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Mechanism and technology study of collaborative support with long and short bolts in large-deformation roadways

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ABSTRACT

Common short bolts of equal length are widely used to support the roofs of roadways in coal mines. However, they are insufficient to keep the roof stable against large deformations, so docking long bolts with high levels of elongation that can adapt to large deformations of the surrounding rock have been adopted. This paper proposes a collaborative support method that uses long and short bolts. In this study, the mechanism of docking long bolts and collaborative support was studied. Numerical simulation, similarity simulation, and field testing were used to analyze the distribution law of the displacement, stress, and plastic failure in the surrounding rock under different support schemes. Compared with the equal-length short bolt support, the collaborative support changed the maximum principal stress of the shallow roof from tensile stress to compressive stress, and the minimum principal stress of the roof significantly increased. The stress concentration degree of the anchorage zone clearly increased. The deformation of the roof and the two sides was greatly reduced, and the subsidence shape of the shallow roof changed from serrated to a smooth curve. The roof integrity was enhanced, and the roof moved down as a whole. Plastic failure significantly decreased, and the plastic zone of the roof was within the anchorage range. The similarity simulation results showed that, under the maximum mining stress, the roof collapsed with the equal-length short bolt support but remained stable with the collaborative support. The collaborative support method was successfully applied in the field and clearly improved the stability of the surrounding rock for a large deformation roadway.

1. Introduction

Bolt support has been a key method of roadway support in coal mine operations. At present, the common short bolt is the primary support component used in support systems of coal roadways. Since the common bolt is too short, it cannot meet the support requirements of large-deformation roadways. Therefore, the anchor cable is widely used at this time. However, the cables have a small extension capacity and are prone to breaking due to roof convergence. They therefore cannot form an effective support system on the roof and cannot adapt to the large-deformation conditions of the roadway. Therefore, the docking long bolt with a high elongation capability that can adapt to large deformations of the surrounding rock is adopted and a collaborative support method with both long and short bolts is proposed under large rock deformation conditions. Bolts with different lengths play different roles in roadway support, strengthening the links between shallow and deep surrounding rock and making bolt support more functional and hierarchical.

Substantial studies of the collaborative support method with long and short bolts have been conducted at home and abroad. After studying the mechanism of the full-size grouted bolt, Wang proposed a support scheme comprised of full-size grouted long and short bolts in the tunnel support and explained how it works as well as presenting the equations that describe the internal stress [1,2]. Using numerical modeling, Wang optimized the composite support of the long and short bolt, greatly improving the safety factor of slopes [3,4]. He concluded that the collaborative support of long and short bolts can effectively improve the antiknock ability of the anchoring tunnels [5]. Chen conducted industrial testing in a high-stress soft rock tunnel, achieving good results [6]. Foreign scholars have also carried out research on composite support with long and short bolts [7–13]. Yeung carried out computer simulations, concluding that arranging the long and short bolts in an alternating pattern is important for forming a highly stable supporting structure [14]. The short bolt can reinforce the shallow rock to form the bearing arch structure and the long bolt can anchor the bearing arch structure to deep rock. Therefore, the

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collaborative support can effectively control the large deformations of the roadway, providing an important engineering reference for roadway support design.

2. Geological conditions and characteristics of roof movement

The Tunlan mining area is located in the central part of Shanxi province and has complex geological conditions. Undulating folds and faults have developed as a result of several tectonic movements. In the mining area, the 12,501 working face is being mined. The haulage roadway of 12,501 currently uses the equal length short bolt support scheme. During roadway excavation, the support method meets the requirements of keeping the roof stable. However, roof subsidence is severe during working face excavation, with the roof collapsing in local areas (Fig. 1), seriously affecting roadway use.

The 12,501 haulage roadway is located in the 2# coal seam of the south panel at the +750 m level. It has a large cross section and passes through geological tectonic regions such as faults. The distance from the coal seam to the ground is approximately 612.5–650.3 m, with an average distance of 626 m. The thickness of the coal seam is 3.8–5.2 m, with an average thickness of 4.25 m. The hardness coefficient of the coal seam is less than 0.8. The coal seam has a simple structure and a relatively developed fracture, belonging to a relatively stable thick seam. It is a nearly horizontal seam with an average inclination of 2.5°, with a maximum of 6°. The immediate roof of this coal seam consists of carbonaceous mudstone and sandy mudstone. The basic roof is composed of siltstone and fine sandstone. The immediate floor is black sandy mudstone and the basic floor is mainly composed of fine sandstone (Fig. 2).

3. Mechanism of collaborative support and optimization of support scheme

To keep the roof of a large deformation roadway stable, a docking long bolt with high elongation that can adapt to the large deformations of the surrounding rock was adopted. The collaborative support method with long and short bolts was proposed and the mechanism of the docking long bolt and collaborative support were studied. The collaborative support scheme was compared with the equal-length short bolt support scheme. The two kinds of support scheme were analyzed using numerical simulations, similarity simulations, and field testing.

Fig. 1. Deformation and failure of the roof in the 12,501 haulage roadway.

3.1. Mechanism and parameters of docking long bolt

(1) The docking long bolt is a kind of steel resin bolt, as shown in Fig. 3. The tail nut and tray of the docking long bolt are the same as those of a common bolt and it is easily installed by a roof bolter. According to the height of the roadway and the designed bolt length, the bolt is processed into two or more segments connected by screw bolts. The two parts are connected together by a roof bolter. The strength of connecting joint is much greater than the anchorage force and no less than 90% of the ultimate tensile strength. Therefore, the lengthening of the bolt can guarantee that the anchorage force will not decrease.

(2) The docking long bolt is made of screw steel with no longitudinal ribs, a yield strength of more than 335 MPa, a tensile strength of no less than 490 MPa, and dimensions that must comply with the requirements of dedicated screw steel for bolts. The elongation of the bolt is greater than 15% and its straightness is less than 2 mm/m.

The bolt diameter is 20 mm, the anchorage force is greater than 105 kN, a tail thread diameter based on the M22 thread, and a strength of no less than 105 kN. The diameter and length of the connecting joint is 26.5 ± 5 mm and 50 mm, respectively. The connecting bolt size is based on the M18 × 2 and the connector strength is greater than 139 kN. The tray strength is no less than 105 kN and the tail thread strength is greater than 105 kN.

3.2. Mechanism of collaborative support with long and short bolt

In the collaborative support system, bolts of different lengths play different roles in roadway support, making the support more functional and hierarchical. After roadway excavation, the shallow surrounding rock inevitably enters the plastic state and interacts with the short bolt to form a reinforced arch structure with a certain bearing capacity. This changes the stress state of the surrounding rock from two-dimensional to three-dimensional, improving the overall strength and limiting the plastic deformation of the surrounding rock. Furthermore, the short bolt can reduce the mutual dislocation between rock formations and the shear stress of the long bolt in shallow rock to avoid shear failure. Furthermore, the long bolt can control the deformation of the deep surrounding rock and can be anchored into the elastic zone, thus suspending the

Strata names	Thickness (m)	Lithological description
Fine sandstone	6.46 (4.82-7.53)	Gray, hard, composition of quartz and feldspar, with much white mica
Siltstone	1.82 (0.87-2.21)	Gray, slow wave and oblique bedding, with a thin layer of fine sandstone
Sandy mudstone	1.44 (1.21-1.72)	Dark grey, brittle, containing plant fossils, developed layered fracture
Carbonaceous mudstone	1.12 (0.79-1.32)	Black, dense, brittle, large amount of horizontal bedding
2# Coal	4.25 (3.81-5.23)	Black, soft, semi-bright, band shape
Sandy mudstone	2.02 (1.85-2.37)	Black, brittle, argillaceous cemented, low intensity

Fig. 2. Characteristics of roof-floor at the 12,501 haulage roadway.