Research Article

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Stress effect & scale effect on shear properties of double saw-tooth rock joint surface

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Abstract: The shear properties of rock joint control the stability of rock and have an important impact on natural disasters such as landslides and debris flow. In order to study the stress effect and scale effect of shear properties of double saw-tooth rock joint, cement mortar is selected as similar material, a series of mix ratio tests are carried out, and the best mix ratio is obtained. Using rock joint integrated mold and joint panel produced by 3D printing technology, several groups of double saw-tooth joint specimens with different saw-tooth heights, saw-tooth widths, and saw-tooth spacings are made. Under multiple levels of normal stress, direct shear tests of different scale specimens are carried out by self-developed multifunctional rock-soil contact damage test system. Results show that the shear failure modes of double saw-tooth rock joint include couple effect of overriding and cutting off, and cutting off effect, which are mainly controlled by the rock joint morphology and normal stress. Peak shear strength increases with the increase of saw-tooth width and spacing, but the change with saw-tooth height is not obvious. Peak shear strength and peak friction angle of the double saw-tooth rock joint have significant characteristics of stress effect and scale effect.

Keywords: Double saw-tooth rock joint; Stress effect; Scale effect; Shear strength; Peak friction angle

1 Introduction

Rock joint is a discontinuity in rock mass, which has a great influence on the stability of rock engineering. Engineering practice shows that when rock joint is subjected to engineering disturbance, rainfall, and other conditions, the shear resistance of joint is not enough to resist the shear force, resulting in shear failure, sliding along the weak joint, and then causing landslides and other disasters. Morphology, scale, and engineering environment of rock joint are important factors affecting its shear properties. The research on the shear properties of rock joint can realize the evaluation of rock mass stability, which is of great significance to geotechnical engineering.

There are multiple types of rock joint in nature, which can be divided into two types: regular and irregular. In the aspect of irregular joint, Barton [1, 2] obtained 10 classical curves through statistical analysis on a large number of joint specimens, gave the definition of joint roughness coefficient (JRC) corresponding to the curve, and put forward a widely used calculation formula. Xia *et al.* [3] improved Barton's formula by considering the relationship between peak shear displacement and normal stress. Ban *et al.* [4] discussed the relationships between the peak shear strength and the two roughness parameters and proposed a new criterion for predicting the peak shear strength of rock joints. In the aspect of regular joint, the morphology is mainly saw-tooth. Li *et al.* [5] used concrete to make saw-tooth joint specimens with different saw-tooth angles and carried out shear tests under different normal stresses. It was found that the shear failure mode of saw-tooth rock joint was mainly affected by saw-tooth angle. The joint with small saw-tooth angle will wear out, while the joint with large saw-tooth angle will cut off. Zhao *et al.* [6] established a new strength model of natural rock joints, FRC-JCS model, which comprehensively reflect the influence of joint morphology on shear strength. Shen and Zhang [7, 8] used water, cement, and sand as similar materials to produce regular saw-tooth joint specimens with different saw-tooth angles, studied the shear strength under different normal stresses and saw-tooth angles, and elaborated the shear properties of regular saw-tooth rock joint. Luo *et al.* [9] have developed a rapid

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and integrated manufacturing mold of rock joint, which ensures the consistency between the upper and lower rock joints and shortens manufacturing period.

Barton *et al.* [10, 11] pointed out that stress effect and scale effect are two important aspects of shear strength. In the aspect of stress effect, Patton [12] believed that the shear properties of rock joint are related to normal stress through direct shear tests, and on this basis, proposed a bilinear strength formula. Homand *et al.* [13] conducted cyclic direct shear test on granite joint under low normal stress, small size, and small undulation. The results show that the wear of saw-tooth joint will be more serious with the increase of normal stress. Seidel *et al.* [14, 15] explained that the dilatancy angle decreased significantly with the increase of effective normal stress from the view of energy transfer consumption through indoor direct shear test on artificial regular saw-tooth joint specimens. Indraratna *et al.* [16] confirmed that the ratio of shear strength and normal stress varies bilinear with the increase of normal stress. Based on three-dimensional morphology of rock joint, Grasselli *et al.* [17–20] proposed the shear failure criterion of rock joint and pointed out that peak friction angle decreased with the increase of normal stress. In the aspect of scale effect, Barton *et al.* [21] has found that with the increase of the specimen scale, the average shear strength is nonlinear attenuation. When specimen scale is larger than a certain value, peak shear stress tends to be stable. Du *et al.* [22, 23] calculated the error between the empirical value of JRC-JCS criterion and the measured value under different humidity and considered that the reliability of the estimation of joint shear strength under dry or saturated conditions is questionable. Huang *et al.* [24, 25] improved the similar materials and test technology of rock and realized a direct shear test of multi-scale specimen. Lin *et al.* [26, 27] proved that the frost heaving force of water bearing joints in cold regions increases with the increase of scale. Liu *et al.* [28] observed there is an overall negative scale effect on the shear characteristics of rock joint, but there may also be a positive scale effect or no scale effect within a limited joint length range.

In conclusion, many scholars have made a lot of achievements in the shear properties of rock joint, but stress effect and scale effect of double saw-tooth joint still need a further research. According to previous research, normal stress is divided into few levels, and the obtained scale effect variation rules are quite different. In this study, 3D printing technology and rock joint integrated mold are used to produce double saw-tooth joint specimens with different saw-tooth heights, saw-tooth widths, and saw-tooth spacings. The stress effect and scale effect of double saw-tooth rock joint are studied by the self-developed multi-

functional rock-soil contact damage test system, and the variation law of shear properties is revealed.

2 Experiments

2.1 Self-developed multifunctional rock-soil contact damage test system

A self-developed multifunctional rock-soil contact damage test system is used to study stress effect and scale effect of rock joint. The test system is composed of loading frame, hydraulic system, electro-hydraulic servo loading actuator, and computer controller (Figure 1). It is also equipped with auxiliary devices such as shear box, specimen mold, and conveying device. It can be used for horizontal shear test of rock with joint surface under vertical loading.

The maximum normal load supported by the system is 1000kN, the maximum shear load is 1000kN, and the maximum shear displacement is 200mm. By adjusting the number and arrangement of filler blocks, shear tests of specimens with scale of 100×100×100mm, 200×200×200mm and 300×300×300mm can be achieved. The load measurement accuracy is 1% of the indication, the load measurement range is 40-1000kN, and the displacement measurement resolution is 0.01mm.

Figure 1: Self-developed multifunctional rock-soil contact damage test system

2.2 Similar materials

As a kind of elastic brittle material, rock specimens will be destroyed in the process of shear test, so it is impos-

Table 1: Uniaxial compressive strength of each mix ratio

Cement-Sand ratio	Uniaxial compressive strength / MPa
1:0.8	31
1:0.9	36
1:1	42

Table 2: Physical and mechanical parameters of similar material

Gravity / ($\text{kN}\cdot\text{m}^{-3}$)	Compressive strength / MPa	Elastic modulus / GPa	Cohesion / MPa	Friction angle / °
2.73	42	35	5.6	33

sible to reuse. On-site sampling of original rock joint has the disadvantages of high risk, high cost, and difficulty in transportation. Furthermore, it is difficult to ensure the consistency of specimens in terms of roughness, strength, and internal structure.

As a common similar material, cement mortar has been widely used in direct shear tests and compression tests. Compared with original rock, cement mortar specimen has similar brittleness, stable physical and mechanical properties, large adjustment range of strength, specimen manufacturing process, and easily accessible materials. In order to ensure the physical and mechanical properties of cement mortar as close to rock as possible, compression tests are carried out under three mass mix ratios.

Similar materials are P·O 42.5 common portland cement, ISO standard sand, early strength agent, and water. Three cube specimens are made for each mix ratio, and the uniaxial compression test is performed after 28 days of constant temperature curing to obtain the corresponding compressive strength. The test results are shown in Table 1.

Comparing three ratios, the mix ratio is selected as cement: sand: water: early strength agent=1:1:0.33:0.015, whose compressive strength is 42 MPa. Physical and mechanical parameters of selected similar material are shown in Table 2.

2.3 Specimen production

3D printing is a technology based on digital model, using PLA adhesive materials to construct objects with specific morphology through layer-by-layer printing. Compared with steel joint panel, producing 3D printing joint panel can effectively improve production efficiency and save production cost. Producing process for 3D printing joint panel is shown in Figure 2.

Figure 2: Producing process of 3D printing joint panel

Flatness, porosity of specimens, and fit degree of upper and lower plates have important influence on direct shear test, so pouring quality of joint specimens is particularly important. Traditional mold has some defects, such as long production time, complex steps, rough surface, and so on. Therefore, the rock joint integrated mold is developed, which has the advantages of simple process, convenient assembly, and easy vibration. Furthermore, the rock joint

integrated mold can pour upper and lower plates simultaneously, which effectively improves the fit degree and ensures the consistency of the mechanical properties of upper and lower plates. Production process of rock joint specimen is as follows:

- (1) Mold cleaning and oiling. Clean the mold with clean water, and then evenly apply release agent on the inner wall of the mold.
- (2) Mold assembling. The joint panel made by 3D printer can be inserted into the side plate and located in the middle of the mold. Assemble the plates in sequence and tighten them with bolts to avoid loosening during vibration.
- (3) Material weighing. In order to ensure uniformity, three specimens are made for each batch. Weigh the cement, sand, water, and early strength agent respectively according to the mix proportion.
- (4) Material mixing. Put the cement and sand into the mixing tank for preliminary mixing, then mix and dissolve the early strength agent and water, pour it into the mixing tank, and mix for five minutes to make it uniform.
- (5) Material adding. Put the evenly stirred material into the mold. The material is added in three steps, and the height of each time is about 1/3 of the total height.
- (6) Specimen vibrating. Place the mold on the vibration table and vibrate until there are no bubbles on the mortar surface. The vibration time shall not be less than 20 seconds.
- (7) Repeat steps (5) – (6) for the following two times of material addition and vibration, and then smooth the surface.
- (8) Specimen curing. In order to make the specimen reach the expected strength, the mold and the specimen are placed in the standard curing room for 28 days. The curing temperature is $20 \pm 2^\circ\text{C}$, and the humidity is greater than 50%.
- (9) Demolding and labelling. In order to reuse the mold and improve the preparation efficiency, take out the mold after curing for one day when the strength has reached a certain strength. After demolding, label on the specimen, and then put the specimen back into the standard curing room to continue the subsequent curing.

Production material of rock joint specimen is shown in Figure 3, and typical double saw-tooth joint specimen is shown in Figure 4.

Figure 3: Production material of rock joint specimen

Figure 4: Typical double saw-tooth joint specimen

3 Stress effect on shear properties of double saw-tooth rock joint

3.1 Test scheme

Saw-tooth height, saw-tooth width, saw-tooth spacing, and saw-tooth number are the main factors affecting the shear properties of double saw-tooth rock joint. Figure 5 is the schematic diagram of double saw-tooth joint, in which H is the saw-tooth height, L is the saw-tooth width, and S is the saw-tooth spacing. In order to study the influence of the main factors, joint specimens with saw-tooth height of 5mm, 10mm, and 15mm, saw-tooth width of 10mm, 15mm, and 20mm, and saw-tooth spacing of 20mm and 40mm are selected for direct shear test. Meanwhile, single saw-tooth joint specimen with saw-tooth height of 10 mm and saw-tooth width of 10 mm is selected as a control group. The morphology parameters of joint specimens are shown in Table 3.

The level of normal stress should be divided as detailed as possible to obtain more accurate data. The value of normal stress is determined by uniaxial compression test and preliminary shear test. Normal stress ranges from 0.5MPa to 30MPa. Moreover, it is divided into eight levels: 0.5MPa, 1MPa, 5MPa, 10MPa, 15MPa, 20MPa, 25MPa, and 30MPa.

Table 3: Morphology parameters of joint specimens

Joint label	H /mm	L /mm	S /mm
ST-1	5	10	20
ST-2	10	10	20
ST-3	15	10	20
ST-4	10	15	20
ST-5	10	20	20
ST-6	10	10	40
ST-7	10	10	-

Figure 5: Schematic diagram of double saw-tooth rock joint

According to the test results of ST-1 under various shear velocities, the accuracy of the system will decrease with the increase of shear velocity, and the test time will increase exponentially with the decrease of shear velocity. When the shear velocity is 1.2mm/min, test time can be saved while ensuring high accuracy. The shear stress has reached the peak shear strength before the shear displacement reaches 15mm, and can fully show the characteristics after the peak. Therefore, 1.2mm/min is selected as the shear velocity and 15mm shear displacement is selected as the termination condition. In the process of direct shear test, normal stress is loaded by constant force in the vertical direction, shear stress is loaded at a constant velocity in the horizontal direction. Apply the normal stress to a predetermined value, and then start shearing. When the shear stress reaches peak shear strength, the stress-strain curve will show a significant slope change, and it can be inferred that the specimen has undergone shear failure. Then continue to load until the shear stress is stable.

3.2 Shear failure mode of double saw-tooth rock joint

For saw-tooth rock joint, the shear failure modes mainly include overriding effect, coupling effect of overriding and cutting off, and cutting off effect [29]. Coupling effect of overriding and cutting off of double saw-tooth rock joint is shown in Figure 6, and the cutting off effect is shown in Figure 7. Direct shear tests are carried out on specimens with seven kinds of morphology under eight levels of normal stress, and the shear failure modes are recorded as shown in Table 4.

Results show that the shear failure modes of double saw-tooth rock joint include coupling effect of overriding and cutting off, and cutting off effect, but not overriding effect. With the increase of normal stress, the failure mode of double saw-tooth rock joint with different morphologies changes from coupling effect of overriding and cutting off to cutting off effect. The normal stresses corresponding to the change of failure mode are also different. Comparing the results of ST-1, ST-2, and ST-3, it is found that the larger the saw-tooth height, the lower the normal stress corresponding to the change of failure mode. Comparing the results of ST-2, ST-4, and ST-5, it is found that the larger the saw-tooth width, the higher the normal stress corresponding to the change of failure mode. Comparing the results of ST-2 and ST-6, it is found that the larger the saw-tooth spacing, the higher the normal stress corresponding to the change of failure mode.

Figure 6: The coupling effect of overriding and cutting off **Figure 7:** Cutting off effect

Table 4: Shear failure modes

Normal stress /MPa	ST-1	ST-2	ST-3	ST-4	ST-5	ST-6	ST-7
0.5	Coupling	Coupling	Coupling	Coupling	Coupling	Coupling	Coupling
1	Coupling	Cutting	Cutting	Coupling	Coupling	Coupling	Coupling
5	Coupling	Cutting	Cutting	Cutting	Coupling	Coupling	Cutting
10	Cutting	Cutting	Cutting	Cutting	Cutting	Cutting	Cutting
15	Cutting	Cutting	Cutting	Cutting	Cutting	Cutting	Cutting
20	Cutting	Cutting	Cutting	Cutting	Cutting	Cutting	Cutting
25	Cutting	Cutting	Cutting	Cutting	Cutting	Cutting	Cutting
30	Cutting	Cutting	Cutting	Cutting	Cutting	Cutting	Cutting

note: Coupling is coupling effect of overriding and cutting off, Cutting is cutting off effect.

3.3 Stress effect on shear stress-displacement curve of double saw-tooth rock joint

3.3.1 Flat rock joint

Figure 8 shows the relationship of shear stress and displacement obtained from direct shear test of flat joint specimens under eight levels of normal stress. Results show that the shear stress under different normal stresses increases with the increase of shear displacement before the shear stress reaches peak shear strength for flat rock joint. The higher the normal stress, the higher the increase of shear stress. When normal stress is lower (≤ 10 MPa), with the increase of shear displacement, the shear stress reaches peak and remains stable. When normal stress is larger (≥ 15 MPa), with the increase of shear displacement, shear stress decreases

after reaching peak, and then remains stability, which reflects the characteristics of post-peak shear softening.

3.3.2 Double saw-tooth rock joint

Figure 9 is the shear stress-displacement curve of ST-2 (saw-tooth height of 10 mm, saw-tooth width of 10 mm, saw-tooth spacing of 20 mm) under different normal stresses. Results show that the shear stress of double saw-tooth joint increases first, then decreases, and finally tends to be stable with the increase of shear displacement, which reflects the characteristics of pre-peak shear hardening and post-peak shear softening. The shear displacement corresponding to peak shear strength increases with the increase of normal stress. Peak shear strength and residual shear strength increase with the increase of normal stress.

Figure 8: Shear stress-displacement curve of flat rock joint under different normal stresses

Figure 9: Shear stress-displacement curve of double saw-tooth rock joints under different normal stresses (ST-2)

3.4 Stress effect on shear strength of double saw-tooth rock joint

Figure 10 shows the variation law of shear strength with normal stress of double saw-tooth rock joint with different saw-tooth heights. Figure 11 shows the variation law of shear strength with normal stress of double saw-tooth rock joint with different saw-tooth widths. Figure 12 shows the variation law of shear strength with normal stress of double saw-tooth rock joint with different saw-tooth spacings. Results show that the shear strength of the double saw-tooth

Figure 10: Relationship between shear strength and normal stress under different saw-tooth heights

Figure 11: Relationship between shear strength and normal stress under different saw-tooth widths

Figure 12: Relationship between shear strength and normal stress under different saw-tooth spacings

rock joint with various morphologies increases with the increase of normal stress. Compared with flat rock joint ($H = 0 \text{ mm}$), the shear strength change rate of double saw-tooth rock joint decreases with the increase of normal stress, showing a nonlinear variation law. The shear strength of the double saw-tooth rock joint does not change with the increase of saw-tooth height, *i.e.*, saw-tooth height has no obvious effect on shear strength. Under the same normal stress, the shear strength increases with the increase of saw-tooth width and spacing.

3.5 Stress effect on peak friction angle of double saw-tooth rock joint

For the purpose of studying the relationship between peak friction angle and normal stress, the arctangent formula of peak shear strength and normal stress is adopted as follows:

$$\phi_p = \arctan \left(\frac{\tau_p}{\sigma_n} \right) \quad (1)$$

where the τ_p is peak shear strength, the σ_n is normal stress corresponding to peak shear strength.

The specimens with saw-tooth number of 0, 1, and 2, saw-tooth height and saw-width of 10 mm (flat joint, ST-2, and ST-7) are selected for comparison. By substituting the shear test results into Formula (1), the relationship between peak friction angle and normal stress is obtained as shown in Figure 13. Result shows that the peak friction angle of double saw-tooth and single saw-tooth rock joint decreases with the increase of normal stress, and finally tends to a

constant value, showing a nonlinear variation law. Peak friction angle of flat rock joint does not change with normal stress basically, so there is no obvious stress effect. The variation rate of peak friction angle with normal stress decreases with the increase of normal stress. Under the same normal stress, peak friction angle increases with the increase of the number of saw-tooth. Therefore, for double saw-tooth rock joint, the influence of buried depth, ground load, and other factors should be considered in engineering practice, and the shear performance parameters should be modified.

The stress effect of peak friction angle of double saw-tooth rock joint is closely related to shear failure mode. Compared with Table 4, when normal stress is in the range of 0–5 MPa, the peak friction angle is large, and the decline rate is high. Meanwhile, the failure mode is mainly the coupling effect of overriding and cutting off. When normal stress is more than 5 MPa, the decline rate of peak friction angle decreases obviously and the peak friction angle tends to a constant value, and the failure mode changes to cutting off effect. It can be inferred that the change of failure mode is an important reason for the decrease of peak friction angle. The overriding effect will increase the peak friction angle. When the cutting off effect in the coupling effect of overriding and cutting off gradually occupies the main part, the peak friction angle will also decrease and tend to a constant value.

Figure 13: Relationship between the peak friction angle and normal stress of rock joint with different saw-tooth numbers

4 Scale effect on shear properties of double saw-tooth rock joint

4.1 Test scheme

For the purpose of studying scale effect on shear properties of double saw-tooth rock joint, specimens with scale of $100 \times 100 \times 100$ mm, $200 \times 200 \times 200$ mm, and $300 \times 300 \times 300$ mm are made by cement mortar. The saw-tooth height, width and spacing of double saw-tooth specimen with scale of $100 \times 100 \times 100$ mm are 10 mm, 10 mm, and 20 mm respectively. For the sake of the consistency of normal stress distribution, the joint morphologies of other scale specimens are determined by the method of equal scale amplification.

Considering the influence of instrument range, the mix ratio of similar materials is further optimized. The mix ratio of cement, sand, and water is adjusted to 1:4:1, of which the uniaxial compressive strength is 3.0 MPa. Normal stress ranges from 0.25 MPa to 1.75 MPa. Moreover, it is divided into seven levels: 0.25 MPa, 0.5 MPa, 0.75 MPa, 1 MPa, 1.25 MPa, 1.5 MPa, and 1.75 MPa. Normal stress is loaded by constant force in the vertical direction, shear stress is loaded at a constant rate of 1.2 mm/min in the horizontal direction, and the termination condition is selected as shear displacement of 15 mm. Double saw-tooth joint specimens with different scales are shown in Figure 14.

Figure 14: Double saw-tooth joint specimens with different scales

4.2 Scale effect on shear stress-displacement curve of double saw-tooth rock joint

Figures 15–17 show the relationship between shear stress and shear displacement under different normal stresses for three scales of double saw-tooth joint specimens. Results show that the relationship between shear stress and shear displacement of specimens with different scales is basically the same in the process of shear, *i.e.*, the shear stress increases with the increase of shear displacement. The higher the normal stress, the higher the shear stress

Figure 15: Shear stress-displacement curve of double saw-tooth rock joints under different normal stresses (scale=100mm)

Figure 16: Shear stress-displacement curve of double saw-tooth rock joints under different normal stresses (scale=200mm)

increases. When reaches peak shear strength, the shear stress of specimens with different scales will decrease and tend to be stable, showing the characteristics of post-peak shear softening. The higher the normal stress, the larger the shear displacement corresponding to peak shear strength. Peak shear strength and residual shear strength increase with the increase of normal stress.

Figure 17: Shear stress-displacement curve of double saw-tooth rock joints under different normal stresses (scale=300mm)

Figure 18: Relationship between shear strength and scale under different normal stresses

Figure 19: Relationship between peak friction angle and scale under different normal stresses

4.3 Scale effect on shear strength and peak friction angle of double saw-tooth rock joint

Figure 18 shows the relationship between peak shear strength and scale of double saw-tooth rock joint under different normal stresses. Figure 19 shows the relationship between peak friction angle and the scale of double saw-tooth rock joint. Results show that the higher the normal stress, the higher the peak shear strength. The scale effect of peak shear strength is characterized by decreasing as the scale increases.

5 Conclusions

The double saw-tooth rock joint specimens with different saw-tooth heights, saw-tooth widths, saw-tooth spacings, and scales are made by the integrated mold. The direct shear tests are carried out on the double saw-tooth rock joint specimens under different normal stresses by the self-developed multifunctional rock-soil contact damage test system. The main conclusions are as follows:

- (1) Based on the similarity principle, cement mortar is selected as the similar material of rock, the mix ratio is determined, and indoor direct shear tests are conducted by the self-developed multifunctional rock-soil contact damage test system. The system has the advantages of high precision, wide range of parameter adjustment, and easy operation.

- (2) The failure modes of double saw-tooth rock joint include couple effect of overriding and cutting off and cutting off effect, which are mainly controlled by the rock joint morphology and normal stress.
- (3) Morphology of rock joint is an important factor affecting the shear strength of double saw-tooth rock joint. The shear strength of double saw-tooth rock joint increases with the increase of saw-tooth width or spacing, but saw-tooth height has no influence on the shear strength.
- (4) There is significant stress effect and stress effect on the shear properties of double saw-tooth rock joint. Normal stress and scale have a weakening effect on the peak friction angle and the growth rate of the peak shear strength with the normal stress. However, there is no stress effect and scale effect on the shear properties of flat rock joint.

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