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An experimental study on anchorage strength and deformation behavior of large-scale jointed rock mass

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ABSTRACT

By adopting the similarity theory, a large-scale model experiment system (the dimension of specimen is 500 × 500 × 480 mm) is firstly self-developed, which not only has a good loading, restraint and measuring function, but also satisfy the strength and stiffness of the large-scale experiment. In the experimental system, optical fiber dynamometric bolt based on Bragg grating is adopted to measure internal force of anchorage jointed rock mass with a high precision. Secondly, the molds for the large-scale jointed model specimen are fabricated, and the materials (including the rock-like material and the supporting material) are all developed successfully. And then, the anchoring strength behavior of large-scale jointed rock mass is analyzed in detail. The experimental results shows that the anchoring strength of the large-scale rock mass with different joint angles of 30°, 45°, and 60° are greater than that of jointed rock mass without any bolts, but being dependent to joint angle. The peak strength increases nonlinearly with the increase of bolt number for the same joint angle. The anchoring mechanism of peak strength strengthening is explained by the following three parts: the peak strength of jointed rock mass without any bolts under the uniaxial stress, the peak strength contributed by the initial equivalent restraint stress, and the peak strength contributed by the deformation equivalent restraint stress. With the increase of the initial equivalent restraint stress, the peak strength of anchorage jointed rock mass will increase linearly. Moreover when the joint angle is bigger, the contribution of initial equivalent restraint stress on the peak strength is larger. In the end, the effect of bolt number and joint angle on the deformation and dilatancy behavior of jointed rock mass is analyzed. In general, the elastic modulus increases nonlinearly with the increase of bolt number for the same joint angle. For anchorage rock mass with the same joint angle, the value of the negative ratio of circumferential strain to axial strain at the peak stress increases gradually with the increase of bolt number; but for anchorage rock mass with the same bolt number, the value of the negative ratio of circumferential strain to axial strain at the peak stress is dependent to the joint angle. The dilatancy stress of large-scale jointed rock mass increases nonlinearly with the bolt number but increases linearly with the equivalent restraint stress.

1. Introduction

Rock mass is a kind of complex geological medium, which usually contains a lot of non-consistent flaws (such as fissures, joints, faults and weak surfaces, etc.) due to long-term action of geological tectonic movement. The existence of these fissures or joints changes the mechanical behavior of rock mass (Yang et al., 2008).

Due to easy fabrication for joints or fissures in model materials, many physical tests on rock-like specimens containing two, three or multiple fissures under uniaxial and biaxial compression have been carried out in the past decades. Wong and Chau (1998) and Wong et al. (2001) presented the experimental results on the peak strength of rock-like material containing two and three fissures (the dimension of the rectangular specimen was 60 × 120 × 25 mm) under uniaxial compression, which showed that the peak strength of the specimens did not depend on the initial crack density but on the actual number of pre-existing flaws involved in the coalescence. Sagong and Bobet (2002) tested a number of specimens (the dimension of the rectangular specimen was 101.6 × 203.2 × 30 mm) made of gypsum with three and 16 fissures under uniaxial compression, which obtained the influence of continuity and ligament length on the crack coalescence stress. Prudencio and Van Sint Jan (2007) presented the results of biaxial tests performed on physical models of rock with non-persistent

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joints (the dimension of the rectangular specimen was $150 \times 300 \times 50$ mm). Their results showed that the failure mode and the peak strength depended on the joint distribution, the orientation of the principal stresses, and the ratio between intermediate stress and compressive strength of intact material. Chen et al. (2012) investigated the combined influence of joint inclination angle and joint continuity factor on deformation behavior of jointed rock mass for gypsum specimens (the dimension of the rectangular specimen was $150 \times 150 \times 50$ mm) with a set of non-persistent open flaws in uniaxial compression. Zhou et al. (2013) carried out uniaxial compressive tests for rock-like specimens containing four flaws with dimensions of $90 \times 150 \times 70$ mm, which observed five types of cracks at or near the tips of pre-existing flaws, including wing crack, quasi-coplanar secondary crack, oblique secondary crack, out-of-plane tensile crack and out-of-plane shear crack.

In order to avoid the unstable failure of jointed rock mass in underground engineering, some physical model experiments of rock mass were carried out to explore the failure mechanism of underground rock engineering. He et al. (2010) employed a new approach of Physically Finite Elemental Slab Assemblage (PFESA) for construction of the physical model simulating tunnel excavation in stratified rocks, which monitored and captured rock response to the excavation in real-time and over the entire field by using infrared (IR) thermography, incorporated with such image processing procedures as data statistics, noise removal and two-dimensional DFT (Discrete Fourier Transformation) for extracting features from the resulting thermographics. Zhu et al. (2011) reported an experimental setup using a stiff modular loading frame, hydraulically applied simulated loads and in vivo excavation to represent cavern construction at the depth. The results demonstrated that for conditions of high horizontal stresses, failure was limited under stress/strength ratios less than 1.5. When stresses to strength ratios increased above 1.5, model deformations increased and failure initiated by spalling.

Besides physical tests on rock-like materials, some real rock specimens have also been carried out the physical tests to investigate the strength and deformation behavior of rock containing all kinds of joints or fissures. Yang et al. (2012) made an experimental investigation for brittle sandstone specimens containing three fissures (the dimension of the rectangular specimen was $80 \times 160 \times 30$ mm), which characterized the effect of ligament angle on the peak strength of brittle sandstone material. But, in the above experimental studies, all the fissures in the rock specimens are all parallel. In nature, rock masses do not always contain parallel fissures and are generally composed of unparallel fissures (Lajitai et al., 1994; Lee and Jeon, 2011). Yang et al. (2013) carried out an experimental investigation to explore the strength, deformation behavior of red sandstone specimens (with the dimension of $80 \times 160 \times 30$ mm) containing two unparallel fissures. The results showed that the peak strength and deformation parameters of red sandstone containing two unparallel fissures was increased as the angle of fissure ② (α_2) from 0° to 90°, and then decreased as α_2 from 90° to 180°.

Taking into account the disadvantageous effect of joints or fissures on the stability and safety of underground rock engineering, the anchoring technology is often adopted for supporting the surrounding rocks of tunnels. But in all the above experimental studies for model materials or real rock materials containing all kinds of joints or fissures, the anchoring mechanical behaviors have not been investigated. Ferrero (1995) investigated the shear strength of reinforced rock joints, which showed that shear resistance was heavily influenced by the quoted parameters. Yielding steel provided the highest contribution to the global reinforced joint shear resistance when using bars or tubes. Stronger and stiffer rock materials led to higher shear stresses in the steel and consequently lower overall resistance. Pellet and Egger (1996) proposed a new analytical model for the prediction of the contribution of bolts to the shear strength of a rock joint. By adopting the model, the complete curve of the bolt contribution as a function of the displacement along the joint could be computed, and the maximum bolt contribution was obtained by dissociating the bolt cohesion and the confinement effects. The comparison of the performances of this analytical model with test results showed its capacity to describe the observed test phenomena. Cai et al. (2004) discussed the interaction mechanism of a single rock bolt and the rock mass, and proposed an analytical model for the grouted rock bolts in the soft rock mass, which was testified as a sufficient way to predict the axial force of the grouted rock bolt for tunnelling design. Moreover, according to the model, the induced axial force in the rock bolt was strongly related to the released displacement of rock mass.

However, in the tunnels with higher in-site stress, the lower pre-stress and the smaller anchorage strength often result in being pulled off or entire fail of the bolts in the rock mass. Thus, even though with the higher anchoring density, the surrounding rocks of tunnels still occur the large deformation failure, which has a significant effect on the stability and safety of tunnels. Moreover up to now, the strength and deformation behavior of jointed rock mass with different anchorage densities have not been fully investigated due to the limitation of large-scale model experiment system. Therefore, the objective of this research is to develop a large-scale model experiment system in accordance with the similarity theory, to fabricate large-scale joint model specimen by developing the rock-like material and the supporting material, and to analyze the influence of joint angle and bolt number on the anchorage strength and deformation behavior of large-scale jointed rock mass.

2. Large-scale model experiment system

Considering the smaller bolt diameter, the smaller hole diameter and the anchorage force in-site tunnels engineering, it is more difficult to investigate quantitatively the mechanical behavior and anchorage control characteristics by adopting model experiment with smaller similarity ratio. So, a large-scale model experiment system (i.e. the size of model specimen is $500 \times 500 \times 480$ mm) is developed, which can be used to simulate real rock mass scale with $2500 \times 2500 \times 2400$ mm. In this research, the similarity ratio of geometric size C_L equals to 5, and the similar ratio of unit weight C_r is 1.2.

2.1. Surrounding rock and large-scale model loading condition

The background of large-scale model experiment is the 3–5# panel track tunnel engineering in Yongding mine located in Datong city, Shanxi province. This track tunnel has a semicircle arched section with a size of 5900×4250 mm, and the buried depth of tunnel is 488 m. Due to the damage suffering from lamprophyre intrusions, joints and fissures in coal and rock mass are very more. Besides, coal seam occurs to incline due to being squeezed, and local coal and rock mass has an angle of 30° with the horizontal direction, which can be seen from the occurrence of coal and rocks exposed by excavation (Fig. 1).

Large-scale model experiment system can be designed on basis of the following consideration. An anchorage unit body of jointed rock mass can be separated from the periphery of tunnel, as shown in Fig. 2. And then, the joint length and ligament length were all kept a constant, but varying joint angle and anchorage density. Thus, we can investigate the influence of joint angle and anchorage