summer from May to September. The Zheduohe River flows through the front of the Maojiagou gully from northwest to southeast.

Fig. 2 The location of the study point.

2.2 Geological and slope structure

Two active geologic tectonic structures are present in the study area: the SW-NE oriented Longmenshan thrust fault and the SE-NW oriented Xianshuihe strike-slip fault belts, which intersect nearby. Due to vigorous tectonic activity, the rock strata are heavily fragmented and the fracture development extensively. The exposed lithology within the study area mainly weathered granite, metamorphic granite and plagiogranite with intense disintegration, which enhances the development of high-risk rock zones (Fig. 3a and b). The gully bed is thus vulnerable to valley rock avalanches caused by several large collapses at different altitude positions of the mountain on both valley slopes.

At the study point P (29°58'00" N, 101°50'30" E), the elevations of the highest collapse and mountain feet are approximately 4600 and 3580 m, respectively, with an average slope angle of approximately 34.2°. A variety of loose Quaternary accumulation is distributed on the inclinations or foot of the slope.

Fig. 3 Collapses in Maojiagou gully and the character of their deposits

2.3 Character of collapse and accumulation

Through field surveys, we obtained the basic parameters of the collapse: position; slope angle; accumulation volume; and particle size.

According to the survey data, the region in which the collapses occur is mainly between the snowline and timberline. In this region, the temperature frequently varies around zero in different seasons, hence the freeze-thaw action of the soil-rock body is intensive. Most fractured rocks are easily broken under hydraulic splitting or ice wedging forces with temperature fluctuations.

Rock collapses can occur in this region during any season but are more common in early spring, a rainy summer, and late autumn. They widely distribute in the freeze-thaw alternation area or near the glacial retreat area caused by global warming. Their accumulations are not thick or far from the source. The particles vary in size, shape, and sorting owing to different formation mechanisms, but aside from

125 some meter-scale boulders, most particles are small on the mm to cm scale.

126 To determine the characteristics of collapse particles, we collected accumulation source material
127 in the Maojiagou gully and tested the distribution of grain size. As shown in Fig. 3(c), the dimensions
128 of 91.6% of previous fall particles from situ collapse accumulations observed on the slope or gully are
129 smaller than 0.25 m in radius, whereas the largest radius material (0.6 m) was from the most dangerous
130 rock collapse.

131 2.4 Qualitative analysis of collapse in the freeze-thaw zone of mountains during different seasons

132 The temperature in mountains shown in Fig. 4 drops by 0.6 °C with an elevation rise of 100 m (Du
133 et al. 2017) and rainfall increases with increasing altitude over a certain range, thus the average
134 monthly air temperature at different altitudes in study area can thus be estimated (Table 1) using the
135 surface temperature data mentioned in Section 2.1.

136
137 **Fig. 4** Sketch of water-heat combination in mountains of the study area.

138 As shown in Fig. 5(a, b), as geologic bodies, perilous rocks contain numerous primary fractures (e.g.,
139 cracks, joints, faults), many of which are filled with snow or ice in the high mountains of the study
140 area. Because ice mechanics is sensitive to temperature, the stability of ice-filled cracks is influenced
141 by changes of water-heat combinations at different altitudes and/or in different seasons. The survey
142 revealed that fractures mainly distribute on the surface of perilous rocks and penetrate too far smaller
143 depths than climate-influenced depths. Hence, the temperature of filled cracks is directly affected by
144 the atmosphere and can be assumed to be the same as the local air temperature (Table 1).

145
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Table 1
Maximum and minimum average monthly temperatures estimated at different altitudes.

Altitude (km)	3.22	3.58	3.6	3.8	4.0	4.2	4.4	4.6	4.8
Maximum in summer (°C)	8.3	6.1	6.0	4.8	3.6	2.4	1.2	0.0	-1.2
Minimum in winter (°C)	-14.1	-16.3	-16.4	-17.6	-18.8	-20.0	-21.2	-22.4	-23.6

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Fig. 5 Idealized schematic diagram of (a-b) perilous rock and (c) the cracking process in different seasons

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Moreover, the temperature of cracks in the study area changes and varies seasonally. At altitudes lower than 3800 m, the temperature typically decreases below zero in cold seasons and rises above zero in warm seasons, which induces serious freezing stress in autumn or winter and high hydrostatic pressure in spring or summer. When the altitude is 3800 m and higher, the temperature is negative year-round and freezing stress dominates the development of perilous rocks.

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Data from the field investigation also indicate that seasonal freezing and hydraulic splitting under different water-heat combinations contribute to the collapses in study area. Hence, to illustrate the entire propagation process of cracks in different seasons, the influence of water phase changes at different temperatures on the collapse mechanism in mountains must be considered (Fig. 5c).

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3 Models of crack stress caused by filled water/ ice in perilous rock with season variation

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For simplicity, we idealized the perilous rock as a 2D model in Fig. 6 with a major crack that is l long, w wide, and θ incline. Here taking the crack mouth as the origin, the x -axis is built along the

cracks and make assumptions as follows:

Fig. 6 Model for crack propagation in perilous rocks. Note the angle θ is positive when the crack inclines outward.

a) The water in the crack is incompressible but the ice is elastic. The constraint provided by crack is rigid prior to initiation and propagation.

b) The ice in the crack is a rigid elastic solid, which has a high cohesion (0.5–1 MPa) and can form dry calving cliffs or deep cracks with tens of meters in depth in a real iceberg (Bassis and Walker 2011). Hence the lateral pressure on the crack induced by ice gravity does not to be considered.

c) Due that the temperature of filled cracks is seen as the same as the local air temperature according to section 2.4, the water-ice phase change can thus occur instantaneously without considering the hysteresis process of heat conduction.

d) The crack surface is rough and the friction with the ice induced by ice gravity must be considered, although its influence on cracking is typically less than that of the transverse stress induced by ice expansion.

e) The width w of the crack is substantially smaller than its length l . Hence, ice expansion along the x -axis can be neglected and no shear strain nor friction occurs due to ice expansion.

Fig. 7 Stress on the surface (a) of a water-filled crack in summer, (b) of an ice-filled crack in winter, and (c) when the ice melts with increasing temperature in spring

3.1 Hydrostatic pressure on the surface of a water-filled crack in hot summer

Studies revealed that the frequency of rockfalls significantly increases in mountainous permafrost areas during warm months, and attributed this phenomenon to the loss of ice-bonded forces when filling ice melts and emphasized that the disappearance of the ‘adhesion’ of ice to rock cause the failure (Dramis et al. 1995). However, these studies do not explain how cracks develop and how damage accumulates for a rock slope that is stable prior to being filled with ice. Here, we propose that the melt-water of ice during warm weather or abundant rainfall in rainy seasons fill the cracks, generating hydrostatic pressure and causing hydraulic fracturing. As shown in Fig. 7(a), the triangular distribution of hydrostatic pressure acting on a crack surface:

$$p_w = \gamma_w x \cos \theta \quad 0 \leq x \leq l \quad (1)$$

where γ_w is water’s unit weight. Obviously, at the crack tip, its maximum value is $\gamma_w l \cos \theta$.

Note the length of the immersion surface differs on either side of an inclined crack, thus real hydrostatic stress on both surfaces is only expected to be similar (but different). However, in our study, the crack length is substantially longer than its width, hence a reasonable approximate value is given as Eq. (1).

3.2 Stress on surface of an ice-filled crack in cold winter

In cold winter, water in cracks completely freeze. There are two stresses on the crack surface (Fig. 7b), one is the gravity components perpendicular to the crack:

$$p_g = \gamma_i w \sin \theta \quad (2)$$

where p_g is the normal pressure on the low surface caused by ice gravity, γ_i is ice’s unit weight.

Another part is friction on the rough surface induced by the ice gravity component along the x -direction, which can be expressed based on the above assumption as:

$$f_g = \mu p_g = \mu \gamma_i w \sin \theta \quad (3)$$

where f_g is the surface friction and μ is the friction factor between ice and rock, which depends on temperature and is <0.1 for the lubrication of melting of ice at a high negative temperature (>-10 °C) (McCarthy et al. 2017). The x-component of ice gravity $\gamma_i l \cos \theta$ can thus not be balanced only by friction in Eq. (3) and imposes a residual pressure on the crack tip as follows:

$$p_{tip} = \gamma_i l (\cos \theta - \mu \sin \theta) \quad (4)$$

where p_{tip} is the pressure on the crack tip caused by ice gravity.

3.3 Stress on the surface of an ice-water-filled crack upon increasing temperature in warm spring

Upon the arrival of spring, the ice within cracks begins to melt with temperature rise. As shown in Fig. 7(c), meltwater in the upper section of a crack with length l_w poses a hydrostatic pressure (Eq. 1) on the crack surface. For the low crack segment (l_i), the ice gravity results in normal pressure p_g and friction f_g on the lower surface, as given in Eqs. (2, 3).

The friction f_g caused by the normal component of ice gravity in Eq. (3) cannot usually balance the ice gravity component $\gamma_i l \cos \theta$, let alone the maximum hydrostatic pressure imposed on top of the ice column. Hence, residual pressure is generated on the crack tip as:

$$p_{tip} = \gamma_i l (\cos \theta - \mu \sin \theta) + \gamma_w l_w \cos \theta \quad (5)$$

where p_{tip} is the pressure induced by ice gravity on the tip of crack.

3.4 Stress on surface of an ice-water-filled crack when the temperature drops in cool autumn

When the crack water begins to freeze with the temperature drop, it undergoes a 0.09 expansion for freezing and can expand nearly to 0.135 linearly at -22 °C, thus an outward force generates on crack and wedges the rock apart (Hallet 2006). On the assumption that the crack can provide a rigid constraint prior to cracking and ice strain only occurs perpendicular to the crack surface, the freezing stress applied on the crack is expressed as:

$$p_i = \varepsilon(t) \cdot E(t) = E(t) \left(0.09 - \frac{0.045}{22} t \right) \quad (6)$$

226 where $E(t)$ is ice elastic modulus (MPa) and is expressed as $6600(1-0.012t)$ (Godbout et al. 2000), $\varepsilon(t)$
 227 is the strain, t is the temperature ($^{\circ}\text{C}$). Considering the ice exhibits viscous-plastic behavior under high
 228 pressure although it is brittle under most natural conditions, the freezing stress may be overestimated
 229 by Eq. (6) and need to be modified with a correction factor (0.185) (Wu et al. 2020).

231 **Fig. 8** Stress on ice-water-filled crack when the temperature drops in cool autumn

232 Natural water in cracks is usually gradually frozen from the top (crack mouth) to the bottom (crack
 233 tip) with decreasing temperature. In most cases (Fig. 8a), when the weather becomes cool in autumn,
 234 a water-filled crack in cold mountains will be filled with ice on the upper segment (l_i) and water on the
 235 lower segment (l_w).

236 (a) Stress on the upper segment of the crack surface

237 Because of the normal component of the ice gravity given normal to surface in Eq. (2), the pressure
 238 on each side of the crack surface in Fig. 8(b) differs as:

$$239 \quad \begin{cases} p_{\text{up}} = p_i \\ p_{\text{down}} = p_i + \gamma_i w \sin \theta \end{cases} \quad (7)$$

240 Friction on the rough surface is mainly induced by the tangential component ($\gamma_i w \cos \theta$) of ice
 241 gravity along the x -direction. In most cases, the friction is sufficient to support the ice pillar and can
 242 be expressed as:

$$243 \quad \begin{cases} f_{\text{up}} = \frac{p_{\text{up}} \gamma_i w \cos \theta}{p_{\text{up}} + p_{\text{down}}} \\ f_{\text{down}} = \frac{p_{\text{down}} \gamma_i w \cos \theta}{p_{\text{up}} + p_{\text{down}}} \end{cases} \quad (8)$$

244 where p_{down} , p_{up} , f_{down} and f_{up} are the pressure and friction on each side of the surfaces of the crack.

245 However, when the bearing capacity provided by the surface along the x -direction is less than the
 246 gravity component $\gamma_w \cos \theta$, the friction on the surface and excess hydrostatic pressure generated on
 247 water in lower segment of crack are:

$$248 \quad \begin{cases} f_{\text{up}} = \mu p_{\text{up}} \\ f_{\text{down}} = \mu p_{\text{down}} \\ p_{\text{iw}} = \gamma_i l \cos \theta - \mu (p_{\text{up}} + p_{\text{down}}) \end{cases} \quad (9)$$

249 where p_{iw} is the excess hydrostatic pressure generated by water, which together with friction on the
 250 surface uphold the upper ice.

251 (b) Stress on the lower segment of the crack surface

252 On the lower crack surface, not only the hydrostatic pressure induced by water gravity in Eq. (1)
 253 but also the excess hydrostatic pressure p_{iw} in Eq. (9) occur. The surface pressure in Fig. 8(c) is thus:

$$254 \quad p_w = \gamma_w x \cos \theta + p_{\text{iw}} \quad l_i \leq x \leq l \quad (10)$$

255 Specially on the crack tip, the pressure reaches its maximum value of $\gamma_w w \sin \theta + p_{\text{iw}}$.

256 The temperature fluctuates during not only the transition between seasons but also between day
 257 and night. Especially in warm spring or cool autumn, the temperature can fluctuate above or below the
 258 freezing daily. The above model includes the process of crack cooling/heating and can be used to
 259 illustrate crack propagation with daily temperature changes in the same way.

260 4 Mechanism of cracking and its simulation

261 To study the fracture mechanism of rock collapse in the freeze-thaw zone of eastern Sichuan-Tibet
 262 Mountains based on the above models, we review the criteria of crack initiation, study the crack
 263 extension and use XFEM to simulate cracking according to fracture mechanics.

264 4.1 Criteria of crack initiation

265 In fracture mechanics (Erdogan and Sih 1963), modes I and II SIFs K_I and K_{II} induced by ice

266 gravity, ice expansion forces, friction, and hydrostatic pressure given in section 3 must satisfy the
 267 following formulations to maintain crack stability:

$$268 \quad \begin{cases} K_I \sin \varphi = K_{II} (1 - 3 \cos \varphi) \\ K_0 \leq K_C \end{cases} \quad (11)$$

269 where $K_0 = \cos(0.5\varphi)[K_I \cos^2(0.5\varphi) - 1.5K_{II} \sin(\varphi)]$ is a compound value of SIF considering both
 270 contributions of modes I and II fracturing, K_C is the rock fracture toughness, and φ is the fracture angle,
 271 which is measured **anticlockwise** from the original crack direction (Fig. 9).

272
273 **Fig. 9** Schematic diagram of the crack propagation direction

274 By solving these formulas, the fracture angle and critical stress that determine the initiation of
 275 crack failure can be obtained.

276 4.2 Crack extension (length) after initiation and propagation

277 Most deep cracks of perilous rocks continue to extend after initiation to propagate and lead to
 278 collapse due to increasing water depth and hydrostatic pressure during abundant rainfall, unless the
 279 propagation direction or extension path is not suitable for failure.

280 However, for cracks that initiate to propagate under water-freezing stress, their extension would be
 281 easier to terminate with crack opening and ice stress release. Hence, a certain extension length must
 282 exist during a continuous cooling process.

283
284 **Fig. 10** Calculation sketch of the crack propagation length

285 In this case, the freezing stress on a crack would continue to decline from the maximum value (Eq.

6) with ongoing propagation. When the stress becomes lower than its critical value, extension eventually terminates. Thus, the releasing strain of ice during this process (Fig. 10) can be given as:

$$\Delta\varepsilon = \varepsilon_0 \left(1 - \frac{\sigma_{c1}}{p_i} \right) = 0.09 - \frac{0.045}{22} t_0 - \frac{\sigma_{c1}}{E(t_0)} \quad (12)$$

where σ_{c1} is the critical stress that determines whether a crack (l_0) with a propagation length (Δl_0) initiates and propagates or not, p_i and ε_0 are the freezing stress on the crack and free strain of ice after crack propagation, respectively, when the temperature drops from zero to t_0 , and $\Delta\varepsilon$ is the release of ice strain during crack opening.

Note that the freezing stress in Eq. (6) is a maximum value on the assumption that the crack can provide a rigid constraint prior to initiation. However, when the freezing stress exceeds the critical stress (σ_{c0}), the crack begins to propagate and the stress no longer increases. Hence, the work of freezing stress on cracks with unit width (along the horizontal extension direction of the perilous slope) can be calculated as:

$$W = \frac{\sigma_{c0} + \sigma_{c1}}{2} \cdot w \cdot \Delta\varepsilon \cdot l_0 \quad (13)$$

where σ_{c0} is the critical stress that causes the initiation of a crack with an original length (l_0), w is the crack width, and W is the work of the freezing stress.

According to Griffith theory (Griffith 1921) of fracturing, the extension length of a crack is:

$$\Delta l_0 = \frac{W}{G_c} \quad (14)$$

where Δl_0 is the propagation length, G_c is the energy release rate.

4.3 Numerical simulation according to XFEM

Crack loading conditions are complicated in nature, which makes it difficult to analyze the fracture mechanism of rock collapses using an analytical solution. Numerical methods provide a simple way to analyze and visualize the crack propagation process and its impacts on perilous rock stability. For

example, by coupling with J-integral methods, FEM is a common way to evaluate SIFs. However, near the tip of crack, the mesh needs to be refined and conforms to the crack geometry, which cause inaccurate fracture mechanics solutions and cost expensive computationally.

In this study, we use XFEM added with high-order terms (Wang and Waisman 2018) to solve our fracture problems, which alleviate the cost of re-meshing with crack propagation and offer a more accurate solution near the crack tip. the Heaviside function $L(x)$ used to describe the displacement jump on the crack face and the XFEM displacement approximation $\mathbf{u}^h(\mathbf{x})$ are as we mentioned in our work (Wu et al. 2020):

$$\begin{cases} L(x) = \begin{cases} +1 & \text{above crack} \\ -1 & \text{below crack} \end{cases} \\ \mathbf{u}^h(x) = \sum_{O \in S} N_O(x) \mathbf{u}_O + \sum_{O \in S_T} N_O(x) \sum_{\alpha=1}^n f_{\alpha}(x) \mathbf{b}_{\alpha O} + \sum_{O \in S_L} N_O(x) L(x) \mathbf{a}_O \end{cases} \quad (15)$$

where $\mathbf{u}_O$ denoted by $N_O(x)$ is the standard FE shape functions related to the DOF (standard degree of freedom), x represents the spatial coordinate, S_L is the node-set which can be split by crack entirely, S_T is node-set located in the crack tip to support their basis functions, while S represents the domain node-sets. $f_{\alpha}(x)$ are crack-tip branch functions expressed by terms of (r, θ) in polar coordinates taking the origin on the tip, $\mathbf{a}_O$ and $\mathbf{b}_{\alpha O}$ are DOFs of nodes corresponding to functions L, f_{α} . n is the number of enrichment functions using near-tip asymptote.

5 Calculation and analysis

According to the field survey in the study area, we take perilous rock of the most common dimensions as an example to illustrate the fracture mechanism of rock collapse in a freeze-thaw zone. As shown in the 2D model in Fig. 11(a), the width (not including the crack width) and height of the perilous rock is 3.7 m and 3.5 m respectively. A crack with a length of 1.3 m and vertical inclination of 10° develops at the upper part of the rock within 2.0 m to the far-right end (point D) of the rock-free face. In the model, all the degrees of freedom on the bottom BC and horizontal degree of freedom

on boundary AB are fixed.

To quantitatively carry out a parametric study on SIFs and fracture angles, we model the free face of the perilous rocks as a double broken line ODC in Fig. 11(b), where the horizontal inclination of OD is 20° and the vertical inclination of DC is α . The crack length and vertical inclination are expressed as l_0 and θ_0 , respectively. Note that all these parameters are sensitive to the specific different calculation purposes, as described in section 5.4. The stress on the crack induced by hydrostatic or ice expansion pressure can be given according to Eqs. (1-10).

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5.1 Material properties

Granite samples are medium-fine-grained biotite granite collected from the collapse accumulation site, which has a grayish-white and blocky structure. As an igneous rock, the samples mainly consist of 41.2% microcline, 22.4% quartz, and 27.3% plagioclase. Experiments such as density test and MTS (Mechanical Testing & Simulation) test (Fig. 12) were carried, and the properties of rock are obtained (Table 2). The standard geometrical dimensions of the specimens used to test the fracture mechanics properties are given in Figs. 12(b, c).

Table 2

Calculation parameters of the model

Parameters	water	Ice (0 °C)	granite
ρ (10^3kg/m^3)	1.0	0.9	2.8

346

347

Fig. 11 Computational analysis model of perilous rocks.

E (10^9pa)	-	6.6	41
G (10^9pa)	-	2.48	16.4
ν	-	0.33	0.25
R_c (MPa)	-	-	22.52
R_t (MPa)	-	-	2.75
K_C ($\text{MPa}\cdot\text{m}^{1/2}$)	-	-	0.806
G_c (kJ/m^2)	-	-	0.015

Fig. 12 Mechanical property test of granite

According to CCNBD test (Fowell et al. 1995) and PTS/CP experiment (Backers and Stephansson 2012), the fracture toughness is:

$$\begin{cases} K_{IC} = 0.10224P_{\max} \\ K_{IIC} = 7.74 \times 10^{-2} F_{\max} - 1.80 \times 10^{-3} P_c \end{cases} \quad (16)$$

where $P_{\max}$ is the yield load (kN), P_c is the confining pressure (MPa), $F_{\max}$ is the peak load (kN). K_{IC} , K_{IIC} represents the I/II mode fracture toughness ($\text{MPa}\cdot\text{m}^{0.5}$).

The crack energy release rate G_c is given as $K_C^2(1-\nu^2)/E$, and K_C can be obtained in Eq. (11).

5.2 Parametric study on fracture characters

Under seasonal fluctuations of water-heat combinations, rock collapse is determined by whether a crack in the perilous rock can fracture and along which direction and how far it propagates. All of these can be estimated by some fracture factors, such as SIFs, fracture angles, and propagation length, which are usually affected by the geometry of the crack or perilous rock and ambient temperature variation. Considering the seasonal change of temperature and rainfall, extensive parametric studies including the perilous rock geometry characteristics and ambient temperature (cases 1 to 7, Table 3) were conducted as follows:

Table 3
Geometric data of perilous rock and temperature data in the parametrical study

	Hydrostatic pressure rainy seasons late spring or summer			Freezing stress cooling seasons autumn or early winter		Hydrostatic pressure + stress induced by	
	Case A	Case B	Case C	Case D	Case E	freezing stress	ice gravity
l_0 (m)	0.4/0.7/1/1.3/ 1.6/1.9/2.2/2.5	1.3	1.3	1.3	0.01/0.05/0.1/ 0.5/1.0/1.3	1.3	
l_i (m)	—	—	—	—	—	0.001/0.005/0.01/ 0.02/0.04/0.08/0.16/ 0.32/0.64/1.28	
l_w (m)	—	—	—	—	—	—	0.3/0.6/0.9/ 1.2/1.3
θ_0 (°)	10	30/20/10/0 -10/-20/-30	10	10	10	10	
α (°)	17	17	34/17/ 0/-17	17	17	17	
w	0.05	0.05	0.05	0.025/0.05/0.075 0.1/0.125/0.15	$w/l_0=0.1$	0.05	
Δt (°C)	—	—	-5	-5	-1/-5/-10/ -15/-20	-20	—

(a) In the rainy season (late spring or summer), the hydrostatic pressure calculated by Eq. (4) is applied to the water-filled cracks with different lengths l_0 (case A) and vertical inclinations θ_0 (case B), which follows a triangular distribution and its maximum value is given in Table 4 at the crack tip.

(b) In the cool season (autumn or early winter), water-freezing stress owing to frost heave is applied on the surfaces. With a temperature drop of 5 °C during a single night from 0 °C, its value given by Eq. (6) is 129.6 MPa regardless of how large the vertical inclinations of the rock-free surface a (case C) or crack width w (case D) are. In case E, as shown in Table 5, the freezing stress at different length cracks changes with different temperature drops (Δt) during the seasonal alternations.

Note that the friction along the crack face induced by ice gravity begins to occur in these three

cases. Its value on both crack surfaces is nearly the same (38.289 Pa) even in different cases according to Eq. (10) because the freezing stress is substantially higher than ice gravity in the crack.

Base on case E, we also study crack extension (length) according to Eq. (17). In the calculation, the critical stress σ_{c0} and σ_{c1} , which determine whether propagation continues or not, is obtained by trial. We first assume a propagation length (Δl_0) and calculate the critical stress, and then obtain the calculated extension length using Eq. (17) and compare it with our assumed value. When the extension length given by the formula is consistent with the trial length, it is taken as the solution.

(c) When temperature drops 20 °C from 0 °C during autumn, the water gradually freezes and different lengths of frozen ice (l_i) form in the crack of case F. In this case, the freezing stress remains at 198.2 MPa and the water pressure changes according to Eqs. (6) to (7), as listed in Table 6.

In case G, the ice melts gradually in spring. Except for the hydrostatic pressure, stress induced by gravity of the unmelted ice (l_i) calculated by Eqs. (1) to (5) is also generated, as listed in Table 6.

The average static friction coefficient in our calculation model between rock and ice is given as 0.45 according to laboratory tests and literature values (Mamot et al. 2018), without considering its change with temperature or pressure.

5.3 Simulation on the dynamic evolution of crack extension and investigation of the collapse mechanism during different seasons

In the freeze-thaw zone of the eastern Sichuan-Tibet Mountains, the crack temperature is directly determined by surrounding air temperature and fluctuates dramatically with the seasons, resulting in the phase change of water in the crack and the breaks of the fractured rocks. Hence, the seasonal fluctuation of temperature needs to be considered in collapse simulation. Based on the local meteorological data given in Table 1, a temperature change series (Table 7) is adopted to calculate the crack propagation in a realistic perilous rock at an altitude of 3800 m in Fig. 11(c), and show the collapse mechanism in the freeze-thaw zone.

400 **Table 4**
401 The hydrostatic pressure on the tip of different lengths (l_0 , case A) and vertical inclinations (θ_0 , case B) crack

l_0 (m)	0.4	0.7	1	1.3	1.6	1.9	2.2	2.5	
Pressure (kPa)	3.86	6.76	9.65	12.55	15.44	18.34	21.23	24.13	
θ_0 (m)	-30	-20	-10	0	10	20	30	40	50
Pressure (kPa)	11.0	11.9	12.5	12.7	12.5	11.9	11.0	9.76	8.19

402 **Table 5**
403 Freezing stress applied on the internal surfaces of different cracks with different temperature drops (case E)

Temperature ($^{\circ}\text{C}$)	-1	-5	-10	-15	-20
Δt ($^{\circ}\text{C}$)	1	5	10	15	20
Pressure (MPa)	113.7	129.6	150.9	173.7	198.0

404 **Table 6**
405 Stress applied on internal surfaces of cracks with different lengths of frozen ice in autumn or unmelt ice in spring (case F
406 and case G)

Case F freeing process		Case G melting process		
l_i (m)	Maximum hydrostatic pressure (kPa)	l_i (m)	Maximum hydrostatic pressure (kPa)	p_{tip} (kPa)
0.01	12.64	1.3	-	11.09
0.02	12.54	1.0	2.94	11.47
0.04	12.35	0.7	5.88	11.85
0.08	11.96	0.4	8.82	12.23
0.16	11.17	0.1	11.76	12.61
0.32	9.60	0	12.74	-

407 **Table 7**
408 Temperature changes at an engineering point (3800 m) over a year.

	Cold winter	Warm spring	Hot summer	Cool autumn	Cold winter
Monthly average temperature ($^{\circ}\text{C}$)	-17.6	-6.3	4.8	-6.5	-17.6

409 6 Results and discussion

410 6.1 Fracture mechanism of rock collapse induced by the hydrostatic pressure of crack water in 411 rainy seasons

412 In late spring or hot summer, the ice in cracks of perilous rocks completely melts and the abundant
413 seasonal rainfall leads the hydrostatic pressure to dominate the initiation and propagation of such deep
414 cracks, which leads to collapse events on mountains. In this subsection, we systematically study the
415 influence of length (case A) and vertical inclination (case B) of a crack on the fracture characteristics
416 of perilous rocks under gravity and the hydrostatic pressure (Table 4).

417 Fig. 13(a) depicts the variation of SIFs with crack length. It is clear that a longer crack counts
418 against the stability of the crack. There exists a critical value of crack length l_c that induce the
419 propagation starts, which is 5.75 m. Hence the scale of collapse induced by rainfall in summer can be
420 several meters. Because our model ignores the influence of mechanical property deterioration of

perilous rock during rainfall, the calculated result is slightly larger but nearly agrees with our field study, as discussed in subsection 2.3.

Fig. 13 Influence of the crack length on (a) K_0 and its contributions (b) fracture angle, and (c) propagation (case A). The suffixes (**Gravity**, **Hydro**) are used to mark the load conditions under rock gravity and hydrostatic pressure, respectively.

Comparing with the contribution of gravity terms to the SIF values, the effect of hydrostatic pressure is increasingly significant with increasing crack length. This can be expected because the gravity does not change with crack length but hydrostatic pressure loading does, which also can be verified by the change of fracture angle in Fig. 13(b).

We also can observe how a crack propagates with a mixed-mode considering both hydrostatic pressure and gravity loading in Fig. 13(b). Obviously, the crack propagation angle, which ranges from -34.2° to 22.3° , is close to the contribution from gravity at first and then gradually tends to that of gravity with the increased crack length. More importantly, as shown in Fig. 13(c), compared with a shorter water-filled crack, the propagation of a longer one is more toward the outside of the slope and

436 facilitates collapse.

437

438

439 **Fig. 14** Change of (a) compound SIF K_0 , K_I and K_{II} , (b) fracture angle, and (c) crack propagation direction with the
440 vertical inclination of crack (case B).

441 Apart from crack length, crack inclination also strongly affects the fracture character. For a vertical
442 crack ($\theta_0 = 0$) in Fig. 14(a), K_I achieves its highest value whereas K_{II} is nearly zero, which indicates
443 the fracture follows a purely tensile mode. However, as the crack tends inward ($\theta_0 < 0$) or outward ($\theta_0 >$
444 0), K_{II} increases, which implies that the role of hydrostatic pressure dominates at low crack angles but
445 is gradually replaced by rock gravity as the angle increases.

446 The highest compound SIF K_0 , which indicates the most unstable scenario, appears at a fracture
447 angle of 20° . A negative related fracture angle in Fig. 14(b) will result in larger rock mass collapse, as
448 illustrated in Fig. 14(c). However, in this case, the propagation requires more energy owing to its
449 inward direction (i.e., toward the inner slope).

450 In late spring or summer, fractured rocks with longer and modest outward-inclined cracks are more

prone to serious collapse during rainfall. The critical crack length is typically no less than several meters, which indicates a large volume collapse of perilous rocks unless collapse cannot occur under abundant rainfall.

6.2 Fracture mechanism of rock collapse induced by freezing stress on a fully ice-filled crack during cooling seasons

In autumn or early winter, freezing stress is generated on a crack face when the water begins to freeze with decreasing temperature, which becomes a new dominant factor that determines whether a crack will propagate and if a collapse will occur. In this subsection, by considering the stress driving crack evolution such as freezing stresses (section 5.2 (b), Table 5) and gravity, the effects of vertical inclination of the rock-free face (case C), crack width (case D), and different temperature drops (case E) on the fracture characteristics were studied systematically.

Fig. 15 Variation of SIFs and ϕ with (a) rock-free surface inclination α (case C) and (b) crack width w (case D)

In Fig. 15(a), we illustrate how rock-free surface inclination α influence the fracture character of a frozen crack. The compound SIF K_0 declines quickly with a reduction of α from positive to negative, indicating that the slope with an inward-inclined face ($\alpha > 0$) is more prone to fail than one with an outward face ($\alpha < 0$). The fracture angle (ϕ) remains positive and is beneficial to collapse during this entire process.

The crack width also influences the fracture character. As shown in Fig. 15(b), a wider crack with

470 a smaller slenderness ratio has a smaller value of K_0 and φ and is comparatively stable.

471 The SIFs in the ice-filled crack with the temperature drop in autumn are approximately two orders
 472 of magnitude bigger than those for the water-filled crack in rainy seasons. The critical length calculated
 473 for a crack under freezing stress in case E is only 0.016 m, which is substantially smaller than that
 474 given in a water-filled crack in Fig. 13(a), which indicates that collapses caused by freezing stress
 475 would be very minor most of the time compared with rainfall-induced collapses in summer.

476 **Fig. 16** Effect of crack length and temperature drop Δt on (a) SIFs and (b) propagation length (case E)

477 Fig. 16(a) shows the effect of a temperature drop on SIFs when the crack is frozen in autumn. It
 478 can be easily concluded that larger Δt from 0 °C are associated with higher SIFs at the tip, regardless
 479 of length of the ice-filled crack. Hence, a continuous, sharp, wide-range cooling process could lead to
 480 a large-scale but minor collapse of saturated-fractured rocks, such as freeze-thaw weathering in
 481 mountains, which explains the character of collapse accumulation and agrees well with our field study
 482 discussed in subsection 3.3.

484 We also study the crack propagation length with different temperature drops (Δt) according to Eqs.
 485 (12-14). Fig. 16(b) shows clearly that extension increases for all length cracks in case E when the
 486 temperature drop is bigger, which further confirms that minor collapses (freeze-thaw weathering) are
 487 more likely to occur during rapidly cooling weather, such as cold waves.

488 An important detail to mention is the temperature drop and freezing stress may more strongly affect

the propagation length for a longer crack. As shown Fig. 16(b), the extension increases by no less than five orders of magnitude while the original length of crack varies from 0.01 to 1.3 m, which indicates that propagation during continuous several freeze-thaw cycles is an accelerated process and that longer cracks become longer. This well explains why fractured rocks containing deep cracks can develop comparatively quickly and are prone to collapse.

In autumn or early winter, longer-thinner ice-filled cracks can easily crack under abrupt temperature drops and lead to fracturing, especially for rocks with an inward-inclined face collapse. The freezing stress is so huge that leads to a tiny critical length, which means nearly all visible cracks in nature can be frozen to propagate and cause small collapses easily, like erosion.

6.3 Fracture characteristics of cracks filled with different lengths of frozen ice in autumn or meltwater in spring

The natural variation of temperature is not instantaneous and the freezing/melting of water in cracks is a progressive process. In this subsection, considering the different stresses during the freezing or melting process (Table 6, section 5.2 (c)) and the gravity, the effect of frozen ice length (case F) and meltwater length (case G) on the fracture characteristics was studied systematically.

Fig. 17 Variation of φ , K_0 , K_I , and K_{II} with the length of (a) freezing ice in autumn and (b) meltwater in spring.

Fig. 17(a) shows that the compound SIF K_0 and its individual modes (K_I and K_{II}) on the tip enlarge with the ice length increment during crack freezing in autumn. This indicates more complete freezing during a rapid cooling process, which implies that longer ice in cracks can more easily cause collapse.

Note that the compound SIF K_0 is very close to its individual mode K_I but not K_{II} , which means

that freezing stress dominates the cracking. It can be inferred that a purely tensile fracturing mode may nearly occur when the frozen ice in a crack is sufficiently long. For example, the fracture angle declines sharply when the frozen ice is longer than 0.1 m in Fig. 17(a).

As shown in Fig. 17(b), longer meltwater in a crack is associated with smaller SIFs. Obviously, without considering the softening effect of saturated rock, the stress induced by ice gravity rather than hydrostatic pressure is easily sufficient to split a crack. Moreover, the absolute value of a fracture angle increases when the crack ice melts, indicating the mixed-mode of crack changes gradually from the purely tensile fracturing mode to the purely shear fracturing mode.

In summary, as the temperature continually drops in autumn, cracks extend more easily with the frozen ice growing within them. When the ice melts in warm spring, the crack tends to be stable if not considering the rainfall supply and rock softening.

6.4 Dynamic evolution of crack extension and collapse mechanism

Realistic fracture models (Fig. 11c) were studied to determine the collapse mechanism of fractured rocks during different seasons in the eastern Sichuan-Tibet Mountains. The load conditions are given by the models in section 3 with temperature data in Table 7.

525

Fig. 18 Evolution of crack path and stress contours of perilous rocks during the first (a–d) and second (e–i) autumn.

(d) The final pattern of crack at the end of the first autumn and the initial stress state at the beginning of the second autumn. (i) The final pattern of crack at the end of the second autumn.

528

As shown in Fig. 18, the original crack is 0.5-m long and full of water. In autumn of the first year, only the upper 0.2 m of water is frozen. The calculation reveals that when the temperature drops 17.6 °C below zero, the freezing stress and friction on the crack face reach 186 MPa and 217.15 Pa, respectively, which directly causes the crack to propagate. Figs. 18(a) to (d) show that stress concentrates at the crack tip and causes 0.995 m of propagation under freezing stress during the first autumn. Note that although the crack grows to 1.495 m, it does not meet the critical length and continues to extend in the following winter, spring, and summer.

Propagation occurs again when autumn returns in the second year. As shown in Fig. 18(d), the new crack is almost full of water except for 0.5 m in the upper section. When the temperature drops from zero to −17.6 °C, about 0.3 m of ice forms. As shown in Figs. 18(e) to (i), the crack propagates along nearly a straight line and extends 1.705 m with mode I, which differs from the counterclockwise propagation at the beginning of the first-year autumn, indicating the overwhelming influence of freezing stress when the crack grows longer. When propagation terminates at the end of the temperature drop in second-year winter, the final crack length in Fig 18(i) is 3.2 m.

Fig. 19 Crack propagation under hydrostatic pressure in the summer of the third year and the dynamic evolution of the collapse process.

Due to crack growth in the past 2 years, the rock damage is aggravated and the influence of gravity is enhanced. The calculation shows that the critical crack length decreases to 3.05 m under hydrostatic

stress. Hence, in the third-year spring and autumn when the ice melts and precipitation is abundant, the crack fills with water and begins to propagate again. As shown in Fig. 19, the crack initially propagates clockwise with a fracture angle of -62.2° , which differs substantially from the propagation direction under freezing stress in the previous 2 years. But the trend reverses with later crack growth mainly because hydrostatic pressure dominates the fracture. During the final stage, when the crack extends to 5.8 m, deformation increases sharply from Fig. 19(f) to (g) and collapse eventually occurs.

In brief, the collapse of fractured rocks in different seasons is the result of initiation, propagation, and connection of a primary crack under the fluctuation of water-heat combinations. During this process, freezing stress in the cooling seasons is the major driving force that weathers, breaks, and ultimately destroys a fractured rock with any length cracks, which is as a precondition and first step to collapse. While hydrostatic pressure in the rainy season exerts more of a promoting factor on long cracks with sufficiently small critical length and can directly lead to collapse. Rock damage accumulation due to crack growth can rapidly reduce stability and lead to collapse.

7 Conclusions

A theoretical model of different stresses that drive fracture propagation corresponding to different seasons is proposed based on a field investigation. According to these models, SIFs, fracture angle, and extension are calculated by the fracture mechanics, and the effects of crack characteristics under the seasonal combination of water-heat on crack stability and rock collapse patterns are analyzed. With the help of XFEM, the propagation of the crack is simulated to explain the rock collapse mechanism by applying new theory into practical examples. Some conclusions are obtained as follows:

- 1) Owing to the fluctuation of water-heat combination during different seasons, freezing stress and hydrostatic pressure are generated on internal crack surfaces and become two dominant loads that drive crack evolution in cooling and rainy seasons, respectively.

- 2) Freezing stress dominates whereas hydrostatic stress is relatively small. The critical length of a

572 frozen crack is thus substantially smaller than that of a water-filled crack.

573 3) Almost any longer crack in a natural perilous rock can easily fracture under freezing stress,
574 which mostly results in more frequent, wide-spread, and small-scale collapses (i.e., rock disintegration)
575 during cooling seasons, although some large collapses can also occur. On the contrary, owing to the
576 large critical length, only a few sufficiently long cracks can propagate under hydrostatic pressure,
577 which causes collapse in rainy seasons to become volumetrically larger.

578 4) The extension length of a frozen crack is relatively stable during one continuous cooling process,
579 whereas crack extension during abundant rainfall continues until collapse.

580 5) Freezing stress in the cooling season is the major driving force that weathers, breaks, and
581 destroys fractured rock with cracks of any length, which is a precondition and first step to collapse.
582 Hydrostatic pressure in the rainy season plays more of a role in promoting long cracks that have a
583 critical length, and can directly lead to collapse.

584 6) In general, fractured rocks with longer and modest outward-inclined cracks are more prone to
585 serious collapse during rainfall in late spring or summer. In autumn or early winter, longer and thinner
586 ice-filled cracks more easily crack under the sharp drop of temperature and cause fractured rocks,
587 especially those with inward-inclined faces, to undergo serious collapse.

588 7) As the temperature continually decreases in autumn, cracks become easier to extend with frozen
589 ice growth. When the ice melts in warm spring, the meltwater is more unlikely to cleave the cracks if
590 rainfall supply and rock softening are not considered.

591 8) The collapse of fractured rocks in different seasons is the result of initiation, propagation, and
592 connection of the primary crack under freezing stress or hydrostatic pressure. Collapse is essentially a
593 process of rock damage accumulation owing to crack growth under fluctuating combinations of water
594 and heat.

595 **Declaration of competing interest**

596 The authors declare that they have no known competing financial interests or personal relationships
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659

Figures

Figure 1

Collapse bodies, perilous rock, and cracks in the mountains

Figure 2

The location of the study point. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 3

Collapses in Maojiagou gully and the character of their deposits

Figure 4

Sketch of water-heat combination in mountains of the study area.

Figure 5

Idealized schematic diagram of (a-b) perilous rock and (c) the cracking process in different seasons

Figure 6

Model for crack propagation in perilous rocks. Note the angle θ is positive when the crack inclines outward.

Figure 7

Stress on the surface (a) of a water-filled crack in summer, (b) of an ice-filled crack in winter, and (c) when the ice melts with increasing temperature in spring

Figure 8

Stress on ice-water-filled crack when the temperature drops in cool autumn

Figure 9

Schematic diagram of the crack propagation direction

Figure 10

Calculation sketch of the crack propagation length

Figure 11

Computational analysis model of perilous rocks.

(a) Experimental instrument and specimens

(b) The geometry of a CCNBD specimen

(c) The geometry of a PTS/CP specimen

Figure 12

Mechanical property test of granite

Figure 13

Influence of the crack length on (a) K_0 and its contributions (b) fracture angle, and (c) propagation (case A). The suffixes (Gravity, Hydro) are used to mark the load conditions under rock gravity and hydrostatic pressure, respectively.

Figure 14

Change of (a) compound SIF K_0 , K_I and K_{II} , (b) fracture angle, and (c) crack propagation direction with the vertical inclination of crack (case B).

Figure 15

Variation of SIFs and φ with (a) rock-free surface inclination α (case C) and (b) crack width w (case D)

Figure 16

Effect of crack length and temperature drop Δt on (a) SIFs and (b) propagation length (case E)

Figure 17

Variation of φ , K_0 , K_I , and K_{II} with the length of (a) freezing ice in autumn and (b) meltwater in spring.

Figure 18

Evolution of crack path and stress contours of perilous rocks during the first (a–d) and second (e–i) autumn. (d) The final pattern of crack at the end of the first autumn and the initial stress state at the beginning of the second autumn. (i) The final pattern of crack at the end of the second autumn.

Figure 19

Crack propagation under hydrostatic pressure in the summer of the third year and the dynamic evolution of the collapse process.