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A study about the influence of joint roughness on the volume of rock blocks

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Abstract

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Keywords

rock block volume, rock structure, joint roughness, joint disc model

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A study about the influence of joint roughness on the volume of rock blocks

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Abstract: The structure of a rock mass directly controls its mechanical and hydraulic properties, and the distribution of rock block volumes can directly reflect the structural characteristics of the rock mass. Currently, many studies simplify the joint surfaces as planes and ignore the influence of roughness on the volume of rock blocks. In this study, the Hurst exponent (H) and root-mean-square height (R_q) were used to characterize joint roughness, and the influence of joint roughness on the quantity and volume distribution of rock blocks was investigated. The results show that: (1) H and R_q control the roughness of the joint, and the roughness increases with the increase of R_q and decreases with the increase of H; (2) the quantity of rock blocks is generally positively correlated with joint roughness, that is, it increases as the roughness increases; (3) the influence of R_q and H on the distribution of rock block volumes is mainly achieved by changing the proportion of small-volume blocks, and the mean and median volumes of rock blocks decrease as the roughness increases; (4) when the joints are orthogonal and spaced closely, the variation in the quantity of rock blocks can be divided into three stages with respect to the roughness: a stable stage, an initial growth stage, and a rapid growth stage, where R_q and H jointly control the relative distribution range of each interval. Finally, based on the data collected by photogrammetry, we establish a joint model of the rock mass, and study the distribution of rock block volumes in a slope along a certain highway in Dalian, which verifies the correctness of the above conclusions.

Keywords: rock block volume; rock structure; joint roughness; joint disc model

1 Introduction

Rock structure controls the mechanical and hydraulic properties of the rock mass[1]. Joints cut rock masses into rock blocks. The distribution of rock block volumes can directly reflect the development of joints, which is one of the important quantitative metrics evaluating the rock mass structure. Accurate assessment of the rock block volume is the fundamental for rock mass quality classification, hydrogeological analysis, and rock engineering calculations [2–3].

At present, the estimation of rock mass volume can be mainly divided into the following two categories. First, analytical solution. This is based on the joint data obtained in the field, and uses empirical formulas or analytical methods to directly calculate the rock block volume and thereby deriving the distribution function of the rock block volume. Cai et al. [4] propose the equations for calculating rock block volume based on joint spacing, angle and ductility factor. Wang et al.[5] predict the cumulative distribution of the on-site rock mass volumes based on the empirical equations and the coefficient tables. Based on their work, Lu et al.[6] consider the influence of joint spacing and ductility, and further improve and apply this method. Stavropoulou[7] assumes that the joint spacing follows a negative exponential distribution, and derives the analytical solution for the cumulative distribution of the rock volumes under the orthogonal conditions of the three sets of joints. Second, numerical simulation. This often uses the joint data obtained in the field to establish a numerical model describing the discrete fracture network, which is then used to simulate the rock mass structure and to calculate the rock volume distribution. Elmouttie et al. [8] propose a method to estimate the on-site rock block volume distribution based on Monte Carlo simulation. They analyze the effects of joint ductility and spacing on the volume distributions of rock block. Katherine et al.[9] analyze the cumulative distribution of the rock block volumes in the rock mass joint model, and propose a method to characterize the shape and volume distribution of rock blocks. Vazaios et al.[10] use discrete fracture network to model the joint characteristics of Brockville tunnels. They use the rock block volume to quantify the range of the geological strength of the rock mass, and then evaluate the quality of the rock mass at the site. Macciotta et al. [11] estimate the volume distribution of fragmented rock blocks based on a discrete fracture network model, and apply it to the structure design of rockfall protection facilities. Buyaer et al.[12] establish a discrete fracture network model based on the photogrammetry and a semi-automated extraction of joint data. They use the model to determine the distributions including block sizes, block shapes and main orientation of the blocks. Kong et al.[13] use remote sensing and various programming algorithms to build their discrete fracture network model. They establish a multi-dimensional block indicator system used for the rock block characterization. As shown by

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the studies listed above, numerical simulation has been widely applied in rock block volume evaluation, because of its high accuracy, various usefulness as well as its ability to derive directly the rock block volume distributions [14–15].

However, current studies on rock block volume often ignore the effects of joint surface morphology and simplify the joint surface as a smooth and planar surface. In nature, the joint surface appears as a rough undulating surface. Joint roughness is a geometric measure of the undulation of a joint surface relative to its averaged main surface. The International Society for Rock Mechanics (ISRM) [16] states that joint roughness can be characterized by two features, waviness, referring to the wavelike large fluctuations; and unevenness, referring to the random small undulations. Many studies have shown the use of statistical methods and fractal methods to quantify the joint roughness. Among them, the root mean square (RMS) of the asperity height is a widely used amplitude parameter for quantifying the joint roughness on its two-dimensional profile line [17]. The parameter samples the height along the joint centerline at set intervals, and quantifies the random fluctuations of the joint surface height using RMS. However, this parameter does not describe the local geometric characteristics of the joint surface, and the joint roughness cannot be reconstructed by this single parameter. On the other side, since the joint surface exhibits fractal characteristics[24–25], its structural features can be described and reconstructed using the Hurst index H[26]. However, when using only H to reconstruct the joint, the amplitude of the joint surface height lacks a quantitative description.

Roughness controls the joint geometry, and it has an important impact on the volume distribution of rock blocks. Simplifying the joint surface into a smooth and planar surface makes the joint strength of the rock mass (the total area of joint surface per unit volume of the rock mass) less than the actual case. This in turn leads to the established joint model cannot accurately simulate the real rock mass structure, which reduces the accuracy of the research results. For this reason, this study uses both the Hurst index H and the root mean square of the asperity height to characterize the joint roughness. The non-planar joint disk model is developed for the joint reconstruction, and we study the effects of joint roughness on the rock block quantities and their volume distribution. Finally, the field joint development information is collected by close-up photogrammetry on a highway slope in Dalian city, China. We build the corresponding non-planar joint disk model to demonstrate the correctness of our research conclusions.

2 Methods

2.1 Effects of joint roughness on the joint disk model

Figure 1 shows the schematic plot illustrating the joint roughness. To achieve the real shape of joint rough undulation, the fractal method is adopted to reconstruct the joint roughness. Based on that, a non-planar joint disk model is established to study the impact of the joint roughness on the rock block volumes. The build of a non-planar joint disk model is dominated by four major parameters: occurrence, diameter, density, and joint roughness. The joint roughness is controlled by H and R_q. The workflow for building the non-planar joint disk model is described as follows. First, obtain the joint information of the rock mass, and calculate the joint roughness and the joint occurrence. The joint information is shown by the coordinates of the trace elbow points exposed at the outcrop of the rock mass. Second, the joints of the rock mass are divided into different groups. For each group, the average trace length and the joint density are calculated[27], so that the diameter and density can be derived which are necessary for establishing the joint disk model[28]. Third, according to the joint roughness, reconstruct the individual non-planar joint disk. Fourth, based on the occurrence, diameter, and density, build the non-planar joint disk model that can represent the rock mass.

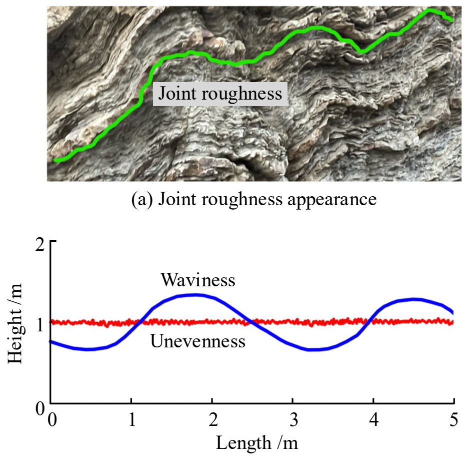


Fig. 1 Schematic diagram of joint roughness

The non-planar joint disk model considers the roughness of the joints and represents the joint surfaces as fractal surfaces. In this study, we use the surface reconstruction method proposed by Candela et al.[26] to build the joint surface disk and adjust the height of the disk to the specified values using Eq. (1). A single non-planar joint disk is generated after its boundary cut by the disk. And this process is repeated according to the parameters of each joint group until the non-planar joint disk model can be built. By using this method, the height of the profile line of the joint follows a normal distribution.

$$R_q = \sqrt{\frac{1}{L}\int_0^L z^2 \mathrm{d}z} \quad (1)$$

where L is the length of the trace; z is the distance between the points on the trace and the averaged trace.

Figure 2 shows the non-planar joint model with highlighting the geometry and the 2D profile of a single joint. The joint model is constructed as a cube with a side length of L. The profile lines can be obtained by cutting the joint using any cross-section normal to the joint surface. The root mean square of the profile line height determines the wavy amplitude of the height of the line. The Hurst index H that describes the fractal scale, controls the irregularity of the fluctuation of the profile line. They both influence the shape of the joint roughness waviness. The joint surfaces simulated by using the same R_q and H are not the same, but they share similar roughness waviness and similar height distributions. The height z of the points on the joint profile lines follows a normal distribution, and the probability density is

$$f(z)=\frac{1}{\sqrt{2\pi}R_q}\exp(-\frac{(z-\mu)^2}{2{R_q}^2}) \quad (2)$$

where z is the height of the point on the joint profile, μ is height of the centerline of the joint profile line. Eq.(2) can be written as $z \sim N(\mu, {R_q}^2)$.

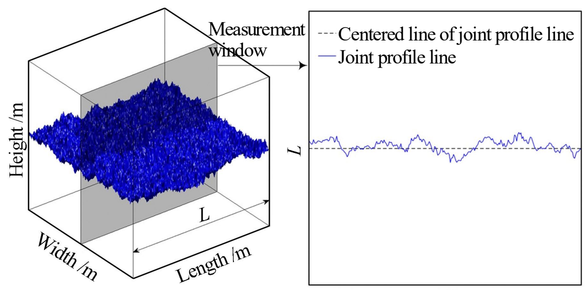


Fig. 2 Geometry and the 2D profile of a single joint

Suppose that J_1 and J_2 are two identical joints parallel to each other, and their profile lines z_1 and z_2 obey $N(\mu_1, {R_q}^2)$ and $N(\mu_2, {R_q}^2)$, respectively. Since the linear combination of normally distributed variables also follows a normal distribution, the length of the core segment between the two joints obeys:

$$z_2 - z_1 \sim N\left(\mu_2-\mu_1, 2{R_q}^2\right) \quad (3)$$

Figure 3 shows the profile lines of J_1 and J_2 and the length of the core segment between them, where the centerlines of joints J_1 and J_2 are spaced with S. Due to the effects of joint roughness, the amplitude of joint waviness increases with the increase of R_q, and there can be the possibility of contact between joints J_1 and J_2. When R_q increases to a certain extent, the intersection between the two joints leads to the cut. The condition of no cut between joints J_1 and J_2 is that the length of the core segment between the two joints is always greater than zero. According to the 3σ principle of normal distribution: the probability of a normally distributed random variable z falling outside the range $(\mu-3\sigma, \mu+3\sigma)$ is less than 3‰, and thus the interval $(\mu-3\sigma, \mu+3\sigma)$ can be approximately regarded as the actual possible range of the random variable z. Therefore, to have the length of the core segment greater than 0 at any position between the two joints, it needs to satisfy:

$$(\mu_2-\mu_1)-3\sigma = S-3\left(\sqrt{2}R_q\right) \geqslant 0 \quad (4)$$

where S is the spacing between the centerlines of the joints J_1 and J_2. Therefore, the threshold for cutting inside the parallel joint set is

$$R_q=\frac{\sqrt{2}S}{6} \quad (5)$$

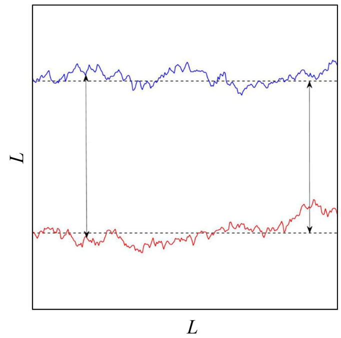
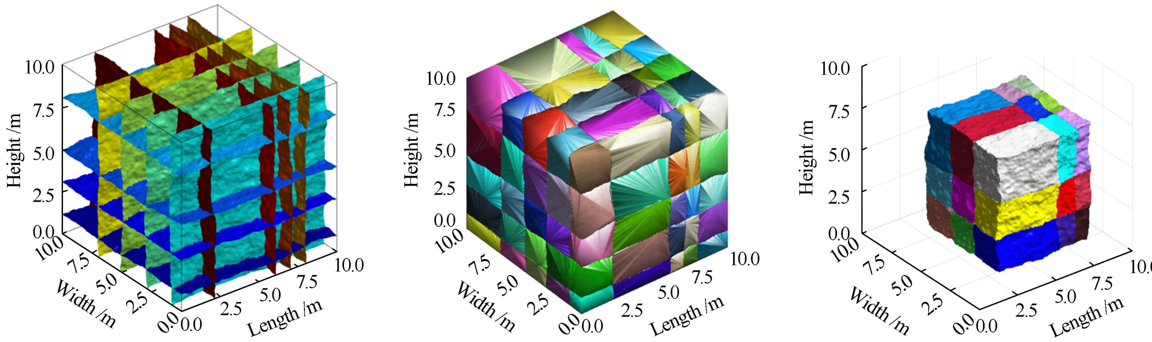


Fig. 3 Length of an intact rock core piece between the joint profiles J_1 and J_2

It is worth noting that normal distributions of random variables are defined within infinite intervals. The range of R_q described in Eq.(4) is the confidence interval at a certain confidence level derived from a probability perspective. The threshold of R_q given by Eq.(5) is only a reference for the corresponding critical values.

2.2 Block volume calculation based on the non-planar joint disk model

This study is a reconstruction method based on the non-planar joint disk model. We use geometric Boolean operations and write the MATLAB programs to simulate the cut on the joint model. With the program, the number and volume of the rock blocks resulted by the cut can be directly obtained, as well as other parameters. Figure 4 shows an example that how a joint model produces the rock blocks through numerical simulation. Figure 4(a) shows a model with three random and orthogonal sets of non-planar joint disks. Figure 4(b) shows all the resultant rock blocks given by cutting the rock mass using the joint model. When using discrete fracture network to study the rock block volumes, it is necessary to exclude the rock blocks generated by the inclusion of hypothetical surfaces, so that to ensure that the geometric features of the rock block are not affected by the model boundaries[9, 12, 29]. This is especially important for the rock blocks cut by the non-planar joint disk models. When using the program to simulate the model cut and to calculate the block volumes, the rock blocks can be divided into two types according to the different outer surfaces. Type 1 is the non-planar joint rock block formed entirely by non-planar joint surfaces. Type 2 is the rock blocks formed by both the hypothetical surfaces (rock mass boundaries) and non-planar joint surfaces. In order to study the effects of roughness on rock blocks, we adjust the corresponding program to exclude those rock blocks involved with any hypothetical surfaces during the block volume calculation, and consider only the non-planar joint blocks as our research objects. For all the rock blocks shown in Fig.4(b), we exclude those rock blocks if any model boundary surfaces have been involved during the cut, and obtain the non-planar joint rock blocks as shown in Fig. 4(c).



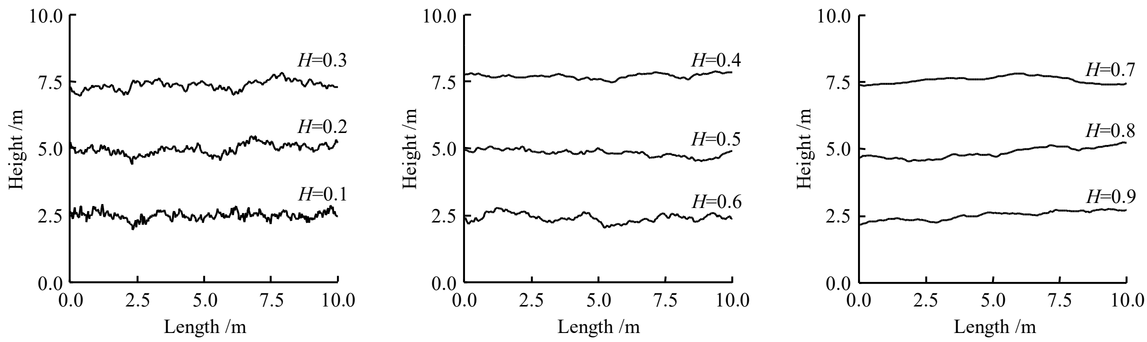
(a) Non-planar joint disc model (b) All the rock blocks (c) Rock blocks only cut by non-planar discs

Fig. 4 The rock blocks cut by a non-planar joint disc model

3 Effects of joint roughness on rock blocks

The rock blocks in the rock mass are usually formed by the cutting of joints with different orientations. This study focuses on the effects of individual geometric features of joint roughness on the volume and quantity of rock blocks and aims to obtain general conclusions. This study considers the simplest yet the most common joint development model in the rock mass, and assumes the three groups of joints development are equally spaced and orthogonal to each other inside the rock mass, where we study the effects of joint roughness on the volume and quantity of rock blocks. The numeric model is simulated by a cube with a side length of 10 m. The joint spacing is 1 m, and the diameter of the joint disks are assumed to be infinite.

According to Eq.(5), the range of R_q is $R_q <$ 0.23 m where cut does not occur inside the same joint set. That is, the threshold for whether a cut occurs inside the same joint set is 0.23 m, which is written as $R_{qs} = 0.23$ m. The experiment sets R_q with the range of 0–0.4 m and with the interval of 0.04 m. Five groups of values are selected and distributed on each side of the critical value R_{qs}, R_{qs} value denotes whether the cutting would occur inside the same joint set. The value range of H is $0 < H < 1$[26]. Figure 5 shows the variation of a single joint roughness with respect to the H value (taking 0.20 m as an example). The joint roughness increases with the decrease of H. When H >0.7, the joints are too smooth; when H <0.3, the joints are too coarse. In this experiment, the range of H is set to 0.3–0.7. Using 0.1 as the interval, we set 5 different values for the parameter H. With all the possible combinations of H and R_q, a total of 50 joint models are generated, with the specific parameters listed in Table 1. To minimize the effects of randomness on numerical simulation, each parameter combination is repeated 10 times to produce the joint models, and we use the averaged results for statistical analysis.



(a) H=0.1, 0.2, 0.3 (b) H=0.4, 0.5, 0.6 (c) H=0.7, 0.8, 0.9

Fig. 5 Variation of the single joint roughness with H (R_q=0.20 m)

Table 1 Parameters of the equally-spaced, non-planar joint disc model

Joint group	Joint spacing /m	Range of H	Range of R_q /m	Dip angle /(°)	Dip direction /(°)
1	1	[0.3, 0.7]	[0.04, 0.40]	0	0
2	1	[0.3, 0.7]	[0.04, 0.40]	90	0
3	1	[0.3, 0.7]	[0.04, 0.40]	90	90

3.1 Effects on the block quantity and volume

Figure 6 shows an example of the equidistant non-planar joint disk model. By cutting the model at the measurement window, the two-dimensional geometric features of the joints and the blocks can be observed. Figure 7 shows the 2D profiles of the model at the measurement windows with respect to different combinations of H and R_q. The model is cut so as to calculate the quantity and volume of the rock blocks in the joint model. The block volume is analyzed statistically, calculating the probability density histogram and the cumulative density function of the block volumes (shown in Fig.8). To minimize the effects of randomness on numerical simulation, each model is generated 10 times repeatedly, and the averaged block quantity is used as the final calculation result, as shown in Table 2. Figure 9 shows the variation of the rock block quantity inside the model. Considering a planar joint model, a total of 1 000 blocks are generated first. After excluding those blocks that formed with hypothetical surfaces involved, there are in total 512 cubic blocks generated with the volume of 1 m^3 each.

R_q determines the amplitude of the height of the profile line, and H controls its irregularity. They both affect the waviness and the appearance of the joint roughness. The larger the R_q and the smaller the H, the greater the roughness of the joint, the more complex the geometry of the profile line, and therefore the more complex the shape of the rock blocks formed by it (as shown in Fig.7). The block quantity generally increases with the increase of roughness (as shown in Fig. 9 and Table 2). The variation of block quantity can be divided into three stages with respect to the roughness, including a stable stage, a slow growth stage, and a rapid growth stage.

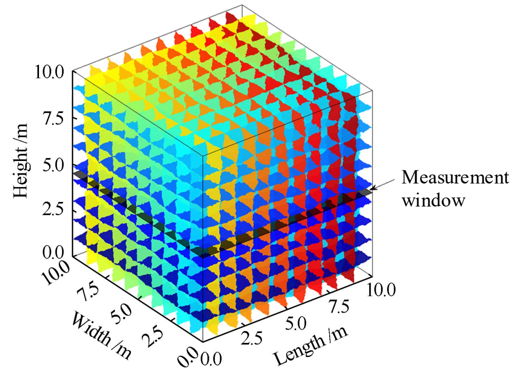


Fig. 6 An example of the equally-spaced, non-planar joint disc model (H=0.5, R_q=0.04 m)

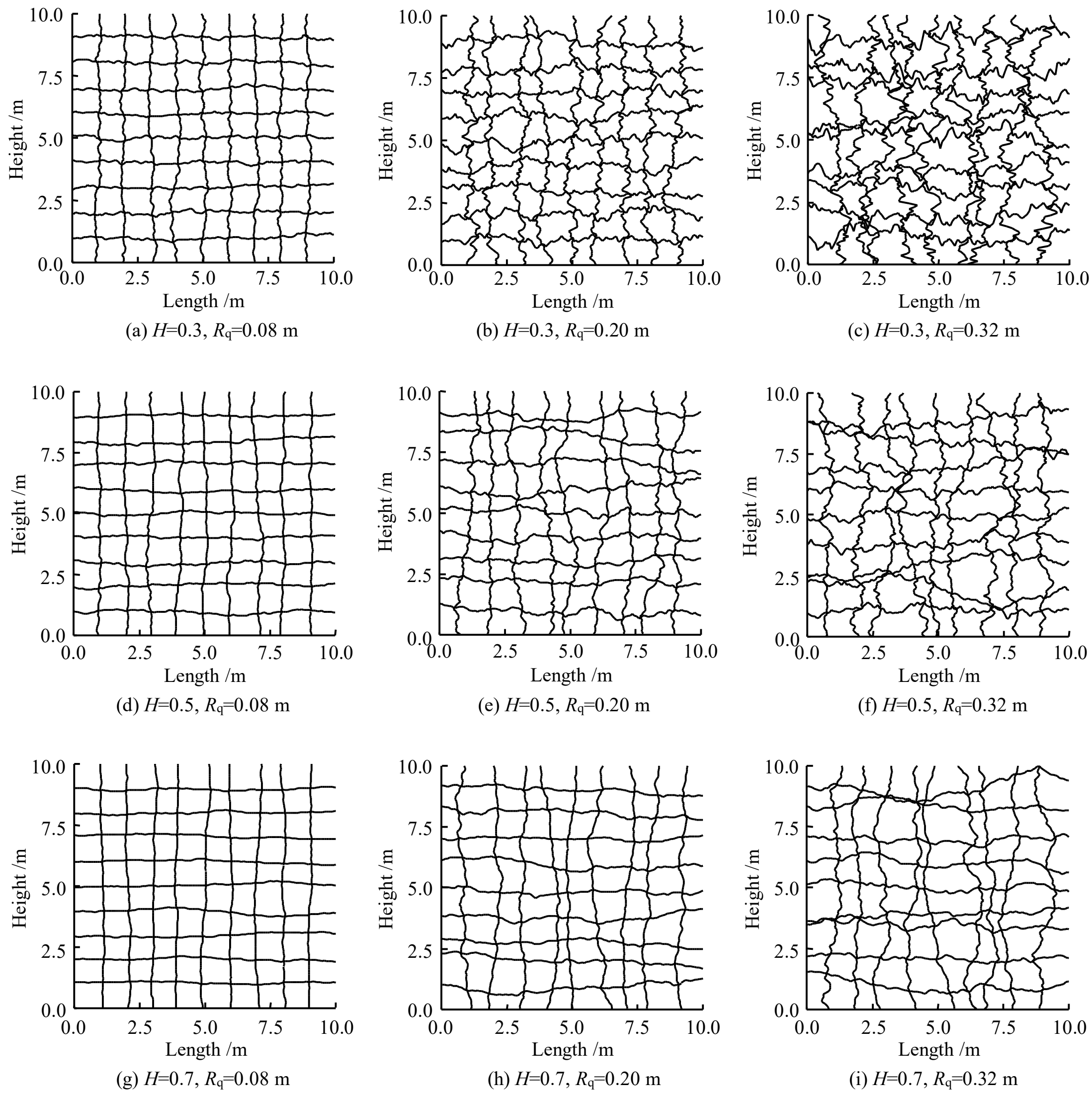


Fig. 7 2D profiles of the models with different Hs and R_qs

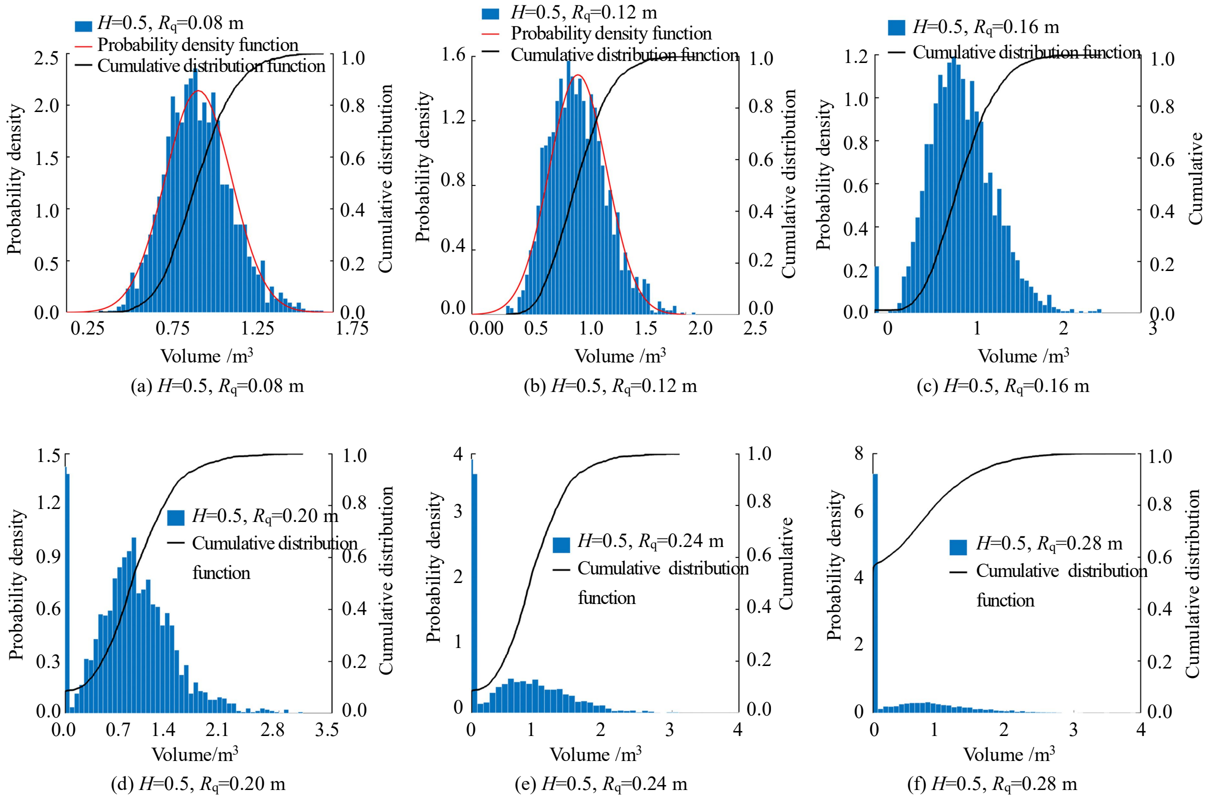


Fig. 8 Probability density histogram and cumulative distribution function of the rock block volume

Table 2 Calculation result of rock block quantity

R_q /m	Rock block quantity				
	H=0.3	H=0.4	H=0.5	H=0.6	H=0.7
0.04	512	512	512	512	512
0.08	512	512	512	512	512
0.12	587	519	512	512	512
0.16	1 048	574	520	512	512
0.20	2 087	831	570	537	515
0.24	3 717	1 402	819	544	522
0.28	6 474	2 728	1 200	647	632
0.32	10 352	4 529	1 922	1 084	837
0.36	15 217	6 242	2 901	1 593	946
0.40	20 582	10 263	4 268	1 949	1 236

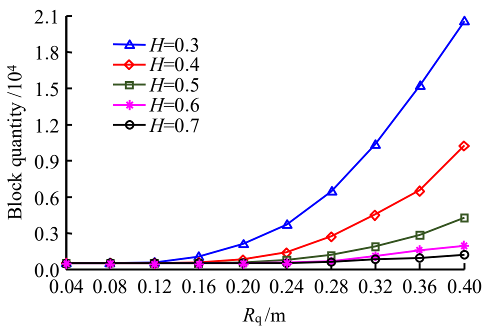


Fig. 9 Rock block quantity with different *H*s and R_qs

In the stable stage, the rock block quantity does not change with the increase of roughness. The block quantity generated by the non-planar model is the same as that of the planar joint model. Let R_{q0} denote the value of R_q at the end of this stage. The value of R_{q0} is related to *H*. As shown in Table 2, when *H*=0.3, R_{q0} = =0.08 m; when *H* = 0.5, R_{q0} = 0.12 m. The model profiles at this stage are shown in Figs. 7(a), 7(d), 7(g). Figures 8(a) and 8(b) show the probability density histogram and the cumulative distribution function of the block volume. During this time, the waviness of the joint roughness is relatively small, and there is no cutting inside the same joint set. The distribution of the block volume in the model appears to follow a normal distribution.

In the slow growth stage, $R_{q0} < R_q < R_{qs}$, the rock block quantity increases due to the mutual cutting among different joint sets. The block quantity increases with the increase of roughness. The model profiles at this stage are shown in Figs. 7(b), 7(e) and 7(h). Figures 8(c) and 8(d) show the probability density histogram and the cumulative distribution function of the block volume. At this stage, no cutting appears between the parallel joints within the same set in the model. The chance of cutting between different joint sets increases, resulting in the blocks with small volumes. The small-volume rock blocks are shown by the concentrated bins in the histogram.

In the rapid growth stage, $R_q > R_{qs}$. At this time, the cut occurs within the same joint set, and a complex network with intersections has been formed by the joints in the model. The rock block quantity increases rapidly with the increase of roughness. The model profiles at this stage are shown in Figs. 7(c), 7(f) and 7(i). Figures 8(e) and 8(f) show the probability density histogram and the cumulative distribution function of the block volume. During this stage, massive small volume rock blocks have been generated with the increase of roughness.

3.2 Effects on the block volume distribution

Figure 10 shows the cumulative distribution functions of the block volumes with different R_q values when H = 0.5. We record the block volumes corresponding to different combinations of H and R_q, and analyze the effects of joint roughness on the block volume distributions. Table 3 shows the variations of V_{mean} (block volume mean) and V_{mid} (block volume median) with the joint roughness. When the joints are modelled as planar surface, there are a total of 512 cubes generated with the volume of 1 m^3, where V_{mean} and V_{mid} are both 1 m^3, correspondingly.

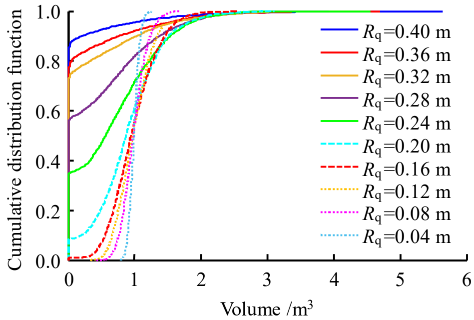


Fig. 10 Variation of the cumulative distribution function (with *H*=0.5)

Table 3 Calculation result of V_{mean} and V_{mid}

R_q	V_{mean} /m^3					V_{mid} /m^3				
/m	H=0.3	H=0.4	H=0.5	H=0.6	H=0.7	H=0.3	H=0.4	H=0.5	H=0.6	H=0.7
0.04	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.08	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.98	0.99	0.99
0.12	0.87	0.98	1.00	0.99	1.00	0.95	0.97	0.98	0.98	0.98
0.16	0.49	0.91	0.97	0.98	1.00	0.18	0.90	0.93	0.97	0.98
0.20	0.24	0.62	0.91	0.95	0.99	2.50×10^{-5}	0.62	0.89	0.92	0.93
0.24	0.14	0.37	0.63	0.94	0.98	2.24×10^{-5}	3.00×10^{-4}	0.60	0.84	0.88
0.28	0.08	0.19	0.43	0.75	0.82	2.02×10^{-5}	3.47×10^{-5}	1.30×10^{-3}	0.61	0.69
0.32	0.05	0.11	0.26	0.47	0.60	1.72×10^{-5}	2.30×10^{-5}	8.75×10^{-5}	0.02	0.29
0.36	0.03	0.08	0.17	0.31	0.50	1.67×10^{-5}	2.36×10^{-5}	4.47×10^{-5}	7.10×10^{-4}	0.13
0.40	0.02	0.04	0.12	0.26	0.40	1.60×10^{-5}	2.67×10^{-5}	3.84×10^{-5}	2.58×10^{-4}	0.01

With the increase of roughness, the proportion of small volume blocks increases, and the distribution of block volume shows more dispersion (as shown in Fig.10). The roughness parameters R_q and H show significant effects on V_{mean} and V_{mid}, and the effects are similar. Both V_{mean} and V_{mid} decrease with the increase of roughness, and their values are both smaller than those when the joints are modelled as planar surface (as shown in Table 3). In fact, V_{mean} is a function of the block quantity, and it is negatively correlated with the number of blocks in the model. At the same time, V_{mid} describes the volume distribution of the newly generated blocks to some extent, since the new ones are massively small volume blocks.The analysis above shows that joint roughness has a significant impact on the block quantity and block volume distribution. It is mainly shown in the following two perspectives. First, it increases the number of rock blocks. The joint area increases with the increase of roughness. The cutting probability between joints increases correspondingly, which leads to the increase of the number of the generated rock blocks. Second, joint roughness changes the resultant block volumes and influences the volume distributions. For a rock mass with a certain volume, the block volumes must decrease with the increase of the number of blocks.

4 Case study

The study slope is adjacent to Fengcai Road and facing Longwangtang Reservoir, located in Dalian city, Liaoning province. It is a potential geological hazard area with a risk of rockfall. The slope presents well-developed joints, and the rock mass is blocky and densely distributed. The study area has a length of 28 m and a height of 6 m. We use close-up photogrammetry for joint data acquisition. The 3D point cloud model of the slope is shown in Fig.11.

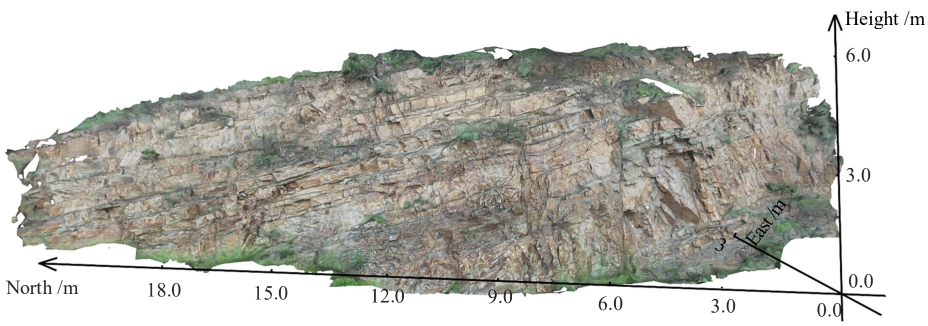
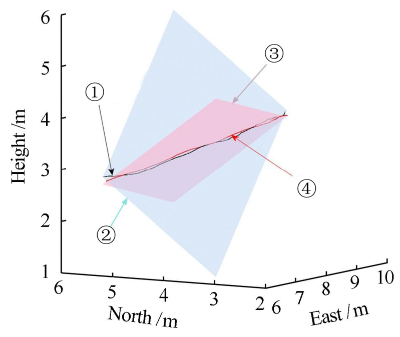


Fig. 11 The 3D textured point cloud model of the studied slope

A total of 1 030 joint traces have been extracted from the 3D point cloud model, each consisting of dozens of inflection points. Figure 12 shows the workflow to obtain the geometric parameters from a joint trace. We use the least-square method to fit the inflection point coordinates to obtain the joint plane, and then calculate the joint orientation according to the normal vector of the plane. We then set a plane normal to the joint plane and project the trace onto the plane. The projected traces on the normal plane are used as the 2D profile lines for the joints. The roughness parameters R_q and H can then be calculated based on the 2D profile lines. After obtaining the geometric parameters, the 1 030 joints are divided into three groups according to the joint attitude. In general, we assume the joint attitude and the trace length follow the Fisher distribution and the lognormal distribution, respectively. We calculate the parameters of the Fisher distribution. We use the circular measurement window method[27] to estimate the average trace length and joint density of each joint group, and then derive the diameter and the density of the joint disk of each group[28]. The coordinates of the joint disk central points are assumed to follow the Poisson distribution. Table 4 shows the parameters of the joint disk models derived for the study area.



①–A trace that extracted from the 3D model; ②–Joint surface fitted on the trace; ③–Projection surface normal to the fitted joint surface; ④–Projected line on the normal plane.

Fig. 12 A trace method to obtain geometric parameters for a single joint

Table 4 Case study parameters used for the non-planar joint disc model of the rock mass

Joint group	Joint bulk density /m^{-3}	Attitude (Fisher distribution)			Diameter (Log-normal distribution)		R_q/m		H	
		Dip direction /(°)	Dip angle /(°)	K_F	Mean /m	Variance /m^2	Range	Mean	Range	Mean
1	0.25	281.0	21.0	10.3	1.82	9.19	[0.00, 0.25]	0.05	[0.41, 1.00)	0.64
2	1.68	194.5	71.9	9.2	0.50	0.27	[0.00, 0.11]	0.03	[0.39, 1.00)	0.63
3	0.73	108.7	65.3	7.4	0.54	0.3	[0.01, 0.14]	0.03	[0.43, 1.00)	0.64

Three types of joint disc models have been built by varying the parameters R_q and H. Table 5 lists the specific parameters. Type 1 is the planar joint disk model where the R_q of the joints equal to 0 m. This model does not consider the effect of roughness and assumes the joint disks are planes. Type 2 and Type 3 are non-planar joint disk models. The R_q and H of Type 2 are the average values of each joint group. Type 2 simulates the regular state of joint roughness in the rock mass. It should be a non-planar joint disk model representing the rock mass in the studied field. In type 3, R_q corresponds to the maximum value, and the H corresponds to the minimum value. Type 3 simulates the limit values of parameters that can be combined, and it is the theoretical limit form of rock joint roughness. We establish the three types of joint disks, cut the rock models, and calculate the resultant block quantities and volume distributions. The results are shown in Table 5. Figure 13 shows an example of a non-planar joint disk model. Figure 14 shows the two-dimensional profiles of the three types of joint models at the measurement window. Figure 15 shows the cumulative distributions of rock block volumes for the three types of models.

According to the calculation results: (i) The joint roughness in model Type 1, 2, and 3 increases in order, and the joints appear to be more complex, accordingly. It results in more and more complex joint intersection networks, as shown in Fig.14. (ii) Inside the rock mass, the small volume blocks prevail, and the proportion of small-volume blocks increases with the increase of joint roughness, as shown in Fig.15. (iii) The quantity of blocks increases with the increase of joint roughness, whereas V_{mean} and V_{mid} decrease with the increase of joint roughness, as shown in Table 5. The case study results are consistent with the simulation results discussed in Section 3, which demonstrates the effects of roughness on the rock block volumes. This study has used the fractal method to characterize and reconstruct the joint roughness, and has established the non-planar joint disk models from the geometric perspective, so that the research on the roughness effects can be achieved. However, considering real-world rock structure, the geometry of joint roughness is affected by mechanical mechanisms, where the roughness of adjacent joint surfaces can merge and interfere with each other. Therefore, the problems that need to be studied in the future work includes, for example, how to take account of the interaction between real-world rock joints when building the non-planar joint disk model; and how to improve the algorithms to make more accurate simulations on the non-planar joints and joint network reconstruction, etc.

Table 5 Calculation results of the studied slope

Model	R_q /m			H			Rock block quantity	V_{mean} /m³	V_{mid} /m³
	Joint group 1	Joint group 2	Joint group 3	Joint group 1	Joint group 2	Joint group 3			
1	0.00	0.00	0.00	—	—	—	11 440	8.68×10^{-3}	3.62×10^{-4}
2	0.05	0.03	0.03	0.64	0.63	0.64	17 095	5.82×10^{-3}	1.07×10^{-4}
3	0.25	0.11	0.14	0.41	0.39	0.43	102 561	7.29×10^{-4}	2.38×10^{-6}

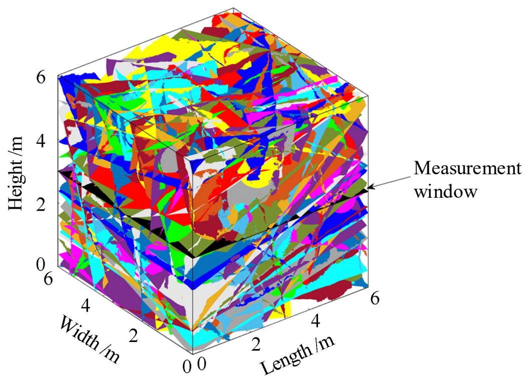


Fig. 13 An example of the non-planar joint disc model (Type II)

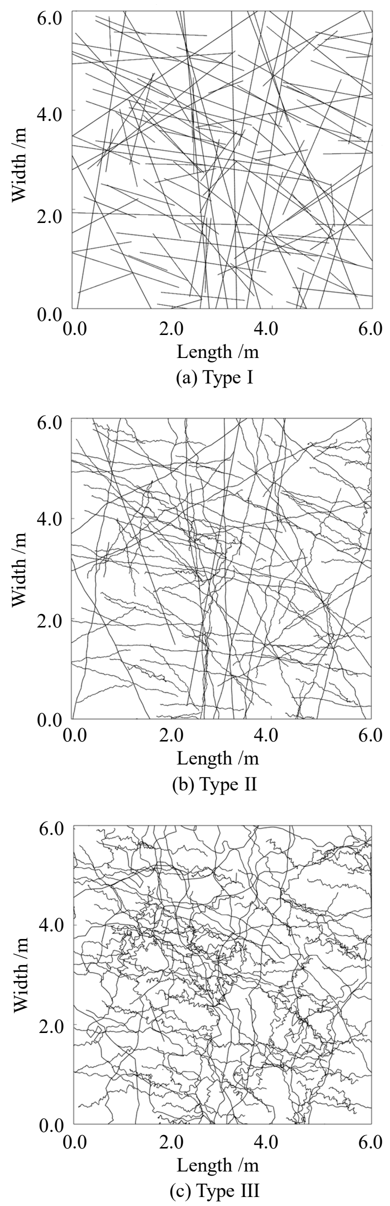


Fig. 14 2D profiles of the three models

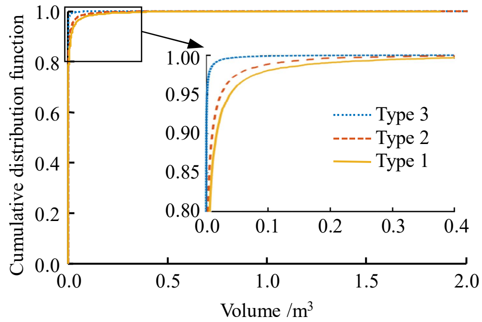


Fig. 15 Cumulative distribution functions of the rock block volume of the three types of models

5 Conclusion

Based on the non-planar joint disk model, we study the effects of roughness on the rock block quantity and the block volume distribution. We demonstrate the results by a case study in the field. The following conclusions can be drawn.

(1) Joint roughness is determined by both R_q and H, and it increases with the increase of R_q and with the decrease of H. Joint appearance and joint network become more complex with the increase of joint roughness.

(2) The number of rock blocks is overall positively correlated with the joint roughness, that is, it increases with the increase of R_q and decreases with the increase of H.

(3) Joint roughness affects the block volume distribution. With the increase of roughness, the proportion of small-volume blocks in the rock mass increases. As a result, the mean and median of the block volume decrease, correspondingly.

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