Research Article

Determination of Joint Surface Roughness Based on 3D Statistical Morphology Characteristic

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1. Introduction

Rock joints widely exist in rock engineering [1–4]. The mechanical properties of rock joints are considered as the controlling factors of rock mass engineering stability [5–8]. Previous research studies have shown that the roughness remarkably affects the friction angle, shear expansion, and peak shear strength of jointed rock mass [9–13]. By considering the roughness of joint (JRC) and presenting 10 standard joint contour curves, Barton and Choubey [14] established the JRC-JCS shear strength model, which is popular in evaluating rock mass stability in geotechnical engineering. Despite empowering a significant efficacy in the shear strength calculation of jointed rock mass, it incurs some controversies with respect to the quantification to the joint roughness, promoting a wide pursue of the determination method of JRC in recent years [15–17]. For example, Tse et al. [15] studied the relationship between 11 joint parameters and JRC value. Gadelmawla et al. [18] enumerated 59 parameters describing joint surface morphology. Li et al. [19] normalized the symbols of many joint parameters and optimized the calculation formula between these parameters and the JRC. Some other scholars [20–22] introduced the fractal theory into rock mechanics to evaluate the JRC and achieved expectant results.

The measurement to the joint surface relief morphology is usually executed via the needle profile comb [23–25], which neglects the fluctuation characteristics smaller than the measuring interval and extra terraced characteristics to the original profile [26]. Experimental evidences [27] showed that the difference of the JRC is up to 4 when the error of fluctuation measurement is 1 mm. In this case, some other optional methods, such as statistical parameter, straight edge, elongation, and geometric fractal methods, have been developed to quantitatively determine the value of JRC [16, 17, 28–30]. However, the straight edge
method can only consider the large fluctuations of the joint, the elongation method totally ignores the influence of fluctuations, and the roughness described by fractal theory significantly varies for different joint samples. Based on strict mathematical calculation, the statistical parameter method shares a sufficient accuracy on the measurement to the joint surface relief morphometry, which can avoid the error caused by subjective factors and is convenient to calculate the value of JRC. Almost all the statistical parameter methods are only used for the description of JRC in 2D, which may result in distortion in practical application. Due to the limitation of the amount of information, the parameter values have large deviations and limitations. Therefore, 3D JRC profiles must be developed to account for the variation of roughness profiles in 3D space [31].

In this study, a new method based on the 3D scanning technique and Python code was presented to accurately describe the roughness of joints. Particularly, the joint surface was divided into several rectangular regions. For each region, the 3D scanning technique was applied to obtain the 3D coordinate data, the Python code was used to extract the roughness profile, and the value of JRC was calculated via the statistical parameter methods, where $Z_2$ (the first derivative root mean square of roughness profiles), structure function (SF, representing the changes in surface texture), and $R_p$ (the length ratio of the trace line to the straight line) were selected. Then, the arithmetic average of JRC of all regions was solved to represent the roughness of the joint surface, denoted as $JRC_p$, which avoids the subjective estimation. To obtain accurate JRC values, the shear direction is also considered [32]. In addition, the calculated $JRC_p$ is embedded in the current shear strength formula of joint, and the calculating results by the proposed $JRC_p$ determination method present a significant consistency with the test results, which verified the validity and accuracy of the proposed method. Finally, the influencing factors of roughness profile extraction on the accuracy of $JRC_p$, such as the measuring point interval, profile number, and measuring direction, were investigated.

2. Joint Surface Morphology Acquisition

2.1. Preparation of Samples. Four mortar samples (100 mm × 100 mm × 100 mm in size) with 45° sawtooth were prepared, and the failure surfaces by direct shear test under four different normal stresses were, therefore, selected as the research objects (see Figure 1). For convenience, the failure surface was numbered by its normal stress, at the ascending order, which corresponds to sample No. 1–4. The samples were produced according to the proportion of white cement: fine sand: water = 1.5: 1.5: 0.8 and maintained under standard conditions for 28 days. After the specimens are cured, the Brazilian split test and uniaxial compression test can be performed. The size of the sample used in the Brazilian splitting test is a cylinder of 25 mm × 50 mm (height × diameter), and the surface flatness of the test sample is in the range of 0.02 mm. The cylindrical end portion is perpendicular to the axis of the specimen, with a tolerance of ±0.25°. Before the test begins, the steel rod needs to be glued on both the sides of the cylindrical end portion to conduct compressive stress. During the test, the load was loaded at a small displacement of 0.5 mm/min. When the sample in the radial tensile failure, the tensile strength of the material can be obtained according to experimental data recording and experimental curves. The size of the sample used in the uniaxial compressive strength test is a cylinder of 100 mm × 50 mm (height × diameter), the sample has the same tolerance as the Brazilian cracked disk test [33, 34], and the compression load is 400 N/S. The uniaxial compressive strength of the sample is 18.97 MPa, and the tensile strength measured by the Brazilian splitting test is 1.64 MPa. Direct shear tests were conducted at the normal stresses of 0.8 MPa, 1.2 MPa, 1.6 MPa, and 2.0 MPa, respectively. The shear box size is 100 mm × 100 mm × 100 mm, and the shear strain rate is 1 mm/min in the direct shear test.

2.2. Test Apparatus. The apparatus used in this study is HL-3DC color 3D scanner, which is mainly composed of computer, control unit, laser scanning device, and data acquisition software. The laser scanning device is the core of the apparatus, which consists of a central projection unit sensor head and two charge-coupled device (CCD) cameras. During the scanner operation, the central projection unit projects a series of continuous grating stripes with different widths on the joint surface, and the two CCD cameras record the related scanning information from two different angles and integrate them into the measuring head to determine the coordinate data on the surface of the object (see Figure 1). The details of the surface can be captured by laser measurements due to the introduction of high data density. Briefly, the scanner shares high scanning speed and remarkable scanning accuracy.

2.3. Procedures to Extract Roughness Profiles. The procedures for the roughness profiles extraction of the failure surfaces are expressed in detail as follows:

1. Affixing marking points on the failure surface: the target surface should be divided into parts and scanned because the laser projected by a 3D laser scanner cannot cover the entire failure surface at the once time. The marked points must be affixed on the failure surface to accurately splice the scanned data of each part (see Figure 1(a)).

2. Scanning failure surface: next, the failure surface is scanned on the scanning platform, which is rotated or moved after each scan to ensure that the entire failure surface has been scanned (see Figure 1(b)).

3. Point cloud processing: the built-in software automatically splices the scanning data to obtain the point cloud data of the entire surface based on the marking points (see Figure 1(c)).

4. Digital modeling of the failure surface: the point cloud data are processed to obtain the digital model of the failure surface, and the 3D coordinates of each scanning point can be outputted based on the required precision (see Figure 1(d)).
(5) Extracting the roughness profiles of the failure Surface: processing the 3D coordinates based on the self-compiled Python code, the roughness profiles of the failure surface can be extracted (see Figure 1(e)).

3. Determination of Surface Roughness

3.1. Description of Statistical Parameters for Roughness Profiles. In previous research studies, there have been numerous statistical parameters, such as the root mean square of the surface height of joint, the average of the center line, average roughness, the average roughness angle, and the standard deviation of the roughness angle, proposed to describe the roughness characteristics of the shear surface [35–37]. However, in this study, the roughness was characterized by statistical parameters $Z_2$, $SF$, and $R_p$. Specifically, $Z_2$ is the mean square root of the first derivative of profile, as shown in equation (1), which is widely used in surface roughness analysis and is first proposed to measure the light scattering property of the metal surface [15]. The structure function (SF) is used to represent the changes in surface textures, which can be calculated using equation (2). In addition, El-Soudani [38] proposed that the ratio of trace length to straight line length ($R_p$) can be used to represent the linear roughness of object surface, as shown in equation (3). The larger the value of $R_p$ is, the rougher the profile will be. Due to the constant relationship of $R_p \geq 1$, $R_p - 1$ is usually adopted for research convenience.

$$Z_2 = \left[ \frac{1}{L} \int_{x=0}^{x=L} \left( \frac{dy}{dx} \right)^2 dx \right]^{1/2},$$  

(1)

$$SF = \frac{1}{L} \int_{x=0}^{x=L} \left[ f(x + \Delta x) - f(x) \right]^2 dx$$

(2)

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

(3)

The roughness profile is shown in Figure 1. $x_i$ represents the horizontal coordinates along the profile, $y_i$ represents the vertical coordinates corresponding to $x_i$ on the profile, $L$ represents the horizontal length of the profile, and $n$ is the total number of measuring points of the profile. The statistical parameters of $Z_2$, $SF$, and $R_p - 1$ corresponding to each profile extracted can be calculated according to equations (1)–(3). Jang and Kang [39] studied 10 standard JRC curves of Barton by using an accurate digitization technique and obtained the relationship between the statistical parameters $Z_2$, $SF$, $R_p - 1$, and JRC of joints, which are expressed as follows:
To obtain joint surface roughness, several profiles were taken along a certain direction of the joint, dividing the joint surface into several rectangular regions (see Figure 2). \( \Delta x \) is the interval between the two profiles. Profiles AB and CD are infinitely close to each other when \( \Delta x \) is sufficiently small, in which case the roughness of AB and CD can be considered approximate. Thus, the roughness of the rectangular region ABCD can be represented by the average roughness of profiles AB and CD. Similarly, the arithmetic average of the roughness of all the rectangular regions can be assumed as the roughness of the entire joint surface. The surface roughness of the joint obtained by the proposed method is denoted as \( \text{JRC}_p \), \( m \) is the number of rectangular regions, and the calculation method is shown as follows:

\[
\text{JRC}_p(Z_2) = \frac{1}{m} \sum_{i=1}^{m} \text{JRC}_p(Z_{2i}),
\]

\[
\text{JRC}_p(SF) = \frac{1}{m} \sum_{i=1}^{m} \text{JRC}_p(SFi),
\]

\[
\text{JRC}_p(R_p - 1) = \frac{1}{m} \sum_{i=1}^{m} \text{JRC}_p(R_p - 1)_i.
\]

### 3.2. Shear Strength of the Joint Based on \( \text{JRC}_p \)

To verify the validity and accuracy of the proposed method, the calculated \( \text{JRC}_p \) is embedded into Barton’s shear formula to calculate the shear strength of the joints, as shown in equation (8), and the comprehensive comparison of shear strength between the calculating results and the test results was carried out in this study.

\[
\tau = \sigma_n \cdot \tan \left[ \text{JRC}_p \times \left( \frac{\text{JCS}}{\sigma_n} \right) + \varphi_b \right],
\]

where \( \tau \) is the peak shear strength of the joint, \( \sigma_n \) is the normal stress, \( \text{JRC}_p \) is the roughness coefficient of the joint parallel to the shear direction, and \( \text{JCS} \) is the uniaxial compressive strength of the joint. For the unweathered shear surface, \( \text{JCS} \) can be represented by the uniaxial compressive strength, which is 18.97 MPa as previously described. The method proposed by Xia and Sun [40] was adopted to obtain the basic friction angle of rock via direct shear tests of flat joint. The shear stress-shear displacement curves of flat joints under different normal stresses are shown in Figure 3.

Note that slight cohesion emerges on the shear surface since the upper blocks were directly cast on the lower blocks when producing the samples, resulting in the occurrences of the peak in shear stress-shear displacement curves. Consequently, the shear strength after stabilization was selected to calculate the basic friction angle. The relationship between normal stress and shear strength was fitted in Figure 4, which indicates a basic friction angle of 33.82°, underpinned by the Mohr–Coulomb criterion [41, 42]. Afterwards, the theoretical shear strengths of joints were calculated with equation (8), as shown in Table 1.

Previous research studies show that the shear strength obtained by the secondary shear test of the joint basically approximates to the residual strength of the first shear test under the same loading condition [43]. Thus, in this study, the residual strength of the first shear test was considered equivalent to the shear strength of the secondary shear test. The shear stress-shear displacement curves are shown in Figure 5. The relative error of shear strength was selected to evaluate the feasibility of the proposed \( \text{JRC}_p \), which can be calculated as follows:
The shear strength calculated by equation (8) was compared with the test shear strength, as shown in Table 1. The smaller the relative error is, the closer the calculated value to the test value will be. It is evident in Table 1 that the shear strengths calculated by JRC_p agree well with the test results, which proves that the proposed method is reliable in determining the surface roughness of joint. For clarity, the test results and calculating results are plotted in Figure 6 to intuitively assess their consistency, and there exist few differences between the calculating results and the test results, especially for the shear strength calculated by the roughness statistical parameter Rp−1. Therefore, the determination method of joint roughness by Rp−1 was suggested.

3.3. The Influencing Factors of Roughness Profile Extraction.
The previously described strategy of roughness determination in this study indicates that the real challenge to obtain an accurate value of the JRC of joint emerges as extracting appropriate roughness profiles, which is quite susceptible by subjective factors. As a result, the influencing factors of the measuring point interval and profile number, as well as profile extraction direction, were further investigated.

3.4. Effect of Measuring Point Interval on Profile Roughness.
To investigate the effect of measuring point interval on the profile roughness, one profile was digitized by Python code at the measuring point intervals of 0.5 mm, 1.5 mm, and 2.5 mm, respectively (see Figure 7). Obviously, similar shapes and general fluctuation trend of digital profiles obtained at different measuring point intervals can be observed. With the increase of the measuring point interval, however, the number of measuring points decreases and local details of profiles are easily ignored, accompanied with distortion of digitized profiles. Specifically, the digital description of the profile with highest precision emerges when the measuring point interval is 0.5 mm, while the digital profile of 1.5 mm measuring point interval is distorted. Part local details can no longer be captured at the measuring point interval of 2.5 mm. In contrast, the digital profile with a greater measuring point interval is smoother than that with a smaller measuring point interval. Despite the morphology of the shear surface can be reflected when using the
measuring point intervals of 0.5 mm, 1.5 mm, and 2.5 mm to the profile, theoretically a smaller interval can produce a more accurate joint shear surface. Therefore, it is suggested to adopt the measuring point interval as small as possible when extracting the profile.

3.5. Effect of the Profile Number on Statistical Parameters and JRCp. As previously described, the joint surface was divided into several rectangular regions by profiles, and the joint roughness was represented by the arithmetic average of the roughness of those regions. In this case, whether the number of profiles affects the determination of joint roughness should be investigated. The shear surface of No. 4 sample, that is, the surface obtained via the shear test under the normal stress of 2.0 MPa, was selected to be the research object, and different numbers of profiles in the shearing direction were extracted, as shown in Figure 8, for the investigation of the influence of the profile number on statistical parameters and JRCp. The number of profiles in this study was set as 4, 6, 8, 10, and 12. The corresponding statistical parameters and JRCp are shown in Table 2.

The arithmetic averages of statistical parameters \( Z_2 \), SF, and \( R_p - 1 \) in Table 2 were calculated, respectively. The relationships between statistical parameters and the number of profiles are plotted in Figure 9. Distinctly, the average values of \( Z_2 \), SF, and \( R_p - 1 \) share a similar trend of decrease with the increase of profile number from 4 to 12. Therein, a greater decreasing rate of \( Z_2 \) and SF can be observed compared to that of \( R_p \) when the profile number increases from 4 to 8, which are slowing down after that. However, the turning point in decreasing rate of \( R_p \) is found to be located in the profile number of 10. According to the above phenomenon, to avoid the overestimate of the roughness parameters of joint surface and unnecessary workload, 10–12 profiles are considered appropriate.

3.6. Determination of JRCp in Parallel and Vertical Shearing Directions. The profiles were extracted with an isometric distance parallel to the shearing direction (y direction) and
Table 2: Influence of the profile number on statistical parameters and JRC

| Number of profiles | Profile number | $Z_2$   | SF     | $R_p-1$ | JRC ($Z_2$) | JRC (SF) | JRC ($R_p-1$) |
|--------------------|---------------|---------|--------|---------|-------------|----------|---------------|
| 4                  | 1             | 0.334113 | 0.027908 | 1.041132 | 17.14367    | 17.16313 | 15.49015      |
|                    | 2             | 0.323575 | 0.026175 | 1.037607 | 16.66137    | 16.68062 | 14.81893      |
|                    | 3             | 0.336752 | 0.028351 | 1.039223 | 17.26334    | 17.28285 | 15.13186      |
|                    | 4             | 0.516084 | 0.066586 | 1.080583 | 24.56686    | 24.59143 | 21.51547      |
| 6                  | 1             | 0.334113 | 0.027908 | 1.041132 | 17.14367    | 17.16313 | 15.49015      |
|                    | 2             | 0.271739 | 0.018461 | 1.029877 | 14.17328    | 14.19167 | 13.17641      |
|                    | 3             | 0.324212 | 0.026278 | 1.036949 | 16.69073    | 16.70999 | 14.68901      |
|                    | 4             | 0.365211 | 0.033435 | 1.052989 | 18.52686    | 18.54702 | 17.48888      |
|                    | 5             | 0.28327  | 0.020601 | 1.031734 | 14.74481    | 14.76335 | 13.59582      |
|                    | 6             | 0.516084 | 0.066586 | 1.080583 | 24.56686    | 24.59143 | 21.51547      |
| 8                  | 1             | 0.334113 | 0.027908 | 1.041132 | 17.14367    | 17.16313 | 15.49015      |
|                    | 2             | 0.280668 | 0.019694 | 1.031494 | 14.61681    | 14.63532 | 13.08202      |
|                    | 3             | 0.332411 | 0.027624 | 1.042903 | 17.06624    | 17.08566 | 15.81223      |
|                    | 4             | 0.28135  | 0.019789 | 1.02947  | 14.6504     | 14.66892 | 13.08202      |
|                    | 5             | 0.317278 | 0.025166 | 1.038411 | 16.36962    | 16.38874 | 14.97589      |
|                    | 6             | 0.252274 | 0.015911 | 1.038002 | 16.09442    | 16.11343 | 14.89633      |
|                    | 7             | 0.391934 | 0.038403 | 1.055081 | 19.67193    | 19.69276 | 17.80791      |
|                    | 8             | 0.391647 | 0.038347 | 1.06269  | 19.65981    | 19.68063 | 18.90214      |
| 10                 | 1             | 0.334113 | 0.027908 | 1.041132 | 17.14367    | 17.16313 | 15.49015      |
|                    | 2             | 0.308664 | 0.023818 | 1.036554 | 15.96614    | 15.9851  | 14.61013      |
|                    | 3             | 0.291631 | 0.021262 | 1.034531 | 15.15236    | 15.17103 | 13.96464      |
|                    | 4             | 0.323575 | 0.026175 | 1.037607 | 16.66137    | 16.68062 | 14.81893      |
|                    | 5             | 0.29824  | 0.022237 | 1.033366 | 15.40702    | 15.4895  | 13.95051      |
|                    | 6             | 0.348908 | 0.030434 | 1.044766 | 17.80894    | 17.82872 | 16.14123      |
|                    | 7             | 0.336752 | 0.028351 | 1.039223 | 17.26334    | 17.28285 | 15.13186      |
|                    | 8             | 0.279495 | 0.018625 | 1.02944  | 14.23358    | 14.25198 | 13.07505      |
|                    | 9             | 0.286452 | 0.020514 | 1.032467 | 14.90056    | 14.91915 | 13.75682      |
|                    | 10            | 0.368939 | 0.034029 | 1.044936 | 18.6889     | 18.70915 | 16.17077      |
| 12                 | 1             | 0.28874  | 0.020843 | 1.031503 | 15.01205    | 15.03068 | 15.34462      |
|                    | 2             | 0.31391  | 0.024241 | 1.038002 | 16.09442    | 16.11343 | 14.89633      |
|                    | 3             | 0.269838 | 0.018203 | 1.028985 | 14.07799    | 14.09635 | 12.96833      |
|                    | 4             | 0.306261 | 0.023449 | 1.037605 | 15.85262    | 15.87154 | 14.81867      |
|                    | 5             | 0.32068  | 0.025709 | 1.040139 | 16.52758    | 16.54676 | 15.30524      |
|                    | 6             | 0.289813 | 0.020998 | 1.033059 | 15.06423    | 15.08278 | 13.88487      |
|                    | 7             | 0.345613 | 0.029862 | 1.046337 | 17.66194    | 17.68165 | 16.41125      |
|                    | 8             | 0.303448 | 0.027299 | 1.043801 | 16.97674    | 16.99612 | 15.97202      |
|                    | 9             | 0.35227  | 0.015911 | 1.025084 | 13.18208    | 13.20025 | 12.0022       |
|                    | 10            | 0.255891 | 0.01637  | 1.025643 | 13.36889    | 13.3871  | 12.14687      |
|                    | 11            | 0.321166 | 0.025787 | 1.040347 | 16.55005    | 16.56925 | 15.33727      |
|                    | 12            | 0.370488 | 0.034315 | 1.048407 | 18.756      | 18.77628 | 16.75744      |
Figure 9: Relationship between statistical parameters and the number of profiles.

Figure 10: Relationship between JRC\(p\) and the number of profiles.

Table 3: Influence of extraction direction of profile on statistical parameters.

| Shear surface | Profile number | \(Z_2\) (x) | SF (x) | \(R_p\) (x) | \(Z_2\) (y) | SF (y) | \(R_p\) (y) |
|--------------|---------------|--------------|--------|-------------|--------------|--------|-------------|
| 1            | 1             | 0.343042     | 0.029419 | 1.051248    | 0.334809     | 0.028024 | 1.044827    |
| 2            | 0.261163      | 0.017052     | 1.032576 | 0.350642    | 0.030737     | 1.045732 |
| 3            | 0.35155       | 0.030897     | 1.054283 | 0.333896    | 0.025872     | 1.042271 |
| 4            | 0.373058      | 0.034793     | 1.061777 | 0.342821    | 0.039382     | 1.055555 |
| 5            | 0.3997367     | 0.039947     | 1.064871 | 0.342821    | 0.029382     | 1.055555 |
| 6            | 0.377267      | 0.035583     | 1.056107 | 0.4576      | 0.052349     | 1.060914 |
| 7            | 0.412579      | 0.042555     | 1.055478 | 0.525343    | 0.068996     | 1.102716 |
| 8            | 0.362058      | 0.032772     | 1.052836 | 0.30805     | 0.023724     | 1.040881 |
| 9            | 0.390999      | 0.038044     | 1.058005 | 0.404181    | 0.040841     | 1.070758 |
| 10           | 0.443775      | 0.047938     | 1.073249 | 0.372061    | 0.034607     | 1.063165 |
Table 3: Continued.

| Shear surface | Profile number | \( Z_{2} (x) \) | SF (x) | \( R_{p} (x) \) | \( Z_{2} (y) \) | SF (y) | \( R_{p} (y) \) |
|---------------|----------------|----------------|--------|----------------|----------------|--------|----------------|
| 2             | 1              | 0.334113       | 0.027908 | 1.041132       | 0.224982       | 0.012654 | 1.02422        |
|               | 2              | 0.308664       | 0.023818 | 1.036554       | 0.24325        | 0.014793 | 1.028303       |
|               | 3              | 0.291631       | 0.021262 | 1.034531       | 0.361477       | 0.032666 | 1.040065       |
|               | 4              | 0.323575       | 0.026175 | 1.037607       | 0.66201        | 0.109564 | 1.075167       |
|               | 5              | 0.29824        | 0.022237 | 1.033366       | 0.336357       | 0.028284 | 1.051063       |
|               | 6              | 0.348908       | 0.030434 | 1.044766       | 0.236292       | 0.013958 | 1.024576       |
|               | 7              | 0.336752       | 0.028351 | 1.039223       | 0.249817       | 0.015602 | 1.029733       |
|               | 8              | 0.272945       | 0.018625 | 1.02944        | 0.238031       | 0.014165 | 1.026865       |
|               | 9              | 0.286452       | 0.020514 | 1.032467       | 0.350299       | 0.030677 | 1.04701        |
|               | 10             | 0.368939       | 0.034029 | 1.044936       | 0.365196       | 0.033342 | 1.048151       |
| 3             | 1              | 0.457593       | 0.052348 | 1.07205        | 0.221649       | 0.012282 | 1.02363        |
|               | 2              | 0.296956       | 0.022046 | 1.03302        | 0.251538       | 0.015818 | 1.029965       |
|               | 3              | 0.240434       | 0.014452 | 1.022398       | 0.336627       | 0.028329 | 1.044274       |
|               | 4              | 0.231826       | 0.013436 | 1.020668       | 0.374093       | 0.034986 | 1.053469       |
|               | 5              | 0.268352       | 0.018003 | 1.028363       | 0.386864       | 0.037382 | 1.04766        |
|               | 6              | 0.230802       | 0.013317 | 1.020365       | 0.361977       | 0.032757 | 1.042685       |
|               | 7              | 0.192003       | 0.009216 | 1.012592       | 0.326857       | 0.026709 | 1.048839       |
|               | 8              | 0.261574       | 0.017105 | 1.026244       | 0.275096       | 0.018919 | 1.03532        |
|               | 9              | 0.330512       | 0.027309 | 1.044239       | 0.302523       | 0.02288 | 1.041375       |
|               | 10             | 0.278776       | 0.019429 | 1.031265       | 0.224518       | 0.012602 | 1.017939       |

Figure 11: Comparison of JRC\(_{p}\) extracted profiles from the \( x \) and \( y \) directions.
perpendicular to the shearing direction (x direction) in Figure 8. The difference between the roughness statistical parameters and JRC$_p$ along the two directions was investigated, which provides a basis for a reasonable determination of roughness and shear strength of joints. In this study, 10 profiles were extracted from the x and y directions of the shear surface in Figure 8. Spacing of 10 mm between two profiles was adopted, and the measuring point interval for each profile was 0.5 mm. The values of $Z_p$, SF, and $R_p$ were determined with equations (1)–(3), as shown in Table 3. The roughness of each profile can be calculated with equations (4)–(6), and JRC$_p$ of the joint surface can be obtained based on the roughness of profiles and equations (4)–(6).

JRC$_p$ ($Z_p$), JRC$_p$ (SF), and JRC$_p$ ($R_p - 1$) calculated in x and y directions of four shear surfaces are plotted in Figure 11. Distinct differences exist between the values of JRC$_p$ obtained via extracted profiles from x and y directions, which indicates the directional heterogeneity. JRC$_p$ ($Z_p$), JRC$_p$ (SF), and JRC$_p$ ($R_p - 1$) obtained via extracted profiles in the y direction are slightly greater than those obtained via extracted profiles in the x direction. Such a phenomenon can be attributed to the influence of rotation and tension shear failure when shearing, which leads to greater roughness along the shear direction on the failure surface.

Meanwhile, Figure 11 illustrates that the values of JRC$_p$ ($Z_p$), JRC$_p$ (SF), and JRC$_p$ ($R_p - 1$) decrease with the increase of normal stress in either direction. Specifically, JRC$_p$ ($Z_p$) obtained via extracted profiles from the x direction is taken as an example for analysis. JRC$_p$ ($Z_p$) gradually decreases when the normal stress increases from 0.8 MPa to 2.0 MPa, indicating that the joint surface becomes smoother. This owes to the shear failure and grind of the sawtooth with the increase of normal stress, resulting in the decrease of roughness and a smoother shear surface.

4. Conclusion

In regard of the difficulty in accurately determining the value of roughness of 3D joint, that is, the JRC, a new determination method, based on the 3D laser scanning technique and self-compiled Python code as well as the statistical parameter methods, was proposed in this study. The following conclusions are obtained:

1. The joint was divided into several rectangular regions by roughness profiles, and the JRC of joint was assumed as the arithmetic average of the JRC of profiles, which overcomes the disadvantages of traditional 2D JRC determination methods and provides certain theoretical guidances for the calculation of 3D JRC.

2. Equipped with the 3D laser scanning technique, the accurate 3D coordinate data of joint surface were easily obtained, and therefore, the data were processed via a self-compiled Python code, extracting the precise roughness profiles of the joint. The value of JRC of each roughness profile was calculated via the statistical parameter methods, where the statistical parameters $Z_p$, SF, and $R_p$ were selected.

3. The shear strength of jointed rock was evaluated via the JRC-JCS model, and therefore, a comprehensive comparison between the calculating results and experimental results was executed, which presents an excellent consistency of shear strength between the calculating values and experimental results, verifying the validity and accuracy of the proposed method.

4. The influencing factors of roughness profile extraction on the accuracy of the JRC, such as measuring point interval, the profile number and direction, were investigated. A smaller measuring point interval can produce a more accurate digital profile. To a certain extent, the more the numbers of profiles, the smaller the value of JRC. The profile number of 10 was suggested in this study. Finally, the determination of JRC is directional, resulting in different values in the parallel and perpendicular direction of shearing.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

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