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Design and Stability Analysis of Support Structure in Deep Roadway of Coal Mine

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Abstract: This article discusses the design principle, scheme implementation and stability evaluation of coal mine roadway supporting structure. Firstly, according to the geological conditions, cross-section shape and service life of the roadway, the composite supporting structure combined with anchor net cable and scaffolding is designed comprehensively, and the specifications, layout and construction technology of supporting materials are expounded. Subsequently, the stability of the supporting structure is analyzed by combining numerical simulation with field monitoring. The numerical simulation results demonstrate that the composite support form significantly controls surrounding rock deformation, with field monitoring data validating the support design's rationality. Additionally, the paper analyzes factors influencing the stability of the supporting structure and offers optimization suggestions, providing a scientific foundation for the long-term safe use of coal mine roadway.

1. Introduction

In the process of coal mining, roadway, as the key passage of mine production, transportation, ventilation, drainage and personnel passage, its stability is directly related to the safety and efficiency of coal mine production [1]. With the increasing depth of coal mining, the geological environment in which the roadway is located is increasingly complex, and the influence of geostress, groundwater and mining on the stability of the roadway is more and more obvious [2]. Therefore, the scientific and reasonable design of roadway supporting structure and its stability analysis are particularly important.

In the long-term coal mining practice, people gradually realize that it is often difficult to maintain the long-term stability of roadway only by the self-supporting capacity of naturally formed surrounding rock [3]. Especially in the complex geological conditions such as deep mining, soft rock roadway and large cross-section roadway, the deformation and destruction of surrounding rock of roadway are particularly prominent, which brings huge security risks and economic losses to coal mine production [4]. Therefore, it is of great significance to carry out the design and stability analysis of coal mine roadway support structure for improving roadway stability and ensuring coal mine production safety.

In recent years, with the rapid development of materials science, rock mechanics, computer science and other disciplines, coal mine roadway support technology has also made remarkable progress. The emergence of various support forms, from traditional wood support and masonry support to modern bolting and shotcreting support, scaffolding support and composite support, provides more choices for coal mine roadway support [5]. However, there are significant differences in the effects of different support forms in adapting to geological conditions, controlling surrounding rock deformation and improving roadway stability. Therefore, how to scientifically and reasonably select the support form and optimize the design according to the geological conditions and mining requirements of the specific roadway has become an important direction of the current research on coal mine roadway support technology [6].

This article aims to provide scientific basis and technical support for coal mine roadway support through in-depth research on the design and stability analysis of coal mine roadway support structure. The significance of this study is mainly reflected in the following aspects:

(1) Improve the stability of roadway: Through scientific and reasonable design of supporting structure, the deformation and damage of surrounding rock of roadway can be effectively controlled, and the overall stability of roadway can be improved.

(2) Reduce economic cost: Unreasonable support design can not only ensure the stability of roadway, but also cause material waste and cost increase. By optimizing the design of supporting structure, this study improves the supporting efficiency and helps to reduce the economic cost of coal mine production.

(3) Promote technological innovation: With the increase of coal mining depth and the complexity of geological conditions, higher requirements are put forward for roadway support technology. This study is helpful to promote the innovation of coal mine roadway support technology by exploring new support forms and optimization methods.

2. Roadway characteristics and geological conditions

2.1. Basic situation of roadway

In this study, the design of supporting structure and stability analysis of coal mine roadway are discussed by taking the second level of a coal mine (the second auxiliary bottom) as an example. The vertical depth of the main roadway of the yard is 1000m. As the key hub of mine production and transportation, the bottom yard undertakes multiple tasks such as equipment transportation, ventilation, drainage and personnel passage, and its design length reaches 676.884 meters.

The stress field characteristics and deformation rules of surrounding rock will be very complicated due to the repeated construction disturbance in the deep tunnel and roadway of complex and high ground stress, which poses new challenges to support design, disaster prediction and control technology of surrounding rock. Especially for some key chambers and tunnels, from the service nature, it is required to achieve maintenance free after its completion and operation.

The cross-section shape of roadway adopts straight wall semi-arch shape, which can not only effectively use space, but also disperse the surrounding rock pressure to some extent and improve the stability of roadway. According to the different requirements of support design, the section size of roadway is also different.

2.2. Geological conditions

The complex and variable geological conditions at the bottom of the second level mine pose significant challenges to roadway stability. Geological report data and actual exposure reveal that the primary lithologies in this area include silty sandstone, sandy mudstone, coal line, spotted mudstone, siltstone, and medium-fine sandstone, each with distinct physical and mechanical properties requiring different supporting structures.

Based on surrounding rock conditions, three types of rock samples were selected, namely, silty sandstone, sandy mudstone and porphyry mudstone, which were transported back to the laboratory for processing, and their rock mechanical properties were obtained, as shown in Table 1.

Table 1: Characteristics of surrounding rock and strength parameters of rock samples

NO.	Lithology description	Surrounding rock characteristics	Sample strength	
1	Silty sand rock: Relatively intact rock mass, Minor structural plane;		Compressive strength	53.6
			Cohesive force	40
			Angle of internal friction	8.5
2	Sandy mudstone: Complex composition, structural plane is relatively developed;		Compressive strength	47.0
			Cohesive force	52
			Angle of internal friction	7.6
3	Porphyry mudstone: Becomes muddy when it meets water, structural plane is complex;		Compressive strength	27.1
			Cohesive force	24
			Angle of internal friction	0.7

Moreover, there's a fault with a 2m throw disrupt the continuity of rock strata, causing local surrounding rocks to fracture and develop cracks, thereby exacerbating the difficulty of roadway support. Faults can also lead to groundwater gushing and geostress concentration. Therefore, roadway support design must consider fault influence and implement targeted measures.

High ground stress at km depth is a crucial factor affecting roadway stability, and its redistribution after excavation demands robust supporting structures. Tunnel excavation disrupts the original rock's stress state, causing surrounding rock to move towards the tunnel space and release energy. This energy release can lead to surrounding rock deformation and destruction, impacting roadway stability. Thus, the supporting structure must possess sufficient bearing capacity and deformation adaptability to control surrounding rock deformation and failure effectively.

3. Supporting structure design

In the design of supporting structure of coal mine roadway, the geological conditions, section shape, service life and mining mode of roadway should be comprehensively considered to ensure that the supporting structure can not only effectively control the deformation of surrounding rock, but also meet the requirements of economic rationality. This section will elaborate the selection of support forms, the determination of support parameters and the selection of support materials.

3.1. Selection of support form

Selecting the appropriate supporting form is the fundamental task in supporting structure design. Based on geological conditions, surrounding rock strength, and the roadway's size and shape, common support forms include bolt-mesh-cable support, scaffolding support, shotcrete support, and their composites.

(1) Bolt-mesh-cable support is ideal for roadways with intact surrounding rock and strong self-stabilizing capabilities. Metal mesh, secured by bolts, forms a continuous support system, enhancing the overall strength of the surrounding rock. Anchor cables, serving as reinforcing support, penetrate deep into the rock, providing greater anchoring force and support stiffness.

(2) Scaffolding support suits roadways with soft, fractured surrounding rock and poor self-stabilization. It involves installing metal supports to prevent roof and sidewall caving. While scaffolding support offers strong bearing capacity and adaptability, it is costly and challenging to construct.

(3) Shotcrete support serves as an auxiliary measure, sealing the roadway surface with sprayed concrete to prevent surrounding rock weathering and peeling. It also enhances the rock's overall strength. Shotcrete support boasts fast construction and relatively low costs, but its standalone effectiveness is limited.

3.2. Combined support mechanism

Based on the high ground stress condition of the original rock in deep rock roadway, the support goal should be to exert the self-bearing capacity of the rock mass, that is, to form a stable load-bearing compressive rock arch in the rock mass through support (Fig.1). First of all, it should meet the stability of the center of the single anchor reinforcement area without damage, and then the overall support system needs to have a certain anti-disturbance ability. Therefore, for the traditional anchor reinforcement arch structure, through the addition of U-shaped steel scaffolding support, play the following roles:

1) Improve the wall strength and stiffness of the supporting system, and enhance the overall anti-disturbance ability.

2) Limit the shear slip of fractured rock mass outside the anchor compression arch.

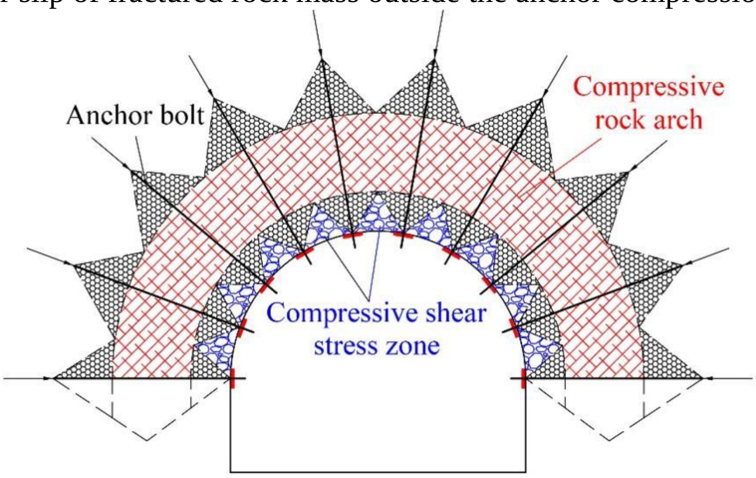


Figure 1: Load-bearing compressive rock arch

In order to achieve a better combined support effect, the back of the U-shaped steel support must be packed tightly, and the design uses high-rigidity steel mesh as the backplane to increase the gap between the bag graded gravel filling and the rock wall.

After the above process is completed, the deformation monitoring of the roadway is carried out, and when the deformation rate becomes stable, the surrounding rock surface is closed with shotcrete. The last process is grouting, first using shallow hole grouting, and then drilling deep holes for grouting.

1) Shallow hole grouting is mainly filled with graded gravel after consolidating the wall, and the spray layer, U-shaped steel and broken surrounding rock form an overall structure.

2) Deep hole grouting mainly fills the pressure fracture space in the surrounding rock, consolidates the rock mass in the compressive rock arch, and enhances its self-stability.

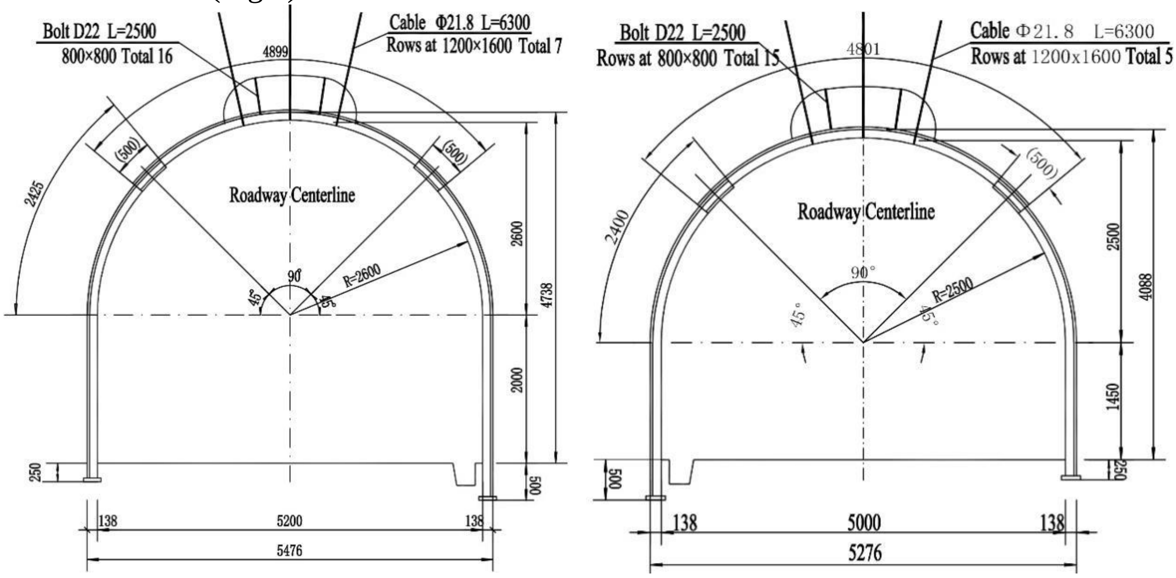
3.3. Determination of support parameters

The determination of support parameters includes the specifications of anchor rods, spacing and row distance, anchoring methods, specifications and overlapping methods of mesh sheets, specifications and spacing of support frames, etc. The reasonable setting of these parameters is directly related to the effectiveness of the support.

Taking bolt-mesh-cable support as an example, this project adopts MSGLW-400/φ22×2500mm high-strength anchor rods with a spacing and row distance of 800×800mm. The top anchor rods are fully anchored and used with K2860 and Z2850 anchoring agents. The cable specifications are SKP22-1/1860/6300mm, arranged in a "7-7" or "5-5" pattern, with a spacing and row distance of 1200×1600mm. The metal mesh is made of 8# hot-dip galvanized low-carbon steel wire into a diamond shape, with a size of 5000×1100mm. The overlapping length is not less than 100mm, and it is fastened with double-stranded 14# iron wire.

For frame support, 36U steel frames are selected with a spacing of 800mm. The overlapping length of the frame beams and legs is 500mm, and two sets of clamps are installed at each overlapping point, with a spacing of 400mm between the clamps. Each frame is reinforced with four angle steel braces of L=1880mm in length, used with φ16mm hooks. The space between frames is reinforced with Φ10mm steel bars.

Shallow hole grouting has 6 holes in each row, 2000mm grouting pipe is adopted, the spacing between rows is 2.4×4.0m, the final grouting pressure is 1-2MPa, and the grouting will be stopped in time after the surface leakage. The deep-hole grouting is mainly aimed at the middle of the bottom plate. 5000mm capsule pipe is used for grouting, the row distance is 4.0m, and the final grouting pressure is 4-6MPa. (Fig.2)



(a) Seven cables per row (b) Five cables per row

Figure 2: Layout of roadway supporting section

4. Stability analysis of supporting structure

The stability analysis of supporting structure is the key link to ensure the safe use of roadway. In this section, the stability of supporting structure will be analyzed by means of numerical simulation, field monitoring and so on, combining with engineering examples.

4.1. Numerical simulation analysis

In order to predict the deformation and failure characteristics of supporting structure under complex geological conditions, advanced numerical simulation software (FLAC3D) is used to analyze the stability of supporting structure. The numerical simulation considers the physical and mechanical properties, in-situ stress distribution, support form and parameters of surrounding rock, and simulates the excavation and support process of roadway by constructing a three-dimensional geological model, and analyzes the control effect of support structure on the deformation and stress of surrounding rock.

The maximum deformation of roof is selected as the observation index. The numerical simulation results show that the combined support form of bolt-mesh-cable support and scaffolding support is excellent in controlling the deformation of surrounding rock. Specifically, the effective anchorage of anchor rod and anchor cable significantly improves the overall strength of surrounding rock and reduces the displacement of roof and two sides; Scaffolding support effectively prevents the collapse of surrounding rock through its strong bearing capacity. Table 2 shows the maximum displacement of roadway roof under different support forms in numerical simulation.

Table 2: Maximum displacement of roadway roof under different supporting forms in numerical simulation

Support Form	Maximum Roof Displacement (mm)
Unsupported	295.3
Bolt-mesh-anchor Support	117.6
U-shaped Steel Set Support	78.4
Composite Support (Bolt-mesh-anchor + U-shaped Steel Set)	49.2

Through comparative analysis, it is known that the composite support form is the most effective in controlling the roof displacement of roadway.

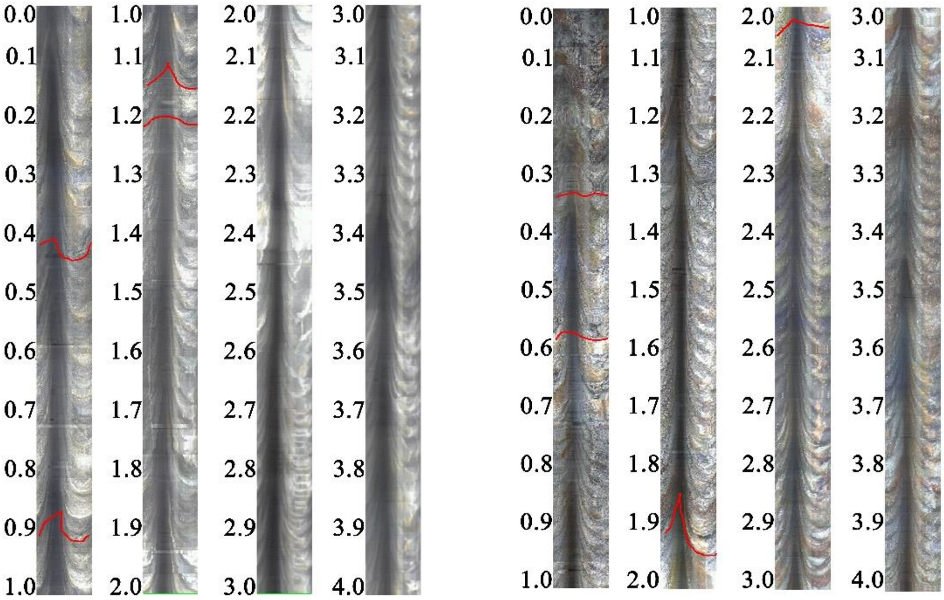
4.2. On-site monitoring data analysis

In order to verify the reliability of numerical simulation results, this study also arranged monitoring equipment such as multi-point displacement meter and borehole observation on the spot to monitor the deformation and crack of surrounding rock of roadway in real time. The field monitoring data provide an important basis for the stability analysis of the supporting structure.

Table 3: Comparison of displacement of roadway roof between field monitoring and numerical simulation

Support Form	Roof Displacement in Numerical Simulation (mm)	Roof Displacement in Field Monitoring (mm)
Bolt-mesh-anchor Support	117.6	112.3 ±9.5
U-shaped Steel Set Support	78.4	73.6 ±7.8
Composite Support (Bolt-mesh-anchor + U-shaped Steel Set)	49.2	47.5 ±5.9

Table 3 shows the actual displacement of roadway roof under different support forms in field monitoring and its comparison with numerical simulation results. It can be seen that the field monitoring data are basically consistent with the numerical simulation results, which further verifies the rationality of the support structure design. (Fig.3)



(a) Station 1 (b) Station 2

Figure 3: Measurement of split seam in roof of roadway surrounding rock

In order to analyze the injectivity before grouting, two observation stations of roof separation fissure are set up at the crossing points. The crack range of the surrounding rock of the cross-roadway at station 1 can be measured as 1.3m, and the crack development range of the cross-roadway at station 2 can be measured as 2.0m. The development of cracks in surrounding rock cannot be completely controlled by the support of anchorage and scaffolding alone.

In-situ monitoring also found that the deformation of surrounding rock is still relatively large in key parts such as roadway intersection and stress concentration area, although strengthening support measures are adopted. This shows that in these special parts, it is necessary to further optimize the support design or take other reinforcement measures to improve the stability of the support structure.

4.3. Analysis of influencing factors of stability

To sum up, in order to improve roadway stability, thee following optimization suggestions:

(1) The composite support form of combining bolt, mesh and cable with scaffolding shows obvious advantages in controlling the deformation of surrounding rock of roadway. This support not only improves the overall strength of surrounding rock, but also significantly reduces the displacement of roof and two sides, ensuring the stability of roadway. Strengthen the quality control in the construction process to ensure that the quality of supporting materials reaches the standard and the construction operation is standardized.

(2) During the use of roadway, strengthen the monitoring of surrounding rock deformation, and find and deal with the damage of supporting structure in time.

5. Conclusions

(1) With proper spacing arrangement of group anchors, the combined action can form a pressure superposition area and form a pressure arch effect; Maintaining the stability of the pressure arch is

the key to ensure the long-term safety of the deep soft rock roadway support system in coal mine.

(2) When using anchor support, the development of internal cracks in surrounding rock cannot be completely controlled. There is a certain compressive shear zone between each anchor rod, and rock cracks develop on the roadway wall.

(3) The combined support of "anchor-net-frame-shoting-injection" can form a common interaction between surrounding rock and support, especially grouting consolidation has a significant effect on controlling surrounding rock deformation, and is an indispensable technical means for deep soft rock roadway support.

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