Research Article

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Direct Shear Test and Shear Strength Model of Clay-Filled Joints

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Abstract: To better study the shear characteristics of infilled joints with soil having different moisture contents, the influence of the moisture content on the shear characteristics of the infilled joint was explored in this paper, and a revised shear strength model of infilled joint surface is proposed. The results show that the shear dilatation modes of joints can be divided into four types: pure shear dilatation, pure shear compression, shear dilation-shear compression and shear compression-shear dilation. As the joint roughness coefficient (JRC) value increases, the normal displacement of the joint surface gradually increases during the shearing process and the normal stress has an inhibitory effect on dilatation. The infill material will weaken the peak shear stress of the joint surface. When the JRC value of joint surface is small, the weakening effect of soil with moisture content of 30% on peak shear stress is obvious. The revised joint roughness coefficient-joint wall compressive strength (JRC-JCS) model of infilled joint is proposed and the maximum shear stress value calculated by the model has a good linear relationship with the test value.

Keywords: Infilled joints; direct shear test; moisture content; JRC; shear characteristics.

1 Introduction

Rock mass is a geological body composed of structural body and joint surface. The existence of joint surface seriously

affects the integrity of rock mass, which is one of the critical reasons for the instability and failure of rock mass in practical engineering. The research on shear strength and dilatation characteristics of infilled joints has practical application on stable rock mass. Therefore, the study on the shear characteristics of the infilled joint is a hot topic for dealing with the stability of underground rock engineering.

On the basis of previous research results [1–4], many rock mechanics workers continue to study shear strength of jointed rock mass. Fang [5] introduced a Fourier transform method to predict the shear strength of joints under constant normal stiffness. Bndraratna [6] carried out the shear tests on soft joints with filling materials under constant normal stiffness in the laboratory, and found that the shear strength of joints would be significantly reduced when an asperity height to infill thickness ratio is greater than 1.8. Deng [7] simulated the complete shear behavior of filled rock joints by establishing model. Davies [8] explored the effect of low temperature and normal stress on the shear strength of rock joints filled with ice. Philipp Mamot [9] conducted shear tests on gneiss and mica schist with ice joints. The results show that the shear peak strength of rock joints increased slightly at freezing temperature. Pereira [10] designed a rotating shear test to study the shear characteristics of the discontinuous surfaces of the filled thin sand, and compared it with the results of the unfilled and planar discontinuous shear test. It is finally found that the shear strength of the discontinuous plane filled with thin sand is always lower than that of the unfilled discontinuity. Zhuang [11] studied and compared the crack growth behavior of filled and unfilled cracks by testing rock samples under uniaxial compression. Mokhtarian [12] designed different types of triaxial compression test of infilled joints, and the results showed that the filling material had a significant effect on the failure criterion parameters of the joints. Jahanian [13] conducted a series of constant normal load direct shear tests to study the shear strength of joints with different roughness and filling characteristics. Cui [14] designed the ring shear test of compacted low plasticity filling jointed soil, the influence of water content and particle breakage on the shear characteristics of filling jointed soil

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was explored. Zhao [15] studied the shear behavior of the joint surface filled with sand and clay.

Although many researchers have made some achievements in the study of rock mass joint surfaces, there is few studies on the lubrication effect of filling moisture content of joint surface. Therefore, in this paper, direct shear test of rock-like material infilled joint is designed to obtain peak strength, normal displacement and shear displacement of joint surface filled with soil with different moisture contents, and the influence of water content on the shear characteristics of joint surface is obtained. In this paper the weakening coefficient λ is introduced and the revised JRC-JCS model is proposed. The JRC-JCS formula proposed by Barton is further improved, and the application scope is expanded, which is closer to the real situation in practical application.

2 Specimen preparation and testing

2.1 Mold preparation

The direct shear tests were conducted on the RYL-600 Rock Mechanics Shear Rheometer. The cube mold is made of steel plate with a thickness of 3 mm. The length, width and height of the cube are 160 mm, 100 mm and 100 mm, respectively. According to Barton's ten classical profiles, four curves with JRC values of 3, 7, 15 and 19 were selected to make joint surfaces with different roughness, as shown in Figure 1.

2.2 Specimen preparation

The cement used for specimen was ordinary Portland cement with type of P32.5. Aggregate is sand of 0.1-0.85 mm in diameter. The cement, sand and water were mixed at a ratio of 26:25:10 by weight to produce the mortar, and then start pouring specimen. After pouring, the specimen needs natural maintenance for 24 hours before removing the mold, and then the test can be carried out in the standard maintenance room for 28 days. Four groups were designed in this test, with 15 specimens in each group, and some specimens are shown in Figure 2.

2.3 Filling material preparation

The clay sample used in this test was taken from clay soil that is widely distributed in Xiangtan City, Hunan Province. The clay soil sample is crushed and exposed to the sun for

Figure 1: Standard roughness profile

Figure 2: (a)–(b) RYL-600 Rock mechanics shear rheometer; (c) Part of the specimens

a week, and then put it in a drying oven at 105°C–110°C for 24 hours, which means that the moisture content of the soil is considered to be zero. The dried soil was screened by 0.5 mm standard soil sieve to remove the larger particles, which can be used to prepare the soil with different moisture contents. The liquid limit moisture content and plastic limit moisture content of the clay were 38.66% and 19.81%, respectively, by using the LG-100D digital soil hydraulic limit test instrument. Using the determination results of liquid limit and plastic limit of clay, clay filling materials with different moisture contents were prepared: semi-solid soil (moisture content of 15%), plastic soil (moisture content of 30%) and liquid soil (moisture content of 40%). Since the filling material is made of clay with different moisture contents, it has the same characteristics as clay, that is, the filling material has the characteristics of low strength, large compressibility and good bonding performance.

2.4 Test part

In this paper, the influence of moisture content on the shear characteristics of infilled joint surface is studied through direct shear test. The test has three groups of variables, which are the joint surface roughness, normal stress and fillings with different moisture content. Before the test, the four groups of specimens with different JRC values are numbered: the upper part of the first specimen in the first group was marked as J3-1b, and the lower part was marked as J3-1a. Each specimen in the other groups was marked according to this analogy.

The normal stresses were set to 0.5 MPa, 1.0 MPa and 1.5 MPa, respectively. The JRC values of the joint surfaces are 3, 7, 15, 19, respectively; and the filling conditions are unfilled, and filled with semi-solid soil (moisture content of 15%), filled with plastic soil (moisture content of 30%), and filled with liquid soil (moisture content of 40%). Indraratna [16] and others found that the shear strength of the joint surface with relatively thick filling was mainly controlled by the shear strength of the filling. Therefore, in order to control the variables in the experiment, the filling thickness was designed to be 3 mm. During the test, the lower plate remains stationary, and the upper plate moves towards the left under the action of shear force. The rolling contact mode is used between the upper plate and the upper plate to minimize the friction between the upper plate and the upper plate in the shear process.

3 Analysis of test results

According to the direct shear test data of infilled joints under normal stresses of 0.5 MPa, 1.0 MPa, and 1.5 MPa, the change of displacement with shear displacement was observed, and the specific influence of various factors on shear pressure and dilatation characteristics was analyzed.

3.1 Shear characteristics of joint surfaces

Figures 3–6 show the measured shear stress and normal displacement versus shear displacement curves for different fillings and under normal stresses of 0.5 MPa, 1.0 MPa, and 1.5 MPa, respectively. It can be found that the shear characteristics of the joint surfaces are affected by roughness, filling material, and normal stress.

According to the relationship between the normal displacement and the shear displacement curves (Figures 3–5), the dilatation modes of the joint surface are divided into the following types: pure shear dilatation (D), pure shear compression (C), shear compression-shear dilatation (C-D), shear dilatation-shear compression (D-C), as shown in Figure 6. For pure shear dilatation, only the dilatation displacement appears during shearing process and keeps growing; for pure shear compression, it is only have shear displacement during shearing process; for shear compression-shear dilatation, shear compression occurs at the initial stage of the test, and then becomes dilatation after reaching the maximum amount of shear compression; for shear dilatation-shear compression, dilatation occurs first in the process of shear test, and then compression occurs after reaching the maximum dilatation displacement.

As shown in Table 1 and Figures 3–5, it can be seen that when the normal stresses are 0.5 MPa and 1.0 MPa, the unfilled joint surface occurs on pure shear dilatation phenomenon when the JRC value is 3, and shear compression-dilatation phenomenon occurs in other cases. The peak shear stress and peak shear displacement of the unfilled joint surface are mainly affected by the JRC value and the normal stress: in general, the peak shear stress increases with the increase of the normal stress or slightly with the increase of the JRC; when the JRC value is small (joint surface with JRC of 3, 7), the shear displacement increases with the increase of the normal stress and the JRC value. For the infilled joint, when the JRC value is small (joint surface with JRC of 3, 7), the pure shear compression phenomenon occurs under the three normal stresses; when the JRC value is large (joint surface with JRC of 15, 19), more shear compression-shear dilatation phenomenon occurs.

Figure 3: Shear stress (SS) and normal displacement (ND) versus shear displacement (SD) curves under normal stress of 0.5 MPa: (a) without filling; (b) semi-solid soil; (c) plasticized soil; and (d) Liquid soil

Figure 4: SS and ND versus SD curves under normal stress of 1.0 MPa: (a) without filling; (b) semi-solid soil; (c) plasticized soil; and (d) liquid soil

Figure 5: SS and ND versus SD curves under normal stress of 1.5 MPa: (a) without filling; (b) semi-solid soil; (c) plasticized soil; and (d) liquid soil

Table 1: Peak shear displacement and shear dilatation modes under different filling states.

JRC	σ_n (MPa)	Without filling		Semi-solid soil 15% MC		Plasticized soil 30 % MC		Liquid soil 40 % MC	
		Peak SD (mm)	shear dilatation modes	Peak SD (mm)	shear dilatation modes	Peak SD (mm)	shear dilatation modes	Peak SD (mm)	shear dilatation modes
3	0.5	15.1	D	12.3	C	27.1	C	11.5	C
	1	27.2	D	14.1	C	13.8	C	19.6	C
	1.5	27.5	C-D	16.8	C	6.84	C	6.12	C
7	0.5	15.3	C-D	17.2	C	16.4	C	34.9	C
	1	28.8	C-D	7.52	C	14.1	C	27.4	C
	1.5	29.6	C-D	14.8	C	11.8	C	13.7	C
15	0.5	32.2	C-D	15.1	C	21.8	C	30.1	C-D
	1	37.2	C-D	38.2	C	29.6	C-D	23.6	C-D
	1.5	22.6	C-D	14.4	C	17.9	C-D	6.73	C-D
19	0.5	23.7	D-C	8.12	C	29.4	C	22.5	C-D
	1	22.3	C-D	24.9	C-D	13.6	C	11.8	C-D
	1.5	16.4	C-D	8.30	C	6.81	C	7.56	C-D

Note: σ_n = Normal stress; MC = moisture contents; C = pure shear compression; D = pure shear dilatation; C-D = shear compression-shear dilatation; D-C = shear dilatation-shear compression.

Figure 6: Shear dilatation modes of joints: (a) pure shear dilatation; (b) pure shear compression; (c) shear compression-shear dilatation; and (d) shear dilatation-shear compression

By observing Figures 3–5, it is found that the peak shear stress of unfilled joint surface is the largest. It can be inferred that the filling has a significant weakening effect on the peak shear stress of the joint surface. Especially for the joint with small JRC value, the weakening effect of filling is more obvious. This is because the shear strength of the soil is smaller than that of rock-like materials, and the lubrication of the water in the soil further weakens the peak shear stress. For infilled joint, the peak shear stress of filled with semi-solid soil (moisture content of 15%) and plastic soil (moisture content of 30%) is the smallest, and most of them are infilled joints of semi-solid soil. Because of the small shear strength of the plastic soil, the lubrication effect of water, and the reduced mobility of plastic soil compared to the liquid soil, it will not flow to the concave of the joint surface due to the normal stress. Besides, when the JRC of joint surface is 3 and 7, the moisture content of filling increases from 15% to 30%, and the internal friction angles decrease from 4.6° to 3.1° , respectively. Therefore, the weakening effect of filling material with 30% moisture content is the most significant.

3.2 Effect of normal stress on the characteristics of shear compression and shear dilatation

Test curves of normal displacement and shear displacement of different joint surfaces under different normal stresses are shown in Figures 7–10.

It can be seen from Figure 7 that for the unfilled joint surface, when the normal stress is small, the normal displacement is large. When the normal stress gradually increases, the normal displacement gradually decreases. Therefore, the normal stress has a certain inhibitory effect on the dilatation of joint surface, and the normal stress is positively correlated with the inhibitory effect.

Figures 8–10 show that for infilled joint surface, when the JRC value of joint surface is small (JRC of joint surface is 3, 7), shear compression occurs under three-level normal stress. Because the joint surface has small undulations, the compression between the fillings is greater than the dilatation between the bulges of the joint surfaces, so the shear compression occurs. When the JRC value is large (JRC of joint surface is 15, 19), the shear compression of the joint surface increases gradually with the increase of the normal stress and the shear compression-dilatation phenomenon occurs under a large normal stress. This is because at the initial stage of shearing, the fillings will compress and produce a larger amount of shear shrinkage. When the shear displacement increases gradually and the compression between the fillings reaches the maximum, the amount of shear dilatation produced by the climbing between the bulges of the joint surface also increases slowly, and finally produces the dilatation displacement. So the shear compression-dilatation phenomenon appears in the shear process.

3.3 Effect of the moisture content of the filling on the shear compression and shear dilatation characteristics of the joint surface

Figures 11–13 show the normal displacement and shear displacement test curves of the joint surfaces of different filling materials under the normal stress of 0.5 MPa, 1.0 MPa and 1.5 MPa, respectively. The influence of filling state on shear characteristics is analyzed.

It can be found from Figures 11–13 that under the three-level normal stress, the dilatation displacement of the unfilled joint surface is the largest. For the infilled joint surface, the influence of the filling material on the dilatation characteristics of the joint surface is also different due to the different moisture content of the filling material. When the JRC value is small (JRC of joint surface is 3, 7), the infilled joint surfaces exhibit shear compression. The shear compression displacement of the filled semi-solid soil and plastic soil is large, and that of filled liquid soil is smaller. This is because semi-solid soil and plastic soil have low

Figure 7: Normal displacement versus shear displacement curves for without filling joint

Figure 8: Normal displacement versus shear displacement curves of joints filling with semi-solid soil

Figure 9: Normal displacement versus shear displacement curves of joints filling with plastic soil (30% MC)

Figure 10: Normal displacement versus shear displacement curves of joints filling with liquid soil

Figure 11: Test curve of ND and SD in different filling (NS is 0.5 MPa): (a) JRC=3; (b) JRC=7; (c) JRC=15; and (d) JRC=19

Figure 12: Test curve of ND and SD in different filling (NS is 1.0 MPa): (a) JRC=3; (b) JRC=7; (c) JRC=15; and (d) JRC=19

Figure 13: Test curve of ND and SD in different filling (NS is 1.5MPa): (a) JRC=3; (b) JRC=7; (c) JRC=15; and (d) JRC=19

moisture content and good compressibility, so that it can be better consolidated with the joint surface, therefore, there is a larger shear displacement during shearing. When the JRC value of the joint surface is large (the JRC value is 15, 19), with the increase of the moisture content, the joint surface filled with liquid soil will also show a lot of pure dilatation or compression-dilation. Because the soil with a moisture content of 40% is in the liquid limit state and has a certain degree of fluidity, it will overflow from the joint surface under the action of normal stress, and the joint surface bulges will be exposed, so the shear dilatation phenomenon occurs on the joint surface.

3.4 Revised shear strength model of the infilled joint surface

Barton [17] proposed the JRC-JCS formula in 1976:

$$\tau_p = \sigma_n \tan \left[\varphi_b + JRC \log_{10} \left(\frac{JCS}{\sigma_n} \right) \right] \quad (1)$$

Where φ_b is the basic friction angle of joint surface and JCS is the strength of joint surface.

This formula considers the influence of normal stress, basic friction angle of joint surface, J joint roughness coefficient (JRC), joint wall compressive strength (JCS) and

other factors on peak shear stress, while the weakening effect of filling material on peak shear stress of joint surface is not considered. Therefore, in this paper, a weakening coefficient λ is introduced to express the weakening effect of filling on the peak shear stress of joint surface. A revised JRC-JCS model for infilled joint is proposed:

$$\tau_p = \lambda \sigma_n \tan \left[\varphi_b + JRC \log_{10} \left(\frac{JCS}{\sigma_n} \right) \right] \quad (2)$$

The revised JRC-JCS model was used to calculate the peak shear stress of the joint and compare it with the experimental value. The ratio of the peak shear stress to the JRC value was fitted, as shown in Figure 14.

It can be seen from the above figure that the ratio of the calculated value of the JRC-JCS model to the experimental value of the filling structural plane decreases linearly with the increase of the JRC value. The fitting relationship is as follows:

$$\lambda = a + bJRC \quad (3)$$

The fitting parameters a , b of the weakening coefficient λ are obtained from the above figure and the λ values of different JRC under different fillings are calculated as show in Table 2.

According to reliability analysis, it can be seen that there is a good linear relationship between the calculated

Figure 14: The relationship between experimental value and calculation value with different filling joints: (a) semi-solid soil; (b) plastic soil; and (c) soil liquid

Figure 15: The correlation between the calculated value and the experimental value: (a) semi-solid soil; (b) plastic soil; and (c) soil liquid

Table 2: The value of λ in different filling states.

Filling	a	b	λ				Correlation Coefficients
			JRC=3	JRC=7	JRC=15	JRC=19	
Semi-solid soil	0.980	−0.0285	0.894	0.780	0.552	0.438	0.704
Plasticized soil	1.06	−0.0365	0.802	0.510	0.364	0.948	0.743
Liquid soil	1.21	−0.0441	0.899	0.546	0.369	1.08	0.781

value and the experimental value. The lowest correlation coefficient is semi-solid soil (moisture content of 15%), which is 0.863; the highest is liquid soil (moisture content of 40%), which is 0.884, as shown in Figure 15. It can be seen that the results of maximum shear stress calculated by revised JRC-JCS model are reliable.

4 Conclusion

After the direct shear test of rock-like material joints was completed, the shear test results of the joint surfaces of different roughness and different filling materials under different normal stresses are obtained. The effects of various factors on shear stress and dilatation are discussed. The conclusion is as follows:

1. The phenomenon of dilatation or compression of infilled joint is affected by the amount of compression of filling and the amount of dilatation of joint bulges. Normal stress is positively correlated with joint surface compression. The compression-dilation modes of joint surfaces can be roughly divided into four types: pure shear dilatation, pure shear compression, shear dilation-shear compression and shear compression-shear dilation, respectively.
2. Filling will weaken the peak shear stress of joint surface. By comparing the relationship between moisture content and internal friction angle, it can be concluded that the soil with moisture content of 30% has obvious weakening effect on the peak shear stress.
3. Usually, with the increase of JRC value, the normal displacement of the joint surface increases gradually in the shear process. Normal stress has inhibitory effect on joint surface dilatation, and normal stress is positively correlated with weakening effect.
4. The results of the maximum shear stress calculated by the revised JRC-JCS model showed a good linear relationship with the experimental value. The correlation coefficient was up to 0.884.

Discussion: To make the joint surface of rock-like materials closer to the joint surface of natural rock, more advanced technical means can be used to simulate the joint surface of natural rock in the following research, such as 3D printing technology.

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References

- [1] Barton N. Review of a new shear-strength criterion for rock joints. *Engineering Geology*. 1973;7(4):287-332. doi:10.1016/0013-7952(73)90013-6.
- [2] Barton N, Kjaernsli B. Shear strength of rockfill. *Journal of the Geotechnical Engineering Division*. 1981;107(7):873-891. doi:10.1061/AJGEB6.0001167.
- [3] Jing L, Stephansson O, Nordlund E. Study of rock joints under cyclic loading conditions. *Rock Mechanics and Rock Engineering*. 1993;26(3):215-232. doi:10.1007/BF01040116.
- [4] Xie H, Wang JA, Xie WH. Fractal effects of surface roughness on the mechanical behavior of rock joints. *Chaos Solitons & Fractals*. 1997; 8(2):221-252. doi:10.1016/S0960-0779(96)00050-1.
- [5] Fang K, Fall M. Shear Behaviour of Rock-Tailings Backfill Interface: Effect of Cementation, Rock Type, and Rock Surface Roughness. *Geotechnical and Geological Engineering*. 2021;39(3):1753-1770. doi:10.1007/s10706-020-01586-x.
- [6] Indraratna B, Haque A, Aziz N. Shear behaviour of idealized infilled joints under constant normal stiffness. *Geotechnique*. 1999; 49(3): 331-355. doi:10.1680/geot.1999.49.3.331.
- [7] Deng D, Simon R, Aubertin M. Modelling shear and normal behaviour of filled rock joints. *GeoCongress 2006: Geotechnical Engineering in the Information Technology Age*. 2006;1-6. doi:10.1061/40803(187)159.
- [8] Davies M, Hamza O, Harris C. The effect of rise in mean annual temperature on the stability of rock slopes containing ice-filled discontinuities. *Permafrost & Periglacial Processes*. 2010;12(1):137-144. doi:10.1002/ppp.378.
- [9] Mamot P, Weber S, Lanz M, et al. Brief communication: The influence of mica-rich rocks on the shear strength of ice-filled discontinuities. *The Cryosphere*. 2020;14(6):1849-1855. doi:10.5194/tc-2020-18.
- [10] Pereira JP. Rolling friction and shear behaviour of rock discontinuities filled with sand. *International Journal of Rock Mechanics and Mining Sciences*. 1997;34(3-4):244.e1-244.e17. doi:10.1016/S1365-1609(97)00037-3.

- [11] Zhuang X, Chun J, Zhu H. A comparative study on unfilled and filled crack propagation for rock-like brittle material. *Theoretical and Applied Fracture Mechanics*. 2014;72:110-120. doi:10.1016/j.tafmec.2014.04.004.
- [12] Mokhtarian H, Moomivand H, Moomivand H. Effect of infill material of discontinuities on the failure criterion of rock under triaxial compressive stresses. *Theoretical and Applied Fracture Mechanics*. 2020;108: 102652. doi:10.1016/j.tafmec.2020.102652.
- [13] Jahanian H, Sadaghiani MH. Experimental study on the shear strength of sandy clay infilled regular rough rock joints. *Rock Mechanics and Rock Engineering*. 2015;48(3):907-922. doi:10.1007/s00603-014-0643-4.
- [14] Zhao Y, Zhou H, Feng XT, et al. Effects of water content and particle crushing on the shear behaviour of an infilled-joint soil. *Géotechnique*. 2012; 62(12):1133-1137. doi:10.1680/geot.11.P.060.
- [15] Zhao Y, Zhang L, Wang W, et al. Experimental study on shear behavior and a revised shear strength model for infilled rock joints. *International Journal of Geomechanics*. 2020; 20(9):04020141. doi:10.1061 (ASCE)GM.1943-5622.0001781.
- [16] Indraratna B, Haque A, Aziz N. Shear behaviour of idealized infilled joints under constant normal stiffness. *Geotechnique*. 1999; 49(3):331-355. doi:10.1680/geot.1999.49.3.331.
- [17] Barton N. The shear strength of rock and rock joints. *International Journal of rock mechanics and mining sciences & Geomechanics abstracts*. Pergamon, 1976;13(9):255-279. doi:10.1016/0148-9062(76)90003-6.