Method for calculating the shear strength of rock masses with different combined structural planes based on the 3D printing technology

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Abstract. The mechanical behavior of rock masses with different combined structural planes is poorly understood because of the difficulties associated with the performance of rock observations and analyses from the surface, collection of samples during field investigations, specimen preparation, and laboratory tests. The combination of rock mass structural planes has a significant effect on the rock mass mechanical properties. The three-dimensional (3D) printing technology can conveniently create 3D entities with complex structures, thereby providing an unprecedented opportunity to break through this bottleneck. In this study, model samples of structural surface models with different combinations are printed using the 3D printing technology, and a cement slurry with 3:1 water–cement ratio is used as the structural body to produce rock masses with different combined structural planes. The method replicates well the morphological features of natural joints. Moreover, the shear properties and the failure characteristics are stable and consistent. Direct shear tests are also performed on the rock masses of different combined structural planes from the intersection line parallel and perpendicular to the structural planes to obtain the relevant mechanical parameters and rock mass failure modes. The results prove the feasibility of the 3D printing technology in the experimental study of rock mass mechanics and show that the strength and failure modes of rock masses with different combined structural planes are different. A calculation method for the shear strength of rock masses with different combined structural planes is proposed herein based on the experimental data and the Mohr–Coulomb theory, and the method’s feasibility is verified by several examples.

Keywords: direct shear test; rock masses with different combined structural planes; shear strength calculation of rock mass; 3D printing technology
1 Introduction

Rock mass comprises structural planes and bodies. The engineering properties of rock mass, especially its mechanical properties, are not entirely determined by the structural body; they are also determined, to a greater extent, by the structural plane, which comprises material composition, strength, and combined form of the rock mass structural plane (Gu and Wang, 1979; Goodman, 1980; Kwon et al., 2004). The internal structural plane of the cataclastic rock mass is extremely developed (Dong et al., 2018), leading to a small block size, a poor structure, and low physical and mechanical strengths. Once exposed, a slight collision or vibration occurs in the rock mass, which results to a disintegration. A large block, which is the worst type of engineering geological rock mass, is difficult to obtain (Xie, 2011). The cataclastic rock mass is a common rock mass in many large-scale projects. However, obtaining reasonable parameters of the mechanical properties is hard because of the cataclastic rock mass characteristics and the disadvantages of an in-situ test. Therefore, a more reasonable and accurate method for obtaining its strength must be developed. The simulation of the complex structural plane in the rock mass interior has become an important trend and method in which the three-dimensional (3D) printing technology is used. Xu et al. (2019) made 10 groups of structural surface molds with different roughness through 3D printing and poured them with similar materials to obtain samples. They studied the qualitative relationship between structural surface shear strength and roughness under constant normal stress and found that the Button formula was consistent, which verified the feasibility and efficiency of the 3D printing method. Tian et al. (2017) reduced the internal structure of natural sandstone through two processes (i.e., SLS and 3DP) of computed tomography scanning and 3D printing. By analyzing the results of the uniaxial compression and Brazilian split tests, they thought that a large number of repeated tests for samples with a consistent internal structure could be performed by using the 3D printing technology, and the 3DP printing samples were closer to natural sandstone. Yong et al. (2013) used numerical simulation and laboratory tests to study the error effect of the sample preparation in the direct shear test of the rock structural plane and perfected the theoretical analytical correction formula of the shear strength parameters for the structural plane based on this error effect. The 3D printing technology has been widely used in rock structure research in the recent years, but its use had been limited to the verification of the feasibility of printing the structural plane and the shear effect and failure form of the sample with structure. In addition, little research has focused on the specific form of the structural plane distribution in the rock mass (e.g., structural planes with different combined modes in the rock mass). Therefore, using the 3D printing technology is necessary in studying rock masses with different combined structural planes, mainly focusing on the shear failure mode and strength of this type.

In the Mohr–Coulomb strength criterion, the acquisition of the shear strength parameters plays an important role in rock mechanics and engineering (Kahraman et al., 2006; Alejandro and Carranza-Torres, 2011; Gong et al., 2016). In engineering practice, these parameters are often used to assess the damaged area of the rock mass surrounding the excavation and the corresponding support design (Srivastava and Singh, 2015). The $c$ and $\varphi$ determination is the basis for using the Mohr–Coulomb strength criterion to obtain the mechanical properties of specific rock materials. Most mechanical theories belong to continuum mechanics; hence, at present, for the discontinuous rock mass medium with very developed joints and fissures, the $c$ and $\varphi$ values of rock cannot effectively
represent its strength (He et al., 2001). Therefore, the accurate strength must be tested, and the strength relationship must be explored by using an effective method for simulating the rock mass developed in the structural plane. The structural plane of the cataclastic rock mass is short, dense, and often in through state; thus, the integrity and the overall strength of the rock mass are low, showing strong heterogeneity, discontinuity, anisotropy, and other characteristics. This study adopts the 3D printing technology to make a model with two groups of intersecting discontinuities. Sand grains are used to print the structural planes of sandstone in different combinations. The printed structural planes of sandstone are then filled with cement slurry (3:1 water–cement ratio) to simulate a rock mass with a structural plane. A direct shear test of the simulated rock mass is performed. Subsequently, the structural plane effect of different combined structures on the mechanical properties of the rock mass and the different failure modes caused by different combinations are analyzed and compared. An estimation method of the shear strength parameters for the rock mass with different structural plane combination modes is then proposed according to the test results.

2 Test model preparation

2.1 3D printing equipment

In this experiment, we used an S-MAX pro™ 3D printer to print the sample structural planes (Figure 1). Before printing, the powder supply cylinder was filled with the printing material. We propose herein the usage of artificial sand particles to make the rock structural plane model. The feasibility will be explained in Section 2.2. First, a layer of printing material was laid flat in the printing working area. Next, the automatic and efficient printing nozzle was positioned in the cross-section of the printing model set by the computer. Third, a layer of adhesive was sprayed to the core part of the test piece to be printed, such that the sand particles were stuck together (Figure 2). Furan adhesive was used because it is a typical self-hardening adhesive used in the traditional sand-casting application. When the first layer was printed, and the powder was agglomerated, the powder-feeding piston rose to one layer of printing height, while the printing model descended by one layer. We printed the layers one by one following the same method until the whole printing process was finished.

![Figure 1](image1.png) **Figure 1.** Printing principle of the S-MAX pro™ 3D printer

![Figure 2](image2.png) **Figure 2.** Printing materials and basic principles

2.2 Similar materials

Considering that the strength of the structural plane was relatively weak, this study tried to use different printing materials (e.g., clay and sand particles mixed with a binder) to mimic the rock mass structural planes. The structural plane printed with clay swelled with water and was easily cracked...
because of water loss; hence, the unity of style cannot be guaranteed. In contrast, the structural plane printed by the sand particles mixed with a binder not only met the mechanical strength requirements, it also showed good sample integrity and strong operability. Therefore, the rock mass structure planes were printed herein using sand particles mixed with a binder. Cement slurry with 3:1 water–cement ratio is proposed for the structural body because in a previous research on the water–cement ratio, a large number of tests proved that the cement slurry with 3:1 water–cement ratio was a Newtonian fluid with good fluidity and can be filled in the sample box more evenly and uniformly (Qin et al., 2015; Zhang, 2018). Meanwhile, the mechanical strength was close to that of limestone, which is classified as a hard rock.

Direct shear tests were performed on two similar materials without a structural surface to determine the applicability of 3D printing sand particles and cement slurry as similar materials. Table 1 lists the measured strength parameters. The data depicted that the cohesions of the printed structural plane and the rock mass body were 1780 kPa and 3630 kPa, respectively. Moreover, the friction angles of the printed structural plane and the rock mass body were 39.2° and 57.3°, respectively. According to strength, the friction coefficient of the structural plane, which was a hard structural plane with good cementation and not affected by weathering, was 0.806. The difference between the strengths of the structural plane and the structural body was large, thereby better reflecting the effect of the different combined structural planes on the rock strength in this test.

Table 1. Strength parameters of similar materials

| Type              | c (kPa) | φ (°) |
|-------------------|---------|-------|
| Structural plane  | 1780    | 39.2  |
| Structural body   | 3630    | 57.3  |

2.3 Structural plane

Existing research on the strength of rock masses with structural planes mainly concentrated on rock masses with a single structural plane. Although some studies on rock masses used multiple sets of structural planes, these structural planes were mostly prefabricated cracks, and the model making cannot guarantee a complete consistency (Sha et al., 2012; Xiao et al., 2012). The present study mainly focused on rock masses with two sets of structural planes having different combinations, which were mainly reflected in the different structural plane intersection angles of 30°, 60°, and 90°. ANSYS was used to build the printed structural plane model (Yazdizadeh, 2010). The 3DP printing technology was employed to print the structural plane model. The printed structural surface had a low mechanical strength; hence, the printed structure must be filled with fine sand particles to prevent damage (Figure 3).
2.4 Rock mass with a structural plane
A large number of studies (Li et al., 2003; Li, 2015) have shown that in a certain range, the larger the contact surface, the more obvious the size effect. Therefore, test results obtained using a small-scale model are more representative. In this study, the test was conducted using a cube with a 50 mm side length. A high-uniformity cement was selected as the pouring sample mixed according to the abovementioned proportion. A slight vibration was performed during pouring to prevent the bubble-induced unevenness in the sample and reduce the influence of the sample inhomogeneity on the testing results. The cement slurry was used to fill the printed structural planes in the 50 mm × 50 mm × 50 mm model box. The curing time was approximately 72 h. A total of 50 models for each combined model structural plane were prepared (Figure 4). In addition, cement samples with no structural surface were also produced to facilitate a comparative analysis of the later tests.

![Figure 4. Samples with a structural plane](image)

3 Experiment

3.1 Experiment scheme
All tests were conducted using a portable direct shear apparatus (Figure 5) (Su et al., 2005) at the State Key Laboratory of Geohazard Prevention and Geoenvironment Protection at the Chengdu University of Technology. In the direct shear test, the samples with different combined structural surface angles were placed in two different directions (i.e., the shear direction perpendicular to the intersection line of the structural plane and the other direction parallel to the intersection line) (Figure 6). In each direction, each type was shear-tested under normal stresses of 0.5, 1.0, 1.5, 2.0, and 2.5 MPa. At least five samples shall be tested under each normal stress group to avoid affecting the test results due to operation and other problems.

![Figure 5. Portable direct shear apparatus](image)

![Figure 6. Schematic diagram of the cutting direction](image)

3.2 Experiment procedure
The specific test steps are as follows:

a) Sample placement: The specimen was put into the appropriate shear box by adjusting the height of the rigid block at the bottom of the lower shear box. The shear box devices (e.g., rigid force transfer iron and ball bearing) were placed on top of the specimen.

b) Jack position adjustment: The oil pump handle was shaken. The horizontal jack was pressed close to the push plate of the upper shear box, and the initial value was recorded. The piston of the normal jack close to the shear box was pressed. The initial value was recorded. The positive pressure was then applied to the predetermined axial pressure and kept unchanged.

c) Displacement meter installation: The seat displacement meter was installed close to the outside of the moving direction of the upper shear box. Zero adjustment was conducted.

d) Start of shearing: The shear load was applied step by step (0.2 MPa for each step) through the horizontal jack. The readings of the oil pressure and displacement gauges under each shear load level were recorded until the specimen was completely destroyed.

e) Sample unloading and removal: Failure was observed, and the next set of tests was performed.

f) Data analysis: The shear stress–shear displacement curve was drawn according to the recorded data. The cohesion (c) and the internal friction angle (φ) of the sample were calculated according to the Mohr–Coulomb strength theory. Finally, the most reasonable data were selected for analysis.

4 Shear test results

4.1 Shear stress–shear displacement curve analyses

Figures 7(a) and (b) show the shear stress–shear displacement curves of the rock mass model with different combined structural planes and the typical photos of the shear plane after the model was sheared. The curve characteristics of these samples can mainly be interpreted using the failure mode variations, shear stress–shear displacement relation, and curve shape. The peak stress of the samples seemed to increase with the axial pression. The structural plane failure mode of these samples was divided into two types, namely brittle and plastic failures. The structural body was mainly a shear failure.

The curves indicated that the shear failure mode was a brittle failure when the shear direction was perpendicular to the intersection line of the structural planes. The curve can be roughly divided into three stages (Figure 8). The first stage is 0–1, in which the stress and the strain are linearly changed, and the stress at Point 1 is the proportional ultimate strength of the sample. We entered the second stage as the shear stress application continued. In this stage, the microcracks were generated inside the sample; the curve slope decreased; and the stress value at Point 2 was the sample’s yield strength. The displacement change rate increased in the third stage, and the sample was completely destroyed after reaching the peak stress (Point 3). The stress then dropped to residual stress (Point 4). The test photos depicted that the internal structural body of the sample was cut into rock columns by the structural plane (Figure 9). The brittle shear failure of the rock column occurred in this shear direction, further verifying that the failure mode of these samples under the action of the shear force was brittle failure. Figure 9 also shows that the samples with different combined structural planes had different curve types. The shear stress–shear displacement curve of the sample with an included angle of 30° was a yield type, while the intersection angle of 60° was a shear type. The 90° intersection structural plane
was relatively straight in the shear direction, and the stress was more uniform; hence, the maximum shear stress increased with the normal stress increase. This resulted to an increase in the angle of the shear failure surface, which led to increases in the failure surface area and in the shear resistance of the structural plane. In addition, the larger normal stress will cause a greater friction of the structural plane. Therefore, the curve shape of the intersection angle of 90° is a shear type when the shear stress is low. The yield type appeared with the increase of the normal stress.

The failure mode of the samples belonged to plastic failure when the shear stress was parallel to the intersection line of the structural planes. The curve shows a large shear displacement before the sample was completely destroyed. The shear stress was also basically unchanged after the failure. In other words, the sample slid along the shear plane at a certain rate after being completely sheared, which is basically consistent with the shear plane development along the structural plane shown in the test photos. The presented curves are all slip type because of the ultimate failure along the structural plane. The difference in the failure modes between the two shear modes was caused by the different main controlling factors of the rock mass strength. The rock mass strength in the parallel shear was mainly controlled by the structural plane. The failure mode was mainly caused by the slip failure along the structural plane. Meanwhile, the rock mass shear strength in the vertical shear was controlled by both the rock and the structural plane. The influence of the rock mass shear strength was also greater. The failure mode was mainly the rock shear failure.

![Figure 7. Shear stress–shear displacement curves: a) shear stress perpendicular to the intersection line of the structural planes and b) shear stress parallel to the intersection line of the structural planes](image-url)
Figure 8. Shear stress–shear displacement curve stage division

4.2 Shear strength analyses

Figures 10 (a) and (b) show that the shear strength measured by the samples with different combined structural planes was different. Furthermore, the data deviation under various test conditions was objectively reflected by the goodness of fitting or the fitting coefficient (R). A greater R represents less data deviation.

As mentioned in Section 2.2, the $c$ value of the unstructured samples was 3630 kPa; $\varphi$ was 57.3°; and the $c$ value of the structural surface was 1780 kPa with 39.2° $\varphi$. The $c$ values of the samples with 30°, 60°, and 90° combined structural plane angles were 4750, 6080, and 4280 kPa, respectively, when the shear direction was perpendicular to the intersection line of the structural plane. The test photos in Section 4.2 depicted that when the combined angle of the structural plane was 60°, the shear plane fluctuation was the largest, while the 30° and 90° fluctuations were small and close, thereby reflecting a different degree of the tooth cutting effect when cutting a rock column with different combined structural plane angles. This also resulted in different $c$ values. The tooth cutting effect was the strongest when the combined angle of the structural plane was 60°; thus, the $c$ value was the largest. Meanwhile, the $c$ values of 30° and 90° were similar. The $\varphi$ values of the samples with the 30°, 60°, and 90° combined structural plane angles were 60.3°, 37.2°, and 32.6°, respectively. The result showed that the $\varphi$ value of the sample was close to that of the sample without a structural plane when the combined angle of the structural plane was smaller. Accordingly, the $\varphi$ value decreased as the combined angle increased.

The $c$ values of the samples with the 30°, 60°, and 90° combined structural plane angles were 2360, 1200, and 1710 kPa, respectively, when the shear stress was parallel to the intersection line of the structural plane. Figure 11 shows that the stress area of the structural body within the unit shear area was the largest when the combined angle of the structural plane was 30°, and this was the minimum when the combined angle was 60°. We observed the following conclusion when the shear stress was parallel to the structural plane intersection: the larger the area of the structural body within the unit shear area, the larger the $c$ value. The $\varphi$ values of the samples with the 30°, 60°, and 90° combined structural plane angles were 64.9°, 52.6°, and 44.7°, respectively. The analysis depicted that the $\varphi$ value was related to the $c$ value of the structural plane and the undulation degree of the shear plane. Figure 12 illustrates that all the values broke through along the structural plane. During this time, the $\varphi$ value mainly depended on the fluctuation angle of the shear plane. Therefore, when the shear stress was parallel to the structural plane intersection, the $\varphi$ value decreased as the combined angle increased.
increased.

![Figure 10](image1.png)

**Figure 10.** Shear stress–normal stress curves: a) shear stress perpendicular to the intersection line of the structural planes and b) shear stress parallel to the intersection line of the structural planes

![Figure 11](image2.png)

**Figure 11.** Distribution of the force-bearing area of the structural body within the unit shear area

![Figure 12](image3.png)

**Figure 12.** Shear plane fluctuation

4.3 Strength calculation method of the rock mass with different combined structural planes

The data and analyses showed that the shear strength of a rock mass with a discontinuity had a certain regularity. When the rock mass was sheared perpendicular to the intersection line of the structural plane, the sample’s strength was relatively increased because of the tooth cutting effect between the rock columns. Simple and sketchy calculation formulas are presented below (i.e., Eqs. 4.1 and 4.2) on the premise of the shear strength of a rock mass with a structural plane and body being known. When the rock mass was sheared parallel to the intersection line of the structural plane (Section 4.2) above, all rock masses were destroyed along the weak structural plane. The measured strength mainly depended on the proportion of the structural plane in the unit shear area and the $c$ and $\phi$ values for the structural plane. The following estimation formulas are proposed according to these relations (Eqs.
4.3 and 4.4).
\[ c = \frac{4}{3}c_1 + \frac{1}{2}c_2 \cdot \sin \left( \frac{\theta - 30^\circ}{60^\circ} \pi \right) \]  (4.1)
\[ \varphi = 2\varphi_1 \left( e^{\frac{2\theta}{\varphi_2}} \right) + \varphi_2 \]  (4.2)
\[ c = -4c_2 \times S + 2c_2 \]  (4.3)
\[ \varphi = 10\sin \left( \frac{S}{S_3} \pi - \frac{1}{3} \pi \right) + \varphi_2 \]  (4.4)

where, \( c \) and \( \varphi \) are the cohesion and the internal friction angle of the rock mass with two groups of structural planes, respectively; \( c_1 \) and \( \varphi_1 \) are the cohesion and the internal friction angle of the structural body, respectively; \( c_2 \) and \( \varphi_2 \) are the cohesion and the internal friction angle of the structural plane, respectively; \( \theta \) is the combined angle of the internal structural plane of the rock mass in the investigation area; \( S \) is the structural plane proportion in the unit shear area; and \( S_3 \) is the proportion of the three structural planes in the unit shear area.

According to the calculation of the abovementioned formulas, the approximate value of the shear strength for a rock mass with a developed structural plane can be directly obtained when field investigation is performed, even with the inconvenience of a field in-situ test caused by equipment, funds, and other problems, to facilitate direct rock and soil division on the site analysis. This study took a fractured rock mass at a point in the bedding shear zone of the Daguangbao landslide as an example for verification. The field drilling shear test showed that \( c = 1227.4 \) kPa, \( \varphi = 25.7^\circ \) when the structural plane was approximately perpendicular to the shear; \( c = 398.7 \) kPa; and \( \varphi = 32.8^\circ \) when the structural plane was approximately parallel to the shear. Statistics showed that the intersection angle of the joints at this point was approximately 160\(^\circ\); the structural body was \( c_1 = 935 \) kPa, \( \varphi_1 = 40^\circ \); the structural plane was \( c_2 = 210 \) kPa, \( \varphi_2 = 26^\circ \); the proportion of the structural plane in the unit shear area was approximately 0.035; and the three structural planes in the unit shear area were approximately 0.047. Equations 4.1 and 4.2 obtained the cataclastic rock mass of \( c \approx 1298 \) kPa, \( \varphi \approx 26^\circ \), while Eqs. 4.3 and 4.4 yielded the cataclastic rock mass of \( c \approx 391 \) kPa, \( \varphi \approx 35.8^\circ \), which is similar to the strength obtained from the field shear test. The applicability of the formula has been proven.

5 Conclusions

Based on the 3D printing technology, this study made rock samples for direct shear tests and proposed a shear failure mode, a strength change rule, and a calculation method of the rock mass with different combined structural planes. Direct shear tests were performed perpendicular and parallel to the intersection line of the structural plane using the 3D printing technology, artificial sand particles combined with furan adhesive to make weak structural planes, and cement slurry with 3:1 water–cement ratio as the structural body filling. The vertical perpendicular shear was found to be a brittle failure, and its strength was related to the tooth cutting effect between the rock columns formed by the different combined structural planes. Meanwhile, the parallel shear was a plastic failure, and its strength was related to the proportion of the structural planes in the unit shear area. Relevant estimation formulas were put forward herein according to these findings. Importantly, these results can be applied to field analysis. According to the strength of the structural plane and body, the approximate combination angle of the structural plane can be obtained through investigation. The approximate strength value of the rock mass, including a structural plane, can also be obtained.
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