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Research on Total Shear Strength for Rock Masses Considering Intermittent Joints and Connectivity Rate

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Abstract. The shear strength of intermittent joints in rock masses is significantly influenced by the stability of blocky rock system. The connection rate for a single rock joint is crucial for mechanical properties, such as shear strength. To examine the impact of connectivity rate on the structural strength and fracture evolution of intermittent joints, direct shear test is conducted on artificial coplanar intermittent joints with various connectivity rates under numerous different normal stresses. In this paper, a number of theoretical criteria for predicting the shear strength of intermittent joints have been put forth, with the Jennings criterion being the most popular. While the stress distribution and end effect are not taken into consideration, the Jennings criterion simply averages the mechanical properties of the joint surface and rock bridge to determine similar mechanical parameters. The effect of modifications is assessed through comparisons between the shear test data and the modified Jennings criterion. It is demonstrated that the modified Jennings criterion can accurately forecast the shear strength of the rock masses because the computed results closely match our expectations.

Keywords. Intermittent joints, connectivity rate, shear strength, Jennings strength criterion

1. Introduction

The joint is typically the primary factor that determines how strong a rock mass is. The density, degree of penetration, and filler are just a few of the variables that affect the mechanical characteristics and stability of the rock mass [1-3]. In many cases, the failure way is shear, because the shear stress is horizontal. We always study the physical properties of rock by shear test.

Savilabti [4] and Wong [5] performed a direct shear test of plaster models and study the distance of the horizontal and vertical on the structural plane model. Lajtai [6] throughout the direct shear test of double joint gypsum block during graded normal stress, indicates the initial fracture direction of discontinuous planes is different from block shear direction. Zhu et al. [7] throughout the stress concentration in the point of plane show that the basis of fracture mechanics and put forward the formula of structural plane

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shear strength. Ren et al. [8] establish peak strength of composite tensile shear failure by failure mode of discontinuous planes rock in stress condition.

In the discontinuous planes strength theory which is based on the straight shear test, we used the Jennings criterion and Lajtai bridge failure theory. The weighted average strength was determined as shear strength using the Jennings criterion, which was based on the Mohr-Coulomb strength criterion. Tensile failure, shear failure, and extrusion are the three different ways that a rock plane might fail. Using the Jennings strength criterion and presuming that the structural plane's damage was primarily caused by shear failure, and the failure surface parallels the direction of shear. But Lajtai theory overcomes this deficiency, considering the shear strength of solid bridge under different failure modes and shear strength of the plane.

But the Jennings criterion has an inherent shortcoming. Bai et al. [9] found the penetration extension of non-consecutive structural surface rock affect arrangement, the connectivity of joints, and the positive stress. That indicates that the solid bridge will crack and develop inside the bridge during the failure process from direct shear, causing mechanical parameters reduced [10]. Xia et al. [11] throughout direct shear test of non-consecutive joints under different normal stress levels show that the penetration of joint shear strength increases with the increase of joint surface rolling angle. However, the Jennings model used doesn't consider the end effect and differential distribution of press across the rock. Zhou et al. [12] found that the location and size of intermittent joint have an obvious influence on the comprehensive shear strength, and the influence of joint location should be considered in field engineering. Cui [13] found that in the process of shear, the normal stress can control the roughness of the fracture surface and affect the shear behavior of intermittent joints. Yang et al. [14] study the effects of normal stress and connectivity on the failure mode of rock specimens with intermittent joints.

We take the shear test by the artificial joint has different connectivity rate and similar physical properties in the diverse normal press to further study. Then we analyze the influence of connectivity rate on joint shear strength. And we modify the Jennings model by the test result.

2. Methods and Materials

Gypsum and water were combined in a weight ratio of 0.7:1 to create the simulated cuboid jointed rock mass samples, and the mixture's physical and mechanical characteristics are listed in Table 1. The simulated cuboid jointed rock mass model was created by combining components of various sizes, from which cuboid jointed rock mass specimens with dimensions of 10 mm in length, breadth, and height were created. The prepared rock mass specimen of a simulated cuboid joint, as depicted in Figure 1, was allowed to cure for a day in a cool, well-ventilated area. Direct shear testing on artificial rock joints made of model material were used to acquire joint parameters.

Table 1. Mechanical parameters of model material.

Compressive strength of rock /MPa	Tensile Strength of rock /MPa	Cohesion of rock /MPa	Internal frictional angle of rock /°	Cohesion of joint plane /MPa	Internal frictional angle of joint plane /°
2.434	0.262	0.45	49.50	30.10	0.03

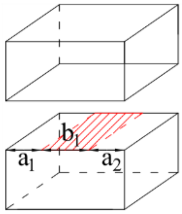
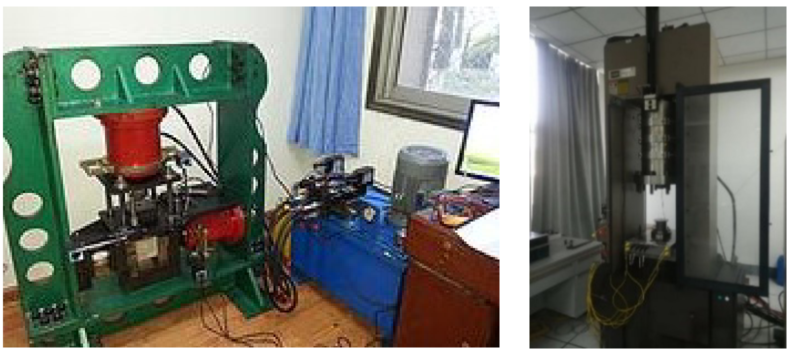


Figure 1. Test blocks.

3. Experiment Equipment and Test Plan

The YDS-2 multi-function rock test system at Chengdu University of Technology's National Key Lab of Geohazard Prevention and Environmental Protection was used to conduct the shear test. The axial and horizontal deformation of the test specimens were measured using a displacement sensor. Additionally, the displacement, shear stress, and axial stress were simultaneously recorded using a digital collector. The digital collector's displacement, shear stress, and axial stress are all simultaneously recorded. Additionally, the MTS815 rock test equipment performed the uniaxial compression test. At a rate of 0.5 kN/min, the axial force was applied. Five replicates were used for each group of a specimen throughout four tests with four distinct connection rates (K=0.2, 0.4, 0.6, and 0.8).

The YDS-2 rock mechanics multi-function testing machine uses the direct shear test developed by Chengdu University of Technology, the device adopts the computer automatic loading, the level of form a complete set pressure system and the vertical compression system, which include the pressurized cylinder, pressure, load, pressure head; The traditional displacement sensor includes the horizontal and axial displacement sensor, while the digital collector synchronously records the displacement, shear stress and axial stress of the shear. The maximum load of the rock mechanics multifunctional testing machine is 600 kN and the maximum load is 300 kN. It can meet the requirements of the load classification and displacement collection of the test.



(a) YDS-2 rock testing system (b) MTS815 rock test system

Figure 2. Testing equipment.

In the point load test is adopted in the YSD-2 type 1 digital point load device. The device adopts the manual loading, and forms a complete set of the vertical pressure system, which include hand horizontal pumps, hydraulic jack, pressure measuring device, equipped with a digital collector. The instrument structure is shown in Figure 2.

4. The Test Results

As illustrated in Figure 3, the peak shear strength was used to fit the peak shear strength curve using the least square approach, and the peak shear strength was then used to calculate the line connectivity rate model of the equivalent cohesiveness with the equivalent internal friction Angle, as shown in Table 2.

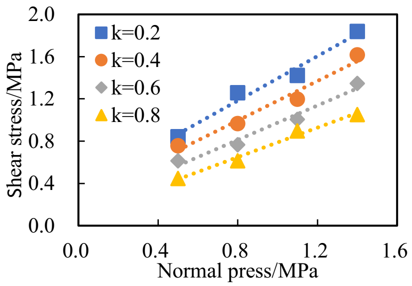


Figure 3. Shear strength curve of the linear joint plane model.

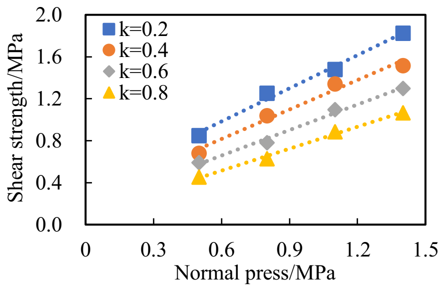


Figure 4. Shear strength curve.

Table 2. The fitting results of shear strength.

Connectivity	Fitted equation	R^2	$\tan\overline{\varphi_l}$	$\overline{\varphi_l}$ /(°)	$\overline{c_l}$ /MPa
0.2	y = 1.0533x + 0.3404	0.9755	1.0533	46.49	0.34
0.4	y = 0.9357x + 0.2463	0.9689	0.9357	43.10	0.25
0.6	y = 0.8131x + 0.1615	0.9714	0.8131	39.11	0.16
0.8	y = 0.6979x + 0.0902	0.9862	0.6979	34.91	0.09

As shown in Figure 4, the peak shear strength was used as the fitting formula for four surface connectivity rate models under various normal stress peak shear strengths, and the calculation line connectivity rate model of the equivalent cohesion with the equivalent internal friction Angle is displayed in Table 3.

Table 3. The fitting results of shear strength.

Connectivity	Fitted equation	R^2	$\tan\overline{\varphi_a}$	$\overline{\varphi_a}$ /(°)	$\overline{c_a}$ /MPa
0.2	y = 1.0526x + 0.3519	0.9893	1.0526	46.47	0.35
0.4	y = 0.936x + 0.2548	0.9782	0.936	43.11	0.25
0.6	y = 0.8101x + 0.1723	0.9903	0.8101	39.01	0.17
0.8	y = 0.6976x + 0.0958	0.9944	0.6976	34.90	0.10

We analyzed the peak shear strength curve of joint planes during different normal stress levels, which indicates with structural plane connectivity rate increases, the joint shear strength toward the normal stress level getting less. The findings of this investigation demonstrated that the structure's connection rate significantly affects shear strength.

5. Experimental Prediction Model

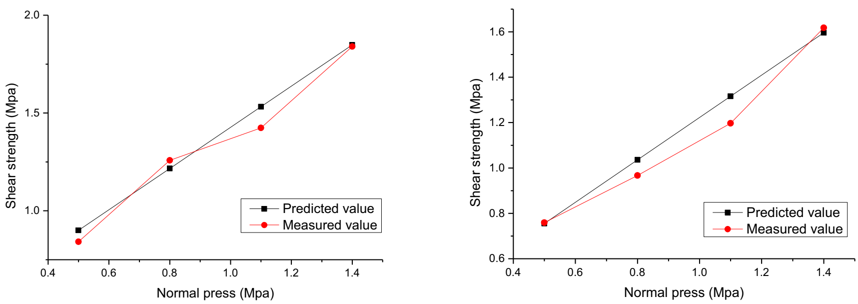
In the principles of discontinuous joint planes strength, the most common of these principles is Jennings criterion form the Mor-Coulomb criterion. The calculation equation is as follows:

$$\tau = \sigma_n \tan\overline{\varphi} + \overline{c} \tag{1}$$

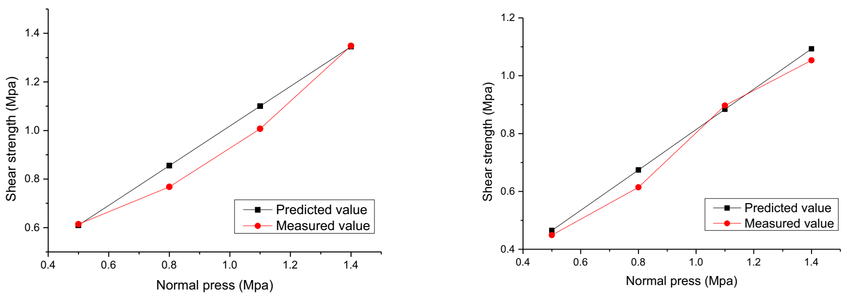
$$\tan\overline{\varphi} = K\tan\varphi_j + (1-K)\tan\varphi_0 \tag{2}$$

$$\overline{c} = Kc_j + (1-K)c_0 \tag{3}$$

In linear connecting rate mode, the part contrasts four sets of wire connecting rate models of the shear test under four kinds of normal stress with the peak shear strength forecast by Jennings strength criterion. And the error between the predicted values and the measured values is calculated as shown in Figure 5.



(a) K=0.2 (b) K=0.4



(c) K=0.6 (d) K=0.8

Figure 5. The comparison of shear strength predicted values and measured values of linear connecting rate mode.

It is not difficult to conclude from the analysis of the experiment that the effect of linear connection rate on the composite shear strength of the structural plane is significantly different. The comparison of the experimental outcomes is displayed in Table 4.

Table 4. The comparison of equivalent cohesive and equivalent internal friction angle.

Connectivity rate	$\overline{c_1}$ **/MPa**	$\overline{c_m}$ **/MPa**	$\overline{\varphi_1}$ **/MPa**	$\overline{\varphi_m}$ **/MPa**
0.2	0.34	0.35	46.49	46.47
0.4	0.25	0.25	43.1	43.11
0.6	0.16	0.17	39.11	39.01
0.8	0.09	0.1	34.91	34.9

The composite shear strength of the discontinuous joint planes varies at the same rate of connectivity as the experiment. Because both the shape and the connectedness of the structure have an impact on the rock mass. Since the cohesion of solid bridges decreased when shear was taken into account, the calculation method for equivalent cohesion was amended as follows: Solid bridge in the formula multiplied by reduction factor(η) to the cohesion of rock bridges.

$$\overline{c}' = Kc_j + \eta(1-K)c_0 \tag{4}$$

The reduction coefficient of rock bridge cohesion can be determined by the test results of the discontinuous joint planes. First determine the equivalent internal friction angle, the angle of internal friction of the rock, the basic friction angle of structural plane connected into the calculation formula of the equivalent friction angle. So the formal could determine the penetration on the surface of the structure equivalent friction angle, fix the equivalent cohesion shall be equal to the block after fitting the measured peak shear strength of cohesion, so its value generation into the formula to determine the reduction coefficient of cohesion of solid bridge. The results of the reduction coefficients under different structural surface connectivity are shown in Figure 6.

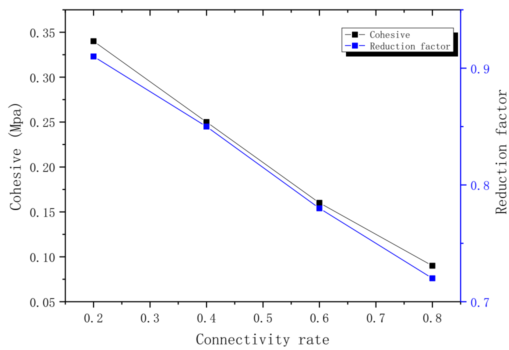


Figure 6. The reduction factor of the cohesion in linear joint plane model.

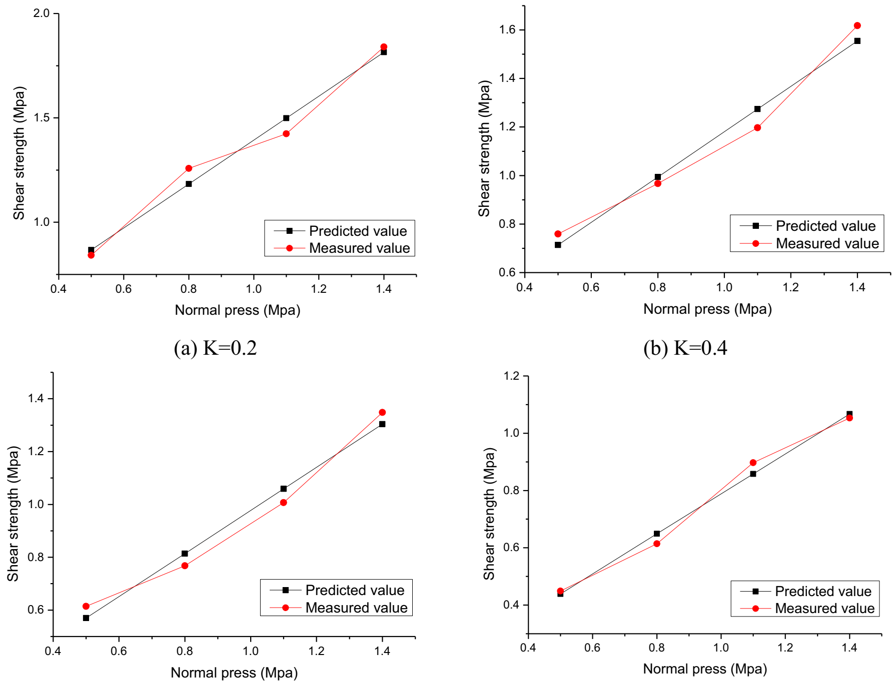
Through the data calculated the reduction factor, put cohesion into the Jennings formula, get through comprehensive structural plane shear strength model.

$$\tau = \sigma_n \tan\bar{\varphi} + \bar{c}' \tag{5}$$

$$\tan\bar{\varphi} = K\tan\varphi_j + (1-K)\tan\varphi_0 \tag{6}$$

$$\bar{c}' = Kc_j + \eta(1-K)c_0 \tag{7}$$

The shear strength of the discontinuous joint planes from each connected rate has been modified by the comprehensive shear strength model and calculated the relative error by comparing with the measured values, as shown in Figure 7.



(a) K=0.2 (b) K=0.4

(c) K=0.6 (d) K=0.8

Figure 7. The comparison of measured shear strength and predicted in the new linear model.

As shown in Figure 7, the prediction values of shear strength are similar to measured values in test, the different rate within 5%. It suggesting that different connectivity rate of shear strength using by Jennings strength criterion can predict well through structural plane model.

It can be found that the reduction factor has a significant linear decline relationship between connectivity rate in the new discontinuous joint plane model. The relationship of reduction factor with connectivity rate can be obtained after fitting the least square：

$$\eta = -0.32K_1 + 0.975 \tag{8}$$

In this study, the reduction factor of the high connecting rate is greater than the low connecting rate. It suggests that the extent of the weakening solid bridge is associated with the complete degree of rock, rock is more complete, the extent of weakening solid bridge is lower.

6. Model Verification

The formula in this paper is substituted into the data of similar experimental. The shear stress of the model with flat surface and the connectivity rate are shown in Figure 8. The shear stress-displacement curve of the test block is used to determine the peak shear strength of the test block under various normal stresses. The outcomes are displayed in Table 5.

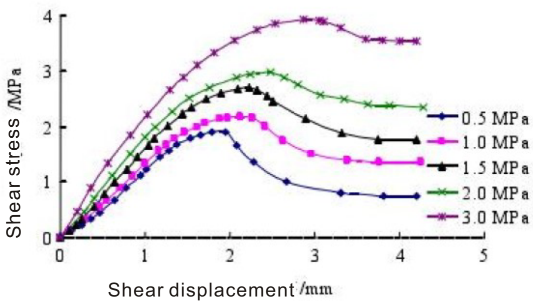


Figure 8. The model's shear stress-displacement curve.

Table 5. The model's maximum shear strength.

Normal press/MPa	0.5	1.0	1.5	2.0	3.0
Shear strength /MPa	1.892	2.179	2.700	2.975	3.930

As the Caichu Xia's test, the plane connectivity rate can be calculated according to the linear connectivity rate, and the structural surface is flat and smooth. Therefore, this article is not well versed in structural plane synthesis model of shear strength reduction factor (η) can be calculated by the equation η = 0.32 K + 0.975, generation into the connectivity rate equal 0.5, get Caichu Xia test pilot block reduction factor of 0.81. So the comprehensive shear strength model of discontinuous joint plane has been obtained.

$$\tau = \sigma_n \tan\bar{\varphi} + \bar{c}' \tag{9}$$

$$\tan\bar{\varphi} = K\tan\varphi_j + (1-K)\tan\varphi_0 \tag{10}$$

$$\bar{c}' = Kc_j + 0.81(1-K)c_0 \tag{11}$$

The results of this study indicate that in this paper, the predicted values calculated by the comprehensive shear strength model are compared with the experimentally measured values. As shown in Table 6.

Table 6. The comparison of predicted values and measured values.

Normal press (MPa)	Predicted values (MPa)	Measured values (MPa)	Difference ratio (%)
0.5	1.961	1.892	3.63
1.0	2.330	2.179	6.95
1.5	2.700	2.700	0.00
2.0	3.070	2.975	3.18
3.0	3.809	3.930	− 3.08

As Table 6 shown, the predicted values of shear strength in the simulation structure tally with measured values and difference ratio within 5%. It suggests that the provided formula could better predict the shear strength of Xia et al. (2010) experiment of simulation structure.

7. Conclusion

In this study, shear test results on simulated jointed rock mass specimens are used to evaluate the lateral deformation characteristics of cuboid joint rock masses under axial compression conditions. The key findings can be summarized as follows:

(1) The analysis of shear test results shows that joint plane in the rock under the same connectivity rate influences comprehensive shear strength. That also means that rock bridges in the same connected rate are more complete, the lower the degree of weakening solid bridge.

(2) This paper has compared measured values and predicted values and reduced the cohesion of solid bridge to get the formula about reduction factor and the connectivity rate.

(3) Another potential problem is that the research target of this paper is flat joint plane and reduced the cohesion of solid bridge. It should add different variables of joint to study the attenuation relations of the internal friction angle further.

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