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Stress evolution and support mechanism of a bolt anchored in a rock mass with a weak interlayer

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ABSTRACT

By applying experimental method, the bolt stress and supporting mechanism is studied during the deformation process of a rock mass containing a weak interlayer. The force measuring bolt is installed manually and instrumented five pairs of symmetrical strain gauges. The experimental results show that the fully grouted bolt suffers tensile, compressive, bending and shear stress at the same time. The bolt stress evolution is closely related to the deformation stages of the rock mass which are very gradually varying stage, gradually varying stage at the pre-peak and suddenly varying stage at the post peak stage. The axial compressive stress in the bolt is mainly induced by the moment. Thus, in most cases the axial compressive stress is distributed on one side of the bolt. For axial stresses, induced by the axial force and the bending moment at the post-peak stage, three types of changing are observed, viz. increasing-increasing type, decreasing-increasing type and increasing-decreasing type. The stress characteristics of the bolt section in the weak interlayer are significantly different from those in the hard rock. The failure models of the anchored bolt are tensile failure and shear failure, respectively. The bolt not only provides constraints on the free surface of the rock mass, but also resists the axial and lateral loading by the bending moment. This study provides valuable guidelines for bolting support design and its safety assessment.

1. Introduction

The weak interlayer is prevalent in field of geotechnical engineering [1]. It swells and gets muddy easily in the presence of water and has a low strength as well as a low deformation modulus, therefore the weak interlayer has a significant effect on the stability of geotechnical engineering, which is one of main inducing factors causing the instability [2–5]. To solve the problem, the bolt support with a unique benefit in controlling stability was introduced. Nowadays, with the wide application of the bolt support, many scholars have devoted to the study of its mechanical characteristics and supporting mechanism [6–9].

Early in the 1970s, Freeman carried out monitoring work on the bolt in Kielder experimental tunnel, monitored the loading process of the rock bolts, observed the distribution of the interface shear stress along the bolts and put forward the concepts of 'neutral point', 'pick up length' and 'anchorage length' [10]. Chen et al. performed monitoring program on the bolt in loess soil tunnel. The results showed that under the condition of the steel arch support, the bolts in the arch part of the tunnel are mainly subjected to compression due to the downward frictional resistance from the soil, while the feet-lock bolts in arch foot are mainly subject to tension [11]. In addition, Li also detected the pressure on the bolt in mining roadways, yet he attributed the pressure to the eccentric force [12]. Song et al. pointed out that the bolt bears bending moment and shearing stress at the same time under the action of shearing loads [13]. However, Kang et al. argued that, under the comprehensive action of shearing, bending and twisting, the bolt suffers from not only tensile stress but also bending moment and torque moment, but the bolt is not anchored in any medium [14]. From the above analyses, it is not difficult to find that scholars have various findings in the studies about the mechanical characteristics of the bolt, since there are many factors, including the characteristic of surrounding rock, the anchorage length and the bolt profile configuration, etc., influence the mechanical characteristics of the bolt [11,12,15,16]. Therefore, it is necessary to make further research on the mechanical characteristics of the bolt by considering the specific working conditions (such as the rock mass containing weak interlayers).

As for the supporting mechanism of the bolt, Ge et al. believed that the bolts are able to prevent the joints from dislocating, and

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to improve the shear resistance of the bolted rock joints [17]. Pellet et al. argued that the bolt support strengthens the cohesion and the compressive stress (positive stress) of the bolted rock joints, but has no effect on its internal friction angle [18]. Yet, Yang suggested that the bolt support increases the cohesion (C) of the rock mass but reduced the internal friction angle (φ) [19]. Hou et al. indicated that the bolt support improves the elastic modulus (E) of the anchorage body, the cohesion (C), the internal friction angle (φ) and the post-peak softening modulus (M) [20]. The studies of Jing et al. showed that the initial equivalent constraint stress (σ_{3i}) caused by the bolt pretension and the equivalent constraint stress (σ_{3b}) caused by bolt deformation are two important parts of the strength of the anchorage body [21,22]. Yang et al. discussed the significant effect of the support resistance applied on the free surface of the anchorage on the strength of the intermittent jointed rock mass [23].

Previous studies above have achieved beneficial results. However, there are still few studies on the mechanical characteristics and the supporting mechanism of the bolt in the rock mass containing a weak interlayer. Hence, this paper aims to study the mechanical characteristics of the fully grouted bolt in the rock mass containing a weak interlayer and analyze its supporting mechanism.

2. Experiment design

According to the practical situation on site, the experimental system was designed. An anchorage unit body A of rock mass with weak interlayer was separated from the roof of the roadway, as shown in Fig. 1a inside the red dashes box. Assuming the horizontal stress as the maximum principal stress, a simplified mechanical model was obtained as shown in Fig. 1b.

In accordance with Fig. 1, the sample loading condition was designed as follow: compressive stress σ_1 was applied in the vertical direction, stress σ_2 was applied in the lateral direction as restraint stress, the rear side's normal displacement was fixed, and the front side was a free surface in order to install the bolt. The loading scheme and the experimental model is as shown in Fig. 2. In accordance with Fig. 2, the σ_1 was applied by the YNS-2000 rock testing machine in the laboratory. The lateral restraint steel plates applied σ_2 on the specimen (apply the pre-tension force to the pull rod by tightening nuts which thereby lead to the pre-pressure on the lateral sides).

The specimen (i.e. the size of 200 mm × 200 mm × 200 mm) used in the experiment contains a 30 mm thick weak interlayer and two 85 mm thick hard rock layers, as shown in Fig. 2a. The weak interlayer was made of cement, gypsum, sand at a weight ratio of 0.4:0.6:6: and water content of 24% of the total weight of the aggregate and binder. The hard rock layer was made of cement and sand at a weight ratio of 1:4.5 and water content of 15% of the total weight of the sand and cement. The physical and mechanical parameters of the hard rock layer and the weak interlayer are as shown in Table 1.

The bolt adopted in the experiment was a φ6 mm × 20 mm aluminum bar, 18 mm of which was anchored into the rock mass (fully grouted). The anchoring agent was epoxy resin. The diameter of the bolt hole was 8 mm and the bolt faceplate size was 30 mm × 30 mm × 1.5 mm, Q235 steel.

In order to measure the forces of the bolt, five pairs of strain gauges were installed symmetrically on the upper and lower sides of the bolt, as shown in Fig. 3. The upper strain gauges Nos. #1, #2, #3, #4 and #5, were located at 20, 50, 80, 110 and 140 mm, respectively, from the bolt head. Similarly, the lower strain gauges Nos. #6, #7, #8, #9 and #10 were 20, 50, 80, 110 and 140 mm, respectively, from the head of the bolt. The position of measuring sections $S1$, $S2$, $S3$, $S4$ and $S5$ are as shown in Fig. 3a. And the measuring sections $S3$ was located in the weak interlayer, as shown in Fig. 2a. The electrical resistance of the strain gauges used in this experiment were about 120 Ω, whose measuring range was about 15,000$\mu\varepsilon$ and sensitivity coefficient was 1%.

3. Results analysis

3.1. Evolution of the axial force and the axial stress of the bolt

The bolt axial stresses in the measuring points (BASMPs) are the basis to calculate its axial force and axial stress, so the evolution of BASMPs during the anchorage deformation process is analyzed initially.

3.1.1. Evolution rules of the bolt axial stress on each measuring point

The evolution rules of the BASMPs are shown in Fig. 4. For the analysis, the direction of $\sigma_1$is named as the axial direction of the specimen.

Fig. 4 shows the main varying rules of the BASMPs, as follow:

(1) During the deformation process of the anchorage, the BASMPs appears changing phase obviously. In general, three are three main changing phases, i.e. very gradual changing phase, gradual changing phase and suddenly changing phase, which are as shown in segments *AB*, *BC* and *CD*, respectively in Fig. 4a. While the compacting phase and 70% of the elastic phases, of the BASMPs changes very gradually, and from 70% of the elastic phase to 36% of the softening phase, of the BASMPs changes gradually. However, at range of 36%–100% of the softening phase, of the BASMPs increases suddenly. In general, the anchorage performance of bolt has a positive correlation with its loads. So, these changing rules suggest that the supporting role of the bolt

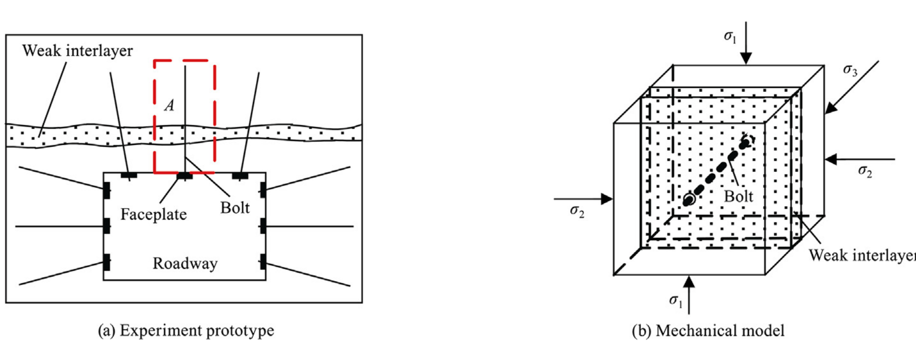

Fig. 1. Experiment prototype and mechanical model.