



# Article Relationship between Joint Roughness Coefficient and Statistical Roughness Parameters and Its Sensitivity to Sampling Interval

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Abstract: Accurate determination of the surface roughness is of significant importance in estimating the mechanical and hydraulic behaviors of rock joints. The correlation between joint roughness coefficient (*JRC*) and various statistical roughness parameters calculated from digitized Barton's roughness profiles was explored with Pearson's correlation coefficient method. The results show the strongest correlation between the standard deviation of the roughness angle and *JRC* following an excellent linear relationship. In addition, the correlation in the *JRC* with textural parameters is better than its correlation with amplitude parameters. Twenty-nine rock joint surfaces from fine sandstone, coarse sandstone and granite joint samples with a wide range of surface morphology were digitized using a high-resolution 3D scanner instrument. Further, the statistical roughness parameter values were calculated for each joint profile at eight different sampling intervals for sensitivity analysis of these statistical roughness parameters with regard to the sampling interval. The result indicated that textural parameters generally have a certain degree of dependency on sampling interval, following a power-law relationship. Specifically, when the sampling interval increases, the structure function value increases whereas it decreases for other textural parameters. In contrast, the dependence of the amplitude parameters on the sampling interval is not significant.

Keywords: rock joint; joint roughness coefficient; roughness parameter; sampling interval

## 1. Introduction

Joints widely exist in geological rock strata and dominate fluid flow and mechanical deformation of rock. This is particularly significant in many rock engineering applications, such as groundwater management, hydrocarbon production, construction of dam foundations, geothermal extraction, CO<sub>2</sub> geological storage and hazardous waste isolation [1–6]. Rock joints are usually rough, the surface morphology of rock discontinuity plays an essential role in rock mass strength and hydraulic conductivity [7–13]. The rock joint surface undulation determines the void spaces between two discontinuity surfaces, affecting the hydraulic aperture distribution and fluid flow tortuosity [14–16]. Mechanically, the roughness affects the shear strength of rock discontinuities such as rock joints and faults [17–19]. Therefore, it has been rock mechanic scientists and engineers' ambition to find methods to accurately characterize rock joint surface roughness and apply it to hydro-mechanical behavior description of rock joints; however, this seems challenging.

The joint roughness coefficient (*JRC*) has been widely used to quantitatively characterize rock joint surface morphology since 1973 [20]. Initially, the *JRC* of the rock joint profile



Citation: Luo, Y.; Wang, Y.; Guo, H.; Liu, X.; Luo, Y.; Liu, Y. Relationship between Joint Roughness Coefficient and Statistical Roughness Parameters and Its Sensitivity to Sampling Interval. *Sustainability* **2022**, *14*, 13597. https://doi.org/10.3390/ su142013597

Academic Editors: Kai Wang, Yubing Liu and Xiaojun Feng

Received: 14 September 2022 Accepted: 17 October 2022 Published: 20 October 2022

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**Copyright:** © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). was determined by visibly comparing it to the ten representative profiles with JRC ranging from 0 to 20 [7]. Afterward, this method was proposed by the International Society for Rock Mechanics (ISRM) commission. Although simple and effective, the JRC obtained using visible comparison may vary. On the one hand, because the user has to match the profiles subjectively; also, the number of Barton's roughness profiles is limited. Another method is to back-calculate JRC with the peak shear strength model (e.g., JRC-JCS) of rock joints based on the direct shear test result [21]. However, this method has relatively limited in practical application due to the peak shear strength of rock joints that can only be predicted by estimating the value of JRC in situ. To avoid the uncertainty of JRC estimation by the subjective comparison method, numerous empirical correlations of JRC with regard to roughness parameters and fractal dimensions of rock joints have been established [22,23]. The commonly used statistical parameters include root mean square of the first derivative  $(Z_2)$ , structure function (SF), roughness profile index  $(R_p)$ , peak asperity height  $(R_z)$ , arithmetic average of the absolute height  $(R_a)$ , root mean square roughness height value  $(R_a)$ , average roughness angle ( $\theta$ ), standard deviation of the roughness angle *i* ( $\sigma_i$ ), the ultimate slope ( $\lambda$ ), profile elongation index ( $\delta$ ) and angular threshold ( $\theta^*_{max}$ ) [22,24,25]. Among these parameters,  $Z_2$ , as a slope-based parameter, is the most popular based on its correlation to the JRC. The fractal dimension (D) can be determined through different fractal analysis methods such as box-counting, divider, variogram analysis, roughness-length and power spectral analysis methods [26–30].

The empirical equations based on roughness parameters can determine the *JRC* objectively and efficiently. Various equations, such as linear, logarithmic, trigonometric and power-law, have been used, even for the same statistical parameters [23,31–33]. It is difficult for the user to decide which correlation is the most suitable for an application. The reliability of JRC estimation based on roughness parameters remains controversial, and further study is needed. On the other hand, the sampling interval used in digitized rough rock joint profile influences the value of some roughness parameters and hence the estimation of JRC. For instance, Yu and Vayssade [34] digitized Barton's roughness profiles at different sampling intervals and found  $Z_2$  and SF could be sensitive to the sampling interval; just as the coefficients of empirical equations between *JRC* and  $Z_2$  are not equal for the sampling interval of 0.25 mm, 0.5 mm and 1.0 mm. Tatone and Grasselli [24] obtained a similar conclusion by digitizing Barton's roughness profiles at the sampling interval of 0.5 mm and 1.0 mm. Li et al. [35] digitized 112 joint profiles retrieved from the literature at sampling intervals ranging from 0.1 mm to 3.2 mm, and two sets of empirical equations of JRC were proposed. The roughness parameters value may vary with the sampling interval [32,36–38]. However, there are still many knowledge gaps regarding the response of roughness parameters to sampling interval, where understanding the dependency of roughness parameters on sampling interval is important.

The characterization of rock joint roughness requires the measurement of its surface morphology. Over the past decades, a variety of instruments and methods have been employed to measure rock joint morphology in the laboratory and in-situ. These measurement techniques include "Contact Methods" (e.g., needle and stylus profilometers, profile combs and shadow profilometry) [7,39,40] and "Non-Contact Methods" (e.g., photogrammetry, structured light techniques and laser scanning) [41–45]. The above measurement technologies provide powerful tools for accurately describing the roughness of rock joints, and they are each subjected to varying limitations. As such, Yong [46] reported that each equipment used to measure the joint surface morphology has a sampling limitation. In addition, some techniques are not convenient for field use and others are time-consuming or destructive. Recently, some non-destructive testing techniques have attracted the attention of field measurement engineers [47], which may provide new insight into the development of advanced field measurement equipment for rock joint topography. At present, three-dimensional scanners and other digital optical measurement devices are the primary means to acquire detailed digitizing joint surface topography images in the laboratory [17,29,48].

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This study first digitized Barton's roughness profiles, and these profiles were used to explore the relationship between statistical roughness parameters and *JRC*. To investigate the dependence of *JRC* on the sampling interval, a total of 261 representative 2D joint profiles with a wide range of roughness were extracted from fine sandstone, coarse sandstone and granite joint samples digitized using a non-contact three-dimensional scanner instrument. The roughness parameters, including  $Z_2$ ,  $R_p$ , SF,  $R_a$ ,  $R_q$ ,  $R_z$ ,  $\delta$ ,  $\lambda$ ,  $\sigma_i$ , and  $\theta$  values, were calculated from the digitized joint profile at eight different sampling intervals (0.1, 0.5, 1.0, 1.5, 2.0, 3.0, 4.0 and 5.0 mm). The dependence between these roughness parameters and sampling interval was also analyzed.

# 2. Material and Methods

In this study, two sets of joint profiles were used to achieve research objectives. The first set is from Barton's roughness profiles, which was used to determine the relationship between roughness parameters and *JRC*. The second set was used to investigate the effect of sampling interval on roughness parameter estimation, which is from fine sandstone, coarse sandstone and granite joint samples formed by splitting the intact rock samples.

## 2.1. Digitization of Barton's Roughness Profiles

The present study used Barton's roughness profiles from Barton and Choubey [7] to determine *JRC*. The images of Barton's roughness profiles from the original publication were scanned using a 1400 dot per inch (dpi) resolution, and then converted the resulting images into bitmap files, and digitizing them at a 0.5 mm sampling interval using MATLAB code (Table 1). The digitized profiles were fitted using the least-square best-fit approach, and it can be seen that the best-fit line is not horizontal as shown in Table 1 but has a non-zero overall slope (Figure 1). Therefore, it is necessary to realign the profiles as suggested by Tatone and Grasselli [24] and Li et al. [35]. The slopes of the best-fit lines relative to the horizontal line were used to calculate the angle of rotation required to make them horizontal (Figure 1). The coordinates determining the aligned Barton's roughness profiles were imported into computer software to calculate the roughness parameters of the profile.



Table 1. JRC and Back-calculation of Barton's roughness profiles suggested by Barton and Choubey [7].



**Figure 1.** Example of realigning from re-digitized at a sampling interval of 0.5 mm: (**a**) the Barton's roughness profile 6 (JRC = 10-12); (**b**) profile 8 (JRC = 14-16) of Barton and Choubey [7]. The dotted and solid blue lines represent the best-fit line through the original and realigned profiles, respectively.

#### 2.2. Joint Sample Preparation

Intact cylindrical samples were cored from three types of rock blocks (fine sandstone, coarse sandstone and granite) with a core diameter of 50 mm and a height of approximately 100 mm. Two ends of these samples were polished to be smooth and parallel to each other using the grinding machine. The cores were spilt using splitting wedges in uniaxial compressive apparatus in a similar manner to the Brazilian split test [49]. A total of twenty-nine rock joint samples with a wide range of joint surface morphology (58 joint surfaces) were prepared (Figure 2). Given that there is a good match between the upper and lower halves of rock joint samples, therefore, only one of the halves of each joint sample was selected for analysis. For convenience and simplicity, the fine sandstone, coarse sandstone and granite joint samples were numbered FS, CS and GR, respectively.







Figure 2. Preparation of rock joint samples: (a) splitting process of intact cylindrical sample; and (b) rock joint samples.

## 2.3. Joint Sample Digitization

The rock joint surface morphology characteristics were measured using a non-contact three-dimensional scanner instrument Cronos [49]. Its precision is up to  $\pm 0.02$  mm in the height direction and the accuracy is up to  $\pm 0.1$  mm in the horizontal direction. After scanning, the point cloud data of the joint surface of all samples were obtained, which can be used to calculate the roughness parameters. Figure 3 shows the digitized fine sandstone joint surface morphology, where the undulation degree of the joint surface can be judged from different colors of the graph, coarse sandstone and granite joint surface morphology are attached in "Supplementary Materials" (See Figure S1 in the Supplementary Materials). These rock joint samples exhibit a wide range of surface roughness. Figure 4 shows the Gaussian fitting of the asperity elevation distributions of fine sandstone joint surface, the Gaussian fitting in coarse sandstone and granite joint surfaces are attached in "Supplementary Materials" (See Figure S2 in the Supplementary Materials). It can be seen that the surface asperity elevation distributions on most rock joints are in good agreement with the theoretical Gaussian distribution function. In addition, each joint surface profile was divided by nine equally spaced lines along the long axis direction; hence, nine two-dimension profile lines were obtained for each sample. The extracted profile lines from joint surfaces were used to calculate the statistical roughness parameter.



Figure 3. Surface morphology of fine sandstone joint samples (all dimensions are in units of mm).



Figure 4. Gaussian fit of the asperity elevation distribution for fine sandstone joint samples.

# 3. Determination of *JRC* Using Statistical Roughness Parameters

## 3.1. Study on the Correlation between Statistical Roughness Parameters and JRC

According to previous study, it can be known that these roughness parameters  $(Z_2, R_p)$ , SF,  $R_q$ ,  $R_q$ ,  $R_z$ ,  $\delta$ ,  $\lambda$ ,  $\sigma_i$ ,  $\theta$ ) can be used to estimate the JRC of rock joints by their empirical correlations with JRC. To further understand the relationship between roughness parameters and JRC of rock joints, a simple correlation analysis between them was conducted with Pearson's correlation coefficient ( $\gamma$ ) method here, and it can be used to evaluate the strength of a linear dependence between two variables [50]. The definition and calculation formula of Pearson's correlation coefficient ( $\gamma$ ) and roughness parameters were presented in the "Appendix A". Where the  $\gamma$  takes on a range of values from -1 to +1, a positive value denotes positive linear correlation, and a negative value denotes negative linear correlation. The closer the value is to -1 or +1, the stronger the linear correlation. Figure 5 shows the Pearson's correlation coefficient of each statistical roughness parameter with respect to *JRC* of Barton's roughness profiles at a sampling interval of 0.5 mm. It can be observed that the Pearson's correlation coefficient  $\gamma > 0.7$  for these statistical roughness parameters except for  $R_a$  where  $\gamma = 0.66$ . This result indicates that the JRC of joint profile is well related to these statistical roughness parameters. Among these statistical roughness parameters, the Pearson's correlation coefficient value of  $\sigma_i$  is the largest, and its value reached 0.9923, denoting the strongest correlation between the  $\sigma_i$  and JRC in rock joint, while  $R_a$  is the smallest, indicating that it has a moderate correlation with JRC. Pearson's correlation coefficient ( $\gamma$ ) value for Z<sub>2</sub> is 0.981 and  $\theta$  is 0.9914, showing that the range of  $\gamma$ value for the two parameters higher than 0.95 is very close to that of  $\sigma_i$ . By comparison, the coefficient ( $\gamma$ ) values for  $Z_2$ , SF,  $R_p$ ,  $\delta$ ,  $\sigma_i$  and  $\theta$  are larger than that of  $R_a$ ,  $R_q$ ,  $R_z$  and  $\lambda$ , demonstrating that a better correlation exists between the parameters  $Z_2$ , SF,  $R_p$ ,  $\delta$ ,  $\sigma_i$ and  $\theta$  and JRC. The parameters  $R_a$ ,  $R_q$ ,  $R_z$  and  $\lambda$  reflect the amplitude distribution of a rock joint profile, therefore,  $R_a$ ,  $R_q$ ,  $R_z$  and  $\lambda$  are categorized as amplitude parameters [25]. By contrast,  $Z_2$ ,  $R_p$  and  $\theta$  describe the texture variation of a rock joint profile, which is grouped as textural parameters. The parameters SF,  $\delta$  and  $\sigma_i$  are also considered as textural parameters given that they also mirror the information of the joint profile, despite not being classified as such before. The roughness of rock joints can be identified by the value of these parameters mentioned above. For instance, in terms of  $Z_2$ , a larger  $Z_2$  indicates a rougher joint profile. Taking Barton's roughness profiles as an example, the 10th roughness profile shows the roughest morphology with a maximum *JRC*, whereas the 1st profile is the smoothest with a minimum JRC.



**Figure 5.** Pearson's correlation coefficient ( $\gamma$ ) between the *JRC* and the statistical roughness parameters calculated from Barton's roughness profiles at a sampling interval (SI) of 0.5 mm.

#### 3.2. Determination of JRC Using Statistical Roughness Parameters

As shown in Figure 5, the Pearson's correlation coefficient value for textural parameters exceeds 0.9, whereas the value for amplitude parameters is between 0.6 and 0.8. Considering that the Pearson's correlation coefficient ( $\gamma$ ) value mirrors the close degree of the correlation between roughness parameters and JRC, the relationship between textural parameters and JRC was evaluated by the correlation between their values from digitized Barton's roughness profiles at a sampling interval of 0.5 mm and the original *JRC* values confirmed by Barton and Choubey [7]. The  $\sigma_i$  parameter has the strongest correlation with *JRC*, therefore, the correlation of *JRC* against the  $\sigma_i$  was analyzed in detail in the present study. In previous study, some relationships between the JRC and the  $\sigma_i$  parameter were established. The approach of using the parameter  $\sigma_i$  to evaluate *JRC* was initially established by Yu and Vayssade [34]. They reported a linear equation and a square root relationship between  $\sigma_i$  and JRC at a sampling interval of 0.5. In contrast, the  $R^2$  are 0.975 and 0.970 of regression analysis for the linear equation and the square root equation, respectively, indicating that the linear equation can slightly better determine *JRC* for the study of Yu and Vayssade [34]. Therefore, the linear equation (Equation (1)) was considered for comparison analysis. In addition, Li and Zhang [51] proposed a linear equation and a power-law formula with zero intercept to define the relationship between  $\sigma_i$  and *JRC* by retrieving joint profiles from the published literature at a sampling interval of 0.4 mm. Likewise, the linear equation (Equation (2)) was also used to compare analysis based on it having a slightly larger  $R^2$  value (0.8843 for the linear equation and 0.8780 for the power-law formula). Recently, Abolfazli and Fahimifar [23] suggested that a natural logarithmic equation given by Equation (3) can describe the relationship between these two variables ( $R^2 = 0.9399$ ).

$$JRC = 1.14(\sigma_i) - 3.88 \tag{1}$$

$$JRC = 1.0419(\sigma_i) - 4.7334 \tag{2}$$

$$JRC = -3.325 + 7.862 \ln(\sigma_i - 5.187) \tag{3}$$

Figure 6a shows the variation in the parameter  $\sigma_i$  values calculated from digitizing Barton's roughness profiles against *JRC*. It can be observed that the *JRC* increases with the parameter  $\sigma_i$  values. Based on the best-fit analysis of the scatter points, the regression line shows that a linear equation given in Equation (4) fits the two variable values well. Most of the data points fall on the solid line of Figure 6a, representing the regression equation except that the data points of the 1st (*JRC* 0–2), the 3rd (*JRC* 4–6) and 4th (*JRC* 6–8) have slight deviation, and the regression  $R^2 = 0.9834$ .

$$JRC = 0.9936(\sigma_i) - 6.5153 \tag{4}$$



**Figure 6.** (a) Correlation of *JRC* and  $\sigma_i$  as calculated from Barton's roughness profiles; and (b) comparison of *JRC* calculated from the equation given in this study and previous studies.

A detailed comparison analysis has been conducted to further validate the linear equation's reliability to determine the *JRC* of rock joints based on the roughness parameter

 $\sigma_i$ . The JRC was calculated using Equations (1)–(4) based on the  $\sigma_i$  parameter values determined from Barton's profiles. The variation in the JRC calculated using these equations proposed by other researchers and introduced in this study, respectively, was depicted in Figure 6b to compare the consistency between these equations. As can be seen in the figure, the variation trend of the JRC calculated using Equations (1) and (2) is very similar to the values determined from Equation (4). In contrast, the JRC calculated by Equation (2) is closer to Equation (4). However, the variation of the data points from Equation (3) is somewhat different from that of other equations. The deviation of the data points calculated by Equation (3) seems to increase as the joint surface roughness decreases, demonstrating that this equation may be sensitive to the joint surface morphology. The result showed that Equation (3) might be more suitable for the rock joint with more significant roughness. Comparing the results of the determination coefficient for both Equation (4) proposed in this study and Equations (1)–(3) suggested in the previous researches, it can be seen that the determination coefficient  $R^2$  for Equation (4) is higher than that of other equations, showing that Equation (4) may be superior to other equations for determining JRC of rock joints.

The potential cause of the difference in these equations may be due to the different sampling intervals applied when calculating the statistical roughness. The sampling interval might shift the establishment of the relationship between *JRC* and roughness parameters. The functional relationship between *JRC* and the  $\sigma_i$  parameter was established at a 0.5 mm sampling interval in the study by Yu and Vayssade [34]. However, it was conducted by Li and Zhang [51] and Abolfazli and Fahimifar [23] at 0.4 mm and 0.02 mm sampling intervals, respectively. It is difficult to confirm that the establishment of these relationships is not affected by the sampling interval. In addition, the methods of digitizing joint profiles and the resolution in the measurement process might result in a difference in the profile data, such as some joint profiles were taken from the literature (e.g., Equations (1) and (2)), whereas others were directly extracted from the rock joint surface (e.g., Equation (3)).

The regression analysis between *JRC* and the textural parameters  $Z_2$ , *SF*,  $R_p$ ,  $\delta$ , and  $\theta$  calculated from the digitizing data in the present study was also conducted by different linear equations, respectively, as presented in Table 2. It can be observed that these fitting equations have relatively high determination coefficients ( $R^2 > 0.8790$ ). Particularly, the determination coefficient of the equation fitted to the roughness parameter  $\theta$  reaches 0.9807, but they are all smaller than that of the equation based on  $\sigma_i$  (0.9834). Nevertheless, this does not mean it is the best choice to calculate the *JRC* of rock joints with these linear equations fitted based on the roughness parameters  $Z_2$ , *SF*,  $R_p$ ,  $\delta$ , and  $\theta$ . As the previous studies have shown some more reliable equations such as the power-law equation of *JRC* with respect to  $Z_2$  proposed to determine the *JRC* of rock joints, the determination coefficient  $R^2$  is 0.960 in Tatone and Grasselli [24]. This result shows that using the power-law equation to quantify the relationship between *JRC* and  $Z_2$  may be more suitable than a linear formula. The nonlinear relationship between *JRC* and the statistical roughness parameters is beyond this research interest. Therefore, this study does not further analyze these equations fitted based on the textural parameters  $Z_2$ , *SF*,  $R_p$ ,  $\delta$  and  $\theta$ .

**Table 2.** Empirical equations derived from this study for *JRC* determination based on roughness parameters  $Z_2$ , *SF*,  $R_p$ ,  $\delta$ , and  $\theta$ .

No.	Variable	Equation	<i>R</i> <sup>2</sup>	Rang <sup>#</sup>
E5	$Z_2$	$JRC = 65.7899(Z_2) - 6.1936$	0.9577	0.1220-0.4036
E6	SF	JRC = 476.2897(SF) + 1.8542	0.8790	0.0037-0.0409
E7	$R_p - 1$	$JRC = 281.8400(R_p - 1) + 1.2289$	0.8956	0.0073-0.0718
E8	θ	$JRC = 1.5969(\theta) - 5.1004$	0.9807	3.6151-15.1640
E9	δ	$JRC = 280.7352(\delta) + 1.1866$	0.9006	0.0073-0.0718

Note: Rang<sup>#</sup> represents the range of variable values used to determine the equation.

Amplitude parameters, as the surface roughness examiner, have also been used to characterize the surface roughness feature of rock joints. Some correlations of these amplitude parameters, such as  $R_a$ ,  $R_a$ ,  $R_z$  and  $\lambda$  against *JRC*, have also been established [22,35,52]. Figure 7 shows the variation in *JRC* against the amplitude parameters value calculated from Barton's roughness profiles. The changing trends of amplitude parameters against *JRC* are similar, which may be attributed to the fact that these parameters are related to the asperity on the rock joint profile. The JRC increase as the amplitude parameters value increase as a whole. Nevertheless, in terms of the parameter  $R_z$ , the value has something abnormal for the 6th (JRC 10-12), 9th (JRC 16-18) and 10th (JRC 18-20) profiles smaller than those of the immediately preceding profiles as seen in Figure 7b. The  $R_q$  parameter value slightly exceeds the  $R_a$  parameter value for the same joint profile as plotted in Figure 7a. As reported by Krahn and Morgenstern [53], the two parameters are very close numerically. However, there is almost no difference in the ratio for the  $R_z$  and  $\lambda$  parameter values, as shown in Figure 7b, which is due to the fact that  $\lambda$  equals the ratio of  $R_z$  to L where it is fixed as defined in the "Appendix A". The relationship between  $R_a$ ,  $R_q$ ,  $R_z$  and  $\lambda$ parameters and JRC calculated from the retrieved joint profiles was defined using linear and power-law equations by Li and Zhang [51]. Considering simplicity and universality for engineering practices, Li et al. [35] suggested a power-law equation for the parameters  $R_z$  and  $\lambda$  to determine JRC. However, the present study has not determined the relationship between amplitude parameters and JRC due to the inconsistency of the changing trend for some joint profiles data. As a joint profile with large *JRC*, the amplitude parameters calculated from the profile may be large or small. This result may be ascribed to the fact that some important information of the joint profile is ignored when the amplitude parameters are used to determine the *JRC*. For example, in terms of  $R_z$ , it can only reflect the local high-order waviness of a rock joint profile while not representing the lower-order waviness characteristics. Therefore, for the amplitude parameters such as  $R_z$ , it may need to combine some other roughness parameters to characterize the roughness of joint profile, which is ongoing in our other work.



**Figure 7.** (a) Evolution of *JRC* against amplitude parameters calculated from Barton's roughness profiles for  $R_a$  and  $R_q$ ; and (b)  $R_z$  and  $\lambda$ .

#### 4. Correlation between Statistical Roughness Parameters and Sampling Interval

The *JRC* calculated based on its relationship with statistical roughness parameters may vary with the sampling interval as argued by Tatone and Grasselli [24], Bao et al. [38] and Huang et al. [54]. The present study examined the relationship between the statistical roughness parameters and the sampling interval using artificial rock joints. Firstly, given that the roughness parameters of rock joints need to be calculated; for this purpose, the scanned data points were imported into MATLAB (MATLAB, 2017) with a specific code created by us. Additionally, then, a series of two-dimensional joint profile lines were extracted at a specific sampling interval. This study considered eight sampling intervals ranging from 0.1 mm to 5.0 mm. It is known that these extracted profile lines are made of a series of equally spaced data points, and the coordinates of these points were used to calculate the statistical roughness parameters at the corresponding sampling interval. The statistical roughness parameters were calculated for each rock joint profile at eight

different sampling intervals (0.1, 0.5, 1.0, 1.5, 2.0, 3.0, 4.0 and 5.0 mm). In addition, the *JRC* of each joint sample was calculated using Equations (1)–(4) at a sampling interval of 0.5 mm, respectively. As presented in Table 3, all *JRC* values calculated using the proposed equation (Equation (4)) fall within the range of 0 to 20. However, the *JRC* of some rock joints calculated using other equations exceeds 20. This result demonstrates that using the proposed equations; therefore, the *JRC* of jointed samples is calculated using the proposed empirical formula (Equation (4)).

Table 3.	JRC of rock	joints.
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Commite Nie	JRC Calculated by $\sigma_i$					
Sample No.	Equation (1)	Equation (2)	Equation (3)	Equation (4) (This Study)		
FS1	12.9	10.6	14.4	8.1		
FS2	14.9	12.4	15.7	9.9		
FS3	14.0	11.6	15.1	9.0		
FS4	13.2	10.9	14.6	8.4		
FS5	16.3	13.7	16.5	11.1		
FS6	17.0	14.3	16.9	11.6		
FS7	16.9	14.3	16.9	11.6		
FS8	18.1	15.4	17.5	12.7		
FS9	15.8	13.3	16.3	10.6		
FS10	17.5	14.8	17.2	12.1		
CS1	19.0	16.2	17.9	13.4		
CS2	16.6	13.9	16.7	11.3		
CS3	18.1	15.4	17.5	12.7		
CS4	18.0	15.3	17.4	12.6		
CS5	19.1	16.3	18.0	13.5		
CS6	24.9	21.6	20.3	18.6		
CS7	18.3	15.5	17.6	12.8		
CS8	23.9	20.6	19.9	17.7		
CS9	23.4	20.2	19.7	17.3		
CS10	17.7	15.0	17.3	12.3		
GR1	23.0	19.8	19.6	16.9		
GR2	22.0	18.9	19.2	16.0		
GR3	20.5	17.5	18.6	14.7		
GR4	21.9	18.9	19.2	16.0		
GR5	18.9	16.1	17.8	13.3		
GR6	26.3	22.9	20.7	19.8		
GR7	25.0	21.7	20.3	18.7		
GR8	23.2	20.0	19.6	17.1		
GR9	26.3	22.9	20.7	19.8		

The results in the fine sandstone joint profiles were taken to illustrate the effect of the sampling interval on the calculating statistical roughness parameters. Figure 8 shows the variation in the statistical roughness parameters of the fine sandstone joint profile with respect to the sampling interval. Among these statistical roughness parameters, the  $Z_2$ ,  $R_p$ ,  $\delta$ ,  $\sigma_i$  and  $\theta$  values decrease with an increase in the sampling interval, indicating that these parameters of rock joint profile are sensitive to the sampling interval. The  $R_a$ ,  $R_q$ ,  $R_z$  and  $\lambda$  parameter (amplitude parameters) values show a slight fluctuation as the sampling interval increases (Figure 8). Specifically, as the sampling interval increases,  $R_z$  and  $\lambda$  values exhibit a slight decrease as a whole for all FS joint profiles,  $R_q$  values show an increasing (e.g., FS10) or decreasing (e.g., FS8) trend in some rock joints,  $R_q$  values show the slightest fluctuation among these parameters, especially for the sampling interval less than 2 mm. The results can be ascribed to the fact that the collected data points involved in calculating the roughness parameters decrease with an increase in sampling interval, where some typical asperities point of the rock joint profile is not captured. Among these statistical roughness parameters, the variation in the *SF* against sampling interval is quite

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different from that of other parameters, where *SF* values increase with an increase in the sampling interval (Figure 8). In addition, the varying rate in the *SF* increases with the sampling interval. This result demonstrates that the *SF* depends significantly on the sampling interval.



Figure 8. Evolution of roughness parameters against sampling interval (SI) for FS joint profile.

Additionally, the maximum change value (MC), defined as the ratio of the maximum to the minimum of the statistical roughness parameters in a specific joint sample for the sampling interval range of 0.1 mm to 5.0 mm, was calculated. Figure 9 shows the evolution of MC with respect to *JRC*, and it can be observed that the MC value is relatively large for most of the texture parameters. Notably, the maximum MC reaches 1071.7 for the parameters *SF*. However, the MC value is mostly between 1 and 1.2 for the amplitude parameters. The larger the corresponding MC of the roughness parameter, the more easily affected by the sampling interval. Therefore, the above results indicate that the texture parameters significantly depend on the sampling interval. In contrast, the dependence of the amplitude parameters on the sampling interval is not significant. In addition, it is difficult to discern any trend for the variation in MC with respect to *JRC* as shown in Figure 9, which indicates that the influence of the sampling interval on the statistical parameters may not be related to the surface roughness degree of rock joints.



**Figure 9.** The variation in the MC of the statistical roughness parameters against *JRC* at the sampling interval (SI) range of 0.1 mm to 5 mm for all artificial rock joint profile.

To further explore the effect of the sampling interval on roughness parameters of the rock joint surface morphology, the regression analysis of textural parameters with respect to the sampling intervals for three types of rock joint profiles was conducted as shown in Figure 10. It can be seen that the textural parameters show a noticeable nonlinear change as the sampling interval increases. Specifically, the roughness parameters  $Z_2$ ,  $R_p$ ,  $\delta$ ,  $\sigma_i$  and  $\theta$  first experienced a rapid reduction and then seemed to be level as the sampling interval increased. However, *SF* slowly increases at small sampling intervals and then rapidly increases with the sampling interval. The regression line (Figure 10) using the best-fit analysis of the textural parameters and sampling interval data shows that a power-law ( $y = Ax^B$ ) function fits the data well. The *y* represents the roughness parameter and the *x* represents the sampling interval. The regression coefficients *A* and *B* were calculated and presented in Table 4. The absolute value of coefficient *B* can indirectly reflect the sensitivity level of the roughness parameter to the sampling interval. The larger the absolute value of coefficient *B*, the stronger the dependency of this parameter on the sampling interval. Among these roughness parameters, coefficient *B* absolute value is the largest for the *SF* 

in the same rock joint sample at the same sampling interval (B = 1.1156-1.6560), further showing that *SF* significantly depends on the sampling interval. In addition, it can be observed that the coefficient *B* absolute value for roughness parameters  $Z_2$ ,  $\sigma_i$  and  $\theta$  is close (0.1036-0.2682 for  $Z_2$ , 0.0868-0.2332 for  $\sigma_i$  and 0.0851-0.2154 for  $\theta$ ), demonstrating that these parameters have a similar dependence on the sampling interval. However, coefficient *B* absolute value is the smallest for the  $R_p$  (0.0058-0.0187), indicating that the sensitivity of  $R_p$  to the sampling interval is not as strong as other texture parameters. The above results confirm the power-law relationship between texture parameters and sampling intervals, and further illustrating that the effect of sampling intervals should be considered when the  $Z_2$ ,  $R_p$ ,  $\delta$ ,  $\sigma_i$ ,  $\theta$  and *SF* are used to determine *JRC* values of rock joints.



**Figure 10.** Regression analysis of roughness parameters as a function of sampling interval (SI) using power-law correlation.

6 1 N	SF				$Z_2$		
Sample No.	A	В	R <sup>2</sup>	A	В	<i>R</i> <sup>2</sup>	
FS1	0.0426	1.1156	0.9851	0.1659	-0.1862	0.8517	
FS2	0.0406	1.4970	0.9975	0.1874	-0.1564	0.8935	
FS3	0.0449	1.2963	0.9970	0.1802	-0.1694	0.8769	
FS4	0.0386	1.4321	0.9996	0.1794	-0.1657	0.8893	
FS5	0.0562	1.4893	0.9997	0.2136	-0.1371	0.9029	
FS6	0.0672	1.4452	0.9967	0.2228	-0.1245	0.8693	
FS7	0.0729	1 6212	0.9998	0.2483	-0.1036	0.9013	
FS8	0.0656	1 5973	0.9977	0.2334	-0.1000	0.9114	
FS9	0.0602	1 5307	0.9976	0.2001	-0.1272	0.9034	
FS10	0.0612	1.5638	0.9998	0.2262	-0.1272	0.9055	
CS1	0.0719	1.3030	0.9973	0.2288	0.1200	0.9367	
CSI	0.0719	1.2107	0.9943	0.2200	-0.2133	0.9507	
C52	0.0432	1.4341	0.9963	0.2012	-0.2092	0.9043	
C53	0.0622	1.3070	0.9963	0.2224	-0.1697	0.9464	
C54	0.0680	1.4151	0.9944	0.2268	-0.1530	0.9313	
CS5	0.0737	1.4222	0.9989	0.2400	-0.1547	0.9252	
CS6	0.1662	1.4621	0.9949	0.3479	-0.1251	0.9143	
CS7	0.0718	1.5797	0.9998	0.2537	-0.1480	0.9543	
CS8	0.1105	1.6560	0.9999	0.3098	-0.1067	0.9385	
CS9	0.1329	1.5127	0.9959	0.3178	-0.1285	0.9096	
CS10	0.0610	1.4574	0.9999	0.2322	-0.1958	0.9695	
GR1	0.0799	1.3361	0.9994	0.2659	-0.2434	0.9472	
GR2	0.0721	1.2827	0.9991	0.2529	-0.2682	0.9682	
GR3	0.0619	1.2564	0.9988	0.2298	-0.2545	0.9539	
GR4	0.0653	1.3703	0.9997	0.2457	-0.2466	0.9501	
GR5	0.0582	1.2891	0.9996	0.2235	-0.2439	0.9518	
GR6	0.1335	1.5721	0.9996	0.3460	-0.1540	0.9675	
GR7	0.1147	1.5780	0.9996	0.3160	-0.1470	0.9681	
GR8	0.0913	1.2675	0.9950	0.2720	-0.2322	0.9490	
GR9	0.1276	1.4815	0.9999	0.3286	-0.1832	0.9585	
Sample No		$R_p$			δ		
Sample No.				-		-2	
	A	В	$R^2$	A	В	R <sup>2</sup>	
FS1	A 1.0154	B -0.0058	$\frac{R^2}{0.9716}$	A 0.0140	B -0.0460	<u>R</u> <sup>2</sup> 0.8681	
FS1 FS2	A 1.0154 1.0187	B -0.0058 -0.0059	R <sup>2</sup> 0.9716 0.9749	A 0.0140 0.0173	B -0.0460 -0.0341		
FS1 FS2 FS3	A 1.0154 1.0187 1.0176	B -0.0058 -0.0059 -0.0060	<b>R<sup>2</sup></b> 0.9716 0.9749 0.9748	A 0.0140 0.0173 0.0166	B -0.0460 -0.0341 -0.0377	R <sup>2</sup> 0.8681 0.8975 0.8879	
FS1 FS2 FS3 FS4	A 1.0154 1.0187 1.0176 1.0174	B -0.0058 -0.0059 -0.0060 -0.0058	$     \begin{array}{r} R^2 \\     \hline         0.9716 \\         0.9749 \\         0.9748 \\         0.9751 \\         \end{array} $	A 0.0140 0.0173 0.0166 0.0161	$\begin{array}{r} B \\ -0.0460 \\ -0.0341 \\ -0.0377 \\ -0.0366 \end{array}$	R <sup>2</sup> 0.8681 0.8975 0.8879 0.8931	
FS1 FS2 FS3 FS4 FS5	A 1.0154 1.0187 1.0176 1.0174 1.0236	B -0.0058 -0.0059 -0.0060 -0.0058 -0.0064	$\begin{array}{c} R^2 \\ \hline 0.9716 \\ 0.9749 \\ 0.9748 \\ 0.9751 \\ 0.9742 \\ \end{array}$	A 0.0140 0.0173 0.0166 0.0161 0.0224	$\begin{array}{c} B \\ \hline -0.0460 \\ -0.0341 \\ -0.0377 \\ -0.0366 \\ -0.0286 \end{array}$	R <sup>2</sup> 0.8681           0.8975           0.8879           0.8931           0.9040	
FS1 FS2 FS3 FS4 FS5 FS6	A           1.0154           1.0187           1.0176           1.0174           1.0236           1.0254	B -0.0058 -0.0059 -0.0060 -0.0058 -0.0064 -0.0062	$\begin{array}{c} R^2 \\ \hline 0.9716 \\ 0.9749 \\ 0.9748 \\ 0.9751 \\ 0.9742 \\ 0.9524 \end{array}$	A 0.0140 0.0173 0.0166 0.0161 0.0224 0.0247	$\begin{array}{c} B \\ \hline -0.0460 \\ -0.0341 \\ -0.0377 \\ -0.0366 \\ -0.0286 \\ -0.0295 \end{array}$	R2           0.8681           0.8975           0.8879           0.8931           0.9040           0.8755	
FS1 FS2 FS3 FS4 FS5 FS6 FS7	A           1.0154           1.0187           1.0176           1.0174           1.0236           1.0254           1.0307	B -0.0058 -0.0059 -0.0060 -0.0058 -0.0064 -0.0062 -0.0061	$\begin{array}{c} R^2 \\ \hline 0.9716 \\ 0.9749 \\ 0.9748 \\ 0.9751 \\ 0.9742 \\ 0.9524 \\ 0.9602 \end{array}$	A 0.0140 0.0173 0.0166 0.0161 0.0224 0.0247 0.0301	$\begin{array}{c} B \\ \hline -0.0460 \\ -0.0341 \\ -0.0377 \\ -0.0366 \\ -0.0286 \\ -0.0295 \\ -0.0219 \end{array}$	R2           0.8681           0.8975           0.8879           0.8931           0.9040           0.8755           0.9011	
FS1 FS2 FS3 FS4 FS5 FS6 FS7 FS8	A           1.0154           1.0187           1.0176           1.0174           1.0236           1.0254           1.0307           1.0276	$\begin{array}{c} B \\ \hline -0.0058 \\ -0.0059 \\ -0.0060 \\ -0.0058 \\ -0.0064 \\ -0.0062 \\ -0.0061 \\ -0.0059 \end{array}$	$\begin{array}{c} R^2 \\ \hline 0.9716 \\ 0.9749 \\ 0.9748 \\ 0.9751 \\ 0.9742 \\ 0.9524 \\ 0.9602 \\ 0.9661 \end{array}$	A 0.0140 0.0173 0.0166 0.0161 0.0224 0.0247 0.0301 0.0266	$\begin{array}{c} B \\ \hline -0.0460 \\ -0.0341 \\ -0.0377 \\ -0.0366 \\ -0.0286 \\ -0.0295 \\ -0.0219 \\ -0.0224 \end{array}$	R2           0.8681           0.8975           0.8879           0.8931           0.9040           0.8755           0.9011           0.9091	
FS1 FS2 FS3 FS4 FS5 FS6 FS7 FS8 FS9	A           1.0154           1.0187           1.0176           1.0174           1.0236           1.0254           1.0307           1.0276           1.0251	B -0.0058 -0.0059 -0.0060 -0.0058 -0.0064 -0.0062 -0.0061 -0.0059 -0.0062	$\begin{array}{c} R^2 \\ \hline 0.9716 \\ 0.9749 \\ 0.9748 \\ 0.9751 \\ 0.9742 \\ 0.9524 \\ 0.9602 \\ 0.9661 \\ 0.9684 \end{array}$	A 0.0140 0.0173 0.0166 0.0161 0.0224 0.0247 0.0301 0.0266 0.0239	$\begin{array}{c} B \\ \hline -0.0460 \\ -0.0341 \\ -0.0377 \\ -0.0366 \\ -0.0286 \\ -0.0295 \\ -0.0219 \\ -0.0224 \\ -0.0265 \end{array}$	R2           0.8681           0.8975           0.8879           0.8931           0.9040           0.8755           0.9011           0.9091           0.9027	
FS1 FS2 FS3 FS4 FS5 FS6 FS7 FS8 FS9 FS9 FS10	A           1.0154           1.0176           1.0176           1.0174           1.0254           1.0307           1.0276           1.0251           1.0261	B -0.0058 -0.0059 -0.0060 -0.0058 -0.0064 -0.0062 -0.0061 -0.0059 -0.0062 -0.0061	$\begin{array}{c} R^2 \\ \hline 0.9716 \\ 0.9749 \\ 0.9748 \\ 0.9751 \\ 0.9742 \\ 0.9524 \\ 0.9602 \\ 0.9661 \\ 0.9684 \\ 0.9673 \\ \end{array}$	A 0.0140 0.0173 0.0166 0.0161 0.0224 0.0247 0.0301 0.0266 0.0239 0.0252	$\begin{array}{c} B \\ \hline -0.0460 \\ -0.0341 \\ -0.0377 \\ -0.0366 \\ -0.0295 \\ -0.0295 \\ -0.0219 \\ -0.0224 \\ -0.0265 \\ -0.0251 \end{array}$	R2           0.8681           0.8975           0.8879           0.8931           0.9040           0.8755           0.9011           0.9091           0.9027           0.9027	
FS1 FS2 FS3 FS4 FS5 FS6 FS7 FS8 FS9 FS10 CS1	A           1.0154           1.0176           1.0176           1.0174           1.0236           1.0254           1.0307           1.0276           1.0251           1.0261           1.0293	$\begin{array}{c} B \\ \hline -0.0058 \\ -0.0059 \\ -0.0060 \\ -0.0058 \\ -0.0064 \\ -0.0062 \\ -0.0061 \\ -0.0059 \\ -0.0062 \\ -0.0061 \\ -0.0061 \\ -0.0022 \end{array}$	$\begin{array}{c} R^2 \\ \hline 0.9716 \\ 0.9749 \\ 0.9748 \\ 0.9751 \\ 0.9742 \\ 0.9524 \\ 0.9602 \\ 0.9661 \\ 0.9684 \\ 0.9673 \\ 0.9937 \\ \end{array}$	A 0.0140 0.0173 0.0166 0.0161 0.0224 0.0247 0.0301 0.0266 0.0239 0.0252 0.0260	$\begin{array}{c} B \\ \hline -0.0460 \\ -0.0341 \\ -0.0377 \\ -0.0366 \\ -0.0295 \\ -0.0295 \\ -0.0219 \\ -0.0224 \\ -0.0265 \\ -0.0251 \\ -0.0354 \end{array}$	R2           0.8681           0.8975           0.8879           0.8931           0.9040           0.8755           0.9011           0.9091           0.9027           0.9027           0.9027           0.9375	
FS1 FS2 FS3 FS4 FS5 FS6 FS7 FS8 FS9 FS10 CS1 CS2	A           1.0154           1.0176           1.0176           1.0174           1.0236           1.0254           1.0307           1.0276           1.0251           1.0261           1.0293           1.0231	B -0.0058 -0.0059 -0.0060 -0.0058 -0.0064 -0.0062 -0.0061 -0.0059 -0.0062 -0.0061 -0.0062 -0.0061 -0.0122 -0.0097	$\begin{array}{c} R^2 \\ \hline 0.9716 \\ 0.9749 \\ 0.9748 \\ 0.9751 \\ 0.9742 \\ 0.9524 \\ 0.9602 \\ 0.9661 \\ 0.9684 \\ 0.9673 \\ 0.9937 \\ 0.9880 \\ \end{array}$	A 0.0140 0.0173 0.0166 0.0161 0.0224 0.0247 0.0301 0.0266 0.0239 0.0252 0.0260 0.0204	$\begin{array}{c} B \\ \hline -0.0460 \\ -0.0341 \\ -0.0377 \\ -0.0366 \\ -0.0295 \\ -0.0295 \\ -0.0219 \\ -0.0224 \\ -0.0265 \\ -0.0251 \\ -0.0354 \\ -0.0266 \end{array}$	R2           0.8681           0.8975           0.8879           0.8931           0.9040           0.8755           0.9011           0.9027           0.9027           0.9375           0.9652	
FS1 FS2 FS3 FS4 FS5 FS6 FS7 FS8 FS9 FS10 CS1 CS2 CS3	A           1.0154           1.0176           1.0176           1.0236           1.0254           1.0307           1.0276           1.0251           1.0261           1.0231           1.0231	B -0.0058 -0.0059 -0.0060 -0.0058 -0.0064 -0.0062 -0.0061 -0.0059 -0.0062 -0.0061 -0.0122 -0.0097 -0.0100	$\begin{array}{c} R^2 \\ \hline 0.9716 \\ 0.9749 \\ 0.9748 \\ 0.9751 \\ 0.9742 \\ 0.9524 \\ 0.9602 \\ 0.9661 \\ 0.9684 \\ 0.9673 \\ 0.9937 \\ 0.9880 \\ 0.9927 \\ \end{array}$	A 0.0140 0.0173 0.0166 0.0161 0.0224 0.0247 0.0301 0.0266 0.0239 0.0252 0.0260 0.0204 0.0204 0.0242	$\begin{array}{c} B \\ \hline -0.0460 \\ -0.0341 \\ -0.0377 \\ -0.0366 \\ -0.0286 \\ -0.0295 \\ -0.0219 \\ -0.0224 \\ -0.0265 \\ -0.0251 \\ -0.0354 \\ -0.0266 \\ -0.0295 \end{array}$	R2           0.8681           0.8975           0.8975           0.8931           0.9040           0.8755           0.9011           0.9027           0.9027           0.9375           0.9652           0.9450	
FS1 FS2 FS3 FS4 FS5 FS6 FS7 FS8 FS9 FS10 CS1 CS1 CS2 CS3 CS4	A           1.0154           1.0176           1.0176           1.0174           1.0236           1.0254           1.0307           1.0276           1.0251           1.0261           1.0233           1.0231           1.0269	B -0.0058 -0.0059 -0.0060 -0.0058 -0.0064 -0.0062 -0.0061 -0.0059 -0.0062 -0.0061 -0.0122 -0.0097 -0.0100 -0.0081	$\begin{array}{r} R^2 \\ \hline 0.9716 \\ 0.9749 \\ 0.9748 \\ 0.9751 \\ 0.9742 \\ 0.9524 \\ 0.9602 \\ 0.9661 \\ 0.9684 \\ 0.9673 \\ 0.9937 \\ 0.9880 \\ 0.9927 \\ 0.9888 \\ \end{array}$	A 0.0140 0.0173 0.0166 0.0161 0.0224 0.0247 0.0301 0.0266 0.0239 0.0252 0.0260 0.0204 0.0242 0.0254	$\begin{array}{c} B \\ \hline -0.0460 \\ -0.0341 \\ -0.0377 \\ -0.0366 \\ -0.0295 \\ -0.0295 \\ -0.0219 \\ -0.0224 \\ -0.0265 \\ -0.0251 \\ -0.0354 \\ -0.0266 \\ -0.0295 \\ -0.0261 \end{array}$	R2           0.8681           0.8975           0.8975           0.8931           0.9040           0.8755           0.9011           0.9027           0.9027           0.9375           0.9652           0.9450           0.9325	
FS1 FS2 FS3 FS4 FS5 FS6 FS7 FS8 FS9 FS10 CS1 CS2 CS2 CS3 CS4 CS5	A           1.0154           1.0176           1.0176           1.0236           1.0254           1.0307           1.0251           1.0261           1.0293           1.0231           1.0269           1.0269	B -0.0058 -0.0059 -0.0060 -0.0058 -0.0064 -0.0062 -0.0061 -0.0059 -0.0062 -0.0061 -0.0122 -0.0097 -0.0100 -0.0081 -0.0090	$\begin{array}{r} R^2 \\ \hline 0.9716 \\ 0.9749 \\ 0.9748 \\ 0.9751 \\ 0.9742 \\ 0.9524 \\ 0.9602 \\ 0.9661 \\ 0.9684 \\ 0.9673 \\ 0.9937 \\ 0.9880 \\ 0.9927 \\ 0.9888 \\ 0.9866 \\ \end{array}$	$\begin{array}{c} A \\ \hline 0.0140 \\ 0.0173 \\ 0.0166 \\ 0.0161 \\ 0.0224 \\ 0.0247 \\ 0.0301 \\ 0.0266 \\ 0.0239 \\ 0.0252 \\ 0.0260 \\ 0.0204 \\ 0.0204 \\ 0.0242 \\ 0.0254 \\ 0.0275 \end{array}$	$\begin{array}{c} B \\ \hline -0.0460 \\ -0.0341 \\ -0.0377 \\ -0.0366 \\ -0.0286 \\ -0.0295 \\ -0.0219 \\ -0.0224 \\ -0.0265 \\ -0.0251 \\ -0.0354 \\ -0.0266 \\ -0.0295 \\ -0.0261 \\ -0.0286 \end{array}$	R2           0.8681           0.8975           0.8975           0.8931           0.9040           0.8755           0.9011           0.9027           0.9027           0.9375           0.9450           0.9226	
FS1 FS2 FS3 FS4 FS5 FS6 FS7 FS8 FS9 FS10 CS1 CS2 CS3 CS4 CS5 CS6	A           1.0154           1.0187           1.0176           1.0174           1.0236           1.0254           1.0307           1.0251           1.0261           1.0293           1.0231           1.0269           1.0269           1.0269           1.0269	B -0.0058 -0.0059 -0.0060 -0.0058 -0.0064 -0.0062 -0.0061 -0.0059 -0.0062 -0.0061 -0.0122 -0.0097 -0.0100 -0.0081 -0.0090 -0.0116	$\begin{array}{r} R^2 \\ \hline 0.9716 \\ 0.9749 \\ 0.9748 \\ 0.9751 \\ 0.9742 \\ 0.9524 \\ 0.9602 \\ 0.9661 \\ 0.9684 \\ 0.9673 \\ 0.9937 \\ 0.9880 \\ 0.9927 \\ 0.9888 \\ 0.9866 \\ 0.9745 \\ \end{array}$	A 0.0140 0.0173 0.0166 0.0161 0.0224 0.0247 0.0301 0.0266 0.0239 0.0252 0.0260 0.0204 0.0204 0.0242 0.0254 0.0275 0.0522	$\begin{array}{c} B \\ \hline -0.0460 \\ -0.0341 \\ -0.0377 \\ -0.0366 \\ -0.0286 \\ -0.0295 \\ -0.0219 \\ -0.0224 \\ -0.0265 \\ -0.0251 \\ -0.0251 \\ -0.0354 \\ -0.0266 \\ -0.0295 \\ -0.0261 \\ -0.0286 \\ -0.0212 \end{array}$	R2           0.8681           0.8975           0.8975           0.8931           0.9040           0.8755           0.9011           0.9027           0.9027           0.9375           0.9652           0.9450           0.9226           0.9219	
FS1 FS2 FS3 FS4 FS5 FS6 FS7 FS8 FS9 FS10 CS1 CS2 CS3 CS4 CS5 CS6 CS7	A           1.0154           1.0187           1.0176           1.0174           1.0236           1.0254           1.0307           1.0251           1.0261           1.0293           1.0231           1.0269           1.0269           1.0300           1.0537           1.0320	B -0.0058 -0.0059 -0.0060 -0.0058 -0.0064 -0.0062 -0.0061 -0.0059 -0.0062 -0.0061 -0.0122 -0.0097 -0.0100 -0.0081 -0.0090 -0.0116 -0.0096	$\begin{array}{r} R^2 \\ \hline 0.9716 \\ 0.9749 \\ 0.9748 \\ 0.9751 \\ 0.9742 \\ 0.9524 \\ 0.9602 \\ 0.9661 \\ 0.9684 \\ 0.9673 \\ 0.9937 \\ 0.9880 \\ 0.9927 \\ 0.9888 \\ 0.9886 \\ 0.9745 \\ 0.9815 \\ \end{array}$	A 0.0140 0.0173 0.0166 0.0161 0.0224 0.0247 0.0301 0.0266 0.0239 0.0252 0.0260 0.0204 0.0204 0.0242 0.0254 0.0275 0.0522 0.0313	$\begin{array}{c} B \\ \hline -0.0460 \\ -0.0341 \\ -0.0377 \\ -0.0366 \\ -0.0286 \\ -0.0295 \\ -0.0219 \\ -0.0224 \\ -0.0265 \\ -0.0251 \\ -0.0251 \\ -0.0354 \\ -0.0266 \\ -0.0295 \\ -0.0261 \\ -0.0286 \\ -0.0212 \\ -0.0204 \end{array}$	R2           0.8681           0.8975           0.8975           0.8931           0.9040           0.8755           0.9011           0.9027           0.9027           0.9375           0.9652           0.9450           0.9226           0.9219           0.9554	
FS1 FS2 FS3 FS4 FS5 FS6 FS7 FS8 FS9 FS10 CS1 CS2 CS3 CS4 CS5 CS6 CS7 CS8	A           1.0154           1.0176           1.0176           1.0174           1.0236           1.0254           1.0307           1.0251           1.0261           1.0293           1.0231           1.0269           1.0269           1.0300           1.0537           1.0330           1.0471	$\begin{array}{c} B \\ \hline -0.0058 \\ -0.0059 \\ -0.0060 \\ -0.0058 \\ -0.0064 \\ -0.0062 \\ -0.0061 \\ -0.0059 \\ -0.0062 \\ -0.0061 \\ -0.0122 \\ -0.0097 \\ -0.0100 \\ -0.0097 \\ -0.0100 \\ -0.0081 \\ -0.0090 \\ -0.0116 \\ -0.0096 \\ 0.0002 \end{array}$	$\begin{array}{r} R^2 \\ \hline 0.9716 \\ 0.9749 \\ 0.9748 \\ 0.9751 \\ 0.9742 \\ 0.9524 \\ 0.9602 \\ 0.9661 \\ 0.9684 \\ 0.9673 \\ 0.9937 \\ 0.9880 \\ 0.9927 \\ 0.9888 \\ 0.9886 \\ 0.9745 \\ 0.9745 \\ 0.9915 \\ 0.9707 \end{array}$	A 0.0140 0.0173 0.0166 0.0161 0.0224 0.0247 0.0301 0.0266 0.0239 0.0252 0.0260 0.0204 0.0242 0.0254 0.0275 0.0254 0.0275 0.0522 0.0313 0.0452	$\begin{array}{c} B \\ \hline -0.0460 \\ -0.0341 \\ -0.0377 \\ -0.0366 \\ -0.0286 \\ -0.0295 \\ -0.0219 \\ -0.0224 \\ -0.0265 \\ -0.0251 \\ -0.0251 \\ -0.0354 \\ -0.0266 \\ -0.0295 \\ -0.0261 \\ -0.0286 \\ -0.0212 \\ -0.0204 \\ 0.0174 \end{array}$	R2           0.8681           0.8975           0.8975           0.8975           0.9040           0.8755           0.9011           0.9027           0.9027           0.9375           0.9652           0.9450           0.9226           0.9219           0.9554           0.9260	
FS1 FS2 FS3 FS4 FS5 FS6 FS7 FS8 FS9 FS10 CS1 CS2 CS3 CS4 CS5 CS6 CS7 CS8 CS9	A           1.0154           1.0187           1.0176           1.0174           1.0236           1.0254           1.0307           1.0251           1.0261           1.0293           1.0231           1.0269           1.0300           1.0330           1.0471	B -0.0058 -0.0059 -0.0060 -0.0058 -0.0064 -0.0062 -0.0061 -0.0059 -0.0062 -0.0061 -0.0122 -0.0097 -0.0100 -0.0090 -0.0116 -0.0092 -0.0092 -0.0092 -0.0092 -0.0092 -0.0092 -0.0092 -0.0092 -0.0092 -0.0092 -0.0092 -0.0092 -0.0092 -0.0058 -0.0058 -0.0058 -0.0058 -0.0058 -0.0058 -0.0058 -0.0064 -0.0059 -0.0061 -0.0059 -0.0061 -0.0059 -0.0061 -0.0059 -0.0061 -0.0059 -0.0061 -0.0059 -0.0061 -0.0059 -0.0061 -0.0059 -0.0061 -0.0059 -0.0061 -0.0059 -0.0061 -0.0059 -0.0061 -0.0059 -0.0061 -0.0059 -0.0061 -0.0059 -0.0061 -0.0059 -0.0061 -0.0059 -0.0061 -0.0097 -0.0009 -0.0009 -0.0009 -0.0090 -0.0090 -0.0090 -0.0090 -0.0090 -0.0090 -0.0090 -0.0090 -0.0090 -0.0092 -0.0090 -0.0092	$R^2$ 0.9716           0.9749           0.9748           0.9751           0.9742           0.9524           0.9602           0.9661           0.9684           0.9673           0.9937           0.9880           0.9927           0.9888           0.9745           0.9745           0.9797	A 0.0140 0.0173 0.0166 0.0161 0.0224 0.0247 0.0301 0.0266 0.0239 0.0252 0.0260 0.0204 0.0242 0.0254 0.0275 0.0254 0.0275 0.0522 0.0313 0.0453 0.0451	$\begin{array}{c} B \\ \hline -0.0460 \\ -0.0341 \\ -0.0377 \\ -0.0366 \\ -0.0286 \\ -0.0295 \\ -0.0219 \\ -0.0224 \\ -0.0265 \\ -0.0251 \\ -0.0251 \\ -0.0354 \\ -0.0266 \\ -0.0295 \\ -0.0261 \\ -0.0261 \\ -0.0286 \\ -0.0212 \\ -0.0204 \\ -0.0174 \\ 0.2220 \end{array}$	R2           0.8681           0.8975           0.8975           0.8975           0.9040           0.8755           0.9011           0.9027           0.9027           0.9375           0.9450           0.9226           0.9219           0.9554           0.93114	
FS1 FS2 FS3 FS4 FS5 FS6 FS7 FS8 FS9 FS10 CS1 CS2 CS3 CS4 CS5 CS6 CS7 CS8 CS9 CS10	A           1.0154           1.0176           1.0176           1.0174           1.0236           1.0254           1.0307           1.0251           1.0261           1.0293           1.0231           1.0269           1.0269           1.0269           1.0300           1.0471           1.0468           1.0201	B -0.0058 -0.0059 -0.0060 -0.0058 -0.0064 -0.0062 -0.0061 -0.0059 -0.0062 -0.0061 -0.0122 -0.0097 -0.0100 -0.0090 -0.0116 -0.0092 -0.0102 -0.0102 -0.0102 -0.0102 -0.0102 -0.0102 -0.0112	$R^2$ 0.9716           0.9748           0.9751           0.97524           0.9602           0.9661           0.9673           0.9937           0.9880           0.9927           0.9888           0.9945           0.9745           0.9797           0.9684	A 0.0140 0.0173 0.0166 0.0161 0.0224 0.0247 0.0301 0.0266 0.0239 0.0252 0.0260 0.0204 0.0242 0.0254 0.0275 0.0254 0.0275 0.0522 0.0313 0.0453 0.0451 0.0262	$\begin{array}{c} B \\ \hline -0.0460 \\ -0.0341 \\ -0.0377 \\ -0.0366 \\ -0.0286 \\ -0.0295 \\ -0.0219 \\ -0.0224 \\ -0.0265 \\ -0.0251 \\ -0.0251 \\ -0.0354 \\ -0.0266 \\ -0.0295 \\ -0.0261 \\ -0.0261 \\ -0.0286 \\ -0.0212 \\ -0.0204 \\ -0.0174 \\ -0.0229 \\ -0.0210 \end{array}$	R2           0.8681           0.8975           0.8879           0.8931           0.9040           0.8755           0.9011           0.9027           0.9027           0.9375           0.9450           0.9226           0.9219           0.9554           0.9314	
FS1 FS2 FS3 FS4 FS5 FS6 FS7 FS8 FS9 FS10 CS1 CS2 CS3 CS4 CS5 CS6 CS7 CS6 CS7 CS8 CS9 CS10 CS10 CS11	A           1.0154           1.0176           1.0176           1.0174           1.0236           1.0254           1.0307           1.0251           1.0261           1.0293           1.0231           1.0269           1.0269           1.0300           1.0471           1.0468           1.0291	$\begin{array}{c} \textbf{B} \\ \hline -0.0058 \\ -0.0059 \\ -0.0060 \\ -0.0058 \\ -0.0064 \\ -0.0062 \\ -0.0061 \\ -0.0059 \\ -0.0062 \\ -0.0061 \\ -0.0122 \\ -0.0097 \\ -0.0100 \\ -0.0097 \\ -0.0100 \\ -0.0091 \\ -0.0090 \\ -0.0116 \\ -0.0092 \\ -0.0102 \\ -0.0110 \\ 0.0111 \\ 0.$	$R^2$ 0.9716           0.9749           0.9748           0.9751           0.9742           0.9524           0.9602           0.9661           0.9684           0.9673           0.9937           0.9880           0.9927           0.9888           0.9866           0.9745           0.9915           0.9797           0.9684           0.9927	A 0.0140 0.0173 0.0166 0.0161 0.0224 0.0247 0.0301 0.0266 0.0239 0.0252 0.0260 0.0204 0.0242 0.0254 0.0275 0.0254 0.0275 0.0522 0.0313 0.0453 0.0453 0.0451 0.0262	$\begin{array}{c} B \\ \hline -0.0460 \\ -0.0341 \\ -0.0377 \\ -0.0366 \\ -0.0286 \\ -0.0295 \\ -0.0219 \\ -0.0224 \\ -0.0265 \\ -0.0251 \\ -0.0251 \\ -0.0354 \\ -0.0266 \\ -0.0295 \\ -0.0261 \\ -0.0261 \\ -0.0286 \\ -0.0212 \\ -0.0204 \\ -0.0174 \\ -0.0229 \\ -0.0219 \\ -0.0229 \\ -0.0219 \\ -0.0229 \\ -0.0219 \\ -0.0229 \\ -0.0219 \\ -0.0229 \\ -0.0219 \\ -0.0229 \\ -0.0219 \\ -0.0229 \\ -0.0219 \\ -0.0229 \\ -0.0219 \\ -0.0229 \\ -0.0219 \\ -0.0229 \\ -0.0219 \\ -0.0229 \\ -0.0219 \\ -0.0229 \\ -0.0219 \\ -0.0229 \\ -0.029 \\ -0.029 \\ -0.029 \\ -0.029 \\ -0.029 \\ -0.029 \\ -0.029 \\ $	R2           0.8681           0.8975           0.8975           0.8975           0.8975           0.9040           0.8755           0.9011           0.9027           0.9027           0.9375           0.9652           0.9450           0.9226           0.9219           0.9554           0.9114           0.9705           0.9276	
FS1 FS2 FS3 FS4 FS5 FS6 FS7 FS8 FS9 FS10 CS1 CS2 CS3 CS4 CS5 CS6 CS7 CS8 CS9 CS10 GR1 CS2	A           1.0154           1.0176           1.0176           1.0174           1.0236           1.0254           1.0307           1.0251           1.0251           1.0261           1.0293           1.0231           1.0269           1.0269           1.0300           1.0537           1.0330           1.0471           1.0396           1.0291	B -0.0058 -0.0059 -0.0060 -0.0058 -0.0064 -0.0062 -0.0061 -0.0059 -0.0062 -0.0061 -0.0122 -0.0097 -0.0100 -0.0097 -0.0100 -0.0090 -0.0116 -0.0092 -0.0102 -0.0110 -0.0181 -0.0181 -0.0127	R <sup>2</sup> 0.9716           0.9749           0.9748           0.9751           0.9742           0.9524           0.9602           0.9661           0.9684           0.9673           0.9937           0.9880           0.9927           0.9888           0.9745           0.9747           0.9866           0.9747           0.9684           0.9915           0.9797           0.9684           0.9962           0.9801           0.9801	A 0.0140 0.0173 0.0166 0.0161 0.0224 0.0247 0.0301 0.0266 0.0239 0.0252 0.0260 0.0204 0.0242 0.0254 0.0275 0.0254 0.0275 0.0522 0.0313 0.0453 0.0453 0.0451 0.0262 0.0366 0.0366 0.0366	$\begin{array}{c} \textbf{B} \\ \hline -0.0460 \\ -0.0341 \\ -0.0377 \\ -0.0366 \\ -0.0286 \\ -0.0295 \\ -0.0219 \\ -0.0224 \\ -0.0265 \\ -0.0251 \\ -0.0251 \\ -0.0354 \\ -0.0266 \\ -0.0295 \\ -0.0261 \\ -0.0266 \\ -0.0295 \\ -0.0261 \\ -0.0261 \\ -0.0229 \\ -0.0212 \\ -0.0204 \\ -0.0174 \\ -0.0229 \\ -0.0219 \\ -0.0375 \\ -0.0375 \\ -0.0211 \\ -0.025 \\ -0.0212 \\ -$	R2           0.8681           0.8975           0.8879           0.8931           0.9040           0.8755           0.9011           0.9027           0.9027           0.9375           0.9450           0.9226           0.9219           0.9554           0.9376           0.9376	
FS1 FS2 FS3 FS4 FS5 FS6 FS7 FS8 FS9 FS10 CS1 CS2 CS3 CS4 CS5 CS6 CS7 CS6 CS7 CS8 CS9 CS10 GR1 GR2 GR2	A           1.0154           1.0176           1.0176           1.0174           1.0236           1.0254           1.0251           1.0251           1.0261           1.0293           1.0231           1.0269           1.0269           1.0300           1.0537           1.0330           1.0471           1.0396           1.0374	$\begin{array}{c} B \\ \hline -0.0058 \\ -0.0059 \\ -0.0060 \\ -0.0058 \\ -0.0064 \\ -0.0062 \\ -0.0061 \\ -0.0059 \\ -0.0061 \\ -0.0059 \\ -0.0061 \\ -0.0122 \\ -0.0097 \\ -0.0097 \\ -0.0100 \\ -0.0097 \\ -0.0100 \\ -0.0090 \\ -0.0090 \\ -0.0092 \\ -0.0092 \\ -0.0102 \\ -0.0110 \\ -0.0181 \\ -0.0187 \\ -0.$	R <sup>2</sup> 0.9716           0.9749           0.9748           0.9751           0.9742           0.9524           0.9602           0.9661           0.9684           0.9673           0.9937           0.9880           0.9927           0.9888           0.9745           0.9745           0.9797           0.9684           0.9962           0.9801           0.9807	A           0.0140           0.0173           0.0166           0.0161           0.0224           0.0247           0.0301           0.0266           0.0239           0.0260           0.0204           0.0242           0.0252           0.0260           0.0254           0.0254           0.0252           0.0313           0.0453           0.0453           0.0451           0.0262           0.0314	$\begin{array}{c} \textbf{B} \\ \hline -0.0460 \\ -0.0341 \\ -0.0377 \\ -0.0366 \\ -0.0286 \\ -0.0295 \\ -0.0219 \\ -0.0224 \\ -0.0265 \\ -0.0251 \\ -0.0354 \\ -0.0266 \\ -0.0295 \\ -0.0261 \\ -0.0266 \\ -0.0295 \\ -0.0261 \\ -0.0261 \\ -0.0229 \\ -0.0212 \\ -0.0204 \\ -0.0174 \\ -0.0229 \\ -0.0219 \\ -0.0375 \\ -0.0366 \end{array}$	R2           0.8681           0.8975           0.8879           0.8931           0.9040           0.8755           0.9011           0.9027           0.9027           0.9375           0.9652           0.9226           0.9226           0.9254           0.9360           0.9114           0.9705           0.9376	

**Table 4.** Summary of fit parameters of a power-law relationship between the roughness parametersand sampling interval (SI) for different rock joint profile.

GR4	1.0344	-0.0158	0.9767	0.0298	-0.0416	0.9322	
GR5	1.0287	-0.0136	0.9841	0.0247	-0.0399	0.9402	
GR6	1.0585	-0.0166	0.9892	0.0560	-0.0196	0.9588	
GR7	1.0494	-0.0130	0.9911	0.0467	-0.0191	0.9558	
GR8	1.0408	-0.0180	0.9838	0.0358	-0.0386	0.9356	
GR9	1.0557	-0.0177	0.9910	0.0518	-0.0265	0.9411	
		θ	θ		$\sigma_i$	$\sigma_i$	
Sample No.	A	В	<i>R</i> <sup>2</sup>	Α	В	<i>R</i> <sup>2</sup>	
FS1	7.4943	-0.1746	0.8385	11.8211	-0.1782	0.8436	
FS2	8.4746	-0.1492	0.8738	13.8057	-0.1456	0.8815	
FS3	8.1793	-0.1591	0.8619	12.7733	-0.1624	0.8669	
FS4	8.0267	-0.1574	0.8738	12.3054	-0.1634	0.8791	
FS5	9.4741	-0.1234	0.9018	15.2581	-0.1258	0.8989	
FS6	9.9773	-0.1142	0.8497	15.9228	-0.1146	0.8578	
FS7	11.2573	-0.0901	0.8868	16.2786	-0.0995	0.8968	
FS8	10.2509	-0.1062	0.8858	17.1376	-0.1004	0.8987	
FS9	9.9180	-0.1113	0.9205	14.9390	-0.1211	0.9066	
FS10	10.0920	-0.1060	0.8752	16.5286	-0.1073	0.8897	
CS1	9.8305	-0.1873	0.9003	15.8384	-0.1941	0.9173	
CS2	8.9809	-0.1792	0.9472	14.5415	-0.1850	0.9551	
CS3	9.9470	-0.1560	0.9291	15.8793	-0.1672	0.9363	
CS4	10.1814	-0.1333	0.9081	16.3880	-0.1368	0.9174	
CS5	10.5524	-0.1309	0.8883	17.1755	-0.1363	0.9048	
CS6	12.3624	-0.1168	0.9445	22.2406	-0.1103	0.9200	
CS7	11.3631	-0.1314	0.9366	16.4990	-0.1423	0.9471	
CS8	13.0844	-0.0851	0.9243	22.1257	-0.0868	0.9273	
CS9	11.8134	-0.1101	0.9129	21.0558	-0.1120	0.9049	
CS10	9.9365	-0.1708	0.9566	15.7409	-0.1808	0.9602	
GR1	11.2024	-0.1981	0.9184	17.9891	-0.2136	0.9321	
GR2	10.7387	-0.2154	0.9233	17.3103	-0.2332	0.9492	
GR3	9.9227	-0.2086	0.9103	16.3119	-0.2209	0.9354	
GR4	10.4506	-0.1922	0.9181	17.4927	-0.2068	0.9368	
GR5	9.5644	-0.2057	0.9099	15.1834	-0.2223	0.9349	
GR6	14.5471	-0.1268	0.9331	22.7248	-0.1322	0.9526	
GR7	13.1223	-0.1144	0.9240	22.1869	-0.1190	0.9491	
GR8	11.6967	-0.1853	0.9127	18.3945	-0.2034	0.9304	
GR9	13.6499	-0.1380	0.9143	22.2623	-0.1506	0.9398	

Table 4. Cont.

Note that as the sampling interval continues to increase, it seems that the roughness parameters  $Z_2$ ,  $R_p$ ,  $\delta$ ,  $\sigma_i$  and  $\theta$  have a low dependence on the large sampling interval. Nevertheless, it is not appropriate to use these parameters to directly determine the *JRC* without considering the effect of the sampling interval at the small-scale rock joint. The main reason is because much information on the rock joint surface may be ignored under a large sampling interval, hence affecting the accurate assessment of its contribution to hydraulic and mechanical behaviors.

#### 5. Influence of Sampling Interval on Reconstructed Rock Joint Profile

The digitized points of reconstructing rock joint profile reduce as the sampling interval increases. For instance, Figure 11 shows the average joint profile lines of FS1 at eight sampling intervals, and it can be seen that the shape of the rock joint profile has some discrepancies for different sampling intervals. Consequently, the statistical roughness parameter value calculated for the rock joint profile at different sampling intervals may not be equal. There are non-uniform results when using the same empirical equation to estimate *JRC* at different sampling intervals.



**Figure 11.** The rock joint profile lines of FS1 for sampling interval SI = 0.1 mm, 0.5 mm, 1.0 mm, 1.5 mm, 2.0 mm, 3.0 mm, 4.0 mm and 5.0 mm.

In previous studies, the joint profile was decomposed into the primary first-order asperities (primary waviness) and second-order asperities (second roughness). These different orders of asperities (roughness) may play different roles in the mechanical and hydraulic behaviors of rock joints. For instance, Zou et al. [55] reported that the primary waviness mainly determines the local fluid flow directions, whereas the secondary roughness increases the local complexity of fluid flow and solute transport. Barton [20] reported that the first-order asperity controls the shear behavior of rock joints under high normal stress whereas that of the second-order asperity under lower normal stress. However, many second-order asperities are not captured with an increase in the sampling interval as shown in the rectangular box in Figure 11. Even some typical asperities may be overlooked as the sampling interval exceeds a specific value (e.g., 2.0 mm). This result may lead to an inaccurate evaluation of the role of roughness in the hydraulic and mechanical behaviors of rock joints. In addition, the digitized rock joint profile is generally imported into numerical simulation software to establish a joint geometric model and further investigate the effect of roughness on fluid flow and mass transport. In these circumstances, if the primary waviness or secondary roughness of the rock joint profile is ignored, the true response of joint surface roughness on fluid flow regime may be hard to capture. Therefore, when estimating the roughness parameters of the rock joint profile, a reasonable sampling interval should be considered in the specific rock joint scale so as to meet the practical requirements.

# 6. Conclusions

This study examined the relationship between *JRC* and statistical roughness parameters, including amplitude parameters ( $R_a$ ,  $R_q$ ,  $R_z$ ,  $\lambda$ ) and textural parameters ( $Z_2$ ,  $R_p$ , *SF*,  $\delta$ ,  $\sigma_i$ , and  $\theta$ ) based on the digitized Barton's roughness profiles. Further, the statistical roughness parameter was used to determine the *JRC* of the rock joint profile. In addition, the sensitivity of the statistical roughness parameters with respect to the sampling interval has been evaluated using digitized rock jointed samples with different surface morphology. The following conclusions can be drawn from this study:

• It is observed that there is a good correlation between *JRC* and statistical roughness parameters  $Z_2$ , *SF*,  $R_p$ ,  $\delta$ ,  $\sigma_i$ ,  $\theta$ ,  $R_a$ ,  $R_q$ ,  $R_z$  and  $\lambda$  based on the correlation analysis of *JRC* with statistical roughness parameters with Pearson's correlation coefficient ( $\gamma$ ) method. The coefficient  $\gamma$  values for these roughness parameters exceed 0.7 except for  $R_a$  where  $\gamma = 0.66$ . Compared with the amplitude parameters  $R_a$ ,  $R_q$ ,  $R_z$  and  $\lambda$  ( $\gamma$ ranges from 0.66 to 0.8), a better correlation exists between the textural parameters  $Z_2$ , *SF*,  $R_p$ ,  $\delta$ ,  $\sigma_i$  and  $\theta$  and *JRC* ( $\gamma > 0.9$ ).

- Among these parameters, the standard deviation of the roughness angle  $\sigma_i$  has the strongest correlation with *JRC* ( $\gamma = 0.9923$ ). Further, a linear empirical equation between *JRC* and the parameter  $\sigma_i$  is proposed to determine the *JRC* of the rock joint profile.
- As the sampling interval increases, the  $Z_2$ ,  $R_p$ ,  $\delta$ ,  $\sigma_i$  and  $\theta$  parameter values decrease, and the  $R_a$ ,  $R_q$ ,  $R_z$  and  $\lambda$  parameter values show slight fluctuations, whereas *SF* values increase with an increase in the sampling interval. In addition, the evolution in the texture parameters  $Z_2$ , *SF*,  $R_p$ ,  $\delta$ ,  $\sigma_i$  and  $\theta$  with the sampling interval can fit a power-law function well.
- Sensitivity analysis has revealed that the texture parameters ( $Z_2$ , SF,  $R_p$ ,  $\delta$ ,  $\sigma_i$  and  $\theta$ ) significantly depend on the sampling interval as a whole. In contrast, the dependence of the amplitude parameters ( $R_a$ ,  $R_q$ ,  $R_z$  and  $\lambda$ ) on the sampling interval is not significant.

The present results help improve the accuracy of the roughness characterization of rock joints. Additionally, they can provide new insights into quantitatively evaluating the role of roughness in mechanical and hydraulic behaviors of rock joints for rock hydraulics researchers. Dozens of rock joint samples with a wide range of surface morphology are used to achieve the objective of this study. However, the rock joint profile used in this study is difficult to cover the complex and diverse joint surface morphology in the geological rock strata. The machine-learning analysis tool will be used to obtain a large dataset in the following study and further examine the universality of the results.

**Supplementary Materials:** The following supporting information can be downloaded at: https: //www.mdpi.com/article/10.3390/su142013597/s1, Supplementary data associated with this article is attached as a file entitled "Supplementary Material.pdf". These data include the coarse sandstone and granite joint surface morphology, and the Gaussian fitting of the asperity elevation distributions of coarse sandstone and granite joint surfaces. Figure S1: Surface morphology of coarse sandstone and granite joint samples (all dimensions are in units of mm), Figure S2: Gaussian fit of the asperity elevation distribution for coarse sandstone and granite joint samples.

**Author Contributions:** Conceptualization, Y.L. (Yong Luo) and Y.W.; data Curation, Y.L. (Yong Luo); formal analysis, Y.L. (Yong Luo) and H.G.; investigation, Y.L. (Yong Luo); methodology, Y.L. (Yong Luo), Y.W. and Y.L. (Yihui Luo); resources, X.L., Y.L. (Yihui Luo) and Y.L. (Yanan Liu); writing—original draft, Y.L. (Yong Luo); writing—review and editing, Y.W., H.G. and X.L. All authors have read and agreed to the published version of the manuscript.

**Funding:** This study was financially supported by the National Natural Science Foundation of China (No. 51674047 and 51911530152).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

**Data Availability Statement:** The data presented in this study are available on request from the corresponding author.

**Conflicts of Interest:** The authors declare that they have no conflict of interest regarding the publication of this paper.

## List of Symbols

- JRC Joint roughness coefficient
- Z<sub>2</sub> Root mean square of the first derivative
- SF Structure function
- $R_p$  Roughness profile index
- $R_z$  Peak asperity height
- *R<sub>a</sub>* Arithmetic average of the absolute height
- *R<sub>q</sub>* Root mean square roughness height value

- $\theta$  Average roughness angle
- $\sigma_i$  Standard deviation of the roughness angle *i*
- $\lambda$  The ultimate slope
- $\delta$  Profile elongation index
- $\theta^*_{max}$  Angular threshold
- D Fractal dimension
- $\gamma$  Pearson's correlation coefficient
- SI Sampling interval
- *L* The projected length of fracture profile
- $L_t$  True length of the profile
- $z_{max}$  The highest peak
- $z_{min}$  The lower valley

## Appendix A

The calculation formulas of some of the roughness parameters and the Pearson's correlation coefficient:

Z<sub>2</sub>: Root mean square of the first derivative of the profile [56]

$$Z_2 = \left[\frac{1}{L}\int_{x=0}^{x=L} \left(\frac{dz}{dx}\right)^2 dx\right]^{1/2} = \left[\frac{1}{N-1}\sum_{i=1}^{N-1} \frac{(z_{i+1}-z_i)^2}{(x_{i+1}-x_i)^2}\right]^{1/2}$$

where *L* is the projected length of fracture profile along the long axis, dz is the increment of *z* of the profile, dx is the increment of *x* of the profile, *N* is the number of sampling points,  $(x_i, z_i)$  and  $(x_{i+1}, z_{i+1})$  are the coordinate of adjacent points on the fracture profile.

 $R_p$ : Roughness profile index [39]

$$R_p = \frac{L_t}{L} = \frac{\sum_{i=1}^{N-1} \left[ (x_{i+1} - x_i)^2 + (z_{i+1} - z_i)^2 \right]^{1/2}}{L}$$

where  $L_t$  is the true length of the profile.

*SF*: Structure function of the profile [57]

$$SF = \frac{1}{L} \int_{x=0}^{x=L} \left[ f(x+dx) - f(x) \right]^2 dx = \frac{1}{L} \sum_{i=1}^{N-1} \left( z_{i+1} - z_i \right)^2 (x_{i+1} - x_i)$$

 $R_a$ : Arithmetic average of the absolute height of the profile [53]

$$R_a = \frac{1}{L} \int_{x=0}^{x=L} |z| dx = \frac{1}{N} \sum_{i=1}^{N} |z_i|$$

 $R_q$ : Root mean square of the height of the profile [53]

$$R_q = \left[\frac{1}{L}\int_{x=0}^{x=L} z^2 dx\right]^{1/2} = \left[\frac{1}{N}\sum_{i=1}^{N} z_i^2\right]^{1/2}$$

 $R_z$ : Peak asperity height of the profile, equals to the vertical distance between the highest peak and the lowest valley of profile [35].

$$R_z = z_{\max} - z_{\min}$$

where  $z_{max}$  is the highest peak,  $z_{min}$  is the lower valley.

 $\theta$ : Average roughness angle of the profile [34]

$$\theta = \frac{1}{L} \int_{x=0}^{x=L} \tan^{-1} \left| \frac{dz}{dx} \right| dx$$

 $\sigma_i$ : Standard deviation of the roughness angle *i* [34]

$$\sigma_i = \tan^{-1} \left[ \frac{1}{L} \int_{x=0}^{x=L} \left( \left| \frac{dz}{dx} \right| - \tan \theta \right)^2 dx \right]^{1/2}$$

 $\delta$ : Profile elongation index [34]

$$\delta = (L_t - L)/L$$

 $\lambda$ : Ultimate slope of the profile [52]

$$\lambda = R_z/L$$

 $\gamma$ : The Pearson's correlation coefficient [50]

$$\gamma = \frac{Cov(X,Y)}{\sqrt{\sigma_x}\sqrt{\sigma_y}}$$

where  $\gamma$  is the Pearson's correlation coefficient, which is the covariance of the two variables divided by the product of their standard deviations. The  $\gamma$  ranges from -1 to +1, and there are three strength levels: weak correlations:  $\gamma \leq 0.39$ , moderate correlations:  $\gamma = 0.40$  to 0.69, strong correlations:  $\gamma = 0.7$  to 1.0. *X* represents the roughness parameter, *Y* represents the *JRC*,  $\sigma_x$  and  $\sigma_y$  are their variance, respectively. *Cov*(*X*, *Y*) represents the covariance of *X* and *Y*.

$$Cov(X,Y) = E[(X - \mu_x)(Y - \mu_y)]$$

where  $\mu_x$  is the average value of the *X*,  $\mu_y$  is the average value of the *Y*.

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