Investigation on the influence of non-stationary trend on the shear strength of rock joints

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ABSTRACT: The non-stationary trend of rock joints significantly affects the shear strength of rock joints. Taking the least square fitting plane of a rock joint as a reference plane, two trend direction parameters α and β of the rock joint are proposed to characterize the non-stationary trend of rock joints quantitatively. α is the inclination angle of the rock joint along the shearing direction, and β is the deflection angle of the rock joint perpendicular to the shearing direction. Based on the trend direction parameters, the external normal and tangential stresses are decomposed into the normal and tangential stresses on the reference plane. Consequently, a rock joint shear strength model is established. Next, samples of different sizes are obtained from a large rock joint. Based on the established shear strength model, the shear strengths of the rock joint samples in different sizes under the influence of non-stationary trends are statistically analyzed.

Keywords: Rock mechanics, rock joint, roughness, shear strength, non-stationary trend.

1 INTRODUCTION

The shear strength of the rock joints is one of the most important mechanical parameters for the stability evaluation of engineering rock masses (Barton et al. 2023; Wang et al. 2021, 2023). In actual engineering, it is difficult to directly obtain the shear strength parameters of rock joints through in-situ tests and laboratory tests. Commonly, the rock joint of rock mass is cut into rock joint specimens in the same size, and the shear strength of the rock joint is estimated by evaluating the shear strength of each rock joint specimen (Yong et al. 2019; Kulatilake et al. 2021; Wang et al. 2022). According to the direct shear test method suggested by ISRM (Muralha et al. 2013), the shear region of the rock joint specimen should be guaranteed to be parallel to the shear plane. For rough and undulating rock joints, the least squares fitting plane can be taken as the reference plane of the rock joint (Tatone & Grasselli 2010).

As shown in Figure.1, the dotted line is the least square fitting plane of the rock joint, and i_1~i_5 are the angles between the least square fitting plane and the shear plane of the rock joint specimens. Figure 1 shows that when the reference plane of the rock mass structural plane is parallel to the shear plane, there is an angle between the cut rock joint specimen and the shear plane; that is, there is a non-stationary trend. When evaluating the shear strength of rock joint specimens, due to the non-stationary trend, the normal stress and shear stress acting on the actual shear plane is different from the externally applied stress values. If the existing shear strength formula that did not consider the influence of the non-stationary trend of the rock joint is used to calculate the shear strength of the rock joint specimen, the calculated shear strength will be inconsistent with the actual shear strength, which will eventually affect the accuracy of the shear strength estimation of rock mass.

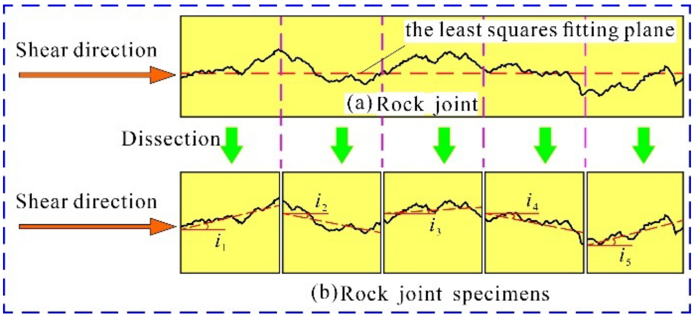

Figure 1. Schematic diagram of trend comparison between rock joint and rock joint specimens.

Some scholars have noticed the influence of the non-stationary trend of rock joints on the evaluation of the shear strength and have conducted some relevant research on it. Kulatilake et al. (1995) took the average inclination angle of the rock joint topography to characterize the non-stationary trend. They obtained several sets of shear strength formulas by fitting the direct shear test data. While the parameters in the formula must be obtained by fitting the test results, and the non-stationary trend direction of the rock joint is calculated based on the two-dimensional section line in the shear direction. Zou et al. (2010) considered the influence of the non-stationary trend direction on the direct shear test results of rock joints based on the spatial stress state of the micro-section elements and the mathematical analysis method. Yong et al. (2013) corrected the theoretical analysis formula of the shear strength parameters of the rock joint according to the relative positional relationship between the shear direction and the trend direction of the rock joint. They verified the correction method of the theoretical analysis through the indoor model test of the smooth rock joints. However, both the research of Zou et al. and Yong et al. were based on the smooth rock joints without considering the effect of roughness on the shear strength of the rock joints. Wang et al. (2019) stabilized the specimens by keeping the plane of the cement mortar parallel to the least squares fitting plane of the structure surface; the influence of the non-stationary trend on its shear strength was eliminated. Therefore, the direct prediction of the shear strength of the rough rock joints with a non-stationary trend still needs further research.

2 JRC-JCS MODEL MODIFICATION

Barton and Choubey (1977) deduced the calculation formula of the JRC-JCS shear strength model through experiments:

$$\tau_{\mathrm{p}} = \sigma_{\mathrm{n}} \tan\left[JRC \cdot \lg\left(\frac{JCS}{\sigma_{\mathrm{n}}}\right) + \varphi_{\mathrm{b}}\right] \tag{1}$$

In the formula: τ_{p} is the shear strength of the rock joint, σ_{n} is the normal stress acting on the rock joint, *JRC* is the roughness coefficient, *JCS* is the joint compressive strength, and φ_{b} is the basic friction angle. Equation (1) is suitable for calculating the shear strength of structural planes without a non-stationary trend. For the rock joint with a non-stationary trend, the applied normal stress and shear stress can be decomposed into its least square fitting plane, and the decomposed shear stress and normal stress are respectively parallel and perpendicular to the least square fitting plane. In this case, the JRC-JCS model can be used to evaluate the shear strength of the rock joint only when the decomposed stress is used for calculation.

The least squares fitting plane of the rock joint specimen is used as the calculation plane to carry out force analysis. As shown in Figure 2, the trend parameters α and β are the parameters that reflect the tilt state of the rock joint. To quantitatively characterize the trend direction parameters, the spatial position relationship between trend direction α and trend direction β and the shear direction is established. The shearing direction is the negative direction of the y-axis, and α is the angle between the least square fitting plane of the rock joint and the positive direction of the y-axis (the angle is positive if it is above the *xoy* plane and negative if it is below the *xoy* plane), β is the angle between the least square fitting plane of the rock joint and the positive direction of the x-axis (the angle is positive if it is above the *xoy* plane, and negative if it is below the *xoy* plane).

The internal normal unit vector and the shear direction unit vector of the least square fitting plane are set to V_0 and V_1 respectively, and the normal external stress and shear stress vectors are, respectively, V_2 and V_3 . θ , γ , ψ , φ are the space angles between vectors V_2 and V_0 , V_0 and V_3 , V_3 and V_1 , V_1 and V_2 respectively, and the above four space angles will be deduced to connect with the trend α and the trend β, and the final calculation formula will also be expressed through α and β.

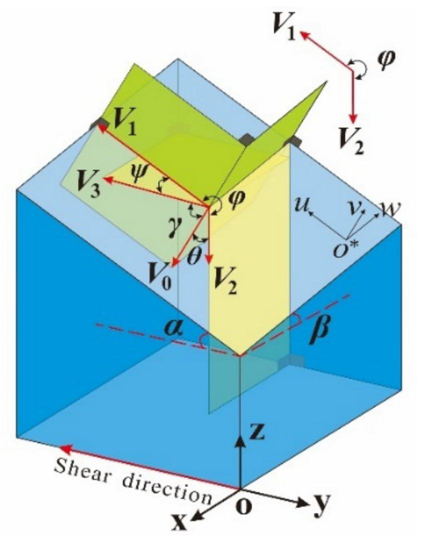

Figure 2. Schematic diagram of the stress relationship on the least squares fitting plane of rock joint with the non-stationary trend.

To facilitate the calculation of the relationship between stresses, the least square fitting plane of the rock joint is used as the datum plane, and the rectangular coordinate system *o*-uwv* is established by rotating the *o-xyz* coordinate system to the datum plane, as shown in Figure 3. Its unit direction vectors are

$$\begin{cases} u = (\sin\alpha\sin\beta, -\cos\alpha, -\sin\alpha\cos\beta) \\ w = (-\cos\beta, 0, -\sin\beta) \\ v = (-\cos\alpha\sin\beta, -\sin\alpha, \cos\alpha\cos\beta) \end{cases} \tag{2}$$

The normal unit vector and the corresponding shear direction unit vector of the least square fitting plane are

$$\begin{cases} V_0 = -v = (\cos\alpha\sin\beta, \sin\alpha, -\cos\alpha\cos\beta) \\ V_1 = u = (\sin\alpha\sin\beta, -\cos\alpha, -\sin\alpha\cos\beta) \end{cases} \tag{3}$$

The direction vectors of the normal stress σ_{n} and the shear stress τ_{n} are respectively set to

$$\begin{cases} V_2 = (0,0,-\sigma_{\mathrm{n}}) \\ V_3 = (0,-\tau_{\mathrm{n}},0) \end{cases} \tag{4}$$

The cosine values of the angle between the direction vector V_2 of the normal stress σ_n and the normal internal vector V_0 of the least square fitting plane and the unit vector V_1 in the shear direction are

$$\begin{cases} \cos\theta = \dfrac{V_2 V_0}{|V_2||V_0|} = \cos\alpha\cos\beta \\ \cos\varphi = \cos(2\pi - \varphi) = \dfrac{V_2 V_1}{|V_2||V_1|} = \sin\alpha\cos\beta \end{cases} \tag{5}$$

The cosine of the angle between the direction vector V_3 of the shear stress τ_n and the normal inner vector V_0 of the least square fitting plane and the unit vector V_1 in the shear direction are respectively

$$\begin{cases} \cos\gamma = \dfrac{V_3 V_0}{|V_3||V_0|} = -\sin\alpha \\ \cos\psi = \dfrac{V_3 V_1}{|V_3||V_1|} = \cos\alpha \end{cases} \tag{6}$$

The components of the direction vector V_2 of the normal stress σ_n on the normal internal vector V_0 of the least squares fitting plane and the components on the unit vector V_1 in the shear direction are

$$\begin{cases} V_{\sigma_n,1} = \dfrac{|V_2|V_0\cos\theta}{|V_0|} = \sigma_n\cos\alpha\cos\beta V_0 \\ V_{\sigma_n,2} = \dfrac{|V_2|V_1\cos(2\pi - \varphi)}{|V_1|} = \sigma_n\sin\alpha\cos\beta V_1 \end{cases} \tag{7}$$

The components of the direction vector V_3 of the shear stress n τ on the normal internal vector V_0 of the least squares fitting plane of the structural surface and the components on the unit vector V_1 in the shear direction are

$$\begin{cases} V_{\tau_n,1} = \dfrac{|V_3|V_0\cos\gamma}{|V_0|} = -\tau_n\sin\alpha V_0 \\ V_{\tau_n,2} = \dfrac{|V_3|V_1\cos\psi}{|V_1|} = \tau_n\cos\alpha V_1 \end{cases} \tag{8}$$

From equations (7) and (8), the normal stress and shear stress of the least square-fitting plane can be obtained as

$$\begin{cases} V_n = V_{\sigma_n,1} + V_{\tau_n,1} = (\sigma_n\cos\alpha\cos\beta - \tau_n\sin\alpha)V_0 \\ V_\tau = V_{\sigma_n,2} + V_{\tau_n,2} = (\sigma_n\sin\alpha\cos\beta + \tau_n\cos\alpha)V_1 \end{cases} \tag{9}$$

Substituting formula (9) into formula (1), we get

$$|V_\tau| = |V_n|\tan\left[JRC \cdot \lg\left(\frac{JCS}{|V_n|}\right) + \varphi_b\right] \tag{10}$$

where $|V_\tau|$and $|V_n|$ are the shear stress and the normal stress of the least square-fitting plane on the rock joint, respectively, and both $|V_\tau|$ and $|V_n|$ are about the function of externally applied shear stress τ_n.

To find the shear strength τ_n, constructing the function $f(\tau_n)$ with τ_n as the independent variable, and the calculation formula is

$$f(\tau_\mathrm{n}) = |V_\mathrm{n}|\tan\left[JRC\cdot\lg\left(\frac{JCS}{|V_\mathrm{n}|}\right)+\varphi_\mathrm{b}\right]-|V_\tau| \tag{11}$$

Substitute formula (9) into formula (11) to get

$$f(\tau_\mathrm{n}) = |\sigma_\mathrm{n}\cos\alpha\cos\beta-\tau_\mathrm{n}\sin\alpha|\tan\left[JRC\cdot\lg\left(\frac{JCS}{|\sigma_\mathrm{n}\cos\alpha\cos\beta-\tau_\mathrm{n}\sin\alpha|}\right)+\varphi_\mathrm{b}\right]-|\sigma_\mathrm{n}\sin\alpha\cos\beta+\tau_\mathrm{n}\cos\alpha| \tag{12}$$

3 COMPARISON OF SHEAR STRENGTH

We collected the topography data of a large-scale natural rock joint and determined the study area, as shown in Figure 3. The maximum length and width of the study area are 2500 mm and 1000 mm, respectively. The large-scale natural rock joint is cut into a series of rock joints at 200mm intervals.

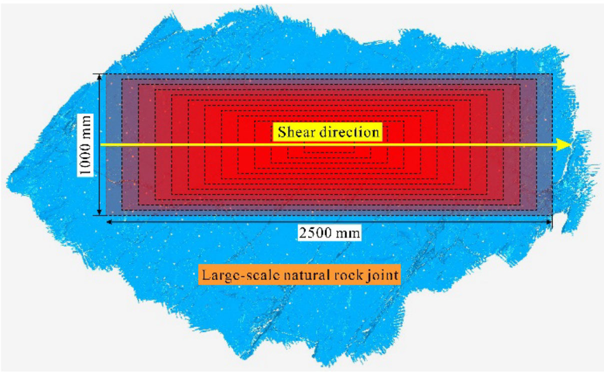

Figure 3. Series size of rock joints.

The shear strength of the series size of rock joints is calculated in the following three ways: (1) The shear strength is directly calculated by the JRC-JCS model; (2) Rotating the rock joints to eliminate the non-stationary trend, and calculate the shear strength through the JRC-JCS model; (3) The shear strength is calculated using the shear strength calculation formula considering the influence of non-stationary trend of rock joint proposed in this paper. The calculation results are shown in Figure 4. The figure shows that the shear strength varies with the rock joint scale. Notably, the results calculated with the proposed method differ from the JRC-JCS model but are similar to the rotated results.

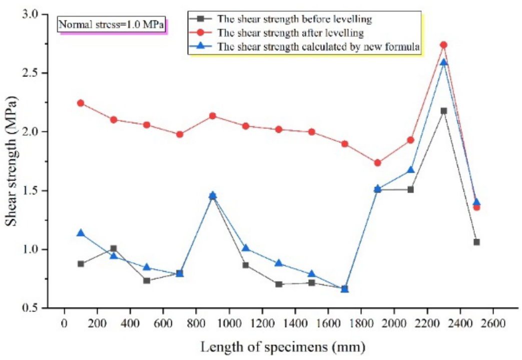

Figure 4. Shear strength of series size of rock joints.

4 CONCLUSION

In this paper, the non-stationary trend of rock joints was quantitatively characterized with two trend direction parameters. Based on the JRC-JCS model without considering the influence of non-stationary trend, an improved shear strength model considering the influence of trend direction was proposed by carrying out stress analysis and numerical analysis. In addition, the topography data of a large-scale natural rock joint was collected. A series of joint specimens with side length ranging from 100 mm to 2600 mm were extracted from the large rock joint. The shear strength values of these specimens were calculated with the JRC-JCS model and the proposed method. The results showed that the results calculated with the proposed method differ from the JRC-JCS model but are similar to the rotated results. It should be noted that the results obtained from this study are limited to theoretical analysis. In the future, direct shear tests on rock joint specimens with various scales will be carried out to validate the feasibility of the proposed method further.

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