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Technical Notes

Large Lateral Deformation Characteristics of Simulated Columnar Jointed Rock Mass under Uniaxial Compression Tests

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Abstract: The columnar jointed rock mass is a common structure in extrusive igneous rocks. Due to the columnar joints network, large lateral deformation may result from slipping along these columnar joints and the corresponding lateral strain ratio may greatly exceed the upper limit of Poisson's ratio. Correct understanding of the large lateral deformation characteristics of columnar jointed rock mass is essential to the design of tunnels and underground caverns where the uniaxial compression condition usually occurs. Therefore, in order to perform uniaxial compression tests, simulated columnar jointed rock mass specimens with different dip angles were prepared using plaster mixtures, and the curve of variation of lateral strain ratio to dip angle was obtained. The shape of the curve resembles as inverted U-typed and the maximum of lateral strain ratio occurs at β = 30°. The mechanism of large lateral deformation is explained in light of the dip angle and failure modes, and an experimental equation is presented to predict the variation of lateral strain ratio to dip angle.

Keywords: rock mechanics, columnar jointed rock mass, lateral strain ratio, uniaxial compression test

1 Introduction

In projects such as tunnels and underground caverns that are constructed in rock mass, joints are usually well developed to control the deformation characteristics of jointed rock masses. With the effects of external disturbance, the rock blocks may slide along joint, which leads to the separation of rock blocks and large deformation. Such deformation, closely relating to the inclination of rock joints, is permanent and unrecoverable. Under the uniaxial compression conditions, if the joint dip angle is close or equal to the extreme value, the lateral deformation of rock masses may be great, and the lateral strain ratio (ratio of lateral strain to axial strain) may be much greater than the limit of Poisson's ratio. Lögters and Voort (1974) have found the lateral strain ratio of rock mass may be as high as 2.77 through field tests, while the corresponding joint dip angle is (45° + φ_j/2), where φ_j is the friction angle of joint. According to the numerical tests on regular joint rock model by Bhasin and Hoeg (1998), the lateral strain ratio was found to be as high as 0.92. Singh and Singh (2008) carried out uniaxial compression tests on 50 groups of simulated jointed rock mass containing three sets of regular joints, and most of jointed rock mass models were found to have a lateral strain ratio exceeding 0.5 and the maximum value is as high as 2.79. Li et al (2012) and Han et al (2012) adopted an equivalent continuous method to study the deformation characteristics of jointed rock mass containing multiple groups of penetration fissures, and equivalent Poisson's ratio was used to represent the lateral deformation characteristics of jointed rock mass. In their research, the variation of equivalent Poisson's

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ratio with dip angle was obtained. However, the effect of dip angle on lateral deformation was not considered. Although high lateral strain ratio of jointed rock mass has already attracted attentions of some rock mechanics experts, researches on high lateral strain ratio of jointed rock mass are inadequate as it is a characteristic that becomes obvious only when some conditions are satisfied.

As a special type of rock mass, columnar jointed rock masses are often formed during the cooling and contraction processes of basalt. The columnar joints can cut intact rock blocks into regular or irregular prisms. When columnar jointed rock mass is cut by groups of small and dense discontinuous joints, its lateral deformation not only shares the similarity of general rock masses but also has its own uniqueness. Over the past years, taking the dam foundation of Baihetan Hydropower Station as background, researches on the mechanical properties of columnar jointed rock mass have been performed, and valuable results have been obtained (Meng 2007, Ning et al 2007, Zheng 2008, Zhu et al 2009, Liu et al 2010, Di et al 2011, Yan et al 2012). However, these researches mainly focus on the anisotropic characteristics of the deformation and strength of columnar jointed rock mass and ignore the lateral deformation properties of columnar jointed rock mass under uniaxial compression conditions. Until recently, Xiao et al (2014) performed uniaxial compression tests on simulated columnar jointed rock mass specimens, and found that the average lateral strain ratio of columnar jointed rock mass were greater than 0.5, or even greater than 1.0 in some cases, which indicated that the lateral deformation of columnar jointed rock mass tended to be significantly large under uniaxial compression condition.

To study the lateral deformation properties of columnar jointed rock mass under uniaxial compression condition, uniaxial compression tests on simulated columnar jointed rock mass have been carried out. Based on the experimental results, variations of lateral strain ratio with dip angle is obtained, and its mechanical mechanism is explained in light of dip angle and failure modes. Finally, an equation is proposed to predict the lateral strain ratio based on experimental data.

2 Uniaxial Compression Tests and Results

The simulated columnar jointed rock mass specimens were prepared using gypsum, cement and water with a weight ratio of 3:1:3.2, and the physical and mechanical parameters of the mixture are shown in Table 1. The simulated columnar jointed rock mass model was made by bonding single prisms together with cement grout in a ratio of 3:2, from which columnar jointed rock mass specimens with a diameter of 50 mm, height of 100 mm and different dip angles relative to vertical directions were drilled. The prepared simulated columnar jointed rock mass specimens, as shown in Fig. 1, were cured in an air oven for a week. The parameters of joint were obtained from direct shear tests on artificial rock joints composed of model material.

Table1 Properties of model material

Parameters	Values	Parameters	Values
Density ρ (g/cm^3)	1.052	Young's Modulus E_i (MPa)	347.0
Poisson's ratio v	0.1	Uniaxial compressive strength σ_{ci} (MPa)	2.638
Cohesion c (MPa)	0.173	Tensile strength σ_t (MPa)	0.584
Internal friction angle φ(°)	18.9	Joint friction angle φ_j (°)	28.5

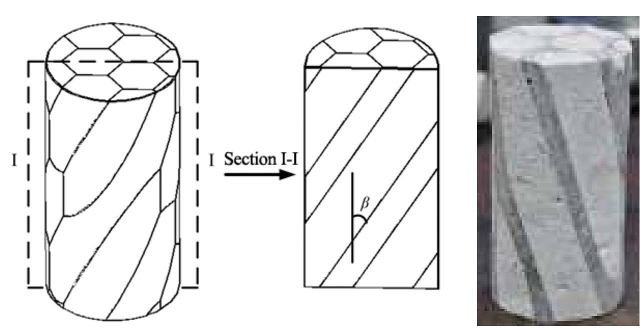


Fig. 1 Sketches of columnar jointed rock mass specimens

The uniaxial compression test was conducted by MTS815 rock test system at the National Key Lab of Geological Hazard Prevention and

Environmental Protection in Chengdu University of Technology. A displacement sensor was used in the test to measure the axial and circular deformation of the specimens, and a chain circular extensometer to measure the circular deformation. The axial force was applied with a rate of 0.5 kN/min. When the axial force reached 1 kN, the loading mode was shifted to displacement control with a rate of 0.1 mm/min. There were a total of 7 tests, corresponding to seven different dip angles, i.e. β = 0°, 15°, 30°, 45°, 60°, 75° and 90°; for each group of specimens, five replicates were tested and the average results were used in the analyses.

According to the results of uniaxial compression test, typical stress-strain curves at different dip angle columnar jointed rock mass are shown in Fig. 2. Noting that limited by the pages, only the axial stress-axial strain curves and axial stress-lateral strain curves corresponding to β =15º, 30º, 45º and 75º were shown, respectively.

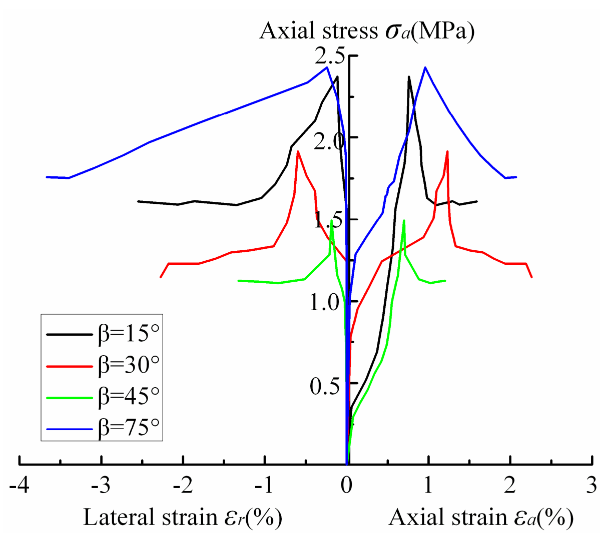


Fig. 2 Typical stress-strain curves of columnar jointed rock mass specimens under uniaxial compression tests

According to the uniaxial compression stress-strain curves and Test Methods of Rock for Highway Engineering (JTG-E41 2005), axial strain ε_a and lateral strain ε_r corresponding to 20% and 80% of peak axial stress were used to calculate the lateral strain ratio v_r. The variation of lateral strain ratio v_r with dip angle β is shown in Fig. 3, from which it can be seen that due to the presence of columnar joints, the lateral strain ratios of columnar jointed rock mass specimens are greater than the Poisson's ratio of intact model material, and the values of lateral strain ratios at β = 30º ~ 60º are greater than the upper limit of Poisson's ratio 0.5 and the maximum value occurs at β = 30º.

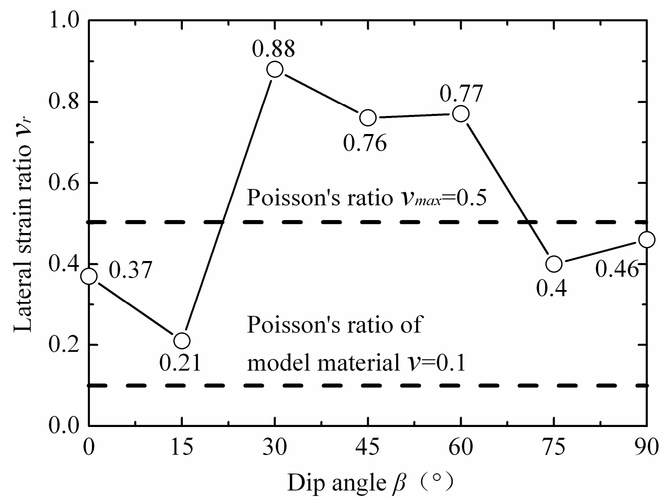
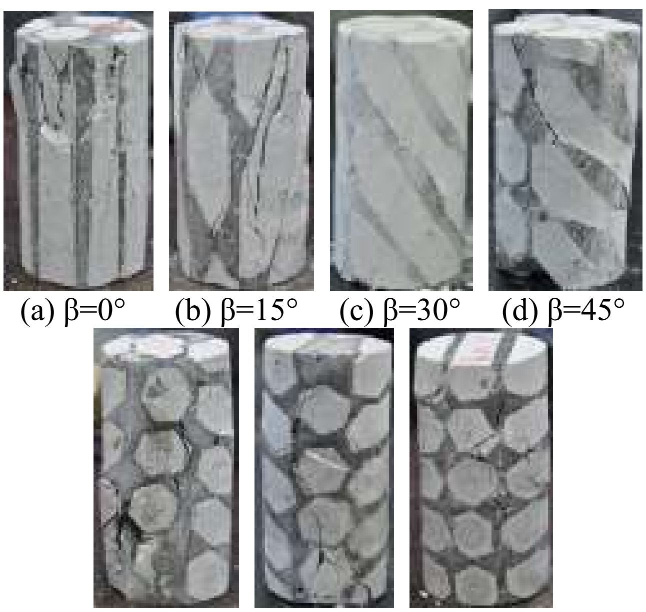


Fig. 3 Variation of lateral strain ratio v_r vs dip angle β

3 Mechanism Analyses

Singh et al (2002) and Singh and Singh (2008) believe that rock masses tend to have large lateral strain characteristics under uniaxial compression or triaxial compression at a low confining pressure, because if the rock mass is not restricted laterally or the lateral restriction is small, the rocks tend to slide plastically under the axial stress action when the joint dip angle in the rock mass is close to a certain limit value. In this case, the rock mass will have voids inside, causing the rock masses to expand obviously and have large lateral strain characteristics eventually. Singh and Singh (2008), through the uniaxial compression test of more than 50 joints, found that the lateral strain ratio was obviously great when failure occurred along joint surface and corresponding lateral strain ratios were as high as 1.39 ~ 1.56, while the lateral strain ratio was lower than 0.5 if the jointed rock mass failure mode was axial splitting. Therefore, large lateral strain of jointed rock mass is closely related to its failure modes, and it is reasonable to investigate the properties of large lateral strain for jointed rock mass through analyzing the mechanism of its failure modes.

Xiao et al (2014) performed uniaxial compression tests on simulated columnar jointed rock mass, and the following four typical failure modes under uniaxial compression condition were summarized: □ axial splitting along the model material; □ sliding failure along the columnar joints surface; □ composite shear failure surface partly through joint surface and partly through the model material; and □ axial splitting along columnar joint surface, accompanied by obvious lateral expansion. In our study, failures of seven groups of columnar jointed rock mass specimens under uniaxial compression conditions are shown in Fig. 4. According to the four typical failure modes mentioned above, the failure of columnar jointed rock mass at β = 0º and 15º corresponded to mode □; when β = 30º and 45º, failure mode □ occurred; when β = 60º, failure mode □ occurred; when β = 75º and 90º, failure mode □ occurred.



(a) β=0° (b) β=15° (c) β=30° (d) β=45° (e) β=60° (f) β=75° (g) β=90°

Fig. 4 Typical failure modes of columnar jointed rock mass specimens

Combining the failure patterns shown in Fig. 4 with corresponding lateral strain ratios in Fig. 3, the conclusions are identical to Singh and Singh (2008) have been drawn, that is, the lateral strain ratio will be far greater than 0.5 when the specimen suffers sliding failure along the joint surface. This phenomenon can be explained using joint shear strength criterion qualitatively, that is, according to Mohr-Coulomb strength criterion, when the inclination of joint relative to uniaxial loading direction equals to (45°-φ_j/2), the shear resistance of joints reaches to the minimum value, where sliding along joint surface will occur, where φ_j is the joint friction angle. For the model material used in this paper, it can be found in Table 1 that the joint friction angle φ_j is 28.5°, then (45° - φ_j/2) equals to 30.75°, which is very close to column dip angle β = 30°. Therefore, the lateral strain ratio of columnar jointed rock mass specimens may reach the maximum value at β = 30º, which is exactly identical to the measured value. Moreover, when β = 0º ~ 15º and β = 75º ~ 90º, the shear resistance of joints will be large, and the failure of sliding along joint surface will be restricted, so the lateral strain ratio is relatively low.

The above analyses are qualitative interpretations of the large lateral strain property of columnar jointed rock mass. Up to now, only a few researches on lateral strain characteristics of jointed rock mass have been reported, and researches on columnar jointed rock mass have not been reported yet. In Section 2, the variation curve of lateral strain ratio vs. dip angle for simulated columnar jointed rock mass under uniaxial compression condition has been obtained. On the basis of this experimental curve, an experimental model for predicting the lateral deformation properties will be proposed in the following section.

4 Experimental Prediction Model

According to Fig. 3, the variation curve of lateral strain ratio v_r with dip angle resembles as inverted "U" shape, which indicates the anisotropy of v_r. Ramamurthy (1993) proposed an empirical model for predicting the uniaxial compressive strength based on the "U" shaped anisotropic strength curve. Herein, according to this model, an experimental equation is suggested for predicting the variation of lateral strain ratio with the column dip angle:

$$v_r = A + D \cdot \cos[2(\beta_{\max} - \beta)] \tag{1}$$

where β_{max} indicates the dip angle corresponding to the maximum lateral strain ratio, generally β_{max} = 30°; and A and D are constants, which can be determined based on uniaxial compression test results at $\beta = 0°$ and $\beta_{max} = 90°$.

In order to determine the constants A and D in Eq. (1), the uniaxial compression test results of columnar rock mass at $\beta = 0°$, $\beta = \beta_{max}$ and $\beta = 90°$ are adopted. According to the test results, $\beta_{max} = 30°$. Then applying the values of lateral strain ratio at $\beta = 0°$, 30° and $\beta = 30°$, 90° into Eq. (1) respectively, the values of constants A and D can be obtained. Finally, introducing the values of A and D into Eq. (1), the experimental equation for predicting the lateral strain ratio of columnar jointed rock mass is shown as follows:

$$v_r = \begin{cases} 1.02\cos[2(\beta_{\max} - \beta)] - 0.14 & 0^\circ \le \beta \le 30^\circ \\ 0.28\cos[2(\beta_{\max} - \beta)] + 0.6 & 30^\circ < \beta \le 90^\circ \end{cases} \quad (2)$$

According to Eq. (2), the empirical predicting curve is shown in Fig. 5, from which it indicates that the empirical forecast curve of the variation of lateral strain ratio with column dip angle matches the measured values well, although the predictions of lateral strain ratio deviate from the measured values to some extent at $\beta = 15°$ and 75°. Therefore, in spite of the discreteness of experimental data, it is reasonable to consider Eq. (2) can predict well the variation of lateral strain ratio of simulated columnar jointed rock mass under uniaxial compression with column dip angle. Furthermore, in the proposed empirical model, the constants can be determined by using uniaxial compression test results of three dip angles, which greatly saves the costs and time.

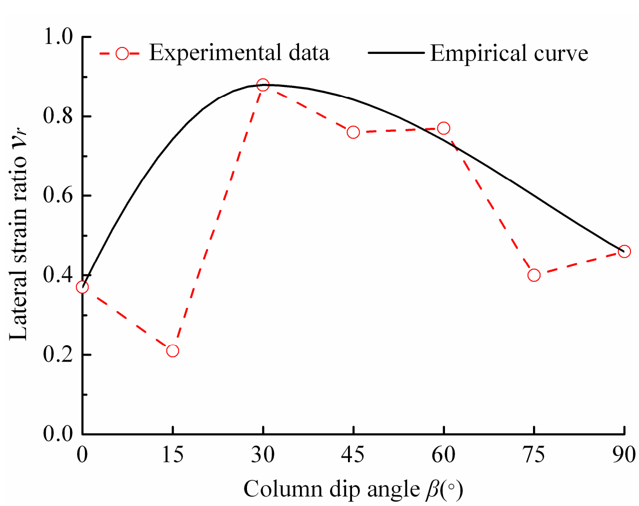


Fig. 5 Lateral strain ratio v_r vs dip angle β

5 Discussions

Large lateral strain is one of the major deformation characteristics of columnar jointed rock mass under uniaxial compression condition, which is shown in Fig. 5. Due to the restrictions of methods for preparing simulated columnar jointed rock mass, the lateral strain ratios of simulated columnar jointed rock under uniaxial compression are not as obvious as that of ideally regular jointed rock mass observed by Singh and Singh (2008). This may be ascribed to a layer of grout exiting between two adjacent prisms due to the irregularity of prisms, which constraints the rock blocks slipping along columnar joint. Therefore, further researches on this aspect must be continued based on more elaborate experiments. Moreover, Eq. (1) is an empirical equation proposed for describing the anisotropy of lateral strain of simulated columnar jointed rock mass, which is also suitable for regular jointed rock masses.

Large lateral strain is one of the major mechanical issues that deserve special attention in the excavation and design of major underground projects. However, theoretical researches on this aspect have been seldom reported. In this paper, gypsum model material is used to prepare simulate columnar jointed rock mass for investigating the lateral deformation properties under uniaxial compression condition. The obtained experimental results are useful for investigating the anisotropy of columnar jointed rock masses. However, the research results are still inappropriate to be directly used in practice, further researches must be performed in the future.

6 Conclusions

In this paper, lateral deformation properties of columnar jointed rock mass under uniaxial compression condition are investigated according to uniaxial compression tests on simulated columnar jointed rock mass specimens. The main conclusions can be described as follows:

(1) The properties of large lateral deformation of columnar jointed rock mass under uniaxial compression condition are obvious and greatly influenced by dip angle. From experimental results, it is found that the lateral strain ratio of

columnar jointed rock mass is high, especially at β = 30º ~ 60º and the maximum value occurs at β = 30º.

(2) Large lateral deformation of simulated columnar jointed rock mass relates to its failure mode. If specimens suffer sliding failure along columnar joint, the corresponding lateral strain ratio will be high.

(3) An experimental equation for predicting lateral strain ratio of columnar jointed rock mass is proposed, which can effectively predict the change tendency of lateral strain ratio of simulated columnar jointed rock mass.

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