Article

A Novel Discontinuity Roughness Parameter and Its Correlation with Joint Roughness Coefficients

Huizhen Zhang ^{1,2,3}, Changsuo Zhang ⁴, Zejin Yang ⁴, Zhiqiang Li ³ and Chenlong Wang ^{3,*} ¹ Shanxi College of Technology, Shuozhou 036012, Shanxi, China; zhanghuizhen@tyut.edu.cn² Polytechnic Institute Taiyuan, University of Technology, Taiyuan 030024, Shanxi, China³ College of Mechanical and Vehicle Engineering, Taiyuan University of Technology, Taiyuan 030024, Shanxi, China; lizhiqiang@tyut.edu.cn⁴ College of Mining Engineering, Taiyuan University of Technology, Taiyuan 030024, Shanxi, China; zhangchangsuo@tyut.edu.cn (C.Z.); yangzejin@tyut.edu.cn (Z.Y.)

* Correspondence: wangchenlong@tyut.edu.cn; Tel.: +86-18234159389

Abstract: Joint roughness determination is a fundamental issue in many areas of rock engineering, because joint roughness has significant influences on mechanical properties and deformation behavior of rock masses. Available models suggested in the literature neglected combined effects of shear direction, scale of rock discontinuities, inclination angle, and amplitude of asperities during the roughness calculations. The main goals of this paper are to establish a comprehensive parameter that considers the characteristics of the size effect, anisotropy, and point spacing effect of the discontinuity roughness, and to investigate the correlation between the proposed comprehensive parameter and joint roughness coefficients. In this work, the Barton ten standard profiles are digitally represented, then the morphological characteristics of the discontinuity profiles are extracted. A comprehensive parameter that considers the characteristics of the size effect, anisotropy, and point spacing effect of the discontinuity roughness is established, and its correlation with joint roughness coefficients (JRC) is investigated. The correlation between the proposed discontinuity roughness parameter and the joint roughness coefficients can predict the JRC value of the natural discontinuities with high accuracy, which provides tools for comprehensively characterizing the roughness characteristics of rock discontinuities. The roughness index $R_{vh[-30^\circ,0]}$ reflects the gentle slope characteristics of the rock discontinuity profiles in the shear direction, which ignores the segments with steep slopes greater than 30° on the discontinuity profiles. The influence of steep slope segments greater than 30° should be considered for the roughness anisotropy parameter in the future.

Keywords: novel discontinuity roughness parameter; joint roughness coefficients; correlation; Barton ten standard profiles; anisotropy of roughness

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1. Introduction

According to the measurement results of the rock discontinuity surface topography, the use of reasonable parameters to characterize roughness has always been a difficult problem in the fields of engineering geology and rock joint mechanics, because joint roughness has significant influences on mechanical properties and deformation behavior of rock masses. Roughness, which refers to the local departures from planarity, influences the friction angle, dilatancy, and peak shear strength. Anisotropy, point spacing effect, and size effect are three principal mechanical properties of rock discontinuities. Only by comprehensively considering these three aspects can the roughness be effectively determined.

To determine joint roughness, researchers have made quantitative analyses based on discrete data points of joint surfaces obtained via various measurement methodologies over the past five decades. This subject originated in 1966 when Patton [1] used regular tooth

undulation angles to express the rock discontinuity surface roughness and for the first time explained the importance of discontinuity surface roughness to its shear strength, namely:

$$\tau = \sigma \tan(\varphi_b + i) \quad (1)$$

where τ is the shear strength of the rock discontinuity; σ is the normal stress acting on the discontinuity surface; φ_b is the basic friction angle of the discontinuity surface; and i is the regular tooth undulation angle. Subsequently, how to determine the specific quantitative expressions of rock discontinuity surface roughness and tooth undulation angle became the research focus.

In 1977, Barton and Choubey [2] proposed the JRC-JCS model, which is still widely used, and it can express as,

$$\tau = \sigma_n \tan(\varphi_b + \text{JRC} \lg(\frac{\text{JCS}}{\sigma_n})) \quad (2)$$

where, τ is the peak shear strength of the discontinuity surface; σ_n is the normal stress acting on the discontinuity surface; φ_b is the basic friction angle of the discontinuity surface; JRC is the joint roughness coefficient of the discontinuity surface; and JCS is the compressive strength of the rock discontinuity surface. The model uses the joint roughness coefficient JRC to define the roughness and quantifies the influence of the discontinuity surface roughness on its peak shear strength. JRC not only affects the shear strength of the discontinuity surface, but also has the following important effects on the seepage law of the discontinuity surface [3].

$$e = \frac{\text{JRC}^{2.5}}{(E/e)^2} = \frac{E^2}{\text{JRC}^{2.5}} \quad (3)$$

where e is the equivalent hydraulic gap width of the discontinuity surface; and E is the mechanical gap width of the discontinuity surface.

According to the type of joint roughness parameters, the JRC evaluation method can be divided into three categories: statistical parameter method, fractal dimension method, and comprehensive parameter method. In order to facilitate the determination of JRC, Barton [4] pointed out that it can be determined by empirical value methods such as rock inclination, push-pull test, or visual comparison with the standard roughness profile. In the tilt and push-pull tests of rock blocks, the JRC back calculation formula can be established according to the stress of the discontinuity surface, and then the JRC value can be obtained. However, these formulas do not involve the surface topography of the discontinuity surface. In addition, the visual contrast method with the standard roughness profile has strong subjectivity, which causes the value of JRC to vary from person to person. For this reason, scholars have explored and studied the quantitative value of the discontinuity surface roughness coefficient JRC, and proposed the straight-edge method [4], the elongation method [5], the modified straight-edge method [6], RMS (root mean square of the height of the protrusion on the surface profile) characterization method [7–9], Z_2 (root mean square of average slope) characterization method [7–14], SF (structure function) characterization method [7–11], R_p (rough profile index) characterization method [8,9,11–16], the maximum apparent inclination of the discontinuity surface element in the shear direction $\theta_{\max}^*$ [12,13], the percentage of light area BAP [17,18], the average secant angle of the discontinuity profile relative to the shear direction $\beta_{100\%}$ [19], the projection area ratio of the potential contact part in the vertical and horizontal directions PAP [20,21], the ratio of the shear resistance of the potential contact surface to the shear resistance provided by the horizontal projection area of the discontinuity surface SFR [20,21], fractal dimension characterization method [22–25], combine characterization method with relative undulation of discontinuity surface profile R_a and elongation of discontinuity surface profile R [26], combine characterization method with discontinuity surface average undulation amplitude coefficient $\bar{h}/L$ and modified root mean square of average slope Z_2' [27], combined characterization method with discontinuity surface average undulation amplitude coefficient A and

average undulation angle $\overline{SR_V}$ [28], and combined characterization method with the characteristic angle of discontinuity surface apparent inclination $\bar{\theta}^*$ and the average height of discontinuity profile h [29].

The statistical parameter method mainly uses a single parameter among RMS , Z_2 , SF , R_p , $\theta_{\max}^*$, BAP , $\beta_{100\%}$, PAP , SFR , R_a , and R to characterize the discontinuity surface joint roughness coefficient. A single parameter index may only reflect a single feature of the discontinuity surface morphology and ignore other features, such as Z_2 can only reflect the characteristics of the slope of the discontinuity but ignores the characteristics of the undulation amplitude. The comprehensive parameter method comprehensively describes the roughness characteristics of the discontinuity surface, and can describe the size effect, anisotropy, and point spacing effect of the discontinuity surface roughness, but the parameter index should not be too high during the study, otherwise it will reduce the evaluation efficiency of the discontinuity surface roughness.

Reviewing the research of discontinuity surface roughness evaluation methods [1–33], the following trends are presented:

- (1) The roughness evaluation index changes from two-dimensional to three-dimensional;
- (2) A single index turns to a combination of multiple indicators;
- (3) Simply considering the geometric characteristics of roughness to develops into considering the size effect, anisotropy, and point spacing effect of roughness in an all-round development.

The main goal of this paper is to establish a comprehensive parameter that considers the characteristics of the size effect, anisotropy, and point spacing effect of the discontinuity roughness, and to investigate the correlation between the proposed comprehensive parameter and joint roughness coefficients. In Section 2, the ten standard profiles from Barton and Choubey [2] with image noise defects such as blank fractures, stray points, and excessively thick lines are digitally represented by denoising and repairing fractures image processing techniques. Subsequently, interpolation processing is performed on the Barton ten standard profiles by image processing, and the morphological characteristics under different interpolation conditions are extracted. By comparing the JRC value calculated by the morphological characteristics and the JRC theoretical value, the Barton standard profiles obtained by interpolation are verified, and a reasonable interpolation method is given by which the Barton standard profiles can be accurately characterized digitally and provide a data basis for establishing new discontinuity roughness parameters. In Section 3, a new joint roughness parameter M_{hl} is proposed based on anisotropic parameter R_{vh} and undulation size parameter $\bar{h}/L$. The new joint roughness parameter M_{hl} and its correlation with joint roughness coefficients is investigated, and the limitation of the proposed correlation and future work is discussed in Section 4.

2. Digital Representation of the Barton Ten Standard Profiles

The comprehensive parameter of discontinuity surface roughness to be established in this work is based on the Barton ten standard profiles. Therefore, appropriate methods should be adopted to accurately characterize the Barton standard profiles digitally. Barton and Choubey [2] in 1977 proposed the JRC–JCS model that is still widely used, and gave ten standard profiles. However, due to the early publication of the literature and the relatively backward image digital representation technology at the time of publication, ten standard profiles with noise defects can be obtained from the literature, as shown in Figure 1.

By inspecting the ten standard profiles shown in Figure 1, it can be seen that the profile image has many noise defects such as blank fractures, stray points, and excessively thick lines, which will inevitably affect the evaluation result of the roughness evaluation index proposed based on the Barton ten standard profiles. Through image processing techniques such as denoising and repairing fractures, the Barton ten standard profiles are shown in Figure 2. The rationality of the Barton ten standard profiles after image processing needs further verification.

Figure 1. Ten joint profiles from Barton.

Figure 2. Barton ten standard profiles after image processing.

2.1. Interpolation Processing of the Barton Ten Standard Profiles after Image Processing

Taking the Barton ten standard profiles after image processing as the original data, appropriate methods and different point spacings are adopted to obtain the profiles with different interpolation conditions. This work adopts five methods: nearest neighbor interpolation, linear interpolation, cubic spline interpolation, piecewise cubic Hermitian polynomial interpolation, and cubic polynomial interpolation, through 0.25 mm, 0.5 mm, 1 mm, and 2 mm. The roughness evaluation index of the profiles obtained by different interpolation conditions is calculated respectively, and the JRC value is calculated by the evaluation index. By comparing the calculated JRC value with the theoretical JRC value, the rationality of the digital representation method of Barton standard contour lines is verified.

The resulting image of the Barton standard profile of JRC 8–10 with a point spacing of 0.5 mm and different interpolation methods is shown in Figure 3. Figure 4 shows the interpolation results of the JRC 12–14 profile with the point spacing of 0.25 mm, 0.5 mm, 1 mm, and 2 mm using cubic spline interpolation.

Figure 3. Different interpolated JRC 8–10 profiles with 0.5 mm point spacing.

Figure 4. Different interpolated JRC 12–14 profiles with 0.5 mm dot pitch.

2.2. Roughness Feature Extraction and Interpolation Effect Verification

In view of the fact that most of the roughness evaluation formulas in existing studies use Z_2 , SF , and R_p , these three indicators are used to characterize the Barton standard profile roughness characteristics obtained under different interpolation conditions. By comparing and analyzing the JRC value calculated by these three indicators and the JRC theoretical value, the Barton standard profiles obtained by interpolation are verified, and a reasonable interpolation method and point spacing are given.

The extraction results of Z_2 , SF , and R_p of the Barton standard profile under different interpolation conditions are shown in Tables 1–3, respectively. It can be seen from Tables 1–3 that the Z_2 , SF , and R_p interpolation results of the piecewise cubic Hermitian polynomial interpolation method and the cubic polynomial interpolation method are consistent, so the JRC value obtained by the cubic Hermitian polynomial interpolation method is not calculated.

When the point spacing is 0.25 mm, 0.5 mm, 1.0 mm, and 2.0 mm, JRC can be obtained by Z_2 using the following relational expressions [11,13]:

$$\begin{cases} \text{JRC} = 28.43 + 28.10\lg Z_2, \Delta x = 0.25 \text{ mm} \\ \text{JRC} = 28.06 + 25.57\lg Z_2, \Delta x = 0.5 \text{ mm} \\ \text{JRC} = 26.57 + 21.32\lg Z_2, \Delta x = 1.0 \text{ mm} \\ \text{JRC} = 54.14Z_2^{0.650} - 6.40, \Delta x = 2.0 \text{ mm} \end{cases} \quad (4)$$

When the point spacing is 0.25 mm, 0.5 mm, 1.0 mm, and 2.0 mm, JRC can be obtained by SF using the following relational expressions [11,13]:

$$\begin{cases} \text{JRC} = 45.25 + 14.05\lg SF, \Delta x = 0.25 \text{ mm} \\ \text{JRC} = 35.42 + 12.64\lg SF, \Delta x = 0.5 \text{ mm} \\ \text{JRC} = 26.49 + 10.66\lg SF, \Delta x = 1.0 \text{ mm} \\ \text{JRC} = 34.49SF^{0.325} - 6.40, \Delta x = 2.0 \text{ mm} \end{cases} \quad (5)$$

When the point spacing is 0.25 mm, 0.5 mm, 1.0 mm, and 2.0 mm, JRC can be obtained by R_p using the following relational expressions [11,13]:

$$\begin{cases} \text{JRC} = 92.97\sqrt{R_p - 1} - 5.28, \Delta x = 0.25 \text{ mm} \\ \text{JRC} = 92.07\sqrt{R_p - 1} - 3.28, \Delta x = 0.5 \text{ mm} \\ \text{JRC} = 95.23\sqrt{R_p - 1} - 2.62, \Delta x = 1.0 \text{ mm} \\ \text{JRC} = 72.85(R_p - 1)^{0.350} - 5.69, \Delta x = 2.0 \text{ mm} \end{cases} \quad (6)$$

The formulations of Z_2 , SF and R_p are given as follows, respectively:

$$Z_2 = \sqrt{\frac{1}{L} \int_{x=0}^{x=L} \left(\frac{dy}{dx} \right)^2 dx} = \sqrt{\frac{1}{M\Delta x^2} \sum_{i=1}^M (y_{i+1} - y_i)^2} \quad (7)$$

$$SF = \frac{\sum_{i=0}^M (y_{i+1} - y_i)^2 (x_{i+1} - x_i)}{L} \quad (8)$$

$$R_p = \frac{\sqrt{\sum_{i=0}^M (x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2}}{L} \quad (9)$$

where L is the length of the profile; x_i and y_i are equally spaced points along the profile on the x- and y-coordinates respectively; and M is the number of straight line segments to these points to form the profile.

According to Tables 1–3, the JRC calculated by Equations (4)–(6) are shown in Tables 4–6. Table 4 shows that the average relative error between the JRC values calculated by Z_2 and their theoretical values under different interpolation methods are all within $\pm 10\%$, and the average relative error has no significant relationship with the point spacing. In view of the JRC value calculated by SF , the average relative error between the JRC values and their theoretical values under different interpolation methods are all within $\pm 10\%$, regardless of the linear interpolation and cubic polynomial interpolation with a point spacing of 0.25 mm. In view of the JRC value calculated by R_p , the interpolation results with the nearest neighbor interpolation method are best. For the three parameters of Z_2 , SF , and R_p , when the nearest neighbor interpolation method is used, the quality of the Barton standard profiles obtained by interpolation with a point spacing of 0.5 mm is the best. Therefore, the Barton standard profiles obtained by the nearest neighbor interpolation method are used as the data basis for establishing new roughness evaluation parameter.

Table 1. The root mean square slope Z_2 of the Barton standard profiles obtained by different interpolation conditions.

JRC Range	Nearest Neighbor Interpolation Method				Linear Interpolation Method				Cubic Spline Interpolation Method				Piecewise Cubic Hermitian Polynomial Interpolation Method				Cubic Polynomial Interpolation Method			
	Point Spacing (mm)				Point Spacing (mm)				Point Spacing (mm)				Point Spacing (mm)				Point Spacing (mm)			
	0.25	0.5	1	2	0.25	0.5	1	2	0.25	0.5	1	2	0.25	0.5	1	2	0.25	0.5	1	2
0–2	0.087	0.074	0.052	0.027	0.085	0.073	0.052	0.027	0.086	0.073	0.053	0.033	0.086	0.073	0.053	0.033	0.086	0.073	0.053	0.033
2–4	0.114	0.101	0.092	0.072	0.113	0.101	0.092	0.072	0.114	0.101	0.092	0.073	0.113	0.101	0.091	0.073	0.113	0.101	0.091	0.073
4–6	0.154	0.134	0.117	0.096	0.151	0.132	0.117	0.096	0.154	0.133	0.116	0.095	0.152	0.133	0.116	0.095	0.152	0.133	0.116	0.095
6–8	0.174	0.161	0.146	0.124	0.172	0.161	0.146	0.124	0.172	0.161	0.145	0.123	0.172	0.16	0.145	0.123	0.172	0.16	0.145	0.123
8–10	0.203	0.192	0.177	0.153	0.201	0.191	0.177	0.153	0.201	0.191	0.176	0.152	0.201	0.191	0.176	0.152	0.201	0.191	0.176	0.152
10–12	0.191	0.175	0.152	0.14	0.189	0.175	0.153	0.14	0.19	0.175	0.152	0.14	0.19	0.175	0.152	0.139	0.19	0.175	0.152	0.139
12–14	0.275	0.253	0.225	0.177	0.273	0.253	0.225	0.177	0.277	0.26	0.229	0.179	0.277	0.26	0.229	0.179	0.277	0.26	0.229	0.179
14–16	0.344	0.308	0.252	0.205	0.343	0.307	0.252	0.205	0.343	0.307	0.253	0.203	0.343	0.307	0.252	0.203	0.343	0.307	0.252	0.203
16–18	0.373	0.343	0.287	0.242	0.37	0.343	0.287	0.242	0.372	0.344	0.289	0.244	0.371	0.344	0.29	0.244	0.371	0.344	0.29	0.244
18–20	0.411	0.375	0.334	0.276	0.402	0.37	0.331	0.274	0.401	0.37	0.33	0.27	0.401	0.37	0.33	0.27	0.401	0.37	0.33	0.27

Table 2. The structural function SF of the Barton standard profiles obtained by different interpolation conditions.

JRC Range	Nearest Neighbor Interpolation Method				Linear Interpolation Method				Cubic Spline Interpolation Method				Piecewise Cubic Hermitian Polynomial Interpolation Method				Cubic Polynomial Interpolation Method			
	Point Spacing (mm)				Point Spacing (mm)				Point Spacing (mm)				Point Spacing (mm)				Point Spacing (mm)			
	0.25	0.5	1	2	0.25	0.5	1	2	0.25	0.5	1	2	0.25	0.5	1	2	0.25	0.5	1	2
0–2	0.001	0.001	0.003	0.003	0.001	0.001	0.003	0.003	0.001	0.001	0.003	0.004	0.001	0.001	0.003	0.004	0.001	0.001	0.003	0.004
2–4	0.001	0.003	0.008	0.021	0.001	0.003	0.008	0.021	0.001	0.003	0.008	0.021	0.001	0.003	0.008	0.021	0.001	0.003	0.008	0.021
4–6	0.002	0.005	0.014	0.037	0.001	0.004	0.014	0.037	0.002	0.004	0.014	0.036	0.001	0.004	0.014	0.036	0.001	0.004	0.014	0.036
6–8	0.002	0.007	0.021	0.062	0.002	0.006	0.021	0.061	0.002	0.006	0.021	0.06	0.002	0.006	0.021	0.06	0.002	0.006	0.021	0.06
8–10	0.003	0.009	0.031	0.093	0.003	0.009	0.031	0.093	0.003	0.009	0.031	0.092	0.003	0.009	0.031	0.092	0.003	0.009	0.031	0.092
10–12	0.002	0.008	0.023	0.078	0.002	0.008	0.023	0.079	0.002	0.008	0.023	0.079	0.002	0.008	0.023	0.078	0.002	0.008	0.023	0.078
12–14	0.005	0.016	0.051	0.126	0.005	0.016	0.051	0.125	0.005	0.017	0.053	0.128	0.005	0.017	0.053	0.128	0.005	0.017	0.053	0.128
14–16	0.007	0.024	0.063	0.168	0.007	0.024	0.063	0.167	0.007	0.024	0.064	0.165	0.007	0.024	0.063	0.165	0.007	0.024	0.063	0.165
16–18	0.009	0.029	0.082	0.233	0.009	0.029	0.082	0.234	0.009	0.03	0.084	0.238	0.009	0.03	0.084	0.239	0.009	0.03	0.084	0.239
18–20	0.011	0.035	0.111	0.303	0.01	0.034	0.11	0.299	0.01	0.034	0.109	0.291	0.01	0.034	0.109	0.292	0.01	0.034	0.109	0.292

Table 3. The roughness profile index R_p of the Barton standard profiles obtained by different interpolation conditions.

JRC Range	Nearest Neighbor Interpolation Method				Linear Interpolation Method				Cubic Spline Interpolation Method				Piecewise Cubic Hermitian Polynomial Interpolation Method				Cubic Polynomial Interpolation Method			
	Point Spacing (mm)				Point Spacing (mm)				Point Spacing (mm)				Point Spacing (mm)				Point Spacing (mm)			
	0.25	0.5	1	2	0.25	0.5	1	2	0.25	0.5	1	2	0.25	0.5	1	2	0.25	0.5	1	2
0–2	1.004	1.003	1.001	1.0	1.004	1.003	1.001	1.0	1.004	1.003	1.001	1.001	1.004	1.003	1.001	1.001	1.004	1.003	1.001	1.001
2–4	1.006	1.005	1.004	1.003	1.006	1.005	1.004	1.003	1.006	1.005	1.004	1.003	1.004	1.005	1.004	1.003	1.004	1.005	1.004	1.003
4–6	1.012	1.009	1.007	1.005	1.011	1.009	1.007	1.005	1.011	1.009	1.007	1.005	1.011	1.009	1.007	1.004	1.011	1.009	1.007	1.004
6–8	1.015	1.013	1.01	1.008	1.014	1.013	1.01	1.008	1.014	1.013	1.01	1.007	1.014	1.012	1.01	1.007	1.014	1.012	1.01	1.007
8–10	1.02	1.018	1.015	1.011	1.019	1.018	1.015	1.011	1.019	1.018	1.015	1.011	1.019	1.018	1.015	1.011	1.019	1.018	1.015	1.011
10–12	1.018	1.015	1.011	1.01	1.017	1.015	1.011	1.01	1.017	1.015	1.011	1.01	1.017	1.015	1.011	1.01	1.017	1.015	1.011	1.01
12–14	1.035	1.03	1.024	1.015	1.035	1.03	1.025	1.015	1.036	1.032	1.025	1.016	1.036	1.032	1.025	1.016	1.036	1.032	1.025	1.016
14–16	1.054	1.045	1.031	1.021	1.054	1.044	1.031	1.021	1.054	1.044	1.031	1.02	1.054	1.044	1.031	1.02	1.054	1.044	1.031	1.02
16–18	1.062	1.054	1.039	1.028	1.062	1.054	1.039	1.028	1.062	1.054	1.039	1.029	1.062	1.054	1.04	1.029	1.062	1.054	1.04	1.029
18–20	1.07	1.062	1.051	1.036	1.068	1.061	1.051	1.036	1.069	1.062	1.051	1.035	1.069	1.061	1.05	1.035	1.069	1.061	1.050	1.035

Table 4. JRC of the interpolated profiles calculated by Z_2 .

JRC Range	Nearest Neighbor Interpolation Method				Linear Interpolation Method				Cubic Spline Interpolation Method				Cubic Polynomial Interpolation Method				Theoretical Value of JRC
	Point Spacing (mm)				Point Spacing (mm)				Point Spacing (mm)				Point Spacing (mm)				
	0.25	0.5	1	2	0.25	0.5	1	2	0.25	0.5	1	2	0.25	0.5	1	2	
0–2	−1.34	−0.93	−0.79	−1.21	−1.71	−1.07	−0.88	−1.21	−1.47	−0.99	−0.65	−0.49	−1.58	−1.04	−0.68	−0.54	0.4
2–4	1.96	2.62	4.46	3.37	1.81	2.6	4.45	3.4	1.91	2.58	4.4	3.44	1.81	2.56	4.39	3.43	2.8
4–6	5.62	5.72	6.68	5.36	5.38	5.6	6.67	5.37	5.59	5.65	6.65	5.3	5.46	5.61	6.63	5.29	5.8
6–8	7.07	7.79	8.74	7.54	6.91	7.74	8.72	7.53	6.98	7.75	8.67	7.45	6.93	7.74	8.66	7.44	6.7
8–10	8.99	9.75	10.53	9.55	8.82	9.68	10.53	9.55	8.86	9.67	10.49	9.5	8.85	9.68	10.49	9.51	9.5
10–12	8.23	8.72	9.11	8.68	8.12	8.72	9.15	8.7	8.15	8.7	9.13	8.65	8.14	8.7	9.13	8.63	10.8
12–14	12.67	12.81	12.77	11.18	12.58	12.81	12.77	11.16	12.76	13.11	12.94	11.28	12.75	13.1	12.93	11.27	12.8
14–16	15.4	14.98	13.8	12.9	15.36	14.94	13.79	12.9	15.36	14.94	13.83	12.8	15.37	14.94	13.8	12.81	14.5
16–18	16.4	16.18	15.01	15.1	16.31	16.16	15.01	15.1	16.36	16.19	15.08	15.24	16.34	16.21	15.1	15.25	16.7
18–20	17.59	17.16	16.4	17.02	17.3	17.02	16.34	16.92	17.28	17.0	16.31	16.71	17.29	17.0	16.31	16.73	18.7
Average relative error (%)	−6.58	−1.8	8.06	−4.02	−8.54	−2.39	7.96	−3.94	−7.41	−2.12	7.78	−4.15	−8.17	−2.28	7.68%	−4.20	

Table 5. JRC of the interpolated profiles calculated by SF .

JRC Range	Nearest Neighbor Interpolation Method				Linear Interpolation Method				Cubic Spline Interpolation Method				Cubic Polynomial Interpolation Method				Theoretical Value of JRC
	Point Spacing (mm)				Point Spacing (mm)				Point Spacing (mm)				Point Spacing (mm)				
	0.25	0.5	1	2	0.25	0.5	1	2	0.25	0.5	1	2	0.25	0.5	1	2	
0–2	−1.44	−0.65	−0.89	−1.24	−1.81	−1.06	−0.89	−1.24	−1.56	−1.06	−0.72	−0.49	−1.68	−1.06	−0.72	−0.53	0.4
2–4	1.86	2.75	4.36	3.37	1.71	2.75	4.36	3.4	1.81	2.53	4.31	3.44	1.72	2.53	4.31	3.43	2.8
4–6	5.57	5.76	6.59	5.36	5.15	5.63	6.59	5.36	5.57	5.63	6.56	5.3	5.15	5.63	6.56	5.28	5.8
6–8	7.02	7.78	8.67	7.53	6.69	7.69	8.63	7.53	7.02	7.69	8.58	7.45	6.69	7.69	8.58	7.45	6.7
8–10	8.93	9.68	10.45	9.54	8.69	9.62	10.45	9.54	8.691	9.62	10.41	9.5	8.69	9.62	10.41	9.51	9.5
10–12	8.18	8.71	9.03	8.68	7.91	8.71	9.07	8.69	8.18	8.71	9.07	8.7	7.91	8.71	9.05	8.63	10.8
12–14	12.54	12.72	12.69	11.17	12.54	12.72	12.69	11.15	12.67	13.02	12.86	11.27	12.67	13.02	12.86	11.26	12.8
14–16	15.31	14.88	13.72	12.9	15.23	14.83	13.71	12.89	15.23	14.83	13.75	12.8	15.31	14.83	13.71	12.81	14.5
16–18	16.3	16.06	14.93	15.09	16.23	16.04	14.93	15.1	16.23	16.08	15.0	15.23	16.23	16.1	15.02	15.25	16.7
18–20	17.51	17.03	16.32	17.01	17.21	16.89	16.26	16.91	17.15	16.87	16.23	16.7	17.21	16.87	16.23	16.72	18.7
Average relative error (%)	−7.58	−1.66	6.99	−4.06	−10.35	−2.24	6.92	−4.02	−8.25	−2.82	6.71	−4.14	−10.16	−2.80	6.67	−4.26	

Table 6. JRC of the interpolated profiles calculated by R_p .

JRC Range	Nearest Neighbor Interpolation Method				Linear Interpolation Method				Cubic Spline Interpolation Method				Cubic Polynomial Interpolation Method				Theoretical Value of JRC
	Point Spacing (mm)				Point Spacing (mm)				Point Spacing (mm)				Point Spacing (mm)				
	0.25	0.5	1	2	0.25	0.5	1	2	0.25	0.5	1	2	0.25	0.5	1	2	
0–2	0.38	1.41	0.81	−0.98	0.22	1.41	0.81	−0.98	0.3	1.41	0.94	−0.6	0.3	1.41	0.94	−0.6	0.4
2–4	2.16	3.3	3.55	3.38	2.1	3.23	3.55	3.38	2.16	3.23	3.48	3.38	0.3	3.23	3.48	3.38	2.8
4–6	4.69	5.31	5.17	5.3	4.52	5.26	5.17	5.3	4.65	5.26	5.17	5.3	4.56	5.26	5.12	5.22	5.8
6–8	5.92	7.05	7.09	7.51	5.76	7.01	7.04	7.51	5.84	7.01	7.0	7.39	5.76	6.97	7.0	7.39	6.7
8–10	7.8	9.0	9.12	9.53	7.64	8.93	9.12	9.53	7.67	8.93	9.08	9.48	7.64	8.93	9.08	9.48	9.5
10–12	7.05	8.0	7.55	8.69	6.95	8.0	7.55	8.69	6.98	7.96	7.55	8.64	6.98	7.96	7.55	8.64	10.8
12–14	12.11	12.75	12.26	11.18	12.01	12.75	12.29	11.14	12.24	13.14	12.56	11.29	12.24	13.14	12.53	11.26	12.8
14–16	16.34	16.19	14.07	13.0	16.3	16.12	14.04	13.0	16.28	16.12	14.12	12.9	16.3	16.12	14.07	12.9	14.5
16–18	17.94	18.13	16.11	15.23	17.78	18.1	16.11	15.23	17.85	18.15	16.28	15.38	17.83	18.19	16.31	15.41	16.7
18–20	19.35	19.68	18.91	17.11	19.02	19.5	18.82	17.0	19.12	19.55	18.78	16.78	19.09	19.52	18.76	16.8	18.7
Average relative error (%)	−9.79	0.93	−2.43	−3.92	−11.34	0.24	−2.55	−4.02	−10.36	0.62	−2.58	−4.30	−18.09	0.55	−2.76	−4.47	

3. A New Joint Roughness Parameter

The rock discontinuity has complex morphological characteristics, and the roughness has the characteristics of size effect and anisotropy. In order to facilitate the rapid evaluation of natural rock discontinuity roughness while considering the size effect and anisotropy characteristics, a new joint roughness parameter M_{hl} is proposed.

During the shearing process, the contact part of the upper and lower discontinuity surface first occurs on the side of the lower surface with a larger slope opposite to the shear direction. The dilatancy movement occurs along the potential contact point, as shown in Figure 5.

Figure 5. Potential contact parts of rock discontinuity for forward and reverse shear. **Left** and **right** subfigure show the potential contact during positive and reverse shear respectively.

During the shearing process, the potential contact parts will undergo compression-shear failure until the shear slip of the discontinuity. It can be seen that the potential contact parts are an important indicator of the roughness. With the difference in the shear direction, the potential contact part changes and has obvious directionality, which can reflect the anisotropic characteristics of the rock discontinuity roughness. Therefore, the average ratio R_{vh} of the vertical to the horizontal projection length of the potential contact part on the shear direction is used to reflect the anisotropic characteristics of the rock discontinuity surface roughness. The positive shear direction is defined as the direction along the positive X axis, and the reverse shear direction is defined as the direction along the negative X axis; the discontinuity profile slope is defined as the angle between the profile and the positive X axis, and the range is $[-90^\circ, 90^\circ]$, where counterclockwise rotation from the positive X-axis direction is positive, and clockwise rotation from the positive X-axis direction is negative. In the case of positive shear, the slope of the potential contact part is less than zero, which is a negative slope; during the reverse shear, the slope of the potential contact part is greater than zero, which is a positive slope.

Parameter R_{vh} reflects the local undulation angle characteristics of the overall discontinuity surface. Using parameter R_{vh} alone to evaluate the roughness will not identify different discontinuities with the same local undulation angle (see Figure 6a). At the same time, the size effect of the roughness cannot be reflected (see Figure 6b). The average undulation amplitude can reflect the overall undulation amplitude of the discontinuity surface. Therefore, the ratio of the average undulation amplitude to the horizontal projection length is used to reflect the size effect characteristics of the discontinuity roughness.

Figure 6. Shortcomings of evaluation of rock mass discontinuity roughness using single parameter R_{vh} ; (a) Two discontinuities with different undulations but same; (b) Two discontinuities with different length but same.

3.1. Average Undulation Amplitude of the Discontinuity Profile

The average undulation amplitude of the discontinuity profile $\bar{h}$ reflects the characteristics of the overall undulation amplitude of the discontinuity, and its expression is:

$$\bar{h} = \int_0^L |F(x)| dx / L = \sum_{i=1}^{m-1} \left| \frac{F(x_{i+1}) + F(x_i)}{2} \right| \frac{(x_{i+1} - x_i)}{L} \quad (10)$$

where $F(x)$ is the undulation amplitude of the discontinuity profile; m is the number of discrete points on the discontinuity profile; and L is the horizontal projection length of the discontinuity profile.

When the discontinuity profile is discrete at equal interval Δx , Equation (10) can be expressed as:

$$\bar{h} = \sum_{i=1}^{m-1} \left| \frac{F(x_{i+1}) + F(x_i)}{2} \right| \frac{\Delta x}{L} \quad (11)$$

Equation (10) shows that the average undulation amplitude $\bar{h}$ mainly depends on the area between the discontinuity profile and the reference line, as shown in Figure 7. As the reference line moves up and down between the maximum undulation height h_p and the minimum undulation height h_l , the area changes (the shaded part in Figure 7), which will cause the average undulation amplitude to change, that is, a discontinuity profile has multiple average undulation amplitudes. For this reason, the minimum value of the average undulation amplitude of the discontinuity profile is adopted as the evaluation parameter of the discontinuity roughness.

Figure 7. Functional representation of a discontinuity profile.

When $\bar{h}$ is taken to the minimum, the following relationship is satisfied:

$$\begin{aligned} \sum_{i=1}^n L_{ui} &= \sum_{i=1}^m L_{di} \\ \sum_{i=1}^n L_{ui} + \sum_{i=1}^m L_{di} &= L \end{aligned} \quad (12)$$

where L_{ui} is the horizontal projection length of each segment of the upper discontinuity profile on the reference line; L_{di} is the horizontal projection length of each segment of the lower discontinuity profile on the reference line; and L is the total projected length of the discontinuity profile on the reference line.

We then compiled a program according to Equations (11) and (12) to determine the reference line position where the average undulation amplitude $\bar{h}$ of the Barton standard profile interpolated by the nearest interpolation takes the minimum and calculated the average undulation amplitude $\bar{h}$ and the area $\int_0^L |F(x)| dx$ between the discontinuity profile and the reference line. When calculating, the program first sets the offset of the reference line along the positive Y axis; the offset is the ratio of the difference between the maximum and minimum undulation amplitudes of the discontinuity profile to the total number of cycles. Second, the average undulation amplitude, the horizontal projection length of each segment of the upper and lower discontinuity profile on the reference line are calculated. Finally, the minimum average undulation amplitude and the position coordinates of the reference line are determined.

The calculation results of the minimum average undulation amplitude of the Barton standard profile obtained by the nearest neighbor interpolation method at different point spacings are shown in Table 7. It can be concluded that the average undulation amplitude decreases with the increase in the point spacing. Figure 8 shows the calculation results of the minimum average undulation amplitude of the JRC 8–10 profile obtained by the nearest neighbor interpolation at different point spacings. The left side image of the figure shows the average undulation amplitude corresponding to the different reference line positions, the upper right-side image shows the initial interpolated JRC profile, and the lower right-side figure shows the JRC profile when the average undulation amplitude takes the minimum.

Table 7. The minimum average undulation amplitude of the Barton standard profile obtained by the nearest neighbor interpolation method (unit: mm).

JRC Range		0–2	2–4	4–6	6–8	8–10	10–12	12–14	14–16	16–18	18–20
Point spacing	0.25	0.1013	0.3631	0.3519	0.4685	1.0219	1.2732	1.2356	1.0752	1.4151	0.8137
	0.50	0.1008	0.3591	0.3520	0.4673	1.0170	1.2725	1.2367	1.0736	1.4158	0.8131
	1.00	0.1000	0.3532	0.3483	0.4647	1.0052	1.2685	1.2425	1.0691	1.4109	0.8078
	2.00	0.0937	0.3383	0.3420	0.4562	0.9733	1.2621	1.2335	1.0619	1.4052	0.8008

Figure 8. The minimum average fluctuation amplitude of the JRC 8–10 profiles obtained by the nearest neighbor interpolation method at different point spacings; (a) Point spacing 0.25 mm; (b) Point spacing 0.5 mm; (c) Point spacing 1.0 mm; (d) Point spacing 2.0 mm.

3.2. Anisotropy Parameter of Discontinuity Roughness

The average ratio R_{vh} of the vertical to the horizontal projection length of the potential contact part of the discontinuity surface in the shear direction is used to reflect the anisotropic characteristics of the discontinuity roughness. The anisotropy parameter R_{vh} can be expressed as:

$$R_{vh} = \begin{cases} \frac{\sum_{i=1}^{m-1} \min(0, \frac{y_{i+1}-y_i}{x_{i+1}-x_i})}{\sum_{i=1}^{m-1} \begin{pmatrix} 1, y_{i+1}-y_i < 0 \\ 0, y_{i+1}-y_i > 0 \end{pmatrix}}, & \text{Forward shear} \\ \frac{\sum_{i=1}^{m-1} \max(0, \frac{y_{i+1}-y_i}{x_{i+1}-x_i})}{\sum_{i=1}^{m-1} \begin{pmatrix} 1, y_{i+1}-y_i > 0 \\ 0, y_{i+1}-y_i < 0 \end{pmatrix}}, & \text{Reverse shear} \end{cases} \quad (13)$$

where m is the total number of discrete points on the discontinuity profile; x_i and y_i are the X and Y coordinate values of the discrete points; $\sum_{i=1}^{m-1} \begin{pmatrix} 1, y_{i+1}-y_i < 0 \\ 0, y_{i+1}-y_i > 0 \end{pmatrix}$ is the total number of discrete segments with a slope less than zero on the discontinuity profile; and $\sum_{i=1}^{m-1} \begin{pmatrix} 1, y_{i+1}-y_i > 0 \\ 0, y_{i+1}-y_i < 0 \end{pmatrix}$ is the total number of discrete segments with a slope greater than zero.

The calculation results of the anisotropy parameters of different cumulative negative slope intervals of the Barton standard profile obtained by the nearest neighbor interpolation are shown in Table 8. The distribution of the discrete segments of the cumulative negative slope interval of the JRC 8–10 profile is shown in Figure 9. The left side of each sub-figure in the figure represents the distribution characteristics of discrete segments in different cumulative negative slope intervals. The discrete segments of slope in the cumulative negative slope interval are represented by bold blue lines, and the cumulative negative slope intervals from top to bottom are $[-10^\circ, 0]$, $[-20^\circ, 0]$, $[-30^\circ, 0]$, $[-40^\circ, 0]$, $[-50^\circ, 0]$, $[-60^\circ, 0]$, $[-70^\circ, 0]$, $[-80^\circ, 0]$, and $[-90^\circ, 0]$, respectively; the right side of the figure is the distribution rose diagram of the negative slope discrete segment of the entire profile.

Table 8. Anisotropy parameter R_{vh} for different cumulative negative slope intervals of Barton standard discontinuity profiles obtained by the nearest neighbor interpolation.

Point Spacing		0–2	2–4	4–6	6–8	8–10	10–12	12–14	14–16	16–18	18–20
0.25 mm	$-10^\circ-0^\circ$	0.1505	0.0956	0.1139	0.1022	0.1022	0.0876	0.1028	0.0830	0.1145	0.1439
	$-20^\circ-0^\circ$	0.1651	0.1282	0.1780	0.1647	0.1624	0.1521	0.1354	0.1522	0.1807	0.1969
	$-30^\circ-0^\circ$	0.1740	0.1309	0.2184	0.2171	0.2094	0.1753	0.1903	0.2124	0.2271	0.3019
	$-40^\circ-0^\circ$	0.1740	0.1309	0.2184	0.2281	0.2261	0.1753	0.2089	0.2464	0.2751	0.3312
	$-50^\circ-0^\circ$	0.1740	0.1309	0.2184	0.2281	0.2261	0.1796	0.2218	0.2624	0.3052	0.3526
	$-60^\circ-0^\circ$	0.1740	0.1309	0.2184	0.2281	0.2261	0.1796	0.2286	0.2624	0.3133	0.3526
	$-70^\circ-0^\circ$	0.1740	0.1309	0.2184	0.2281	0.2261	0.1796	0.2286	0.2624	0.3133	0.3526
	$-80^\circ-0^\circ$	0.1740	0.1309	0.2184	0.2281	0.2261	0.1796	0.2286	0.2624	0.3133	0.3730
	$-90^\circ-0^\circ$	0.1740	0.1309	0.2184	0.2281	0.2261	0.1796	0.2286	0.2624	0.3133	0.3730
0.50 mm	$-10^\circ-0^\circ$	0.0785	0.0758	0.0765	0.0724	0.0852	0.0882	0.0778	0.0798	0.0820	0.1000
	$-20^\circ-0^\circ$	0.1013	0.0932	0.1293	0.1422	0.1406	0.1475	0.1402	0.1542	0.1658	0.1671
	$-30^\circ-0^\circ$	0.1013	0.0932	0.1474	0.1704	0.1830	0.1588	0.1838	0.2287	0.2240	0.2496
	$-40^\circ-0^\circ$	0.1013	0.0932	0.1474	0.1704	0.1830	0.1588	0.1978	0.2422	0.2486	0.2828
	$-50^\circ-0^\circ$	0.1013	0.0932	0.1474	0.1704	0.1830	0.1588	0.2061	0.2422	0.2773	0.2896
	$-60^\circ-0^\circ$	0.1013	0.0932	0.1474	0.1704	0.1830	0.1588	0.2061	0.2422	0.2773	0.2896
	$-70^\circ-0^\circ$	0.1013	0.0932	0.1474	0.1704	0.1830	0.1588	0.2061	0.2422	0.2773	0.3075
	$-80^\circ-0^\circ$	0.1013	0.0932	0.1474	0.1704	0.1830	0.1588	0.2061	0.2422	0.2773	0.3075
	$-90^\circ-0^\circ$	0.1013	0.0932	0.1474	0.1704	0.1830	0.1588	0.2061	0.2422	0.2773	0.3075

Table 8. Cont.

Point Spacing		0–2	2–4	4–6	6–8	8–10	10–12	12–14	14–16	16–18	18–20
1.00 mm	−10°–0°	0.0585	0.0710	0.0705	0.0544	0.0495	0.0834	0.0761	0.0582	0.0726	0.0960
	−20°–0°	0.0585	0.0710	0.1118	0.1110	0.1076	0.1267	0.1302	0.1649	0.1970	0.1769
	−30°–0°	0.0585	0.0710	0.1210	0.1395	0.1524	0.1317	0.1692	0.2077	0.2140	0.2285
	−40°–0°	0.0585	0.0710	0.1210	0.1395	0.1524	0.1317	0.1692	0.2077	0.2230	0.2527
	−50°–0°	0.0585	0.0710	0.1210	0.1395	0.1524	0.1317	0.1692	0.2077	0.2429	0.2705
	−60°–0°	0.0585	0.0710	0.1210	0.1395	0.1524	0.1317	0.1692	0.2077	0.2429	0.2705
	−70°–0°	0.0585	0.0710	0.1210	0.1395	0.1524	0.1317	0.1692	0.2077	0.2429	0.2705
	−80°–0°	0.0585	0.0710	0.1210	0.1395	0.1524	0.1317	0.1692	0.2077	0.2429	0.2705
	−90°–0°	0.0585	0.0710	0.1210	0.1395	0.1524	0.1317	0.1692	0.2077	0.2429	0.2705
2.00 mm	−10°–0°	0.0238	0.0496	0.0949	0.0599	0.0534	0.0712	0.0644	0.0998	0.0659	0.0933
	−20°–0°	0.0238	0.0496	0.1119	0.0939	0.0855	0.1145	0.1217	0.1624	0.1708	0.1222
	−30°–0°	0.0238	0.0496	0.1119	0.1083	0.1260	0.1145	0.1326	0.1972	0.2052	0.2074
	−40°–0°	0.0238	0.0496	0.1119	0.1083	0.1260	0.1145	0.1326	0.1972	0.2052	0.2074
	−50°–0°	0.0238	0.0496	0.1119	0.1083	0.1260	0.1145	0.1326	0.1972	0.2052	0.2074
	−60°–0°	0.0238	0.0496	0.1119	0.1083	0.1260	0.1145	0.1326	0.1972	0.2052	0.2074
	−70°–0°	0.0238	0.0496	0.1119	0.1083	0.1260	0.1145	0.1326	0.1972	0.2052	0.2074
	−80°–0°	0.0238	0.0496	0.1119	0.1083	0.1260	0.1145	0.1326	0.1972	0.2052	0.2074
	−90°–0°	0.0238	0.0496	0.1119	0.1083	0.1260	0.1145	0.1326	0.1972	0.2052	0.2074

(a)

(b)

Figure 9. Cont.

Figure 9. Distribution of discrete segments of each cumulative interval of negative slope and its corresponding R_{vh} for JRC 8–10 profile. (a) Point spacing 0.25 mm; (b) Point spacing 0.5 mm. (c) Point spacing 1.0 mm; (d) Point spacing 2.0 mm.

It can be seen from the results that the anisotropy parameter R_{vh} decreases with the increase in the discrete point spacing. The larger the point spacing, the more obvious the topographical characteristics of the profile loss, which is reflected in the same R_{vh} value in different cumulative negative slope intervals. With the increase in the width of the cumulative negative slope interval, R_{vh} gradually increases, and finally tends to be constant, and the rate of change that tends to be constant is proportional to the discontinuity roughness coefficient JRC. The discrete segments of all profiles range from JRC 0–2 to JRC 18–20 mostly fall within the interval of $[-30^\circ, 0]$. Distribution characteristics of the slopes of the discrete segments of the ten Barton profiles in the interval $[-30^\circ, 0]$ with a point spacing of 0.25 mm are shown in Figure 10. Therefore, R_{vh} in the negative slope interval of $[-30^\circ, 0]$ is used as the anisotropy parameter of discontinuity roughness.

Figure 10. Distribution characteristics of the slopes of the discrete segments of the ten Barton profiles in the interval $[-30^\circ, 0]$.

3.3. New Joint Roughness Parameter and Its Correlation with Joint Roughness Coefficients

The new joint roughness parameter M_{hl} considers the size effect and anisotropy characteristics of discontinuity roughness at the same time, which can be expressed as:

$$M_{hl} = \alpha \left(\frac{\bar{h}}{L} \right) + \beta R_{vh} \quad (14)$$

where α and β are fitting coefficients. The relationship between M_{hl} and JRC is analyzed by the following equation:

$$\text{JRC} = K + Ae^{M_{hl}} \quad (15)$$

where A and K are fitting coefficients.

Table 9 lists the JRC, $\bar{h}/L$, and $R_{vh[-30^\circ, 0]}$ of the Barton profiles used for the fitting analysis. The fitting results are shown in Table 10. The fitting result with a point spacing of 0.25 mm is shown in Figure 11.

Table 9. JRC, $\bar{h}/L$, and $R_{vh[-30^\circ, 0]}$ of Barton standard profiles used for fitting analysis.

JRC Profile		0–2	2–4	4–6	6–8	8–10	10–12	12–14	14–16	16–18	18–20
Point spacing 0.25 mm	JRC	0.4	2.8	5.8	6.7	9.5	10.8	12.8	14.5	16.7	18.7
	$\bar{h}/L (\times 10^{-2})$	0.1013	0.3631	0.3519	0.4685	1.0219	1.2732	1.2356	1.0752	1.4151	0.8137
	$R_{vh[-30^\circ, 0]}$	0.1740	0.1309	0.2184	0.2171	0.2094	0.1753	0.1903	0.2124	0.2271	0.3019
Point spacing 0.50 mm	JRC	0.4	2.8	5.8	6.7	9.5	10.8	12.8	14.5	16.7	18.7
	$\bar{h}/L (\times 10^{-2})$	0.1008	0.3591	0.3520	0.4673	1.0170	1.2725	1.2367	1.0736	1.4158	0.8131
	$R_{vh[-30^\circ, 0]}$	0.1013	0.0932	0.1474	0.1704	0.1830	0.1588	0.1838	0.2287	0.2240	0.2496

Table 9. Cont.

JRC Profile		0–2	2–4	4–6	6–8	8–10	10–12	12–14	14–16	16–18	18–20
Point spacing 1.00 mm	JRC	0.4	2.8	5.8	6.7	9.5	10.8	12.8	14.5	16.7	18.7
	$\bar{h}/L(\times 10^{-2})$	0.1000	0.3532	0.3483	0.4647	1.0052	1.2685	1.2425	1.0691	1.4109	0.8078
	$R_{vh[-30^\circ,0]}$	0.0585	0.0710	0.1210	0.1395	0.1524	0.1317	0.1692	0.2077	0.2140	0.2285
Point spacing 2.00 mm	JRC	0.4	2.8	5.8	6.7	9.5	10.8	12.8	14.5	16.7	18.7
	$\bar{h}/L(\times 10^{-2})$	0.0937	0.3383	0.3420	0.4562	0.9733	1.2621	1.2335	1.0619	1.4052	0.8008
	$R_{vh[-30^\circ,0]}$	0.0238	0.0496	0.1119	0.1083	0.1260	0.1145	0.1326	0.1972	0.2052	0.2074

Table 10. Fitting results of JRC, $\bar{h}/L$, and $R_{vh[-30^\circ,0]}$ of Barton standard profiles.

Point Spacing (mm)	Fitting Results	M_{hl}	Correlation Coefficient R^2
0.25	$JRC = -10.36 + 5.816e^{M_{hl}}$	$M_{hl} = 47.37(\bar{h}/L) + 3.992R_{vh[-30^\circ,0]}$	0.9517
0.50	$JRC = -12.88 + 9.395e^{M_{hl}}$	$M_{hl} = 0.1839(\bar{h}/L) + 4.038R_{vh[-30^\circ,0]}$	0.9615
1.00	$JRC = -27.57 + 24.56e^{M_{hl}}$	$M_{hl} = 0.07917(\bar{h}/L) + 2.319R_{vh[-30^\circ,0]}$	0.9697
2.00	$JRC = -84.91 + 83.12e^{M_{hl}}$	$M_{hl} = 0.03357(\bar{h}/L) + 0.805R_{vh[-30^\circ,0]}$	0.9512

Figure 11. Fitting results of JRC, $\bar{h}/L$, and $R_{vh[-30^\circ,0]}$ of Barton profiles with a point spacing of 0.25 mm.

The JRC expressed by $\bar{h}/L$ and $R_{vh[-30^\circ,0]}$ with different point spacings are:

$$\begin{cases} JRC = -10.36 + 5.816e^{M_{hl}}, M_{hl} = 47.37(\bar{h}/L) + 3.992R_{vh[-30^\circ,0]}, \Delta x = 0.25 \text{ mm} \\ JRC = -12.88 + 9.395e^{M_{hl}}, M_{hl} = 0.1839(\bar{h}/L) + 4.038R_{vh[-30^\circ,0]}, \Delta x = 0.50 \text{ mm} \\ JRC = -27.57 + 24.56e^{M_{hl}}, M_{hl} = 0.07917(\bar{h}/L) + 2.319R_{vh[-30^\circ,0]}, \Delta x = 1.00 \text{ mm} \\ JRC = -84.91 + 83.12e^{M_{hl}}, M_{hl} = 0.03357(\bar{h}/L) + 0.805R_{vh[-30^\circ,0]}, \Delta x = 2.00 \text{ mm} \end{cases} \quad (16)$$

The prediction results of the JRC values of Barton ten standard profiles using Equation (16) are shown in Figure 12. The results show that the JRC evaluation Equation (16) established by the roughness parameter M_{hl} has high prediction accuracy.

Figure 12. JRC and its theoretical values of ten Barton standard profiles calculated using $\bar{h}/L$ and $R_{vh[-30^\circ,0]}$.

4. Discussion

JRC is one of the important parameters to calculate shear strength of rock discontinuities. Available models suggested in the literature neglect combined effects of shear direction, scale of rock discontinuities, inclination angle, and amplitude of asperities during the roughness calculations. Thus, an exponential function between JRC and the roughness parameter M_{hl} is developed, as shown in Equation (16). The ratio of the average undulation amplitude to the horizontal projection length $\bar{h}/L$ is used to reflect the size effect characteristics. The average ratio R_{vh} of the vertical to the horizontal projection length of the potential contact parts of the discontinuity profile in the shear direction is used to reflect the anisotropic characteristics. The exponential function between JRC and the roughness parameter M_{hl} is developed based on Barton ten standard profiles. Through analysis, it is found that the discrete segments of all the Barton profiles range from JRC 0–2 to JRC 18–20 mostly fall within the interval of $[-30^\circ, 0]$, as shown in Figure 10. Therefore, R_{vh} in the negative slope interval of $[-30^\circ, 0]$ is used as the anisotropy parameter of discontinuity roughness in this work.

The roughness index $R_{vh[-30^\circ,0]}$ reflects the gentle slope characteristics of the rock discontinuity profiles in the shear direction, which ignores the segments with steep slopes greater than 30° on the discontinuity profiles. In fact, the segments with steep slopes are the first part that come into contact during shearing and provides shear resistance. Only when the steep segments are broken, the gentle segments then play a role in preventing the shear slip. In addition, the slope interval of $[-30^\circ, 0]$ may not be the advantageous slope interval for all natural rock discontinuities. Therefore, the influence of R_{vh} for steep slope segments greater than 30° should be considered for the roughness anisotropy parameter in the future.

5. Conclusions

An exponential function between JRC and the roughness parameter M_{hl} is developed to provide a characterization method for the evaluation of rock discontinuity surface roughness. The main conclusions are as follows:

1. The comparative analysis of the JRC value calculated by the different interpolation conditions of the Barton standard profile and the JRC theoretical value shows that the interpolation effect of the nearest neighbor interpolation method is the best for Z_2 , SF , and R_p . The nearest neighbor interpolation method is used to digitally characterize the Barton standard profiles and lays a reliable data foundation for the establishment of new discontinuity roughness parameters.
2. The discontinuity roughness parameter M_{hl} also considers the size effect, anisotropy characteristics, and point spacing effects of the rock discontinuity roughness. The ratio of the average undulation amplitude to the horizontal projection length $\bar{h}/L$ is used to reflect the size effect characteristics. The average ratio R_{vh} of the vertical to the horizontal projection length of the potential contact parts of the discontinuity profile in the shear direction is used to reflect the anisotropic characteristics.
3. The average undulation amplitude $\bar{h}$ of the discontinuity profile reflects the characteristics of the overall undulation amplitude, and its value changes with the position of the reference line. The minimum average undulation amplitude is used to indicate the overall undulation amplitude, which is taken as the minimum value as the relationship $\sum_{i=1}^n L_{ui} = \sum_{i=1}^m L_{di}, \sum_{i=1}^n L_{ui} + \sum_{i=1}^m L_{di} = L$ is satisfied. The average undulation amplitude $\bar{h}$ decreases with the increase in the point spacing.
4. The anisotropy parameter depends on the total number of discrete segments of the potential contact part. The key is to determine the potential contact part. In this work, the potential contact part is defined as the discrete segments of the discontinuity profile with a slope in the range $[-30^\circ, 0]$. The relationship between JRC and M_{hl} shows that the selection of potential contact parts is reasonable.
5. Using M_{hl} , the JRC evaluation equation for discontinuity surface roughness with different point spacing is established. The correlation between M_{hl} and JRC can be expressed as:

$$\begin{cases} JRC = -10.36 + 5.816e^{M_{hl}}, M_{hl} = 47.37(\bar{h}/L) + 3.992R_{vh[-30^\circ, 0]}, \Delta x = 0.25 \text{ mm} \\ JRC = -12.88 + 9.395e^{M_{hl}}, M_{hl} = 0.1839(\bar{h}/L) + 4.038R_{vh[-30^\circ, 0]}, \Delta x = 0.50 \text{ mm} \\ JRC = -27.57 + 24.56e^{M_{hl}}, M_{hl} = 0.07917(\bar{h}/L) + 2.319R_{vh[-30^\circ, 0]}, \Delta x = 1.00 \text{ mm} \\ JRC = -84.91 + 83.12e^{M_{hl}}, M_{hl} = 0.03357(\bar{h}/L) + 0.805R_{vh[-30^\circ, 0]}, \Delta x = 2.00 \text{ mm} \end{cases}$$

6. The roughness index $R_{vh[-30^\circ, 0]}$ reflects the gentle slope characteristics of the rock discontinuity profiles in the shear direction and ignores the segments with steep slopes greater than 30° on the discontinuity profiles. During shearing, the steep segments are the first to come into contact. Only when the steep segments are broken, can the gentle segments prevent the shear slip of rock discontinuities. In addition, the slope interval of $[-30^\circ, 0]$ may not be the advantageous slope interval for all natural rock discontinuities. Therefore, the influence of R_{vh} for steep slope segments greater than 30° should be considered for the roughness anisotropy parameter in the future.

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