Degradation characteristics of shear strength of joints in three rock types due to cyclic freezing and thawing

Jian-qiao Mu a,b,*, Xiang-jun Pei a,b,**, Run-qiu Huang a,b, Niek Rengers b,c, Xue-qing Zou a,b

a College of Environment and Civil Engineering, Chengdu University of Technology, Chengdu 610059, China
b State Key Laboratory of Geo-Hazard Prevention and Geo-Environment Protection, Chengdu University of Technology, 610059, China
c Faculty of Geo-Information Science and Earth Observation (retired), University of Twente, Enschede 7500 AE, The Netherlands

A R T I C L E  I N F O

Article history:
Received 30 September 2015
Received in revised form 17 February 2017
Accepted 24 March 2017
Available online 25 March 2017

Keywords:
Rock joint
Shear strength
Freeze-thaw cycles
Damage model

A B S T R A C T

With massive engineering projects carried out in cold regions where freeze-thaw processes can affect the mechanical properties of rock material, the temporal variation of geotechnical stability is highly concerned. Three typical types of jointed rocks were selected to undergo a number of freeze-thaw cycles after which direct shear tests were conducted on samples of joints in the rock material. The degradation characteristics of the rock joints were examined by the changes of the shear parameters after increasing numbers of freeze-thaw cycles. The results show that the cohesion is more sensitive to cyclic freezing and thawing than the joint friction angle and that the influence on cohesion and joint friction angle is different between hard rocks and soft rocks. Based on the damage mechanics theory and the fact that the deterioration degree rises with increasing numbers of freeze-thaw cycles, the damage state variable was redefined to develop an exponential decay model of freeze-thaw cycles. The comparison of the fitting curves obtained by the proposed model with the experimental results shows that the model reasonably well reflects the degradation characteristics of the shear strength under cyclic freezing and thawing. The model can thus be used to predict the tendency of geotechnical strength degradation of rock masses in cold regions.

© 2017 Elsevier B.V. All rights reserved.

1. Introduction

For engineering projects in cold regions, it is of great importance to understand the influence of freeze-thaw cycles on the degradation of rock mass mechanical performance. Numerous authors have already published about the freeze-thaw damage issue of rock masses and its consequences for the safe construction and operation of projects (Weeks, 1969; Hutchinson, 1974; Li et al., 2014). The freeze-thaw damage is usually ascribed to the thermal expansion-contraction and frost-volume expansion forces caused by the volume increase of the pore water in the rock material and the rock joints when freezing to ice (Franssen and Spiers, 1990; Hori and Morihiro, 1998). It involves thermo-hydro-mechanical (THM) field coupling and ice-to-water phase changes (Neaupane et al., 1999; Kang et al., 2013).

The earlier freeze-thaw studies of intact rock samples mainly focus on the physical-mechanical properties and failure characteristics of rock material under cyclic freeze-thaw action. These studies show that temperature, presence of water, rock type, and number of freeze-thaw cycles play a role (Yamabe and Neaupane, 2001; Nicholson et al., 2000; Chen et al., 2004; Takarli et al., 2008; Matsuoka, 1990), and that the rock deterioration is caused by the formation of micro-cracks and the extension of existing cracks (Remy et al., 1994).

To describe the mechanical behavior affected by discontinuities, damage mechanics is a proper method (Kawamoto et al., 1988), and many constitutive models and damage equations have been established (Mazzars, 1982; Loland, 1980; Frantziskonis and Desai, 1987). Afterwards, the method was applied in freeze-thaw damage field to search for the evolution of mechanical damage and strain softening (Lai et al., 2009; Tan et al., 2011; Liu et al., 2015). As for the mechanical property and damage model of jointed rock, some studies on the samples with pre-existing cracks have been made (Li et al., 2003; Lu et al., 2014; Li et al., 2013). However, limited work has been done on the degradation of primary joint in rock, which is usually very important to the stability of rock engineering.

The main objective of this work was to investigate the degradation characteristics of shear strength of rock joints due to cyclic freezing and thawing. A series of direct shear tests were carried out on rock joints in three typical rock types to determine the changes of cohesion and joint friction angle. Moreover, a damage evolution model was proposed...
to describe the relations between the shear parameters and the number of cycles, and then extrapolated the damage evolution. In addition, two degradation modes were proposed to distinguish between the degradation behavior of soft and hard rocks.

2. Direct shear tests

2.1. Apparatus

The equipment used for the direct shear tests is a portable shear box developed by our laboratory (Su, 2008), which can test samples with irregular form such as rock joints by corresponding pretreatment. It is composed of an upper and a lower shear box, normal and shear load systems and gauges. Before direct shear tests, the irregular samples need to be casted in the two parts of shear boxes by concrete to get a standard form, and a gap of approximately 1 cm is left between the upper and lower concrete casts, in such way that the rock joint to be tested is aligned in the middle of the gap (Fig. 1).

2.2. Test samples and sample preparation

Three typical rock types: granite (hard rock), sandstone (medium-hard rock), and phyllite (soft rock) were selected for the cyclic freeze-thaw tests. The joint samples of these rock types were collected by cutting them from their outcrops of which the weathering degree is weak, and were then wrapped in tape to avoid them falling to pieces during transport. 60 Cubical samples (20 samples for each rock type) of approximately 9 cm × 9 cm × 9 cm in size were collected.

Before the cyclic freeze-thaw tests, these samples were water-saturated. To achieve water-saturation, the samples were dried in an oven (at a temperature of 105 °C) for 48 h, until they reached a constant weight, and were then water-saturated. In order to avoid the influence of pore gas pressure, each sample was immersed first for a quarter of its volume, then half, and then for three quarters in water for two hours. Finally, all samples were immersed in water completely for 48 h. The amount of water increase due to suction was calculated. Physical properties of the three rock types are listed in Table 1.

2.3. Cyclic freeze-thaw test

The 20 samples of each rock type were divided into four groups, with approximately 5 samples in each group. Freeze-thaw tests were then conducted on these groups for 0, 15, 30 and 50 freeze-thaw cycles. These freeze-thaw cycles were carried out as follows: (1) The water-saturated samples were put into a thermostatic freezer at −30 °C for 4 h; (2) The samples were then taken out and immersed in water at room temperature to thaw for 4 h; (3) Step 1 and 2 were repeated. Each freeze-thaw cycle had a duration of 8 h in total, which possibly represents the freeze-thaw weathering process for one year in a cold region.

2.4. Shear test program

All samples, after having undergone different numbers of freeze-thaw cycles, were casted in concrete in a standard block form of 15 cm × 15 cm × 15 cm (Fig. 2). The rock joint was aligned in the middle of the gap reserved between the two parts of the concrete casts. The direct shear tests were then conducted along the joint to determine its shear strength.

During the shear test of the five sample groups, the stress normal to the shear plane was maintained at a fixed value of 0.4 MPa, 0.8 MPa, 1.2 MPa, 1.6 MPa and 2.0 MPa respectively. The shear stress was increased progressively. When the value of the shear stress (monitored on the pressure gauge) no longer increased or even decreased, we assumed that the sample had failed in shear (Fig. 3(a)). Each test took about 5–10 min. Finally, we recorded the values of normal and shear stress and measured the area of the sheared plane. In addition, several typical joint samples were selected after they had failed to measure their profiles by a stylus sensing system (Tan et al., 2014), and the calculated joint roughness coefficients (JRC) values are shown in Fig. 3(b), (c) and (d).

3. Direct shear test results of rock joints

3.1. Normal stress-shear stress relation

After test data processing, the peak shear stresses and normal stresses act on the joints of each rock type after different numbers of freeze-thaw cycles were shown in Table 2, and the scatter diagrams
were plotted. The Mohr failure criteria fitting on the points with different numbers of freeze-thaw cycles were drawn in different colors as well, as shown in Fig. 4.

From Fig. 4, the cohesion and the joint friction angle for different numbers of freeze-thaw cycles can be obtained, and are shown in Table 3. The data of the 0-cycle time represent the samples which did not undergo a freeze-thaw cycle.

### 3.2. Damage variables for shear strength degradation

Based on the classical damage formula proposed by Lemaitre (Lemaitre, 1984), the damage variables for cohesion and joint friction angle can be defined as follows:

\[
D_c = 1 - \frac{c_n}{c_0} \quad (1a)
\]

\[
D_\phi = 1 - \frac{\phi_n}{\phi_0} \quad (1b)
\]

Where, \(c_n\) and \(\phi_n\) are the cohesion \(c\) (kPa) and the joint friction angle \(\phi\) (°) after \(n\) freeze-thaw cycles; \(c_0\) and \(\phi_0\) are the initial strength.

From Eq. (1a) and Eq. (1b), the freeze-thaw damage variables \(D_c\) and \(D_\phi\) after different numbers of cycles can be calculated, and the results are shown in Table 4.

Table 4 shows that the cohesion is more sensitive and shows greater damage than the joint friction angle. And during the first 15 freeze-thaw cycles, both the cohesion and the joint friction angle of each rock type are seriously affected. Moreover, it is worth noting that the degradation degrees of cohesion and joint friction angle show significant differences between hard rock and soft rock: at the same number of freeze-thaw cycles, the \(D_c\) of granite and sandstone are greater than that of phyllite. Contrary to this, the cohesion of phyllite decreases faster than that of granite and sandstone. After 50 freeze-thaw cycles, the \(D_c\) of phyllite has already reached 65%, which in the case of granite and sandstone are 44% and 50%.
4. Proposed damage evolution model

4.1. Definition of the damage state variable

According to the damage mechanics theory, and considering the strength before the freeze-thaw cycles as initial state and after undergoing freeze-thaw cycles as damaged state, the basic equation of strength damage can be described as follows:

\[ S_n = S_0 (1 - D) \]  

(2)

Where, \( S_0 \) is the strength of the rock mass at the initial state; \( S_n \) is the strength of the rock mass at the damaged state; and \( D \) is the damage variable.

If a rock joint is considered as a kind of natural material, with variable mineral composition and cementation, it can be possible assumed that the rock joint is composed of micro-units with different material strength. Statistical methods can then be used to study the micro-damage caused by cyclic freezing and thawing. By combination of the continuous damage theory and the statistical strength theory, Krajcinovic and Silva (1982) proposed the following statistical damage model:

\[ \sigma = E \varepsilon \left( 1 - \frac{N_f}{N} \right) \]  

(3)

Where, \( E \) is elastic modulus; \( \varepsilon \) is strain; \( N_f \) is the number of failed micro-units, and \( N \) is the total number of micro-units.

Combining Eq. (2) with Eq. (3), the damage variable \( D \) can be defined as the ratio of the \( N_f \) to the \( N \). Further assuming that the damage probability density function due to damage force \( F \) is \( P[F] \), the damage
The density function suitable for the micro-damage is the Weibull distribution (Weibull, 1951). Therefore, it is possible to express the damage state variable incorporating freeze-thaw cycles. In many studies (Bayram, 2012; Si et al., 2014; Wang et al., 2015), the damage evolution rate $P(n)$, which represents the damage probability density influenced by freeze-thaw cycles $n$, can be written as follows:

$$ P(n) = \frac{dD}{dn} = a \frac{m}{F_0} \left( \frac{an}{F_0} \right)^{m-1} \exp \left[ - \left( \frac{an}{F_0} \right)^m \right] $$

(9)

Taking the number of freeze-thaw cycles as independent variable, in Eq. (8), the equation of damage evolution rate $P(n)$, which represents the damage probability density influenced by freeze-thaw cycles $n$, can be written as follows:

$$ P(n) = \frac{dD}{dn} = a \frac{m}{F_0} \left( \frac{an}{F_0} \right)^{m-1} \exp \left[ - \left( \frac{an}{F_0} \right)^m \right] $$

(9)

At lower numbers of cycles, the damage force $F$ leads to limited destruction of the weak micro-units (see Fig. 5(a)). With an increase in the number of freeze-thaw cycles, further damage is caused to the weak micro-units, which causes macroscopic deterioration of the material (see Fig. 5(b)). Based on Fig. 5, it is assumed that a linear relationship exists between the freeze-thaw damage force $F$ and the number of freeze-thaw cycles $n$, (when $n$ is 0, the $F$ is also 0), thus $F = an$. The linear coefficient $a$ is the growth rate of $F$ with the increase in the number of cycles $n$. Therefore, the damage probability density function $P[F]$ and the damage variable $D$ can be transformed as follows:

$$ P[F] = \frac{m}{F_0} \left( \frac{an}{F_0} \right)^{m-1} \exp \left[ - \left( \frac{an}{F_0} \right)^m \right] $$

(7)

$$ D = 1 - \exp \left[ - \left( \frac{an}{F_0} \right)^m \right] $$

(8)

Taking the number of freeze-thaw cycles as independent variable, in Eq. (8), the equation of damage evolution rate $P(n)$, which represents the damage probability density influenced by freeze-thaw cycles $n$, can be written as follows:

$$ P(n) = \frac{dD}{dn} = a \frac{m}{F_0} \left( \frac{an}{F_0} \right)^{m-1} \exp \left[ - \left( \frac{an}{F_0} \right)^m \right] $$

(9)

According to Eq. (10), we can calculate the $S_n$ for any number of freeze-thaw cycles when the material parameters $F_0/a$ and $m$ are confirmed, and the equation has a certain physical significance.

### 4.3. Calibration of the material parameters and model verification

The method to obtain the material parameters, $F_0/a$ and $m$, only relies on data fitting. After making a simple transform of Eq. (10) and taking a logarithm on both sides of the equation, Eq. (10) is becoming:

$$ - \ln \left( \frac{S_n}{S_0} \right) = \left( \frac{n}{(F_0/a)} \right)^m $$

(11)

The power function of Eq. (11) can be fitted with the shear test results in Table 3. The values of the $F_0/a$ and $m$ are then obtained, and are shown in Table 5.

The correlation coefficients $R^2$ of the fitting curves in Table 5 are all above 0.959. It shows that the derived freeze-thaw damage evolution model is reliable. After entering the fitting results of $(F_0/a)_{c.c}$ and $m_{c.c}$ into Eq. (10), the resulting fitting curves are shown in Fig. 6.
Since the sensitivities of cohesion and joint friction angle to cyclic freezing and thawing are different, it is possible to define the following damaged shear strength by replacing Eq. (10) into the Mohr-Coulomb strength criterion:

$$
\tau_n = c_0(1-D_c) + \sigma \tan \varphi_0 \left(1-D_\varphi\right)
$$

(12a)

$$
D_c = 1 - \exp \left[-\left(\frac{n}{(F_0/a)_{c,\varphi}}\right)^{m_c}\right]
$$

(12b)

In conclusion, the derived model works reasonably well and we assume that it has universal theoretical and practical applicability. However, the curve fitting by only four points for each line is not convincing enough, so the applicability of the model still needs to be further verified.

5. Degradation characteristics and trends in damage evolution

The high degrees of correlation between the fitting curves and the experimental results give the reason to assume that the derived model can correctly describe the degradation characteristics which lead to the following trends in the damage evolution:

1. The degradation of the shear strength of joints in three rock types under cyclic freezing and thawing are nonlinear in trend, and the material parameters $F_0/a$ and $m$ control the characteristics of the degradation.

2. With Eq. (9), the damage evolution rates of cohesion $c$ and joint friction angle $\varphi$, in dependence from the number of freeze-thaw cycles can be obtained. As shown in Fig. 7, the damage rates of cohesion and joint friction angle for each rock type are high during the first freeze-thaw cycles, which means the initial freeze-thaw behavior acting on the material is serious. Comparison shows that the cohesion is more sensitive to cyclic freezing and thawing than the joint friction angle and leads to greater damage. However, with increasing numbers of freeze-thaw cycles, the damage rate decreases gradually which means that the influence of freeze-thaw cycles tends to level off.

As mentioned in Section 2.3, the degradation degrees of cohesion and joint friction angle due to freeze-thaw cycles are different between hard rocks and soft rocks, which can also be seen in Fig. 7. The damage rate of cohesion of phyllite is generally higher than that of granite and sandstone. While the damage rates of joint friction angles are the opposite. For this case, two degradation modes (Mu et al., 2013) could be used to describe the difference:

1. Hard rocks.

Crack extension caused by frost-volume expansion forces is the main degradation mode for hard rocks, such as granite and sandstone. The joint friction angle $\varphi$ is influenced by this mode. It can lead to failure along the expanded discontinuities at lower values of shear stress.

2. Soft rocks.

Particle disintegration is the main degradation mode for soft rocks, such as phyllite. The temperature changes destroy the bonds between the micro-particles, which weakens the cementation degree. The decrease of cohesion $c$ is mainly due to this mode.

It should be noted that the two degradation modes act on rock material at the same time, only with different intensities. Therefore, the values of cohesion $c$ and joint friction angle $\varphi$ are both affected by freeze-thaw cycles.

6. Discussion

The damage to rock joints due to cyclic freezing and thawing brings potential safety hazards to engineering projects in cold regions. Until recently, a simple method used for describing the tendency in strength degradation is statistical analysis. The disadvantage of this method is that it needs a large number of test data and cannot be used to describe the freeze-thaw damage process in-depth. In this study, a new method is proposed to describe the degradation evolution due to freeze-thaw cycles.

However, it is still difficult to measure the magnitude of the freeze-thaw damage force, as the relation between the damage force and the number of freeze-thaw cycles remains to be solved, and the confirmation of the material parameters $F_0/a$ and $m$ still requires more test results.

7. Conclusions

The shear strength degradation of the joint planes in three rock types with different characteristics were investigated by a series of direct shear tests, and the trends in damage evolution were analyzed with a derived model of freeze-thaw cycles.
The conclusions from this research are as follows:

(1) The shear strength of joint plane decreases with increasing numbers of freeze-thaw cycles, but shows an obvious nonlinear behavior. In most cases, the cohesion decreases more seriously than the joint friction angle.

(2) The developed damage model, incorporating freeze-thaw cycles, works reasonably well and reflects the degradation characteristics of three rock types. It can be used to predict the tendency of damage evolution with increasing numbers of freeze-thaw cycles.

(3) Two degradation modes, one characterized by crack extension and the other by particle disintegration are used to describe the different influences of freeze-thaw process on the cohesion and joint friction angle degradations for hard rocks and soft rocks.

Acknowledgements

We would like to thank the reviewers, whose constructive comments were helpful for improving this paper. This research was funded by the Creative Research Groups of China under Grant No. 41521002, and by the National Natural Science Foundation of China under Grant No 41572283.

Appendix A Supplementary data.

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.coldregions.2017.03.011. These data include the Google map of the most important areas described in this article.

References


