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Research on Bolt-Cable Reinforcement Support Technology for Gob-Side Entry Retaining in "Three-Soft" Coal Seams

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Abstract

This paper focuses on the application of the gob-side entry retaining technology under complex surrounding rock conditions in "Three-Soft" coal seams. Numerical analysis was conducted using FLAC to study the ground pressure behavior before and after gob-side entry retention in such seams. The research shows that when applying gob-side entry retaining technology under complex roof conditions in "Three-Soft" coal seams, roof subsidence is difficult to control. By utilizing surrounding rock control technology and combined bolt-cable reinforcement support technology, the bearing capacity of the surrounding rock is fully mobilized. This enables the bolts, cables, and surrounding rock to jointly support the roof, thereby reducing excessive subsidence of the retained entry roof. Under reasonable roadway support conditions, the gob-side entry retaining technology proves to be effective and significantly improves mining efficiency.

Keywords

"Three-Soft" coal seam; Gob-side entry retaining; Surrounding rock control technology; Combined bolt-cable reinforcement support technology

1. Introduction

Gob-side entry retaining is a crucial technique in coal mining, which involves preserving the original roadway as the mining roadway for the next panel after the extraction of the upper panel, through methods such as active support, in-roadway reinforcement, and roadside filling. This technology has undergone long-term development and delivers significant benefits. Since its introduction and initial application in China in the 1950s, gob-side entry retaining has remained an important direction for technological development in the country's coal mining industry. This technique effectively enables pillar-free roadway protection, rational exploitation of coal resources, increased coal recovery rates, extended mine service life, reduced roadway excavation volume, alleviation of mining－excavation succession conflicts, elimination of isolated panels, shortened equipment relocation time, and prevention of spontaneous combustion. By avoiding stress concentration caused by coal pillars, it also reduces the risks of rock burst and coal and gas outburst. Gob-side entry retaining is a major roadway protection technology that contributes to mine safety and improves technical and economic outcomes. Moreover, it serves as the most effective approach for implementing Y-type ventilation in mining methods and addressing the challenge of gas overruns in working faces [1-2].

The mining-induced stress caused by extraction activities in adjacent and current working faces can lead to damage and deformation of the surrounding rock in roadways, posing a serious threat to the safe production of the working face [3]. The failure of coal pillars primarily occurs when the mining-induced stress generated during coal seam extraction and roadway excavation exceeds their load-bearing capacity. The methods for retaining coal pillars in mining roadways mainly include the following three: wide pillar retention, narrow pillar retention, and gob-side entry retaining. As the width of the coal pillar increases, the deformation of the roof and the solid coal rib also increases, which is detrimental to maintaining roadway stability [4-5]. Moreover, excessively wide pillars lead to the waste of coal resources. While narrow pillar designs can effectively improve resource utilization, the stress concentration on both sides of the pillar becomes more pronounced. In contrast, gob-side entry retaining offers significant advantages [6-8]:

①It completely eliminates inter-panel coal pillars, substantially improves coal recovery rates, creates significant economic benefits, and extends the service life of the mine.

② It reduces gas accumulation, enables "Y-type" ventilation, addresses gas accumulation issues in the upper corner and goaf, and facilitates the simultaneous extraction of coal and gas.

③ It alleviates mining-excavation succession conflicts, reduces roadway excavation volume, shortens the relocation time of working faces, eliminates isolated panels, and enables continuous and reciprocating extraction of working faces.

④ It reduces the risk of rockburst caused by stress concentration in coal pillars and optimizes the stress environment of roadways.

Therefore, as an important technology in the coal mining process, gob-side entry retaining is an effective approach to achieving economical, safe, and efficient coal extraction. It holds significant theoretical and practical value for promoting the development of pillar-free mining technology in China. Gob-side entry retaining must employ surrounding rock control technologies to enhance roadway stability.

Currently, roadway surrounding rock control technologies primarily include roadway support technology and roadway pressure relief technology [9-10]. In terms of roadway support, Hou Chaojiong and Zhang Dongsheng [11] conducted similar simulation and numerical simulation studies on the fracture position and shape of the overlying roof in fully mechanized top coal caving faces, the impact of support methods on surrounding rock, and roadside support parameters. Their research findings indicate that the combined bolt-mesh-cable-beam support method can enhance the load-bearing capacity of the surrounding rock in gob-side roadways of fully mechanized top coal caving faces, contributing to the safety and stability of the roadway. Professor Kang Hongpu's team [12], based on summarizing over six decades of application of pillar-free mining technology in China, conducted a detailed analysis of the deformation and failure characteristics of gob-side entry retaining. From the perspective of support mechanisms and timing, they categorized surrounding rock control for gob-side entry retaining into in-roadway support, reinforcement support, and roadside support. They proposed combined support methods such as "bolts/cables + supports," "bolt-mesh-cable-shotcrete + grouting reinforcement," and "bolt-mesh-cable-shotcrete + supports + grouting reinforcement" to control harmful deformation of the surrounding rock. Regarding roadway pressure relief technologies, Zhang Xingyu et al. [13] proposed a cutting-slot compensated pressure relief technique to address the instability of high-stress roadways. This method effectively reduces the load on the roadway surrounding rock, thereby enhancing its stability. Kang Hongpu et al. [14] suggested employing pressure relief methods such as deep-hole blasting and hydraulic fracturing in the far field of the surrounding rock to mitigate the impact of mining-induced stress from the working face on the deformation and damage of the roadway surrounding rock. Chang Jucai [15] Gao Yubing [16] and Shenhao [17] investigated the influence of parameters such as different roof-cutting angles and heights on the effectiveness of roadway pressure relief through numerical simulations and theoretical calculations. Professor He Manchao's research team [18-20] introduced a novel roof-cutting and pressure relief roadway formation technology to address issues associated with traditional gob-side entry retaining methods, such as complex processes, high support costs, and slow retaining speeds. This approach established a surrounding rock control technology system centered on "energy-gathering blasting for roof cutting + constant-resistance large-deformation anchor cables + dense single hydraulic props." The cut roof collapses autonomously to form the roadway rib and provides support to the overlying strata.

This paper focuses on the mining roadway of the 13050 working face in Yunding Coal Mine as the research background. Through theoretical analysis and numerical calculations, reasonable support parameters are proposed, and a roadway support scheme is formulated. Field ground pressure monitoring is conducted, employing theoretical analysis, numerical simulation, and field application as technical means to study the support effectiveness of the combined bolt and cable reinforcement technology in top coal caving roadways.

2. Project Overview

2.1. Coal Seam Occurrence Conditions

Yunding Coal Mine is located in Luoyang City, Henan Province. The 13050 roadway is driven along the roof of the No. 2-1 coal seam. According to the 3D seismic exploration report of the 13th mining district, the working face is generally a monoclinal structure with simple geology. Local variations in the coal seam floor are present, but the coal and rock strata are relatively stable, with a dip angle ranging from 7° to 11° and an average dip angle of 8° . The observed thickness of the No. 2-1 coal seam varies from 1.2 m to 10.4 m, with an average thickness of 5.96 m. The coal seam has a simple structure, uniform coal type, and is mostly minable across the area, with localized thin mudstone partings. It is qualitatively classified as a stable coal seam. The mining method adopted is full-seam-height integrated top-coal caving, and the goaf roof is managed by the complete caving method. The lithological characteristics of the surrounding rock of the 13050 roadway are shown in Table 1.

Table 1. Lithological Characteristics of Roadway Surrounding Rock

Rock Type	Thickness (m)	Characteristics
Fine sandstone	2.29	Gray, quartz-based, with mica, moderate sorting, siliceous cementation
Medium sandstone	6.65	Gray, quartz-dominated, with dark minerals and mica.
Silts tone	1.59	Dark gray, with mica and dark minerals, fractures present.
Medium sandstone	5.4	Light gray, quartz-based, with cross-bedding and fractures.
Silts tone	3.38	Dark gray, with parallel and cross-bedding, local fractures
No. 2-1 coal	5.61	Black, powdery, mainly bright coal.
Muds tone	6.77	Gray-black, with plant fossils
Limes tone	8.37	Dark gray, cryptocrystalline, calcite-based

2.2. Original Support Scheme

The support schemes for coal roadways in the Yunding Mining Area are mostly designed based on engineering experience accumulated over several decades. Among them, the 13050 roadway is a full-seam roadway driven along the coal seam roof, with a trapezoidal cross-section measuring 5.4 m in width, a high side of 4.4 m, and a low side of 3.8 m. Bolts, cables, and other support materials are employed.

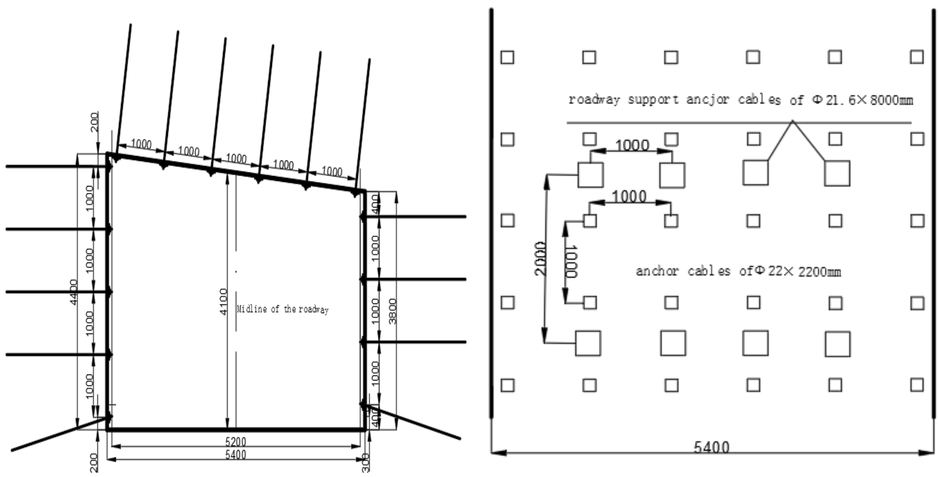
(1) The bolts are made of left-hand threaded steel bars without longitudinal ribs, with a diameter of φ22 mm, a length of 2200 mm, and a yield strength of 335 MPa. Each bolt is equipped with a 150 mm × 150 mm × 10 mm arched bearing plate. For bolt anchoring, one Z2550 and one K2550 resin cartridge are used per bolt, and the pre-tightening torque for all bolts is set at 150 N·m.

(2) The cables are 21-strand low-relaxation prestressed steel strands with a diameter of φ21.8 mm and a length of 8000 mm. For anchoring, two Z2550 and two K2550 resin cartridges are used per cable. Subsequently, a 300 mm × 300 mm × 15

mm arched cable bearing plate, along with locking devices, is installed for tensioning and pre-stressing, with a designed pre-tensioning force of 200 kN.

The specific layout of bolts and cables is as follows:

Six bolts are installed per row in the roof, with a spacing and row spacing of 1000 mm × 1000 mm. Cables are installed between two rows of bolts, with four individual cables arranged every other row. Nine bolts are installed per row in the rib sides: five on the high side and four on the low side, with a spacing and row spacing of 1000 mm × 1000 mm. The original support scheme is shown in Figure 1.



(a)Cross-sectional view (b) Roof Support Drawing

Figure 1. Original Support Scheme drawing

3. Deformation and Failure Mechanism of Roadway Surrounding Rock

Yunding Coal Mine is located in Luoyang City, Henan Province, with relatively complex stratigraphic lithology. The roof and floor of the main coal seam predominantly consist of weak rock layers such as mudstone, carbonaceous mudstone, and siltstone. Structural planes such as joints and fissures are well-developed within the rocks, and both the roof and floor of the main mining coal seam contain weak interlayers, with localized fractured zones present. Roof inspection of the roadway indicates that the surrounding rock is a composite roof composed of multiple thin rock layers. Additionally, the large cross-section of the underground rock roadway, combined with the multiple excavation disturbances from adjacent roadway groups, inevitably leads to significant deformation and failure of the roadway roof.

3.1. Establishment of Numerical Model

Using FLAC3D numerical simulation software and based on the actual geological conditions of the No.2-1 coal seam in Yunding Coal Mine, a numerical model with dimensions of length×width×height = 80 m×20 m×80 m was established, as shown in Figure 2. A uniformly distributed load of 12.37 MPa was applied to the upper surface of the model according to the burial depth of the roadway, with a lateral pressure coefficient of 1. The bottom surface of the numerical model was constrained in displacement along the x, y, and z directions, while the front, back, left, and right surfaces were constrained in displacement perpendicular to their respective surfaces. The Mohr-Coulomb constitutive model was adopted, and the rock layer parameters involved in the numerical calculation are listed in Table 2

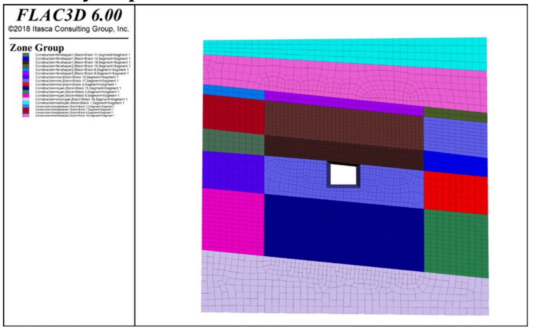


Figure 2. Bottom Layer Model

Table 2. Physical and Mechanical Parameters of the Coal Seam and Its Roof and Floor

Rock Type	Density (kg/m^3)	Elastic Modulus (GPa)	Friction Angle (°)	Cohesion (MPa)	Tensile Strength (MPa)	Poisson's Ratio
Fine sandstone	2754	19.95	34.37	8.2	3.23	0.15
Medium sandstone	2707	25.2	37.3	8.3	7.83	0.16
Silts tone	2837	18.9	36.22	3.8	2.04	0.19
Medium sandstone	2780	25.2	35.64	8.3	4.1	0.17
Silts tone	2837	18.9	36.22	5.1	2.4	0.21
No. 2-1 coal	1435	3.56	35.5	2.99	0.5	0.3
Muds tone	2690	10.5	34.04	4.3	2.94	0.22
Limes tone	2788	28.35	38.67	11.4	5.8	0.17

3.2. Roadway Deformation and Failure Behavior

The contour maps of stress distribution and deformation distribution after roadway excavation are shown in Figure 3.

From Figures 3(c) and 3(d), it can be observed that after roadway excavation, noticeable tensile stress zones appear on the surfaces of the roof, floor, and both sidewalls. The maximum vertical displacement of the roadway occurs in the central part of the roof, while the maximum horizontal displacement is located in the middle of the two sidewalls. In terms of magnitude, controlling the displacement of the roadway roof represents the primary challenge.

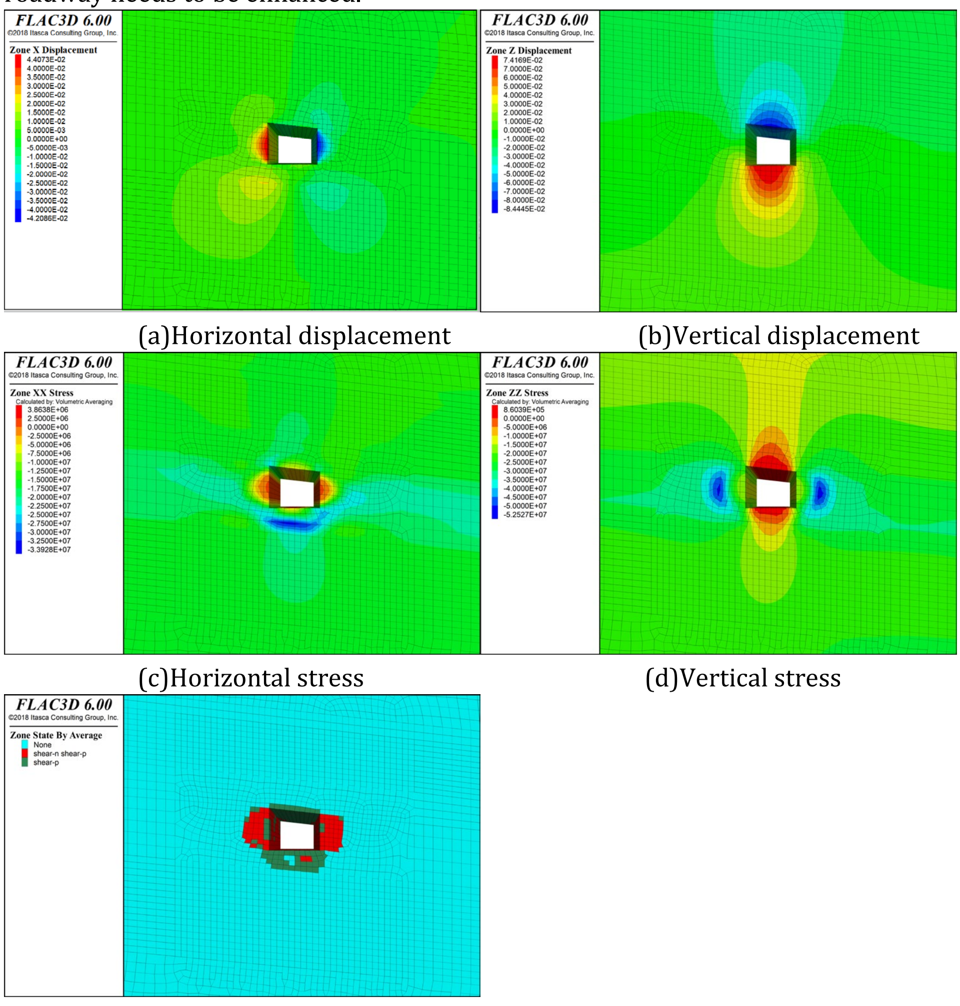
3.3. Analysis of the Causes of Roadway Deformation and Failure

Based on the numerical calculation results, the original support design exhibits certain shortcomings. The main issues are as follows:

(1) The distribution of support strength is uneven, with some sections having insufficient support strength while others are over-supported.

(2) The suspension effect provided by the anchor cables in roadway support varies in intensity, making it difficult to form an effective pressure arch with the bolts and the overlying rock strata to adequately support the roadway.

(3) The displacement in the central section of the roadway roof is greater than that in the sidewalls, indicating that the support strength in the central area of the roadway needs to be enhanced.



(a)Horizontal displacement (b)Vertical displacement

(c)Horizontal stress (d)Vertical stress

(e)Plastic zone

Figure 3. Roadway Deformation-Failure Patterns

4. Bolt-Cable Reinforcement Support Technology

4.1. Support Theory

The Reinforced Arch Theory posits that after applying pre-tension to bolts, a compression arch zone with supporting function forms around the bolts. When multiple bolts are installed in groups, their conical compression zones overlap. This overlapping area is termed the reinforced arch, within which the rock mass exists in a triaxial stress state, significantly enhancing its load-bearing capacity.

The Suspension Theory holds that the primary role of bolts and cables is to suspend unstable rock layers in the roof to overlying stable strata. In the design of coal mine roadway support, bolts and cables are often treated as independent components and designed separately, neglecting their synergistic supporting effect, which considerably diminishes the overall support efficacy.

The Bolt-Cable Synergistic Support Theory, proposed by Shan Renliang, integrates the Suspension Theory and the Reinforced Arch Theory. It utilizes cables to suspend the reinforced arch into deeper stable rock strata, while simultaneously leveraging the self-supporting capacity of both shallow and deep rock masses surrounding the roadway.

4.2. Support Optimization Scheme

To enhance roadway support and reduce roadway displacement while preserving existing effective measures, this paper proposes a reinforcement support optimization scheme based on bolt-cable synergistic support technology. The specific reinforcement support configuration is as follows:

In the roof, cables are arranged in a “6-4” pattern (six in the roof and four in the floor) with a spacing and row spacing of 1000 mm × 1000 mm per row. All roof cables are installed vertically, with a pre-tensioning force of 200 kN.

In the ribs, nine bolts are installed per row: five on the high side and four on the low side, with a spacing and row spacing of 1000 mm × 1000 mm. An additional rib cable is installed in the middle of each row. The two top corner rib bolts are tilted 15° toward the roof, while the two bottom corner rib bolts are tilted 15° toward the floor. The remaining rib bolts are installed horizontally.

The specific layout of bolts and cables is illustrated in Figure 4.

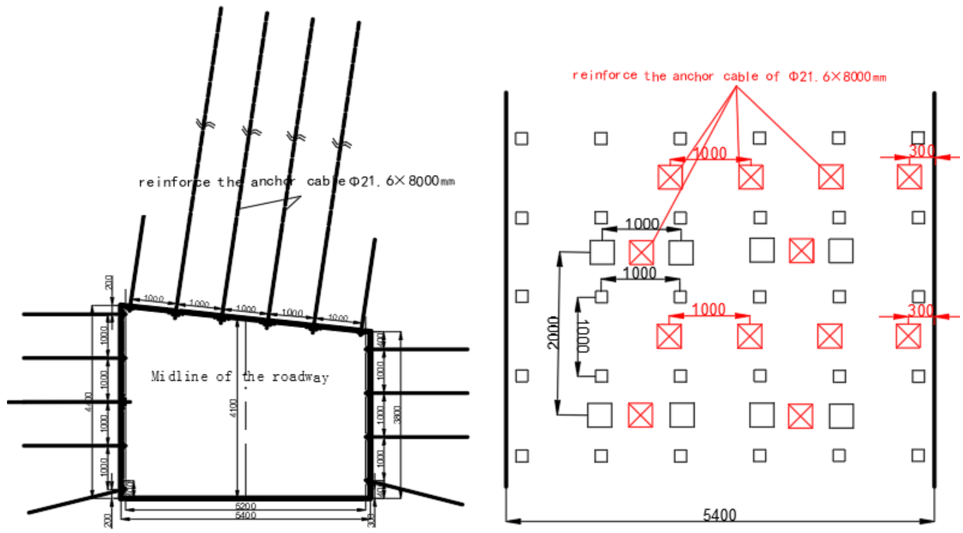
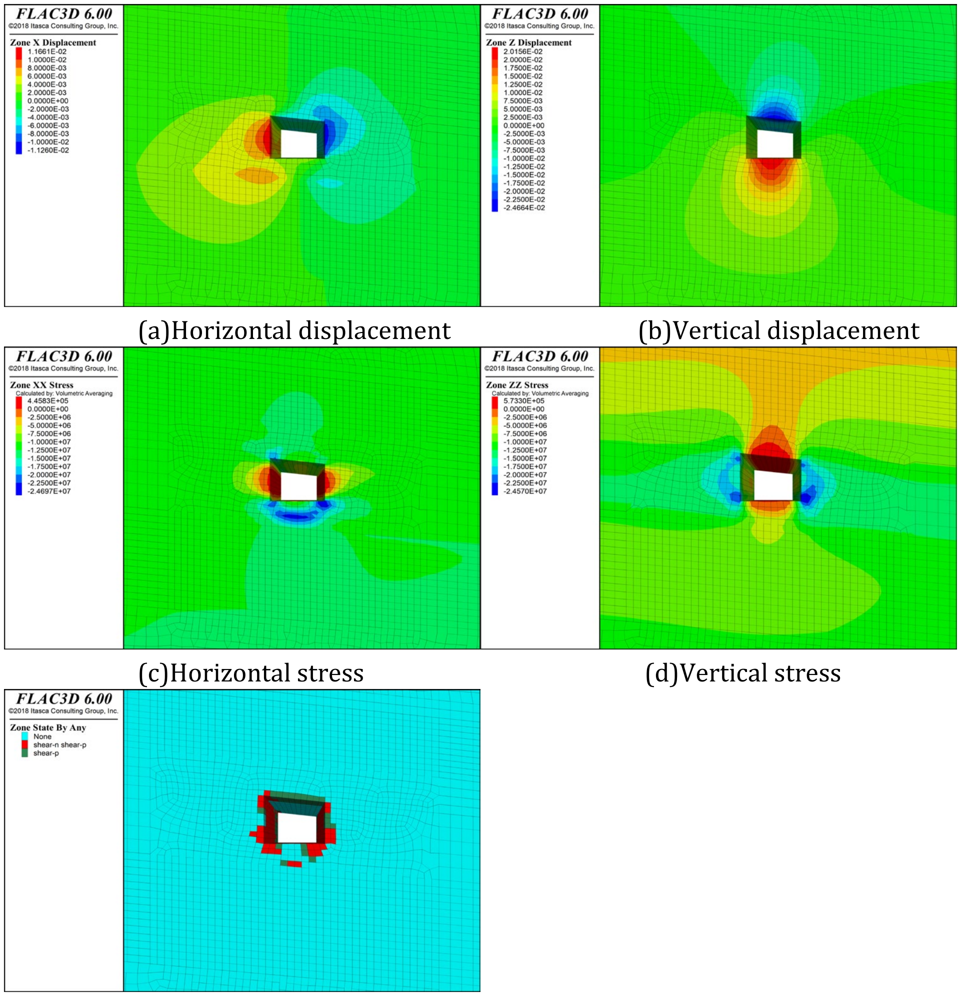


Figure 4. Original Support Scheme drawing

4.3. Analysis of Reinforcement Support Effectiveness

The prestress distribution contour maps after implementing the reinforcement support scheme are shown in Figure 5, where tensile stress is positive and compressive stress is negative. As can be seen from Figure 5, the shapes of the prestress fields formed by both the original support scheme and the reinforcement support scheme are similar, primarily consisting of two parts: a compressive stress zone in the shallow surrounding rock of the roadway and a tensile stress zone in the outer region. However, by comparing Figure 5(a) with Figure 5(b) and Figure 5(c) with Figure 5(d), respectively, it can be observed that for both horizontal stress and vertical stress, as well as horizontal displacement and vertical displacement, the stress contour maps presented by the roadway reinforcement support scheme are significantly reduced. The horizontal and vertical displacements are also notably smaller. This indicates that the roadway reinforcement support scheme can reduce roadway deformation, which is beneficial for roadway stability.

From this, it can be concluded that employing bolt-cable reinforcement support technology can apply greater magnitude and more extensive prestress to the roadway surrounding rock. This more effectively compensates for the stress unloading caused by roadway excavation, increases the minimum principal stress, reduces the Mohr's circle, and places the roadway surrounding rock in a more stable triaxial stress state, thereby significantly enhancing the stability of the surrounding rock.



(a)Horizontal displacement (b)Vertical displacement

(c)Horizontal stress (d)Vertical stress

(e)Plastic zone

Figure 5. Reinforcement Support Simulation Contour

4.4. Engineering Practice

To verify the actual effectiveness of the bolt-cable reinforcement support technology, an on-site sectional test was conducted in the 13050 roadway of Yunding Coal Mine to monitor the deformation of the surrounding rock. In the early stage of the working face advance, the overall deformation of the roadway increased rapidly. Over time, the deformation gradually increased and eventually stabilized. According to the field test results, after implementing the bolt-cable reinforcement support layout technology, the overall deformation of the roadway was relatively small. Specifically, the maximum roof subsidence was 21 mm, and the convergence of the two sidewalls was 25 mm. The roadway deformation was effectively controlled, demonstrating satisfactory support performance.

5. Conclusions

(1) The support principles of the bolt-cable reinforcement support technology were briefly explained. Taking the 13050 roadway of Yunding Coal Mine as the background, an optimized bolt-cable reinforcement support scheme was proposed to address the shortcomings of the original support design.

(2) To address the severe deformation of surrounding rock in gob-side entry retaining, a roadway bolt-cable reinforcement support technology scheme was proposed. After implementing this scheme, the average maximum surface convergence of the roadway roof, coal rib, and coal pillar rib was significantly reduced.

(3) Using numerical simulation as a technical means, the deformation and failure characteristics of trapezoidal roadways in complex rock formations were analyzed. The application of the bolt-cable reinforcement support technology not only effectively reduced support intensity but also successfully controlled roadway deformation, ensuring the stability of the gob-side entry retaining. The strong applicability of the bolt-cable reinforcement support technology in engineering practice has been verified.

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