RQD calculation method based on 3D rock discontinuity network simulation in the dam foundation of Baihetan hydropower station

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Abstract. The original rock quality designation (RQD) index has several limitations, such as one-dimensional (1D) direction and a single threshold. For these reasons, a novel RQD calculation method is proposed by using 3D discontinuity network simulation. In this method, a 3D discontinuity network model (3D-DNM) of the rock mass is generated by Monte–Carlo analogy procedure, in accordance with the optimal probability models of the rock discontinuity’s geometrical elements. Then, the RQD values at different azimuth on the three orthogonal planes of the 3D-DNM can be analyzed statistically. Based on the analysis result, the novel index RQt is put forward. In this index, the threshold corresponding to the maximum standard deviation of the RQD is defined as the optimal threshold. The RQD with an optimal threshold has the greatest capacity to reflect the heterogeneity and anisotropy of rock mass. To illustrate the effectiveness of the proposed method, we apply it on the foundation rock mass of Baihetan hydropower station on Jinsha River. Finally, the optimal threshold is determined as 0.6 m, and the quality and anisotropy of the dam foundation rock mass are fully demonstrated by the generalized RQD0.6.

Keywords: Rock mechanics; Dam foundation; Network simulation; RQD; Anisotropy

1. Introduction

Rock quality designation (RQD) is used to measure the quality of the rock core obtained from a borehole. RQD signifies the degree of jointing or fracture in a rock mass measured in percentage, which was proposed by Deere [1]. In addition, RQD is widely used in rock mass quality evaluation in various engineering fields, such as underground engineering, slope engineering, and foundation engineering, due to its distinct definition and simple application. However, in engineering practice, RQD mainly has the following limitations: (1) One-dimensional (1D) direction. Rock mass is a 3D geological body with evident anisotropy and non-continuity characteristics. However, RQD only expresses the statistical results of borehole cores in 1D direction and cannot consider the overall structural characteristics of rock mass. For example, in sedimentary rock mass, the RQD is different when the borehole direction is parallel or vertical to strata. (2) Single-threshold value. In the original definition of RQD, the threshold of core length is 10 cm, but the rationality of this threshold has not
been fully demonstrated. If all core lengths of different rock mass are greater than 10 cm, then all RQD values are 100%. The further classification of rock mass quality using a single-threshold value in this situation is impossible.

To overcome the above limitations, Palmstrom [2-3] and Sen and Eissa [4] introduced the concept of volume RQD value and gave the theoretical formula. Researchers [5-9] proposed RQD in different directions by a 2D discontinuity network simulation method. Zhang et al. [10-11] studied the optimal arrangement of survey lines and their size and space effects.

In this paper, the foundation rock mass of Baihetan hydropower station on Jinsha River is selected as the research object, and the precise measurement and statistics on discontinuity parameters is conducted to obtain the optimal probability model of each geometric element of each set of discontinuity. Then, the Monte–Carlo method and 3D visualization technology are used to carry out random simulations to generate a 3D discontinuity network model (3D-DNM). The RQD values of 3 orthogonal planes in different directions of the 3D-DNM are statistically analyzed. Thus, the anisotropy of the rock mass is fully considered. On the other hand, a calculation method of optimal threshold is proposed based on the quantitative analysis of the influence of different thresholds on the RQD value. Finally, the RQD values distribution characteristics of the three orthogonal planes of the 3D-DNM under the optimal threshold are analyzed.

2. 3D-DNM

2.1. Grouping of discontinuities

The rock mass of No. 04 bench on the left bank dam foundation of Baihetan hydropower station is selected as the typical research object. The lithology of the dam foundation rock mass is the Emeishan basalt of the Upper Permian Formation, and Figure 1 shows the distribution of discontinuities.

![Figure 1. Discontinuity distribution of No. 04 bench dam foundation rock mass](image)

A statistical analysis is carried out on 202 discontinuous of No. 04 bench, and the discontinuous are grouped into four sets based on the isodensity map of the discontinuous poles. Figure 2 shows the isodensity map of the discontinuous poles. Table 1 presents the grouping parameters of the four sets of dominant discontinuities.
Table 1. Grouping parameters of four sets dominant discontinuities

| Set | Quantity | Range of dip direction | Range of dip angle | Dominant dip direction | Dominant dip angle |
|-----|----------|------------------------|--------------------|------------------------|--------------------|
| 1   | 41       | 35-72                  | 57-86              | 55                     | 72                 |
| 2   | 50       | 85-182                 | 9-50               | 124                    | 27                 |
| 3   | 29       | 123-143; 300-324       | 66-90              | 313                    | 87                 |
| 4   | 19       | 219-261                | 71-86              | 241                    | 79                 |

2.2. Probability models of discontinuity attitude

First, the weighting function method proposed by Kulatilake and Wu [12-13] is used to correct the sampling deviation of discontinuities. According to the combination relationship between the dip direction of discontinuity and strike direction of the measuring window, the weighting function can be calculated by selecting from Formula (1) or Formula (2).

\[
W(\theta, \beta, D, h, w) = [(\cos^2 \theta \sin^2 \beta + \cos^2 \beta)^{1/2} + \frac{\pi D}{4h} \cos \beta \sin \theta + \frac{\pi D}{4w} \cos \theta]^{-1} \tag{1}
\]

\[
W(\theta, \beta, D, h, w) = [(\cos^2 \theta \cos^2 \beta + \sin^2 \beta)^{1/2} + \frac{\pi D}{4h} \sin \beta \sin \theta + \frac{\pi D}{4w} \cos \theta]^{-1} \tag{2}
\]

where \( W \) is the weighting function; \( \theta \) is the dip angle of discontinuity; \( \beta \) is the combination angle of discontinuity and measuring window, determined by dip direction of discontinuity \( \alpha \) and strike direction of the measuring window \( \gamma \); \( D \) is the diameter of discontinuity; \( h \) is the height of the measuring window; \( w \) is the length of the measuring window.
The single-sample K-S goodness-of-fit test (one of the nonparametric test methods) is used to test accurately the assumed probability distribution of the discontinuity attitude (dip angle and direction) after the sampling deviation correction. In general, the main probability distribution forms of the discontinuity attitude are uniform, normal, and lognormal. For each of the above-mentioned probability distribution forms, an accurately test is carried out based on the single-sample K-S goodness-of-fit test method.

An example is the accuracy test of the dip direction probability distribution of the first dominant discontinuity set: for the dip direction data of this discontinuity set after the sampling deviation correction, the bilateral asymptotic significance of the uniform distribution = 0.107 > 0.05. Thus the probability distribution hypothesis is accepted. The bilateral asymptotic significance of the normal distribution = 0.412 > 0.05. Thus, the probability distribution hypothesis is also accepted. The bilateral asymptotic significance of lognormal distribution = 0.153 > 0.05. Thus, the probability distribution hypothesis is also accepted. However, among these forms of probability distribution, the bilateral asymptotic significance of the normal distribution is greater than that of the other two. Therefore, the optimal probability distribution is selected as the normal distribution, with a mean value of 55.330° and a standard deviation of 10.740°.

In accordance with the above analysis procedure, the probability model and corresponding parameters of discontinuity attitude (dip angle and direction) of each set can be determined (Table 2).

**Table 2. Probability model and corresponding parameters of discontinuity attitude**

| Set | Dip direction | Dip angle |
|-----|---------------|-----------|
|     | Model | Expectation | Standard deviation | Model | Expectation | Standard deviation |
| 1   | Normal | 55.330 | 10.740 | Normal | 72.200 | 8.230 |
| 2   | Lognormal | 4.790 | 0.230 | Normal | 29.810 | 12.960 |
| 3   | Normal | 130.230 | 6.490 | Lognormal | 4.440 | 0.110 |
| 4   | Normal | 241.470 | 12.280 | Normal | 79.530 | 4.390 |

Note: The expectation and standard deviation of lognormal distribution equal to the expectation and standard deviation of natural logarithm, respectively.

2.3. Probability models of discontinuity diameter

Kulatilake and Wu [12-13] applied the point estimation method to calculate the average trace length \( \bar{l} \) of discontinuity; the formula is as follows:

\[
\bar{l} = \frac{wh(1 + R_0 - R_2)}{(1 - R_0 + R_2)(wB + hA)}
\]
\[ A = \int_0^{\alpha_1} \int_0^{\theta_1} \cos \theta_\alpha f(\theta, \alpha) d\theta d\alpha \]  
\[ B = \int_0^{\alpha_1} \int_0^{\theta_1} \sin \theta_\alpha f(\theta, \alpha) d\theta d\alpha \]  

where \( R_0 \) is the ratio of discontinuities with both ends censored in the measuring window; \( R_2 \) is the ratio of discontinuities with both ends observed in the measuring window; \( \theta_\alpha \) is the intersection angle of discontinuity and the measurement window.

According to studies by Wu [14], the probability distribution of the trace length of discontinuities mostly follows a negative exponential distribution. On this basis, the relationship between the average diameter \( \bar{D} \) and the average trace length of discontinuity is given by the following:

\[ \bar{D} = \int_0^{\infty} D f_D(D) dD = \int_0^{\infty} D \frac{\mu}{2} e^{-\frac{D}{\mu}} dD = \frac{4\bar{l}}{\pi} \]  

where \( D \) is the diameter of discontinuity; \( \mu \) is the center point density of discontinuity trace, \( \mu = 1/\bar{l} \).

The probability model parameters of discontinuity diameters of each set can be determined by Formula 6 (Table 3).

2.4. Volume density calculation of discontinuity

According to the hypothesis of the circular disks model, the relationship between the linear density \( \lambda_d' \) and volume density \( \lambda_v \) of discontinuity is defined as follows:

\[ \lambda_d' = \frac{\pi \lambda_v}{2} \int_0^{\infty} R f_D(D) dD dR \]  

Given the basic assumption that the trace length of discontinuity follows a negative exponential distribution, the expression of volume density of discontinuity can be further derived as follows:

\[ \lambda_v = \frac{2\lambda_d'}{\pi \bar{D}^2} = \frac{\pi \lambda_d'}{8\bar{l}^2} \]  

Volume density of each set can be determined by using Formula 8. The result is shown in Table 3.
Table 3. Probability model and corresponding parameters of discontinuity diameter and volume density

| Set | Diameter Model | Expectation/m | Linear density / (item·m$^{-1}$) | Volume density / (item·m$^{-3}$) |
|-----|----------------|---------------|----------------------------------|---------------------------------|
| 1   | Negative exponent | 0.772         | 0.711                            | 0.750                            |
| 2   | Negative exponent | 3.394         | 25.995                           | 1.432                            |
| 3   | Negative exponent | 0.797         | 1.700                            | 1.682                            |
| 4   | Negative exponent | 1.049         | 0.346                            | 0.202                            |

2.5. 3D-DNM of the No. 04 bench

Based on the probability models and corresponding parameters of each geometric element of the four sets of discontinuity shown in Tables 2 and 3, the Monte–Carlo method is used to conduct random simulation. A total of 2082 discontinuities are generated in the data generation area with a size of 8×8×8 m$^3$. Then, a data application area is the core data generation area with a size of 5×5×5 m$^3$ (Figure 3).

3. Definition of Generalized RQDt and Its Spatial Effect

The threshold of original RQD is 10 cm, which lacks a rigorous theory and effective argumentation. Therefore, the concept of RQD is improved, and a novel index RQD$_t$ is proposed. The threshold of RQD$_i$ is the variable $t$, instead of a fixed value of 10 cm. Therefore, the core length is included in the RQD calculation when it is greater than $t$. The novel index RQD$_t$ is defined as follows:

$$RQD_t = \frac{1}{L} \sum_{i=1}^{n} x_i^* \times 100\%$$  \hspace{1cm} (9)

where $RQD_t$ is the RQD with threshold $t$; $x_i^*$ is the core length of the No.i segment along the survey line direction which is greater than the threshold $t$; $L$ is the length of the whole survey line.
The spatial effect of the $RQD_t$ of No. 04 bench rock mass is further studied, and three orthogonal planes of the 3D-DNM are selected as the research objects (Figure 4). Then, values of $t=0.1, 0.3, 0.5, 0.7, 0.9$ m as the threshold of the generalized $RQD_t$ are used to calculate the $RQD_t$ values of the three orthogonal planes with spatial orientation, and the results are shown in Figure 5.

![Figure 4. Discontinuity distribution of No. 04 bench dam foundation rock mass](image)

![Figure 5. Discontinuity distribution of No. 04 bench dam foundation rock mass](image)

The results in Figure 5 indicate that $RQD_t$ varies greatly in different orthogonal planes and directions. Thus, the distribution of discontinuities and the integrity of the rock mass are notably anisotropic. This will inevitably lead to large differences in the physical and mechanical properties of the rock mass in different directions. Therefore, the spatial effect of $RQD_t$ is very evident, and the heterogeneity and anisotropy of the rock mass are fully demonstrated.

When $t=0.1$, the $RQD_t$ degenerates to the original $RQD$, the distribution range of the $RQD$ is 0.828 to 0.963 on the XOZ plane, 0.836 to 0.963 on the YOZ plane, and 0.834 to 0.964 on the XOY plane. The results show that the No. 04 bench dam foundation rock mass is relatively integral, and the quality of the rock mass is relatively good. However, the results also show that the original $RQD$ value has relatively small changes in different directions, and the rose diagram is generally smooth. Thus, the accurate reflection of the distribution of rock mass discontinuity is difficult. With the gradual increase in the threshold $t$ value, the mean value of $RQD_t$ shows a gradually decreasing trend, but the $RQD_t$ changes substantially in different directions. Therefore, the capacity to reflect the anisotropy of the
distribution of rock mass discontinuity gradually increases. With the further increase in the t value, \( RQD_t \) further decreases, and the changes in different directions are also reduced. In general, with the change in threshold t value from large to small, the capacity of \( RQD_t \) to reflect the anisotropy of rock mass increases first and then decreases.

4. Optimum Threshold of \( RQD_t \)

The above analysis shows that at a specific threshold t, the \( RQD_t \) has the greatest capacity to reflect the heterogeneity and anisotropy of the rock mass. This specific threshold t is defined as the optimal threshold.

To obtain the optimal threshold t of No. 04 bench rock mass, we set the threshold values to 0.1, 0.2, ..., 0.9. Then, the mean and standard deviation of the \( RQD_t \) in different directions of the three orthogonal planes are statistically analyzed. Table 4 shows the statistical results.

| Statistical index       | Thresholds /m | 0.1  | 0.2  | 0.3  | 0.4  | 0.5  | 0.6  | 0.7  | 0.8  | 0.9  |
|-------------------------|---------------|------|------|------|------|------|------|------|------|------|
| Mean                    |               | 90.4 | 75.0 | 57.8 | 43.2 | 31.3 | 20.6 | 13.7 | 8.4  | 5.6  |
| standard deviation      |               | 1.8  | 5.9  | 11.2 | 14.3 | 16.1 | 16.8 | 14.8 | 13.3 | 11.2 |

The statistical results in Table 3 show that the mean value of the \( RQD_t \) gradually decreases with the increase threshold t, and the standard deviation first increases and then decreases. The larger the standard deviation of the \( RQD_t \), the greater the degree of change in different azimuths and the greater the capability to reflect the anisotropy of the distribution of rock mass discontinuity. Given that the standard deviation of the \( RQD_t \) increases first and then decreases, an optimal threshold t exists. Thus, the standard deviation of the \( RQD_t \) reaches the maximum value. According to the statistical results in Table 3, the optimal threshold value of the 3D-DNM of the No. 04 bench rock mass is 0.6 m, and the corresponding maximum standard deviation is 16.8.

Different rock mass corresponds to various optimal thresholds. The research object of this paper is the No. 04 bench dam foundation rock mass on the left bank of Baihetan hydropower station, with the \( RQD_t \) optimal threshold t = 0.6 m. Figure 6 shows the rose diagram of the optimal threshold RQD0.6 on the three orthogonal planes of the 3D-DNM.

Figure 6 reveals that \( RQD_{0.6} \) well reflects the anisotropy of rock mass quality and discontinuity distribution of the No. 04 bench dam foundation rock mass. Overall, the \( RQD_{0.6} \) values of the XOZ and YOZ planes are relatively large, whereas that of the XOY plane is relatively small.
The distribution range of $RQD_{0.6}$ value on the XOZ plane is 0.0%–71.3%, with an average value of 23.4%. The maximum value appears at the azimuth of 30° and 40° and the minimum at the azimuth of 0°, 60°, 70°, and 180°. The distribution range of the $RQD_{0.6}$ value on the YOZ plane is 0.0% to 71.4%, with an average value of 23.5%. The larger value appears at the azimuth of 40° and 60° and the minimum at the azimuth of 120° and 150°. The distribution range of the $RQD_{0.6}$ value on the XOY plane is 0.0% to 31.5%, with an average value of 21.2%. The larger value appears at 20° azimuth and the minimum at 0°, 100° to 120°, 140°, 160°, and 180° azimuth.

The original $RQD$, which has a single value, cannot reflect the heterogeneity of rock mass in all directions. However, the above $RQD_{0.6}$ distinctly and intuitively expresses the heterogeneity and anisotropy of the rock mass in all directions in three dimensions.

5. Conclusion

Rock mass is a 3D geological body with heterogeneity and anisotropy. Therefore, the calculated $RQD$ varies with different azimuths because of the spatial effect. The 1D direction and single-threshold strategies are used in the traditional $RQD$ calculation method, and they fail to show the heterogeneity and anisotropy of rock mass, presenting a significant challenge. A new $RQD$ calculation method is proposed in this paper, and the spatial effects of $RQD$ are analyzed by using the 3D discontinuity network simulation. Finally, the novel index $RQD_t$ is defined based on the analyzed results of the $RQD$ values of different azimuths on the three orthogonal planes of the 3D-DNM.

The mean value of $RQD_t$ decreases with the increase in the threshold $t$. Meanwhile, the standard deviation of the $RQD_t$ first increases and then decreases. The $RQD_t$ with the maximum standard deviation has the largest relative variation range, and it can significantly show the heterogeneity and anisotropy of the rock mass. Therefore, the threshold corresponding to the $RQD_t$ with the maximum standard deviation is defined as the optimal threshold.

To illustrate its effectiveness, we applied the proposed method on the study of No. 04 bench dam foundation rock mass. The determined optimal threshold is 0.6 m. The field data application demonstrates that the method improves the accuracy of the analyzed result of the rock mass structure and quality of the dam foundation using the optimal threshold $RQD_{0.6}$. 
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