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Effects of freeze–thaw on the determination and application of parameters of slope rock mass in cold regions

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ABSTRACT

Freeze–thaw could significantly affect the deterioration of mechanical properties of slope rock mass, and should be taken into consideration when determining the parameters of slope rock mass in cold regions. In this paper, we first measured the freeze–thaw coefficient using the freeze–thaw cycle test on intact slope rock mass from Mengku Mine, then determined the freeze–thaw correction coefficient by taking field geological investigation and rock hardness into consideration, and established a linear relationship between Geological Strength Index (*GSI*) and Tianshan slope rock mass rating (TSMR) system (a rock mass classification method applicable in cold regions) by incorporating the freeze–thaw correction coefficient into the expression of rock mass effect. The results show that freeze–thaw correction coefficient varies between 0.71 and 0.93, and *GSI* varies between 45 and 63. We further determined the parameters of slope rock mass by employing the generalized Hoek–Brown criterion and using it established a numerical rock slope excavation model and analyzed the rock mechanic features and stability status. The results indicate that the maximum ground deformation of slop rock mass is 15 mm, and the floor rebound is about 42 mm. Overall, the method described in the present paper can be used to select slope rock mass in cold regions and calculate the slope rock stability.

1. Introduction

Accurate rock mass parameters are prerequisites for precise analysis of slope stability in open pit mine. However, due to the complexity of geological evolution, the structure characteristics and mechanical properties of rock mass vary significantly, making it difficult to accurately select rock mass parameters (Feng and Yang, 1999; Swoboda et al., 1999). Although many methods such as empirical analysis, field test, numerical analysis, displacement back analysis and uncertainty analysis have been widely used in current engineering practice for selecting rock mass parameters (Yang et al., 2011), they all have their own merits and drawbacks. It is commonly believed that the methods which combine laboratory rock mechanics test, discontinuity influence and size effect with reduced strength of intact rock can meet the engineering needs. Among these methods, estimation theories based on the Hoek–Brown criterion are the most practicable ones (Su et al., 2009; Wang et al., 2007).

Hoek–Brown criterion is used to determine the rock strength and mainly focused on two aspects: the intact rock parameters as well as the rock mass structures and discontinuity surface conditions. For rock mass, rock mass rating (RMR) is originally used and geological strength index (*GSI*) is recently proposed by Hoek (Benz et al., 2008; Sharan, 2008). Because these indexes are significantly influenced by geological conditions, geographical environment, etc., accurate selection of rock mechanics parameters lies in whether these indexes (e.g., RMR, *GSI*) can be determined accurately.

In the cold regions, pore water and fissure water existing in rock mass usually cause freeze–thaw cycle effect with the change of temperature. This effect is one of the main factors influencing the deterioration of mechanics properties of rocks in cold region, and affecting the selection of rock mass parameters. When applying the Hoek–Brown's criterion to select rock mass parameters, the influence of freeze–thaw on *GSI* must be taken into consideration.

Currently, studies on the effects of freeze–thaw on rock mass are mainly concentrated on the laboratory tests (Inigo et al., 2013; Kodama et al., 2013; Nicholson and Nicholson, 2000; Ozcelik et al., 2012; Takarli et al., 2008; Tan et al., 2011; Xu and Liu, 2005). Although laboratory researches have made many valuable achievements, how to use these laboratory results to select parameters of rock mass in cold regions for engineering practice is still an unsolved problem.

To address the issue, we selected slope rock mass from Mengku Iron Mine, Xinjiang, China, as our study object. Firstly, we determined the freeze–thaw coefficient of intact rocks using indoor freeze–thaw cycle test. Then, we measured the freeze–thaw correction coefficient of rock mass by taking both field geological survey and rock hardness into consideration. Secondly, we employed TSMR method, a classification

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Table 1
Saturated compressive strengths of rock samples after freeze–thaw tests.

Lithology	Average saturated compressive strength/MPa			
	Without freeze–thaw cycle	10 cycles of freeze–thaw	20 cycles of freeze–thaw	30 cycles of freeze–thaw
Granulite	157.1	143.9	137.7	117.1
Amphibole granulite	125.7	116.9	113.2	111.7
Bedding granulite	110.5	100.9	96.8	89.4
Biotite–amphibole–plagioclase gneiss	68.4	60.3	57.4	48.5

Table 2
Freeze–thaw coefficients of rock mass after different cycles of freeze–thaw.

Lithology	Without freeze–thaw	10 cycles of freeze–thaw	20 cycles of freeze–thaw	30 cycles of freeze–thaw
Granulite	1.0	0.92	0.88	0.75
Amphibole granulite	1.0	0.93	0.90	0.89
Bedding granulite	1.0	0.91	0.88	0.81
Biotite–amphibole–plagioclase gneiss	1.0	0.88	0.84	0.71

method for rock mass in cold regions, to evaluate the quality of slope rock mass obtained from the mine, established a linear relationship between *GSI* and TSMR values, and determined rock mass parameters based on generalized Hoek–Brown criterion. Thirdly, on the basis of these parameters, we established a three dimensional numerical excavation model, used four typical cross-sections to analyze the stability of slope rock mass, and analyzed the mechanics features and stability status of the slope rock mass.

2. Rock mass quality evaluation with the consideration of freeze–thaw cycle effect

Mengku Iron Mine is located in a cold and high mountainous area with elevation of above 1000 m. Its temperature varies significantly from season to season. Its average temperature was −27 °C in winter and 26 °C in summer and its lowest and highest temperatures were −50 °C and 43 °C, respectively. Each year there are nearly six months with temperature below 0 °C. Therefore, it is necessary to consider the influence of freeze–thaw cycles when using the rock mass classification method.

2.1. Determination of freeze–thaw coefficient and freeze–thaw correction coefficient

Several representative types of intact rock, such as granulite, amphibole granulite, bedding granulite and biotite–amphibole–plagioclase gneiss, were selected as samples. They were of cylindrical shape with a diameter of 5 cm and height of 10 cm. The specimens of each type of the rocks were frozen to −20 °C by placing in a refrigerator for 12 h and thawed to 20 °C by placing in a water bath for 12 h for 0, 10, 20 and 30 cycles, respectively. After freeze–thaw for 10 cycles, each specimen was subjected to uniaxial compressive strength test. Test results are tabulated in Table 1.

According to the "Specifications for rock tests in water conservancy and hydroelectric engineering" SL264-2001 (YRSRI, 2001), the effect of freeze–thaw cycle on rock damage can be expressed by freeze–thaw coefficient:

$$K_f = \frac{\overline{R_f}}{\overline{R_s}} \quad (1)$$

where K_f is the rock freeze–thaw coefficient; $\overline{R_f}$ and $\overline{R_s}$ are the average of the saturated uniaxial compressive strength after and before freeze–thaw test, respectively. Rock freeze–thaw coefficients after each cycle of freeze–thaw are shown in Table 2. As can be seen from Table 2, freeze–thaw coefficient of these four types of rocks decreases as the cycles of freeze–thaw are increasing, indicating that rock strength decreases as the cycles of freeze–thaw are increasing. However, different rocks have different freeze–thaw coefficient reduction ratios. Generally, rocks with higher strength have larger strength loss than rocks with lower strength, indicating that rock damage caused by freeze–thaw cycles has a relationship with rock hardness. Because the freeze–thaw coefficient was calculated based on the experiments conducted on intact rocks without taking the rock mass structure into consideration, it must be modified according to the rock hardness and field geological survey when used for rock mass. Table 3 shows the relationship between rock freeze–thaw correction coefficient and rock hardness. Table 4 lists the freeze–thaw correction coefficients obtained after combining the joint fissure investigation of the rock mass. The results of uniaxial compression tests (the average saturated compressive strengths without freeze–thaw cycle in Table 1) and the freeze–thaw correction coefficients of different rock masses (Table 4) suggest that granulite stratum and amphibole granulite stratum are hard rocks and bedding granulite stratum and biotite–amphibole–plagioclase gneiss stratum are relatively hard rocks.

2.2. Evaluation of slope rock mass quality

The most widely accepted rock mass classification methods include Q, RMR, SMR and CSMR. Because CSMR method introduces the altitude correction coefficient and discontinuity surface correction coefficient, it is particularly applicable to evaluate the high-steep rock slope (Sun et al., 1997; Jiang et al., 2014). After analyzing the lithology, structural characteristics and morph structure of slope rock mass from Mengku Mine, we chose CSMR method to evaluate the slope rock mass quality. However, this method does not consider the influence of freeze–thaw cycles. Zhang & Huang et al. (2010)

Table 3
Freeze–thaw correction coefficient of different rock masses.

Rock types	Freeze–thaw correction coefficient
Hard rock	≥0.9
Relatively hard rock	0.7–0.9
Relatively soft rock	0.5–0.7
Soft rock	0.2–0.5
Special soft rock	≤0.2

Table 4
Freeze–thaw correction coefficient of rock mass in the study area.

Rock stratum	Freeze–thaw correction coefficient (η)
Granulite stratum	0.9
Amphibole granulite stratum	0.9
Bedding granulite stratum	0.85
Biotite–amphibole–plagioclase gneiss stratum	0.8