Study on the mechanical behaviour of Columnar Jointed Rock Mass under uniaxial compression state

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Abstract. The columnar joint is a special type of primary joints which the cross sections are mostly quadrilateral, pentagonal and hexagonal. Intact rock mass is always cut by columnar joints into regular or irregular rock prisms, resulting in poor properties. With the expansion of large-scale engineering activities, a number of hydropower engineering such as Baihetan hydropower station, Xiluodu hydropower station and Ertan hydropower station, have encountered columnar jointed rock mass. The existence of columnar jointed rock mass poses a challenge to the design, construction and safe operation of these projects. To understand the mechanical behaviour of columnar jointed rock mass, uniaxial compression tests were carried out on artificial specimens made from rock-like materials. In the experiments, a self-designed pouring apparatus was used to prepare the columnar jointed rock-like specimens. Based on the experimental results of axial stress–axial strain curves, the strength and deformation of columnar jointed rock mass were investigated. The effect of columnar joint inclination angle on the mechanical behaviour of columnar jointed rock mass was analysed. It is found that the columnar jointed rock masses are characterized by significant anisotropy. The strength of columnar joint plays a significant role on the mechanical response of columnar jointed rock mass. The study

1. Introduction

Rock mass is a geological body composed of matrix rock and structural plane after a long and complex geological process. Structural plane is an important part of rock mass and a fundamental reason why rock mass is different from other geological bodies [1-2]. The existence of structural plane greatly changes the mechanical behaviour of the whole rock mass, destroys the integrity of the rock mass, degrades the mechanical parameters of the rock mass, showing strong discontinuity, heterogeneity, anisotropy and nonlinear characteristics.

Columnar joint is a special kind of primary joint with cross section of quadrilateral, pentagon and hexagon. It often cuts rock into regular or irregular prism. With the development and utilization of water resources in the world, many large and medium-sized water conservancy and hydropower projects are exposed to the engineering problems of columnar jointed rock mass, such as Grand Coulee Dam in America, Lakhwar Dam in India, Baihetan hydropower station, Xiluodu hydropower...
station and Ertan hydropower station in China. The mechanics of columnar jointed rock masses (CJRM) pose a challenge to the development of rock mechanics and rock engineering.

Over the past years, substantial efforts have been made to understand the geological structure characteristics, formation mechanism and mechanical properties of CJRM. The formation mechanism of columnar jointed rock mass mainly includes cooling shrinkage theory [3], double diffusion convection theory [4] and tension torsion theory [5], among which cooling shrinkage theory is generally accepted. Due to the demands of engineering construction, some progress has been made in the study of mechanical properties of columnar jointed rock mass in recent years, mainly related to the BWIP project in America and the Baihetan Hydropower Project in China. Based on in-situ elastic wave test results, Kim [6] and King [7] preliminarily discussed the anisotropy of basalt with columnar joints in BWIP project. Jiang [8] pointed out that there are three structure-stress failure modes in the surrounding rock with columnar joints. Fan [9], studied the unloading relaxation characteristics and corresponding failure mechanism of columnar jointed rock mass by integrating various field test monitoring technologies, which can provide reference for the excavation and support scheme of columnar jointed rock mass in the cavern of Baihetan project. Based on 3D printing technology, irregular columnar jointed rock-like specimens were prepared by Lin [10] to study the weakening effect of columnar joints on the mechanical properties of rock mass.

To obtain an improved knowledge of the anisotropic mechanical properties of the CJRM, a physical model test is presented in this paper. Uniaxial compression tests are conducted on artificial CJRM specimens with hexagonal distribution structure, which is similar to the actual CJRM. The mechanical behaviour and anisotropic features are analyzed. The test results could provide a good reference engineering practice involved in CJRM.

2. Test scheme

2.1 Specimen preparation

In this paper, the typical hexagonal columnar jointed rock mass is taken as the research object, and artificial CJRM specimens with similar geological structure of the actual CJRM is used. The basalt with columnar joints in the dam foundation has high strength and stiffness without disturbance, and it is closely embedded. It is considered to use high-grade cement mortar for modelling the columnar, and then use high-grade cement slurry to bond each hexagonal column. The cement mortar is composed of cement, water and sand, at a mass ratio of 1:0.3:0.45. The cement slurry is composed of cement and water at a mass ratio of 1:0.45. The cement used for the cement mortar and cement slurry is NO.52.5 Poland cement.

A self-designed pouring apparatus is used to prepare the artificial CJRM specimens. The pouring apparatus is composed of several semi grooved plexiglas, which are spliced together to form the fracture grid of regular hexahedron with columnar joints, as shown in Figure 1. A detailed description about artificial CJRM specimens preparation procedure is show in the literature [11].
Figures 1 [11] (a) the symmetrical pouring mold (b) pouring apparatus (c) The prepared columnar jointed rock mass

2.2 Test apparatus and test procedure
Uniaxial compression tests were carried out using a triaxial rheological test system. The maximum loading capacity of the system is 2700 KN. During the test, the axial deformation of rock mass can be measured by two LVDTs installed on the two sides of the pressure chamber, while the lateral deformation is measured by the lateral strain sensor fixed in the middle of the sample. Test data are collected and stored by the test system, and the dynamic monitoring of the test is carried out in real time. A more detailed description about this test system is shown in the literature [12].

The specimen was first put into the triaxial cell and the sensors were linked to enable the measurement of deformation. After that the triaxial cell was sealed and the uniaxial compression test was conducted. The axial loading was applied at a rate of 0.02mm/min until the specimen broke. During the test, test data was recorded every five second.

3. Experimental results
3.1 Stress-strain curves
Figure 2 shows the uniaxial compression test results for the artificial CJRM specimens with joint angles of 0°, 30°, 45°, 60° and 90°. According to the test results, the stress-strain curves can be divided into four segments:

(1) In the first segment, the stress-strain curves exhibit an upward concave trend, corresponding to a nonlinear deformation stage in the initial stage. The cracks and joints in the specimen are compacted during this stage.

(2) In the second segment, the stress-strain curves show a nearly linear trend, where the strain increases linearly with the increase of deviatoric stress.
(3) In the third segment, the stress-strain curves fluctuate in between ups and downs, indicating the specimens in an unstable stage. With the increase of axial loading, the crack in the specimens propagates unsteadily, and gradually integrated with the joints.

(4) In the fourth segment, the stress-strain curves fall rapidly. The specimen loses its bearing capacity and the stress decreases with the increase of strain in a very short time.

![Figure 2: Stress-strain curves of uniaxial compression tests on the CJRM](image)

It is clear that the existence of columnar joints have great influence on the mechanical behaviour of CJRM. The peak strength of the intact specimen under uniaxial compression is 59.8 MPa, and the strength of the rock mass with columnar joints of different dip angles under uniaxial compression is less than that of the intact specimen. Meanwhile, the CJRM show strong anisotropy, which the strength characteristics are closely related to the dip angle of joints. When the joint dip angle is 60°, the peak strength of CJRM is the smallest, and the minimum value is 10.5 MPa. When the joint dip angle is 90°, the maximum peak strength is 57.6 MPa, and the difference between the maximum and minimum peak strength is 47.1 MPa. When the joint dip angle is 0°, the peak strength of CJRM is 36.7MPa. When the joint dip angle is 30° and 45°, the peak strength of CJRM is 28.6MPa and
13.7MPa respectively. Based on the results of uniaxial compression test, it can be seen that the rock mass with columnar joints is more likely to occur instability failure at dip angles of 45° and 60°.

It can also be seen from Fig. 2.4 that there are multiple stress fluctuations in the stress-strain curve before the specimen reaches the peak strength, which is a typical feature of jointed rock mass under uniaxial compression. With the increase of axial load, the cracks of columnar jointed rock mass initiate near the joint surface, gradually connect and connect, and the weak part of the sample first occurs local failure, which causes the stress to instantly reduce to a certain value. When the sample is damaged, a crisp fracture sound can be heard. However, the specimen can still bear the load. With the increase of deformation, the axial stress continues to increase. After several stress drop fluctuations, the load-bearing capacity of the specimen finally loses, and the strength decreases rapidly after reaching the peak value.

3.2 Anisotropic features

Figure 3 illustrate the variation trend of peak strength and deformation modulus with dip angle for columnar jointed rock mass under uniaxial compression state. Detailed values are listed in Tables 1. It can be observed from Figure 3 that the peak strength and deformation modulus change in a typical U curve, which low on the left and high on the right. The maximum strength appears at joint angle of 90°, while the minimum strength occurs at the angle 60°. The maximum deformation modulus appears at joint angle of 90°, while the minimum deformation modulus occurs at the angle 30°.

![Figure 3](image)

**Figure 3** (a) Peak strengths and (b) deformation modulus of artificial CJRM with various inclination angles

To reflect the strength variation of CJRM along with the joint inclination angles, the anisotropic strength function proposed by Pietruszczak [13] is used in this paper. The function is expressed as follows,

To reflect the strength variation of CJRM along with the joint inclination angles, the anisotropic strength function proposed by Pietruszczak [13] is used in this paper. The function is expressed as follows,

\[ \sigma_c = \sigma_m \left[ 1 + \sum_{n=1}^{r} a(1 - 3\cos^2 \beta)^n \right] \]  

(1)

Where \( \sigma_c \) is strength of CJRM at joint inclination angle \( \beta \), \( \sigma_m \) is the minimum strength value among the CJRM specimens. \( a \) and \( r \) are the fitting parameters. The function is rigorous and simply enough for the description of anisotropic characteristics of CJRM. The fitting accuracy increases with an increase in expansion term \( a(1 - 3\cos^2 \beta) \). It is found that the best approximation is obtained by incorporating the terms up to order 4 in Equation (2).

\[ \sigma_m = 10.05MPa, n = 4, a_1 = -0.76, a_2 = 1.53, a_3 = 1.6, a_4 = 0.41 \]  

(2)

4. Discussion
The mechanical properties of columnar jointed rock mass are mainly controlled by the joint planes. Consolidation grouting technology is mainly used to reinforce columnar jointed basalt to cement the joints more closely. Thus, in this section, the influence of different joint plane strength on mechanical properties of columnar jointed rock mass is discussed.

In the research of Ji [14], 32.5 white cement is used to cement the columnar jointed rock-like specimens, which can regarded as weak-cement columnar joints. In this paper, 52.5 Portland cement is used, which can strong-cement columnar joints. The experimental results under uniaxial compression of columnar jointed rock mass with weak joint plane and strong joint plane are then compared and analysed, which is show in Figure 4.

![Uniaxial compression strength of CJRM with various inclination angles](image)

**Figure 4** (a) Uniaxial compression strength of CJRM with various inclination angles (b) Strength contrast of different joint plane strength

It can be seen from Figure 4 that the strength of columnar jointed rock mass with different joint plane strength both show a U type trend with the change of joint dip angle. The joint plane strength has a significant impact on the strength characteristics of columnar jointed rock mass. The peak strength of columnar jointed rock mass increases significantly with the increase of joint plane strength, especially for joint angle of 30°, 45° and 60°. For joint angle of 30°, the peak strength increases from 19.2 MPa to 28.6 MPa. For joint angle of 45°, the peak strength increases from 5.49 MPa to 13.7 MPa. For joint angle of 60°, the peak strength increases from 4.98 MPa to 10.5 MPa.

5. Conclusion
In this paper, Uniaxial compression tests were carried out on columnar jointed rock-like specimens with different joint angles. Based on tests results, the following main conclusions are made:

1) The presence of columnar joints have great influence on the mechanical behaviour of CJRM. The uniaxial compression strengths of the CJRM is highly orientation-dependent and varies with the joint angles. The maximum strength appears at joint angle of 90°, while the minimum strength occurs at the angle 60°. An anisotropic strength function with a feature of periodical symmetry is used to fit the tested data for the uniaxial compression strengths.

2) The joint plane strength has a significant impact on the mechanical characteristics of CJRM. The peak strength of columnar jointed rock mass increases significantly with the increase of joint plane strength, especially for joint angle of 30°, 45° and 60°.

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