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 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 the shear behavior, a classified and weighted method fitting formula, $JRC=16.09 \log Z_2^{1st} + 12.70 \log Z_2^{2nd} + 33.75$ ($SI = 5.0\text{mm} \& 0.5\text{mm}$), is proposed to estimate *JRC* of the rock joints. 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.

Keywords: statistical parameter, joint roughness coefficient (*JRC*), roughness profile, shear test, parallel joints, shear strength

Abbreviations:

D Fractal dimension (dimensionless)

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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, $SI=0.5\text{mm}$
$P_1(5.0)$	Roughness profile containing the first-order asperities only, $SI=5.0\text{mm}$,
$P_2(0.5)$	Roughness profile containing the second-order asperities only, $SI=0.5\text{mm}$,
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)

1. Introduction

Many studies have been performed to determine the relationship between the 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,

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

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 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 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 profile, Z_2 , was proposed by Myers (1962) in 1962; the structure function, SF , was proposed by Sayles and Thomas (1977) in 1977; 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:

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

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

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

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 correlations between Z_2 and SF with *JRC* values were established by Tse and Cruden (1979), and Eq.5, Eq.6, and R_p was 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 0.25mm, 0.5mm, or 1.0mm, suggesting that the coefficients of these fitting formulas must be changed for different sampling intervals. However, Yang et al. (2001a) questioned the conclusions from Tse and Cruden's (1979) work because enlarging 10cm profiles by 2.5 times resulted in self-transformation, and they proposed fitting formulas 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 $\theta_{\max}^*/(C+1)_{2D}$, which could also be used to quantify the *JRC* values, but are all

associated with sampling interval (Tatone and Grasselli, 2010; Jang, 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 et al. (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 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. 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 are quantified 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 very different from that of a single joint. In this respect, systematic experiments are still needed in order 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 formulas to estimate *JRC* values; and then, the best one was selected and verified during the shear tests. Finally, this approach was used to estimate *JRC* and the peak shear strength during the shear tests of double parallel joints.

2. Correlation between the statistical parameters and sampling interval

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

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 them with the command “polyline”; each generated polyline contains more than four hundred of points (the original $SI \leq 0.25\text{mm}$) to accurately duplicate the original roughness profiles well. 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 0.5mm. 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.

[Fig. 1 goes here]

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 less than 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 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 are 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 1mm. Even so, as shown in Fig.1, there are little obvious differences between the 4th, 5th, and 6th roughness profiles at a same sampling interval of 1mm. Therefore, it is not reasonable to estimate the JRC by using a single statistical parameter.

[Fig. 2 goes here]

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 the 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.

The ten typical roughness profiles were redrawn at two different sampling intervals (SI s) with the same method as described in Section 2. The gap between the two SI s is an order of magnitude, e.g., $SI=5.0\text{mm}$ and

$SI=0.5\text{mm}$, where 5.0mm represents first-order asperity and 0.5mm represents the second-order asperity. Next, the abscissas (x_i) were kept constant and the ordinates (y_i) of the redrawn profiles were subtracted at larger SI from those at smaller SI . Fig. 3a shows the 10th typical roughness profile redrawn at $SI=0.5\text{mm}$, $P_0(0.5)$, which should contain both the first-order and second-order asperities, and the profile at $SI=5\text{mm}$, $P_1(5)$, should contain the first-order asperity only, as shown in Fig. 3b. By subtracting the ordinate (y_i) of Fig. 3b from Fig. 3a, we can obtain the profile for the second-order asperity only, $P_2(0.5)$, as shown in Fig. 3c. Finally, statistical parameters of the classified roughness profiles that are composed of a series of equally spaced points can be calculated at different sampling intervals.

[Fig. 3 goes here]

Fig. 4. shows the classified statistical parameters of $P_0(0.5)$, $P_1(5.0)$, and $P_2(0.5)$ of the ten typical roughness profiles. Although the overall trend of the six statistical parameters is still increasing, significant difference appears between $P_1(5.0)$ and $P_2(0.5)$ as the sequence numbers increase. For instance, Z_2 (Fig. 4a) decreases between the 4th and 6th roughness profiles for $P_2(0.5)$ but increases for $P_1(5.0)$. The opposite tendency is seen for the 8th roughness profile. This result confirms that the 4th roughness profile contains many second-order asperities but lacks the first-order ones. The opposite is true for the 6th and the 8th roughness profiles. With slight differences, the same phenomenon also occurs for the other 5 statistical parameters, SF , R_p-1 , $\log Z_2$, $\log SF$, and $\sqrt{R_p - 1}$. Therefore, it is more reasonable to estimate the JRC by decomposing the typical roughness profiles into the first-order and the second-order asperities.

[Fig. 4 goes here]

On the basis of first-order and second-order asperities of the roughness profiles, the statistical parameters have also been divided into two classes, for instance, Z_2 is decomposed into Z_2^{1st} and Z_2^{2nd} , which represent the first-order and second-order asperities, respectively. For comparison, in addition to the sampling interval combination of 5.0mm and 0.50mm , those of 2.5mm and 0.25mm and 10.0mm and 1.0mm were also examined.

Next, a series of classified and weighted fitting formulas of JRC were obtained, by using the least square method. These formulas contain two parameters that represent the first-order and second-order asperities. To determine the best formula and to compare with the results estimated by the fitting formulas containing a single statistical parameter, the sum of squared error (SSE) was used for quantitative comparison, rather than the commonly used correlation coefficient, because at least two correlated variables were included in the new fitting formulas. As listed in Table 1, the smaller the SSE is, the better fitting effect it achieves.

[Table 1 goes here]

$$JRC=75.11 Z_2^{1st} + 3.33 Z_2^{2nd} - 2.79 \quad (SI = 2.5\text{mm} \& 0.25\text{mm}) \quad (8)$$

$$JRC=91.73 SF^{1st} - 57.13 SF^{2nd} + 3.89 \quad (SI = 2.5\text{mm} \& 0.25\text{mm}) \quad (9)$$

$$JRC=472.16 (R_p-1)^{1st} - 20.42 (R_p-1)^{2nd} + 3.32 \quad (SI = 2.5\text{mm} \& 0.25\text{mm}) \quad (10)$$

$$JRC=16.09 \log Z_2^{1st} + 12.70 \log Z_2^{2nd} + 33.75 \quad (SI = 5.0\text{mm} \& 0.50\text{mm}) \quad (11)$$

$$JRC=11.32 \log SF^{1st} + 5.79 \log SF^{2nd} + 34.17 \quad (SI = 2.5\text{mm} \& 0.25\text{mm}) \quad (12)$$

$$JRC=108.12 \sqrt{R_p-1}^{1st} + 6.31 \sqrt{R_p-1}^{2nd} - 3.66 \quad (SI = 2.5\text{mm} \& 0.25\text{mm}) \quad (13)$$

Obviously, from Table 1, the classified and weighted fitting formulas are better than those containing a single parameter only. For the six statistical parameters, the minimum *SSE* were derived from the classified and weighted fitting formulas, and Eq.8 to Eq.13 list the best fitting formulas for each statistical parameter. To obtain highly accurate *JRC* values by using Eq.8 to Eq.13, it is imperative to use the right sampling interval combination. Specifically, Z_2 , SF , R_p-1 , $\log SF$, and $\sqrt{R_p-1}$ exhibit minimum *SSE* at $SI = 2.5\text{mm} \& 0.25\text{mm}$, but the $\log Z_2$ shows the minimum *SSE* at $SI = 5.0\text{mm} \& 0.50\text{mm}$, and it is the lowest of all *SEEs*.

Thus, the classified and weighted fitting formula of $\log Z_2$ (Eq.11) is the most accurate for estimating *JRC*. The *JRC* values given by Barton and Choubey (1977) and those estimated by using Eq.11 are illustrated in Fig.2. Although the 4th roughness profile is slightly overestimated and the 9th one is slightly underestimated, the other points match reasonably well.

The graphics of classified and weighted *JRC* fitting formulas are planes or surfaces, as shown in Fig.5. Specifically, the fitting graphics of Z_2 , SF , R_p-1 are planes, and those of $\log Z_2$, $\log SF$, and $\sqrt{R_p-1}$ are surfaces. As shown in Fig.5, better fitting means that the points representing *JRC* of the ten typical roughness profiles are all on, or very near the planes or surfaces. Obviously, the surfaces are better than the planes, *i.e.* the fitting effect of $\log Z_2$, $\log SF$, and $\sqrt{R_p-1}$ is better than those of Z_2 , SF , and R_p-1 , respectively, consistent with the results of Table 1.

[Fig. 6 goes here]

4. Verification of the classified and weighted method with shear tests

In order to verify the classified and weighted method for estimating *JRC*, direct shear tests were performed on 5 pairs of sandstone specimens under different normal loading. The mechanical parameters of the sandstone

are listed in Table 2. The size of these specimens is 10mm×10mm, as shown in Fig. 6, they are generated by a method similar to the Brazilian Split test, and thus, the lower-half joint surface and the upper one match well.

[Table 2 goes here]

[Fig. 6 goes here]

[Fig. 7 goes here]

By using the 3D scanning system (Comet L3D), the 3D image of the rock joint surface was retrieved, as shown in Fig. 7. By cutting the profiles along the shear direction, a series of roughness profiles of the joint surface can be obtained. Ten roughness profiles were cut for each joint surface, at a spacing of 9mm (Fig. 7). The *JRC* values of these 5 joints were calculated with Eq.11 and were also estimated with the classical formula given by Tse and Cruden (1979) for comparison, Eq.5.

The calculated results are shown in Table 3. For the 5 sandstone specimens, the average, maximum and minimum *JRC* values calculated by Eq.11 are all a little smaller than those calculated by Eq.5, but the gap between the maximum and minimum *JRC* values calculated by Eq.11 are all larger than those calculated by Eq.5. It is worth mentioning that the minimum *JRC* values calculated by Eq.11 and Eq.5 for the sample No.2 were not based on the same roughness profile, showing the obvious difference between these two equations.

[Table 3 goes here]

Direct shear tests were conducted on the 5 sandstone specimens under normal loading of 5% σ_c , 10% σ_c , 15% σ_c , 20% σ_c , or 30% σ_c , respectively, where σ_c is the uniaxial compressive strength of the sandstone, and the shear rate is fixed at 5mm/min. Fig. 8 shows the shear stress - displacement curves of the 5 sandstone specimens, and the peak shear strengths were compared with the ones estimated by Barton's empirical equation (Eq.1), as listed in Table 4. The sum of the squared errors (*SSE*) was used as a criterion for comparison. The smaller the *SSE* is, the better the estimation of *JRC*. In Table 4, the estimated peak shear strength of the 5 sandstone specimens exhibited the smallest *SSE*, *i.e.* the best estimation effect, by using Eq.11 with the maximum *JRC* values. The next best were those calculated using Eq.5 with maximum *JRC* values.. Furthermore, Table 5 shows the *JRC* values back-calculated with Eq.1 and the estimated ones according to the Eq.11 and Eq.5, respectively. As shown above, the maximum *JRC* values calculated with Eq.11 are the most consistent with the experimental results when they are used to estimate the peak shear strength according to Eq.1.

[Fig. 8 goes here]

[Table 4 goes here]

[Table 5 goes here]

Previous experiments indicated that only a small fraction of the joint surface area was damaged during shearing. In this study, Fig.9 shows the two halves of specimen No.2 after the shear test under normal loading of $10\%\sigma_c$. The white area play the main role during shearing and contribute the majority of shear resistance. Similarly, in the 3D image of the rock joint, the main sheared area is in high elevation and the joint surface profile through this area shows the maximum *JRC*. Thus, it is appropriate to use the maximum *JRC* to estimate the peak shear strength, and these results match well with the experimental results.

[Fig. 9 goes here]

[Table 6 goes here]

Because the maximum *JRC* value is the most suitable to estimate the peak shear strength, it is necessary to verify whether the roughness profile spacing is sufficiently enough to get the maximum *JRC* value. Actually, the maximum *JRC* value of joint surface is difficult to obtain from 2D roughness profile lines, but it can be approximated by gradually reducing the profile spacing. The sandstone specimen size in this shear tests is $10\text{mm}\times 10\text{mm}$, and 10 roughness profiles were used to calculate the *JRC* with a profile spacing of 9mm. For comparison, 18mm and 4.5mm were also used as the profile spacing to cut the digital joint surface, and the calculated *JRC* values are shown in Table 6. We considered that if the relative tolerance between two profile spacings was less than 5%, the larger profile spacing would be acceptable from the viewpoint of practical convenience. Table 6 indicates that the profile spacing of 9mm is suitable in this study, but 18mm does not achieve maximum *JRC* values and 4.5mm is not necessary.

5. Application of new *JRC* estimation in double-joint shear test

The mechanical behavior of multiple joints has been studied (e.g. Yang et al., 1998; Jiang et al., 2015), but few of these studies have focused on the influence of *JRC*. In this section, using the classified and weighted method for estimating *JRC*, direct shear tests on sandstone specimens containing double parallel joints were performed. The *JRC* of each joint was calculated by Eq.11 and its peak shear strength is estimated by Eq.1. The sectional dimension of the joint samples was $10\text{mm}\times 10\text{mm}$, Fig 10. The rough joints were generated by a method similar to the Brazilian Split tests and the smooth joints were generated by being sawed-off.

5.1 Experimental design

Direct shear tests of double parallel rock joints were performed under the CNL (constant normal loading)

condition, Fig 10. The normal stress are $5\%\sigma_c$, $15\%\sigma_c$, or $25\%\sigma_c$ were applied on the samples at a rate of 0.5KN/s. The shear stress was applied by fixing the lower shear box and pushing the upper one at a rate of 5mm/min. Average thicknesses of the interlayer rock were 10mm, 20mm and 40mm (accuracy was guaranteed by using both the Brazilian Split method and sawed-off method). The lower and upper pieces were both 50mm thick. Three types of roughness combinations were adopted in the double-joint shear tests, smooth-smooth joints (S-S joints), rough-smooth joints (R-S joints) and rough-rough joints (R-R joints). The specific experimental design is shown in Fig 11, and these specimens were all intact under normal loading conditions ($5\%\sigma_c$, $15\%\sigma_c$, or $25\%\sigma_c$) before shearing.

[Fig. 10 goes here]

[Fig. 11 goes here]

5.2 Experiment results

5.2.1 Shear stress – shear displacement curves

Similar to the experimental results of the single joint shear test, the shear stress - shear displacement curves are plotted for the double-joint shear tests, as shown in Fig.12. It is worth noting that both the shear stress and shear displacement reflect the overall response of double joints. For comparisons, the peak shear strength of the single smooth joint ($JRC = 0.4$) was estimated by using Eq.1 and that of the weaker joint of an R-R joints, *i.e.*, the peak shear strength of joints with JRC of 13.6, 8.1, and 11.0 were calculated according to Eq.1 under normal stress of $5\%\sigma_c$, $15\%\sigma_c$ or $25\%\sigma_c$. The shear results of single smooth joints are also shown in Fig.12.

[Fig. 12 goes here]

Fig.12a shows the shear results under the normal loading of $\sigma_n=5\%\sigma_c$. The peak shear strengths of the S-S joints, R-S joints, single smooth joint and estimated ones by using Eq.1 are all very close, which indicates that the peak shear strength of double parallel joints is dominated by the weaker one under the lower normal stress condition. Fig.13 shows the failure process of sandstone samples containing double parallel joints: all the samples were sheared off along one joint only. Even for the S-S joints, although there is a very slight difference in roughness between the two smooth joints, it slides along the smoother one.

Remarkably, for the R-R joints, the experimental peak shear strength was 24.5% higher than the estimated one. This phenomenon may be common because for the 40mm thick interlayer rock, both the upper and lower surfaces are rough and torsion is induced in the interlayer when shearing. This further induce additional normal

stress. In general, the normal stress fluctuation of the servo pressure control system is around $1\pm3\%$, but it jumps to $1+8\%$ for these double-joint shear tests, thus suggesting the complex stress condition that is induced during the double-joint shear tests.

Fig.12b and Fig.12c show the shear stress – shear displacement curves of the double-joint shear tests under normal loading of $\sigma_n=15\%\sigma_c$ and $\sigma_n=25\%\sigma_c$, respectively. Fig.14 and Fig.15 show their shear failure patterns. As normal stress increased, the peak shear stress tended to be lower than that of the weaker joint, because of the damage and failure of interlayer rock. At the same time, the influence of interlayer thickness also appears, as shown in the Fig.14 and Fig.15. When the interlayer rock becomes thicker, the dominant vertical tensile crack is more likely to be induced, which leads to a decrease of peak shear strength of the combined specimen. Additionally, under the same interlayer thickness, the peak shear strength of S-S joints is obviously lower than the strength of R-R joints with the same interlayer thickness. The main reason for this phenomenon is that rough joints induce uneven distribution of stress. The contribution of *JRC* in this case is different from that in shear tests of single joint, but the larger *JRC* may also result in the higher peak shear strength.

[Fig. 13 goes here]

[Fig. 14 goes here]

[Fig. 15 goes here]

5.2.2 Dilatancy and peak shear strength

Fig.16 shows the variation of the shear stress and shear dilatancy of S-S joints during the double-joint shear tests. Under lower normal stress ($\sigma_n = 5\%\sigma_c$), shear dilatancy increased gradually with the shear displacement. In contrast, under the higher normal stress ($\sigma_n = 15\%\sigma_c$ and $\sigma_n = 25\%\sigma_c$), shear dilatancy displacement initially increased and then decreased. Its peak corresponds well with the peak shear stress and the overall strength of the combined structure is dominated by the interlayer rock.

[Fig. 16 goes here]

5.2.3 *JRC* and the peak shear strength

Fig. 17 shows the peak shear strength of the S-S joints, R-S joints and the R-R joints under normal loading of $5\%\sigma_c$, $15\%\sigma_c$, or $25\%\sigma_c$, with an interlayer thickness of 40mm. The peak shear strengths of the smooth joint (*JRC* = 0.4) and the rough joints were also calculated by using Eq.1.

Under lower normal stress ($\sigma_n = 5\%\sigma_c$), the interlayer rock does not fail. The peak shear strength of the

double parallel joints was equal to that of the weaker joint. Under higher normal stress ($\sigma_n = 15\%\sigma_c$ and $\sigma_n = 25\%\sigma_c$), tensional cracks occur in the interlayer rock, indicating the peak shear strength is related to the interlayer rock. In this regard, the peak shear strength also increases with increasing *JRC*, but the interrelationships are more complex. Higher *JRC* means higher shear strength for a single joint, but also means stress concentration on the joint surface, which cause tensile cracks in the interlayer rock. It is interesting to note that more evenly distributed tensile cracks were induced in the interlayer of S-S joints under higher normal stress, whose strength is even lower than that of R-R joints. Because the failure of interlayer rock has important effects on the peak shear strength of a double-joint specimen, the peak shear strength of R-R joints is higher than that of the S-S joints.

Overall, for double parallel joints, the peak shear strength increases with normal stress, but gradually tends to be lower than the strength of the weaker joint under the condition of single joint shearing. For example, the 4th sample in Fig.14 (interlayer thickness of 40mm, *JRC* values of the upper joint and the lower are 0.4 and 12.7, respectively) shows a mixed failure mode, indicated this rock sample slid along the smooth joint (but not the rough one) but also results in cracks in the interlayer rock. This phenomenon can clarify that the results of double-joint shear tests are closely related to the *JRC* of the joints, especially that of the weaker joint.

[Fig. 17 goes here]

5.2.4 Interlayer thickness and the peak shear strength

Fig. 18 shows the peak shear strength of the R-S joints with 10mm, 20mm, or 40mm thick interlayer rock. Almost all of the peak shear strengths of the R-S joints are close to the values of smooth joints calculated using Eq.1, except for the sample of 40mm thick interlayer rock was obviously smaller than the others at normal loading of $25\%\sigma_c$. This is because predominant tensional cracks are induced in the interlayer rock, and this phenomenon also happens to S-S joints and R-R joints when the normal loading is $25\%\sigma_c$ and the interlayer thickness is 40mm, as shown in Fig. 15.

Thus, within a certain limit, provided that the interlayer is not thick enough to remain intact during shearing, a larger thickness may lead to lower peak shear strength. Instead, when the interlayer rock becomes thinner, the peak shear strength of double-joint specimen is closer to that of the weaker joint, as shown in Fig. 18.

[Fig. 18 goes here]

In this section, the direct shear tests showed that the maximum *JRC* along the shear direction can be used to estimate the peak shear strength. This is because the joint specimens were generated by a method similar to the Brazilian Split test and the *JRC* values of different roughness profiles were very similar. In other cases, for

example if the maximum *JRC* was much bigger than the other values, this method may be not suitable to use this method to estimate the peak shear strength. In addition, to maximize the contrast, joints were broadly divided into smooth-type and rough-type.. The constant *JRC* value of 0.4 was adopted for the smooth joints, and the classified and weighted method proposed in this study was only adopted for estimating *JRC* of rough joints. Further studies are required to propose a model to estimate the double-joint shear strength based on the *JRC* values and spacing of two joints.

6. Conclusions

Six statistical parameters were investigated in this paper, Z_2 , SF , $R_{p-1, \log(Z_2)}$, $\log SF$, and $\sqrt{R_p - 1}$. These parameters are all sensitive to the sampling intervals used, therefore it is necessary to estimate the *JRC* of a natural rock joint by considering both the first-order and the second-order asperity.

By decomposing the ordinate (y_i) of the roughness profiles, the asperities were divided into the first-order and second-order, and a classified and weighted fitting formula, $JRC = 16.09 \log Z_2^{1st} + 12.70 \log Z_2^{2nd} + 33.75$ ($SI = 5.0\text{mm} \ \& \ 0.5\text{mm}$), was proposed to estimate the *JRC* of rock joints. In addition, shear tests on the sandstone joints indicate that the maximum *JRC* along the shear direction is appropriate to represent the total joint surface and to estimate the shear strength.

The classified and weighted method was adopted to estimate the *JRC* values of double parallel joints that are subjected to double-joint shear tests. Under lower normal stress, the interlayer rock will be intact; and the *JRC* of the weaker joint determines the peak shear strength of a combined rock sample. Under higher normal stress, the peak shear strength of the double-joint specimen is attained when tensional cracks occur in the interlayer rock, and it is dependent on the properties of two joints. Generally, the peak shear strength also increases with the *JRC* values of the double joints, but is dependent on the strength of interlayer rock between two joints.

If the interlayer thickness is not sufficient to remain intact during shearing, a thicker interlayer rock may lead to lower shear strength. When the interlayer rock becomes thinner, the double-joint shear strength may be closer to that of the weaker joint. Overall, shear tests on the double parallel joints are determined by a series of interrelated factors. Accurate estimation of the *JRC* accurately is an important step, but future studies should include other key factors, such as the failure of the interlayer rock.

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Table 1Sum of squared error (*SSE*) of the fitting formulas

Statistical parameters	Sampling interval/mm								
	0.25	0.5	1.0	2.0	5.0	10.0	2.5&0.25	5.0&0.5	10.0&1.0
Z_2	104.58	47.81	22.68	10.69	16.30	30.84	6.04	12.36	12.12
SF	120.48	75.41	53.49	44.16	45.88	59.22	25.28	26.77	40.26
R_{p-1}	113.96	67.09	47.89	36.22	39.85	63.47	22.91	39.11	39.88
$\log(Z_2)$	93.06	32.63	13.02	9.69	13.26	22.37	5.66	3.73	7.45
$\log(SF)$	92.97	32.63	13.04	10.33	13.26	23.63	5.66	8.02	6.70
$\sqrt{R_p - 1}$	100.05	39.95	21.04	8.43	13.28	30.83	5.04	11.92	11.61

Table 2

Physical and mechanical properties of sandstone specimens

Elastic modulus / GPa	Poisson's ratio	Uniaxial compressive strength / MPa	Cohesion / MPa	Tensile strength /MPa	Internal friction angle/°	Basic friction angle/°
8.4	0.29	32.2	5.92	2.29	27.4	34.5

Table 3

JRC values of the 5 sandstone specimens used for the direct shear tests calculated using Eq. 11 or Eq. 5

Serial number	Sample No.1		Sample No.2		Sample No.3		Sample No.4		Sample No.5	
	Eq.11,	Eq.5,	Eq.11,	Eq.5,	Eq.11,	Eq.5,	Eq.11,	Eq.5,	Eq.11,	Eq.5,
	<i>SI</i> =5.0&0.5mm	<i>SI</i> =5.0mm	<i>SI</i> =5.0&0.5mm	<i>SI</i> =5.0mm	<i>SI</i> =5.0&0.5mm	<i>SI</i> =5.0mm	<i>SI</i> =5.0&0.5mm	<i>SI</i> =5.0mm	<i>SI</i> =5.0&0.5mm	<i>SI</i> =5.0mm
1	12.35	13.46	8.79	10.53	13.77	14.84	15.51	16.63	15.38	16.72
2	13.42	14.46	9.73	12.18	14.40	15.39	14.08	15.60	11.70	14.09
3	15.15	16.01	10.71	13.01	15.40	16.24	8.79	11.69	11.91	13.27
4	13.70	15.02	9.79	12.26	14.89	15.73	9.32	11.91	12.88	14.28
5	14.53	16.03	8.67	11.83	14.76	15.93	11.38	13.29	12.23	13.11
6	15.44	16.34	13.50	14.76	15.41	16.24	11.96	13.45	11.88	13.59
7	15.52	16.45	14.42	15.50	14.97	16.20	13.63	14.65	10.82	13.07
8	13.36	14.82	13.24	14.11	11.81	14.18	12.62	14.22	8.86	10.90
9	14.60	15.74	9.47	11.56	14.38	15.09	12.85	14.75	9.11	11.31
10	13.65	14.74	8.70	11.93	14.01	16.44	12.49	14.14	10.28	12.76
Average	14.17	15.31	10.70	12.77	14.38	15.63	12.26	14.03	11.50	13.31
Maximum	15.52	16.45	14.42	15.50	15.41	16.44	15.51	16.63	15.38	16.72
Minimum	12.35	13.46	8.67	10.53	11.81	14.18	8.79	11.69	8.86	10.90

Table 4

Experimental peak shear strength of the sandstone specimens and those estimated by Eq.1

Serial number	Normal pressure	Experimental peak shear strength /MPa	Estimated peak shear strength by Eq.1 /MPa											
			<i>JRC</i> calculated by Eq.11, <i>SI</i> =5.0&0.5mm						<i>JRC</i> calculated by Eq.5, <i>SI</i> =0.5mm					
			Ave <i>JRC</i>	Estimation error	Max <i>JRC</i>	Estimation error	Min <i>JRC</i>	Estimation error	Ave <i>JRC</i>	Estimation error	Max <i>JRC</i>	Estimation error	Min <i>JRC</i>	Estimation error
Sample No.1	5% σ_c	2.191	2.132	-2.71%	2.273	3.75%	1.958	-10.64%	2.250	2.70%	2.378	8.55%	2.062	-5.89%
Sample No.2	10% σ_c	3.838	3.243	-15.51%	3.694	-3.75%	3.021	-21.30%	3.486	-9.18%	3.837	-0.02%	3.223	-16.03%
Sample No.3	15% σ_c	5.628	5.063	-10.04%	5.215	-7.34%	4.702	-16.46%	5.248	-6.75%	5.372	-4.55%	5.034	-10.55%
Sample No.4	20% σ_c	6.207	6.020	-3.01%	6.516	4.98%	5.528	-10.94%	6.287	1.28%	6.698	7.91%	5.936	-4.36%
Sample No.5	30% σ_c	9.014	8.255	-8.42%	8.864	-1.66%	7.860	-12.80%	8.534	-5.32%	9.086	0.79%	8.163	-9.44%
SSE	-	-	-	428.74‰	-	109.58‰	-	1121.28‰	-	167.18‰	-	156.85‰	-	511.09‰

Table 5

JRC of the sandstone specimens calculated by Eq.1 or by Eq.11 and Eq.5

Serial number	Normal pressure	<i>JRC</i> back-calculated by experiments, Eq.1	<i>JRC</i> calculated by estimation formulas											
			<i>JRC</i> calculated by Eq.11, $SI=5.0\&0.5\text{mm}$						<i>JRC</i> calculated by Eq.5, $SI=0.5\text{mm}$					
			Ave. <i>JRC</i>	Estimated error	Max. <i>JRC</i>	Estimated error	Min. <i>JRC</i>	Estimated error	Ave. <i>JRC</i>	Estimated error	Max. <i>JRC</i>	Estimated error	Min. <i>JRC</i>	Estimated error
Sample No.1	5% σ_c	14.75	14.17	-3.92%	15.52	5.22%	12.35	-16.27%	15.31	3.78%	16.45	11.53%	13.46	-8.72%
Sample No.2	10% σ_c	15.50	10.70	-30.98%	14.42	-6.98%	8.67	-44.08%	12.77	-17.65%	15.50	-0.04%	10.53	-32.11%
Sample No.3	15% σ_c	18.04	14.38	-20.29%	15.41	-14.59%	11.81	-34.54%	15.63	-13.38%	16.44	-8.89%	14.18	-21.38%
Sample No.4	20% σ_c	13.51	12.26	-9.25%	15.51	14.75%	8.79	-34.98%	14.03	3.86%	16.63	23.07%	11.69	-13.51%
Sample No.5	30% σ_c	16.29	11.50	-29.38%	15.38	-5.62%	8.86	-45.60%	13.31	-18.31%	16.72	2.66%	10.90	-33.11%
SSE	-	-	-	2335.66%	-	537.89%	-	6703.43%	-	854.72%	-	751.50%	-	2843.02%

Table 6

Maximum *JRC* values calculated by Eq.11 for different profile spacings (*SI*=5.0&0.5mm)

Profile spacing	Sample No.1		Sample No.2		Sample No.3		Sample No.4		Sample No.5	
	Max <i>JRC</i>	Relative tolerance	Max <i>JRC</i>	Relative tolerance	Max <i>JRC</i>	Relative tolerance	Max <i>JRC</i>	Relative tolerance	Max <i>JRC</i>	Relative tolerance
18mm	15.44	-	13.50	-	15.40	-	14.08	-	12.88	-
9mm	15.52	0.52%	14.42	6.38%	15.41	0.06%	15.51	9.22%	15.38	16.25%
4.5mm	15.56	0.26%	15.10	4.50%	15.79	2.41%	15.51	0%	15.38	0%

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(a) Z_2

(b) $\log(Z_2)$

(c) SF

(d) $\log(SF)$

(e) $R_p - 1$

(f) $\sqrt{R_p - 1}$

Fig. 1 Correlation between the statistical parameters and sampling intervals

Fig.2 *JRC* values given by Barton and Choubey (1977) and the estimated ones by using our formula (Eq.11)

Fig.3 The decomposed 10th typical roughness profile for (a) $P_0(0.5)$, (b) $P_1(5.0)$, and (c) $P_2(0.5)$

(a) Z_2

(b) $\log(Z_2)$

(c) SF

(d) $\log(SF)$

(e) $R_p - 1$

(f) $\sqrt{R_p - 1}$

Fig.4 JRC values from Barton and Choubey (1977) and the ones estimated by using our formula

(Eq.11)

(a) Eq.(8): $JRC=75.11 Z_2^{1st}+3.33 Z_2^{2nd}-2.79$
($SI = 2.5\text{mm} \ \& \ 0.25\text{mm}$)

(b) Eq.(11): $JRC=16.09 \log Z_2^{1st}+12.70 \log Z_2^{2nd}+33.75$
($SI = 5.0\text{mm} \ \& \ 0.5\text{mm}$)

(c) Eq.(9): $JRC=91.73 SF^{1st}-57.13 SF^{2nd}+3.89$
($SI = 2.5\text{mm} \ \& \ 0.25\text{mm}$)

(d) Eq.(12): $JRC=11.32 \log SF^{1st}+5.79 \log SF^{2nd}+34.17$
($SI = 2.5\text{mm} \ \& \ 0.25\text{mm}$)

(e) Eq.(10): $JRC=472.16 (R_p-1)^{1st}-20.42 (R_p-1)^{2nd}+3.32$
($SI = 2.5\text{mm} \ \& \ 0.25\text{mm}$)

(f) Eq.(13): $JRC=108.12 \sqrt{R_p-1}^{1st}+6.31 \sqrt{R_p-1}^{2nd}-3.66$
($SI = 2.5\text{mm} \ \& \ 0.25\text{mm}$)

Fig.5 Three-dimensional fitting surface of JRC by using the classified and weighted statistical parameters

Fig.6 Joint surface of sandstone specimen for the shear tests

(a)

(b)

Fig.7 Retrieval of the digital image of the rock joint surface by using the 3D scanning system (a) the Comet L3D 3D scanning system, (b) the 3D image of the rock joint

Fig.8 Shear stress- displacement curves of 5 sandstone specimens

Fig.9 The roughness profile of the main sheared area showed maximum *JRC* value

Fig. 10 Experimental configuration of the double-joint shear tests

Interlayer thickness	Normal stress		
	$\sigma_n=5\%\sigma_c$	$\sigma_n=15\%\sigma_c$	$\sigma_n=25\%\sigma_c$
10mm
20mm
40mm
40mm
40mm

* ” ” denotes the rock joints generated by Brazilian splitting tests, whose *JRC* are estimated by using the classified and weighted method; ” ” denotes smooth cleavage joints generated by sawing off, whose *JRC* are equal to constant value of 0.4.

Fig. 11 Experimental design of sandstone specimens containing double parallel joints

(a) $\sigma_n = 5\% \sigma_c$

(b) $\sigma_n = 15\% \sigma_c$

Fig. 12 The shear stress - shear displacement curves of double-joint shear tests (a) normal stress $\sigma_n = 5\% \sigma_c$, (b) normal stress $\sigma_n = 15\% \sigma_c$, (c) normal stress $\sigma_n = 25\% \sigma_c$

Interlayer thickness	JRC values	Shear displacement		
		<5mm	5-15mm	>15mm
10mm	Upper 0.4 Lower 12.1
20mm	Upper 0.4 Lower 10.7
40mm	Upper 0.4 Lower 0.4
40mm	Upper 0.4 Lower 12.9
40mm	Upper 13.9 Lower 13.6

Fig. 13 Failure processes of the sandstone samples during double-joint shear tests under normal stress of $\sigma_n = 5\% \sigma_c$

Interlayer thickness	<i>JRC</i> values	Shear displacement		
		<5mm	5-15mm	>15mm
10mm	Upper 0.4 Lower 10.5
20mm	Upper 0.4 Lower 18.6
40mm	Upper 0.4 Lower 0.4
40mm	Upper 0.4 Lower 12.7
40mm	Upper 10.5 Lower 8.1

Fig. 14 Failure processes of the sandstone samples under double-joint shear tests under normal stress of $\sigma_n = 15\% \sigma_c$

Interlayer thickness	<i>JRC</i> values	Shear displacement		
		<5mm	5-15mm	>15mm
10mm	Upper 0.4 Lower 12.6
20mm	Upper 0.4 Lower 13.5
40mm	Upper 0.4 Lower 0.4
40mm	Upper 0.4 Lower 12.5
40mm	Upper 0.4 Lower 11.0

Fig. 15 Shear failure processes of the sandstone samples under double-joint shear tests under normal stress of $\sigma_n = 25\% \sigma_c$

Fig.16 The variation of shear stress and shear dilatancy during the double-joint shear tests

Fig. 17 The influence of JRC on the peak shear strength

Fig.18 The influence of interlayer thickness on the peak shear strength