



An innovative support technology employing a concrete-filled steel tubular structure for a 1000-m-deep roadway in a high in situ stress field

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ABSTRACT

As coal mining operations progress to depths exceeding 1000 m, the long-term large-scale deformation of deep roadways has been a subject of serious concern in regions with high in situ stress fields. The instability of these roadways affects the safety and efficiency of deep coal mines. To solve this support problem, a new type of strengthening support structure, the concrete-filled steel tubular support (CSTS), was developed. This support is composed of a seamless steel tube bent to conform to the cross-section of the roadway and filled with concrete. According to both mechanical and structural performance testing, the ultimate bearing capacity of the tested CSTS is between 1664 kN and 2235 kN, values 3–5 times that of a U-type steel support. In addition, the circular cross-section of the steel tube has a higher structural stability than the U-shaped cross-section and is not prone to torsional deformation. Because of the clear advantages of both the high bearing capacity and structural stability, a support system combining both CSTS and a bolt-cable system can effectively control the long-term large-scale deformation of a deep roadway. Following a field application within a 1200-m-deep roadway in the Huafeng coal mine in China, the large-scale deformation of the roadway, which previously exceeded 1000 mm, was reduced to less than 30 mm. Furthermore, this roadway no longer required frequent repair after the application of the CSTS. To date, the CSTS has been successfully applied and providing effective support in over 20 deep mines in China.

1. Introduction

As current shallow coal resources become depleted, coal mining is increasingly being conducted at greater depths. In China, many coal mines are expected to proceed to mining depths of 1000–1500 m in the next 20 years (He et al., 2005; Xie et al., 2015). At these depths, the stress concentration caused by the excavation of roadways can exceed 30–40 MPa. Under the high in situ stress conditions in deep mining, the mechanical behavior of the engineering rock mass will change from linear to non-linear. The rock rheology changes; therefore, the deformation of the deep roadway surrounding rock will not only be large and fast but will also demonstrate an apparent time effect. In this environment, the long-term stability of a deep roadway is difficult to maintain (Sun et al., 2000; Malan, 2002; Srisharan et al., 2015; Tan et al., 2017). Therefore, the long-term large-scale deformation of the rock surrounding a deep roadway is a key issue affecting the safe and efficient exploitation of resources in deep coal mines. Currently, the long-term stability control problem of deep roadways is receiving greater attention from many scholars. Consequently, a large number of

studies have investigated the stress field characteristics, the surrounding rock deformation mechanism and the monitoring and supporting technology in deep roadways (Zhang et al., 2012; Mohammad et al., 2016; Tan et al., 2012; Kang et al., 2014; Walton et al., 2016; Zhao et al., 2009; Lin et al., 2015; Jiang et al., 2017). Under the guidance of these previous studies, scholars in the academic and engineering fields have realized that the utilization of active support technology, such as bolts and cables, is not adequate to ensure the long-term stability of a roadway in a high in situ stress field. The utilization of a high-rigidity and high-strength metal bracket as a secondary reinforcement support has been found to be a more effective measure. Currently, the secondary supporting structures utilized in deep coal mines are mainly the I-beam and the full-section U-type steel support (Li et al., 2006; Yuan et al., 2011; Jiao et al., 2013; Antonio et al., 2016; Sun et al., 2015). However, the corresponding bearing capacity has proven to be limited, with a limit of approximately 300–500 kN. These metal supports cannot withstand the high in situ stress field environment at depths exceeding 1000 meters. Wang et al. (2016) developed a new 3D U-type confined concrete support system and studied the

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Fig. 1. U-type steel support distortion deformation in a 1200-m-deep roadway in the Huafeng coal mine.

mechanical properties along with the deformation and failure mechanisms. The bearing capacity of the U-type steel support was effectively improved, and an improved support effect in the field was achieved. However, the U-type steel support still demonstrates serious structural defects, resulting in weak torsion resistance and structural instability. As an example, during the deformation of the 1200-m-deep central substation roadway in the Huafeng coal mine, located in the eastern mining area of China, the U-type steel supports experienced considerable distortion, resulting in the instability of the entire support system, as presented in Fig. 1.

Based on the aforementioned analyses, increasing the bearing capacity of the supporting structure and ensuring the structural stability are the primary concerns in supporting a deep roadway in a high in situ stress field. In this paper, a new supporting structure type called concrete-filled steel tubular support (CSTS) is proposed based on years of research. Compared to the U-type steel support used in coal mines, the CSTS structure has the clear advantages of both high strength and structural stability (Gao et al., 2010; Li et al., 2013; Huang et al., 2014). The application of CSTS can meaningfully contribute to controlling the long-term deformation of roadways at depths exceeding 1000 m. In this paper, the structural characteristics and mechanical bearing capacity of the CSTS are discussed through both theoretical analysis and experimental methods. Support technology in combination with the CSTS as the main body is also proposed. This approach could represent the key support solution for deep roadways to ensure the safe and efficient production from deep coal mines.



Fig. 2. Structural diagrams of a U-type steel structure and a concrete-filled steel tube.

2. CSTS structure

2.1. CSTS elements

The concrete-filled steel tube has been widely utilized in modern ground building and bridge engineering because it is both very strong and very stable. First, the internal concrete is in a triaxial compressive state due to the constraints of the tubular steel shell. Therefore, the core concrete exhibits a high compressive strength. Second, both the internal concrete and the tubular steel shell bear the axial pressure, thereby enhancing the geometric stability and avoiding the premature local buckling damage of the steel tube wall (Gupta et al., 2001; Johansson et al., 2002; Shin et al., 2008). In addition, the concrete-filled steel tube structure has a cylindrical shape, which is the most scientific and reasonable cross-sectional shape. Compared to the U-type steel structure, the concrete-filled steel tube demonstrates a higher bending stiffness and is not easily distorted; therefore, it is more structurally stable. The structures of both the U-type steel and the concrete-filled steel tube are presented in Fig. 2.

Based on the current support problems of deep coal roadways and the outstanding advantages of the CSTS, the concrete-filled steel tubes were incorporated into a mine roadway supporting structure, as shown in Fig. 3.

The CSTS structure is mainly composed of a seamless steel pipe and internal core-filling concrete. To produce the CSTS structure, an empty



Fig. 3. CSTS installation inside a roadway.

steel pipe is bent into the appropriate shape according to the shape of the roadway section; then, concrete is poured into the empty steel tube support following the installation of the pipe in the roadway. Various types of steel pipes with various core concrete ratios can provide a variety of supporting strength values. Compared to the current U-type steel support, the CSTS features outstanding advantages, such as high bearing capacity, good fatigue resistance and better structural stability. Thus, the CSTS can play an important role in long-term deformation control of roadways at depths exceeding 1000 m.

2.2. CSTS structural characteristics

To facilitate transportation and installation along underground coal roadways, the CSTS is divided into four sections: the top arc section, the left and right side sections and the bottom arc section. Each section of the support is connected by a casing tube. The casing tube diameter is slightly larger than the diameter of the main tube. Both tubes have the same curvature, as presented in Fig. 4. A grouting hole is arranged at the bottom of the support. Following the installation of the empty steel tube, the tube is filled with slurry by a concrete conveying pump

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