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Estimation of the joint roughness coefficient of rock joints by consideration of two-order asperity and its application in double-joint shear tests

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ABSTRACT

Joint roughness has a significant influence on the shear behavior of rock joints. Many different statistical parameters have been used to estimate the joint roughness coefficient (*JRC*) of rock joints, depending on what is most easily available and convenient. Six statistical parameters, Z_2, SF, R_P-1, $\log(Z_2)$, $\log SF$ and $\sqrt{R_P-1}$ of ten typical roughness profiles were calculated at different sampling intervals (*SI*). The results indicate that the *JRC* of rock joints could not be accurately estimated by using only a single statistical parameter. Because the first-order and second-order asperities of joints have different effects on shear behavior, a classified and weighted fitting formula, $JRC = 16.09 \log Z_2^{1st} + 12.70 \log Z_2^{2nd} + 33.75$ ($SI = 5.0$ mm & 0.5 mm), is proposed to estimate the *JRC*. Shear tests on sandstone joints indicate that the maximum *JRC* along the shear direction is appropriate to represent the total joint surface and estimate the shear strength. This formula was adopted to estimate the *JRC* in double-joint shear tests, and the results show that the mechanical behavior of double parallel joints is closely related to the interlayer rock and the weaker joint. Under lower normal stress, the interlayer rock does not fracture, and the weaker joint determines the peak shear strength of the rock specimen. In contrast, under higher normal stress, the peak shear strength is attained when the tensile fractures initiate in the interlayer rock, and it has also relevancy to the *JRC* of double joints and interlayer thickness.

1. Introduction

Many studies have been performed to determine the relationship between joint roughness and shear behavior. Of these approaches, Eq. (1) is widely used and was proposed by Barton (1973) to estimate the peak shear strength of rock joints,

$$\tau = \sigma_n \tan\left[JRC \log\left(\frac{JCS}{\sigma_n}\right) + \varphi_b\right] \tag{1}$$

where τ is the peak shear strength of the rock joint, σ_n is the effective normal stress, *JRC* is the joint roughness coefficient, *JCS* is the joint wall compressive strength, which is equal to the uniaxial compressive strength (*UCS*) of the rock for the fresh rock joints, and φ_b is the basic friction angle. Ten typical profiles were defined for typical *JRC* values by visual assessment (Barton and Choubey, 1977). This method was recommended by the International Society for Rock Mechanics (ISRM) commission on test methods (ISRM, 1978) and this quantitative estimation of *JRC* values has been extensively studied for decades.

Along the shear direction, the joint profile can be determined by using a profile comb. Based on the coordinate values (x_i, y_i) of a joint profile, a series of statistical parameters to quantify the joint profile have been defined, and among them, Z_2, SF, and R_P are the most commonly used ones. The root mean square of the first deviation of the

Abbreviations: D, fractal dimension (dimensionless); *L*, length of joint surface (mm); *JRC*, joint roughness coefficient (dimensionless); $P_0(0.5)$, original roughness profile containing both the first-order and second-order asperities, $SI = 0.5$ mm; $P_1(5.0)$, roughness profile containing the first-order asperities only, $SI = 5.0$ mm; $P_2(0.5)$, roughness profile containing the second-order asperities only, $SI = 0.5$ mm; R_P, roughness profile index (dimensionless); R_P^{1st}, R_P^{2nd}, R_P of the first-order and second-order asperities, respectively (dimensionless); *SSE*, sum of squared error (dimensionless); *SF*, structure function (mm^2); SF^{1st}, SF^{2nd}, *SF* of the first-order and second-order asperities, respectively (mm^2); *SI*, sampling interval of a roughness profile (mm); *T*, thickness of the interlayer rock in a rock sample with double parallel joints (mm); x_i, y_i, coordinate values of a roughness profile (mm); Z_2, root mean square of the first deviation of the profile (dimensionless); Z_2^{1st}, Z_2^{2nd}, Z_2 of the first-order and second-order asperities, respectively (dimensionless); σ_c, uniaxial compressive strength of rock (MPa); σ_n, normal stress of a rock sample (MPa); τ_{peak}, peak shear stress (MPa).

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profile, Z_2, was proposed by Myers (1962); the structure function, SF, was proposed by Sayles and Thomas (1977); and the ratio of the true length of a fracture surface trace to its projected length, R_P was proposed by El-Soudani (1978). Their definitions are as follows:

$$Z_2 = \left[\frac{1}{L}\int_{x=0}^{x=L}\left(\frac{dy}{dx}\right)^2 dx\right]^{1/2} = \left[\frac{1}{L}\sum_{i=1}^{n-1}\frac{(y_{i+1}-y_i)^2}{x_{i+1}-x_i}\right]^{1/2} \quad (2)$$

$$SF = \frac{1}{L}\int_{x=0}^{x=L}[f(x+dx)-f(x)]^2 dx = \frac{1}{L}\sum_{i=1}^{n-1}(y_{i+1}-y_i)^2(x_{i+1}-x_i) \quad (3)$$

$$R_P = \frac{1}{L}\sum_{i=1}^{n-1}\left[(x_{i+1}-x_i)^2 + (y_{i+1}-y_i)^2\right]^{1/2} \quad (4)$$

where L is the length of the joint profile, and x_i and y_i are coordinates of the joint profile.

Next, these indexes were related to JRC. The regression correlation between Z_2 and SF with JRC were established by Tse and Cruden (1979), and Eqs. (5), (6), and R_P were used by Maerz et al. (1990), Eq. (7).

$$JRC = 32.2 + 32.47\ \log Z_2 \quad (5)$$

$$JRC = 37.28 + 16.58\ \log SF \quad (6)$$

$$JRC = 411(R_P - 1) \quad (7)$$

However, the validity of the estimation of JRC based on roughness parameters remains under debate, because parameters Z_2, SF, and R_P and their variants are sensitive to the sampling interval (SI) of roughness profiles. Yu and Vayssade (1991) found that Z_2 and SF changed for sampling intervals of 0.25 mm, 0.5 mm, or 1.0 mm, suggesting that the coefficients of these fitting formulae must be changed for different sampling intervals. However, Yang et al. (2001a) questioned the conclusions from Tse and Cruden's (1979) work because enlarging 10 cm profiles by 2.5 times resulted in self-transformation, and they proposed fitting formulae of JRC with modified coefficients. Jang et al. (2014) noted that Z_2 and R_P decreased as the sampling interval increased, but the SF values increased very rapidly as the sampling interval increased. Additionally, other parameters, such as the fractal dimension D, and $\theta_{max}^*/(C+1)_{2D}$, could also be used to quantify JRC values, but are all associated with the sampling interval (Tatone and Grasselli, 2010; Jang et al., 2014). Thus, it is imperative to consider sampling interval in accurate estimations of JRC.

The asperity of a rough joint can occur on many scales. As early as 1966, Patton (1966) classified the asperity of rough joints into first-order (waviness) and second-order (unevenness) categories, and reported that the shear behavior of rock joints was primarily controlled by second-order and first-order asperity during small and large displacements, respectively. This viewpoint was later supported by Barton (1973) and Hoek and Bray (1981), who found that second-order asperity controlled the shearing process under lower normal stress. However, under higher normal stress, the shearing process was controlled mainly by first-order asperity. Because the JRC is widely adopted in engineering practice, it is quite important to relate the asperity categories and JRC. Yang et al. (2001b) conducted shear tests to clarify the effect of asperity order on the roughness of artificial rock joints, and concluded that by combining the JRC and Hurst exponent H (or fractal dimension D) allowed a more accurate description of roughness behavior due to multi-scale asperities. In addition, Chen et al. (2012) used fractal dimension D and the degree of waviness w_d to estimate the JRC, but the parameter w_d may omit important information, especially for a long roughness profile. Additionally, the best way to quantify the first-order and the second-order asperities to estimate the JRC remains unclear.

In most studies of shear tests on rock joints, only a single joint was tested, and these studies confirm that the JRC has an important influence on the peak shear strength of rock joints. However, in real rockmass, adjacent joints may interact with each other, and therefore, the shear behavior of double rock joints may be very different from that of a single joint. In this respect, systematic experiments are still needed to understand the shear behavior of double rock joints under the influence of JRC values.

In this paper, first, the ten typical roughness profiles were decomposed into two classes of new profiles that separately contain the first-order and second-order asperities. Second, the statistical parameters of the two classes of new profiles were weighted in a series of fitting formulae to estimate JRC values; the best one was selected and verified during the shear tests. Finally, this approach was used to estimate JRC and peak shear strength during the shear tests of double parallel joints.

2. Correlation between the statistical parameters and sampling interval

By using statistical parameters to estimate the JRC of rock joints, any sampling interval would omit some information below a certain threshold. Typically, sampling intervals between 0.1 mm to 2 mm are used. In this study, the ten typical profiles were retrieved using a sampling interval from 0.25 mm to 10 mm.

In order to calculate the statistical parameters of the ten typical roughness profiles, the coordinate values (x_i, y_i) are essential elements. To do this, the image of the joint profiles was imported into the AutoCAD software. The profiles were scaled to 10 cm in length and traced with the command "polyline"; each generated polyline contains more than four hundred points (the original $SI \le 0.25$ mm) to accurately duplicate the original roughness profiles. Next, the polylines that represent the joint profile were sampled and their coordinates of sampling points were imported into a MATLAB programme written by ourselves, in which the roughness profiles were redrawn at a certain sampling interval, such as 0.5 mm. As a result, the new roughness profiles were composed of a series of equally spaced points. Based on the coordinates of these points, the statistical parameters (Z_2, SF, $R_P - 1$ and three typical types of their variations $\log Z_2$, $\log SF$, and $\sqrt{R_P - 1}$) were calculated at different sampling intervals, and the results are shown in Fig. 1.

From Fig. 1, it could be found that the statistical parameters increased with the increased sequence numbers of these profiles. However, when the sampling interval was <1 mm, almost all of the six parameters tended to decrease between the 4th and 6th roughness profiles, which is consistent with the result calculated by Chen et al. (2012) using the fractal dimension D. In addition, when the sampling interval was larger than 1 mm, the six parameters tended to decline between the 8th and 9th roughness profiles, with other fluctuations. In practice, the JRC values given by Barton increase approximately in a straight line, as shown in Fig. 2. From this perspective, this trend of the six statistical parameters occurs only at the sampling interval of 1 mm. Even so, as shown in Fig. 1, there are little differences between the 4th, 5th, and 6th roughness profiles at a sampling interval of 1 mm. Therefore, it is not reasonable to estimate the JRC by using a single statistical parameter.

3. Estimation of *JRC* by weighting the first-order and second-order asperities

The first-order and second-order asperities play different roles during the shearing process, and make different contributions to shear strength. Therefore, the JRC can be estimated by classifying and weighting the statistical parameters based on the effects of the first-order and second-order asperities.