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Research on Optimization of Roadway Support in Metal Mines Based on Engineering Safety

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Abstract

Aiming at the problem of roadway support stability under complex geological conditions in deep metal mines, this study takes Ma cheng Iron Mine, one of the largest underground iron mines under construction in China, as the research object. It systematically analyzes the failure mechanism of the roadway support system during multi-level mining and proposes an optimization scheme based on the collaborative support theory. A hierarchical bolt-mesh-shotcrete + anchor cable + steel arch frame collaborative support system is established: low-prestress resin bolts (anchoring force 180kN) and high-strength steel mesh (mesh density 100×100mm) are introduced, anchor cable parameters are optimized (Φ21.8mm, prestress 250kN), and a dynamic support adjustment mechanism is constructed. The research results provide theoretical basis and technical support for the safe and efficient mining of deep metal mines.

Keywords

Deep mining; Roadway support optimization; Collaborative support; Blasting disturbance control

Introduction

Underground mine roadways are an indispensable part of the mining process, and their support work is of great significance for ensuring the safety of miners and improving mining efficiency. Roadway support can not only effectively avoid mine accidents but also enhance the stability and service life of roadways, ensuring the continuity and stability of production [1–5]. Common roadway support methods include reinforced concrete lining, precast arch supports, bolt support, grouting support, etc. Each of these methods has its own characteristics and application scope, requiring selection and application according to different roadway types and geological conditions. For example, reinforced concrete lining can be adopted in areas with good geological conditions, while bolt support or grouting support can be used in areas with poor geological conditions to improve roadway stability and safety [6–8]. Therefore, strengthening the research and practice of roadway support in metal mines is of important practical and strategic significance for ensuring the safety and stability of mine production, improving mining efficiency, and promoting the sustainable development of the mining industry.

Macheng Iron Mine has a thick and large ore body, multiple mining levels, diverse roadway functions, complex surrounding rock geological conditions, and various roadway cross-sectional sizes. This requires the design to provide multiple support forms to meet the support needs of roadways with different cross-sectional sizes under different levels and various surrounding rock conditions. The roadway support design for each level of Macheng Iron Mine strictly complies with the requirements of the Code for Design and Construction of Ground Anchor and Shotcrete Support Engineering (GB50086-2015). By referring to other underground mining and underground engineering projects, a complete set of support schemes has been proposed [9]..

1. Project Overview

Macheng Iron Mine is located in Macheng Town, Luannan County, Hebei Province, at the top of the Luanhe alluvial-proluvial fan. It has proven iron ore reserves of 1.225 billion tons, making it an important mineral resource base in the Jidong Plain and known as the "Steel Granary" of Hebei Province. The ore body is buried under a Quaternary loose sedimentary layer of more than 100 meters thick, occurring in the metamorphic rock series of the Baimiao Formation of the Proterozoic Dantazi Group. It generally strikes north-south, dips west, with a dip angle of 50° ~60° , and the lithology is mainly magnetite quartzite. The mine is designed with an annual production capacity of 22 million tons of iron ore, making it one of the largest underground iron mines under construction at home and abroad, adopting a shaft-inclined drift combined development system. The mining area is divided into upper and lower mining districts:

Upper mining district: -480m (drilling level), -540m (ore drawing level), -570m (transportation level);

Lower mining district: -840m (drilling level), -900m (ore drawing level), -930m (transportation level).

The cross-sectional size design of roadways at each level comprehensively considers ventilation efficiency, pedestrian safety, equipment passage, and construction convenience. The surrounding rock of the ore body is mainly composed of migmatitic granite, migmzatite, biotite leptynite, and diabase, belonging to hard and brittle rock types. According to the Standard for Engineering Rock Mass Classification (GB/T50218-2014), the surrounding rock quality grade ranges from Class I to Class V, with variable geological conditions and significant heterogeneity of roadway surrounding rock..

2. Overview of Roadway Support in Macheng Iron Mine

2.1. Hierarchical Design of Roadway Support

The width of most roadways in Macheng Iron Mine is less than 10m, and the support design parameters described in this paper are aimed at such medium and small-span roadways, with a cross-sectional shape of straight-wall three-centered arch or semicircular arch. According to the Standard for Engineering Rock Mass Classification (GB/T50218-2014), differentiated support methods are determined based on surrounding rock quality classification (see Table 1).

Table 1. Surrounding Rock Classification and Corresponding Support Forms

Surrounding Rock Class	Support Form	Applicable Conditions (Excavation Span B)
Class I	No support/Shotcrete	B≤5m
Class II	Shotcrete	B≤10m
Class III	Bolt-shotcrete support/Bolt-mesh-shotcrete support	B≤10m
Class IV	Bolt-mesh-shotcrete/Steel arch frame combined support	B≤10m
Class V	Special support scheme	Dynamic evaluation

2.2. Specifications for Support Parameters

(1) Shotcrete Support

Class I surrounding rock: 50mm thick C25 shotcrete is adopted when B⩽5m;

Class II surrounding rock: 100mm thick shotcrete is adopted when B⩽5m; the thickness is increased to 120~150mm when 5m＜B⩽10m.

(2) Bolt-shotcrete Support System

Class III surrounding rock: 100mm thick bolt-shotcrete support is adopted when B ⩽5m; bolts are arranged in a rhombus pattern with a spacing of 0.9~1.0m, and the length is 1.8~2.0m (non-prestressed cement mortar bolts);

Bolt-mesh-shotcrete support: The steel mesh specification is 200×200mm, the gap between the mesh and the surrounding rock is ⩾30mm, and the coverage thickness of shotcrete is ⩾40mm.

(3) Steel Arch Frame Combined Support

Applicable to Class IV surrounding rock under the following conditions: short self-stabilization time of surrounding rock, requiring rapid stabilization of the working face; need to suppress large deformation of surrounding rock.

Construction process:

Initial shotcrete of 50mm thick concrete; laying 150×150mm steel mesh; installing low-prestress resin bolts (spacing 1.0×1.0m); erecting steel arch frames (spacing 500~800mm), reinforcing the 250mm range of column feet, and connecting the arch frames with Φ25 round steel tie rods; secondary shotcrete sealing with a coverage thickness of ⩾40mm.

Steel section selection:

B⩽4m: 25U steel, 4-section straight-leg semicircular arch;

B⩽5m: 29U steel, 4-section straight-leg semicircular arch;

5m＜B≤10m: 36U steel, 5-section straight-leg semicircular arch.

3. Current Problems

Since the trial production, with the successive blasting and mining operations of the ore rooms at the -540m level of the No. V ore body, various degrees of spalling, side collapse, and other phenomena have occurred in the roof and side walls of the ore drawing connecting roadways, ore drawing drifts, cutting drifts, crosscuts, and crosscut ore pass chambers in the ore rooms, and local ore pillars have been damaged. There are significant safety hazards in on-site charging and scraper ore drawing operations (see Figure 1). It is necessary to optimize and adjust the support forms of the ore room bottom structure, ore pass unloading chambers, drilling chambers at the -480m and -840m levels, and the hanging wall and footwall drift and crosscut at the -480m, -540m, -840m, and -900m levels to ensure the safety of personnel and equipment during mining.

Figure 1. Local Concrete Roof Collapse and Spalling

3.1. Influence of Geological Characteristics

There are various sizes of bedding planes and joints/fissures developed in the mining area. According to geological exploration data and on-site exposure, two sets of joints/fissures are mainly developed in the ore body, and local bedding-parallel joints/fissures are well-developed in the stope, with several to dozens of them per meter. On-site observations show that interlayer fissures (joints) in the stope area are well-developed, and three sets of interlayer fissures form an "inverted triangular" unstable structure, which is unfavorable to the stability of the roadway.

3.2. Large Actual Span of Ore Pass Unloading Chambers

To meet the needs of underground scraper ore drawing, the corners and sides of the ore pass chambers in the mining district have been trimmed, resulting in an increase in the exposed area of the roof of the ore pass chambers and further deterioration of the roof stability. Individual ore pass unloading chambers in the crosscuts have the problem of large open stope area. After the blasting of nearby ore rooms, the local roof of the ore pass unloading chambers has experienced varying degrees of roof collapse and side spalling, damaging water and air pipes and cables, and affecting the safe operation of scrapers and normal production organization.

3.3. Influence of Blasting Disturbance from Medium-Deep Holes and Large Diameters

During the ore room mining process, the influence of blasting from medium-deep holes and large diameters on the stability of the roof and side walls of the ore drawing connecting roadways and ore drawing drifts is manifested as follows: when the blasting seismic wave reaches the fissure bedding plane and the free surface of the roadway roof and side walls, it generates a reflected wave, forming tensile stress damage, leading to an increase in the tensile distance of original fissures (joints), and generating secondary fissures centered on the explosion source, resulting in damage to the roof of the roadway in the ore room bottom structure and damage to ore pillars (see Figure 2).

Figure 2. Concrete Spalling Caused by the Combined Action of Blasting Vibration and Rock Mass Stress

4. Optimization Measures

4.1. Optimization of Support Form for Ore Room Bottom Structure

To further improve the stability of the roadway and ore pillars in the bottom structure during ore room mining, the support form of the ore room bottom structure is optimized. The original support form of "adopting plain shotcrete or bolt-mesh-shotcrete support according to surrounding rock class" is adjusted to "all ore drawing connecting roadways, ore drawing drifts, and cutting drifts adopt bolt-mesh-shotcrete support", specifically as follows:

For the part adopting resin bolt support:

Ore drawing connecting roadway: The arch part adopts bolt-mesh-shotcrete support, starting from the arch springing line of the side wall on the left (second mining side) to the arch springing line of the ore pillar side on the right. The

shotcrete grade is C25, with a support thickness of 150mm; the bolts are resin bolts (Φ22mm), with a length of 2.5m, arranged in a rhombus pattern with a spacing of 1m×1m; the mesh is made of 6mm diameter steel bars, with a mesh size of 100mm ×100mm, a lap length of 100mm, and a braided pattern for the mesh bars; the bolts in the ore pillar part of the right side wall are arranged in a rhombus pattern with a spacing of 0.8m×0.8m, and other parameters are the same as those of the arch part.
Ore drawing drift and cutting drift: Bolt-mesh-shotcrete support is adopted. The bolt-mesh starts from 1m above the floor. The concrete grade is C25, with a support thickness of 150mm. The bolts are resin bolts (Φ22mm), with a length of 2.5m, arranged in a rhombus pattern with a spacing of 1m×1m; the mesh is made of 6mm diameter steel bars, with a mesh size of 100mm×100mm, a lap length of 100mm, and a braided pattern for the mesh bars.
For the part adopting split-set bolts with self-propelled bolt jumbo:
The split-set bolt model is required to be MF42/2000, meeting mine safety requirements. Main parameters: rod length 2000mm, diameter 42mm, slot width 18mm, rod wall thickness 2.3mm; tray: 150mm×150mm, thickness 5mm, height 25mm, hole diameter 44mm. Other support parameters are the same as the design requirements for resin bolts.

4.2. Optimization of Support Form for Ore Pass Unloading Chambers

By researching and optimizing the support form of the crosscut ore pass chambers, the support grade of the ore pass chambers is strengthened to enhance the stability of the roof of the ore pass drawing chambers. The support form of the ore pass chambers is optimized by "adding anchor cable support" on the basis of the original "bolt-mesh-shotcrete support", specifically as follows:
The anchor cable strand is Φ21.8mm, 8.6m long (with a gourd-shaped head at the end), including a 4m anchoring section, a 4m free section, and a 0.6m exposed section. After the prestress tensioning is qualified, some exposed anchor cables are cut, and the length of the anchor cable outside the tray is reserved as 100-200mm; the anchor cable drilling diameter is 33mm, anchored with anchoring agent, and a prestress of 250kN is applied to each anchor cable, with staged tensioning to 250kN during prestressing; the steel tray size is 300mm×300mm×16mm; the anchor cable spacing is 4m×4m; the W steel belt is Q235 steel belt, 2.5m long, 280mm wide, 6mm thick, lapped in a horizontal and vertical "well" shape (see Figure 3).

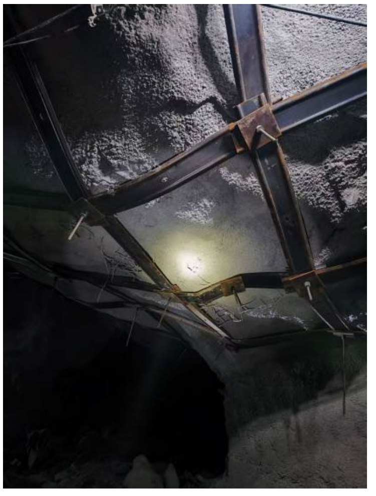

Figure 3. Combined Support of W Steel Belt and Anchor Cable

4.3. Optimization of Support Form for Hanging Wall and Footwall Drifts

At present, the support form of most drifts is only shotcrete. With the mining of ore rooms at the -540m level, the stress redistribution of the roadway has damaged the overall stability of the drifts. In addition, the hanging wall and footwall drifts need to be used for a long time, so they should be focused on protection.

The support forms of the hanging wall and footwall drifts at the -480m and -840m drilling levels and the -540m and -900m ore drawing levels are optimized. By strengthening the support grade, the collapse of the hanging wall and footwall drifts caused by stress concentration after the formation of mining goafs is prevented. The original support form of "adopting plain shotcrete or bolt-mesh-shotcrete support according to surrounding rock class" is adjusted to "adding local bolt-mesh-shotcrete + anchor cable support on the basis of the original support form", specifically as follows:

Bolt-mesh-shotcrete support is supplemented above the arch springing line of the hanging wall and footwall drifts. Initially, anchor cable support is added to 50% of the total length of the footwall drift, and anchor cable support is added at the intersection of the hanging wall drift and the crosscut. The specific support parameters are initially determined as follows:

The anchor cable strand is Φ21.8mm, 6.6m long (with a gourd-shaped head at the end), including a 3m anchoring section, a 3m free section, and a 0.6m exposed section. After the prestress tensioning is qualified, some exposed anchor cables are cut, and the length of the anchor cable outside the tray is reserved as 100-200mm; the anchor cable drilling diameter is 33mm; anchored with anchoring agent; a prestress of 250kN is applied to each anchor cable, with staged tensioning to 250kN during prestressing; the steel tray size is 300mm×300mm×16mm; the anchor cable spacing is 1m, and the row spacing is 2m; the setting of prestressed anchor cables can be reasonably adjusted according to the actual construction situation on site.

4.4. Optimization of Support Form for Crosscuts

The current support system of crosscut roadways is mainly shotcrete, with a single support form. With the continuous advancement of ore room mining at the -540m and -900m levels, the surrounding rock stress field has undergone dynamic redistribution due to mining effects. Since the crosscut roadways need to undertake transportation and ventilation functions for a long time, their long-term stability must be ensured. The existing support strength is difficult to meet the requirements of stress concentration and long-term service, so it is urgent to optimize the support parameters to improve the deformation resistance and durability of the crosscut roadways. The original support form of "supporting according to lithology class" is adjusted to "full roadway bolt-mesh-shotcrete support", specifically as follows:

The bolt-mesh starts from 1m above the floor. The concrete grade is C25, with a support thickness of 100mm. The bolts are resin bolts (Φ22mm), with a length of 2.5m, arranged in a rhombus pattern with a spacing of 1m×1m; the mesh is made of 6mm diameter steel bars, with a mesh size of 100mm×100mm, a lap length of 100mm, and a braided pattern for the mesh bars.

4.5. Research on Optimization of Support Form for Drilling Chambers

The existing support form of drilling chambers is mainly plain concrete shotcrete, with a low support grade. During the mining of ore rooms at the -540m and -900m levels, the pillars of the drilling chambers at the -480m and -840m levels have collapsed due to stress adjustment, leading to an increase in the exposed area of the roof and a decrease in the self-stabilization capacity of the surrounding rock. The risk of roof spalling and collapse has increased significantly. At the same time, the insufficient roof contact rate of the backfill has formed local goafs, posing a serious threat to the safety of subsequent stage transition construction. It is urgent to upgrade the support system to suppress the deterioration trend of the surrounding rock and ensure the continuity of construction.

The support form of the drilling chambers at the -480m and -840m levels is optimized from the original "plain shotcrete or bolt-mesh-shotcrete" to "full bolt-mesh-shotcrete support" (see Figure 4), specifically as follows:

The drilling drifts, internal connecting roadways of drilling chambers, and drilling connecting roadways at the -480m level are first supported according to the surrounding rock class (see ①-⑤ below). For Class I and II surrounding rock, additional bolt-mesh reinforcement support (without shotcrete) is added to the arch top (above the left and right arch springing lines) of the drilling connecting roadways, drilling drifts, and internal connecting roadways of drilling chambers: the bolts are resin bolts (Φ22mm), with a length of 2.5m, arranged in a rhombus pattern with a spacing of 1m×1m; the mesh is made of 6mm diameter steel bars, with a mesh size of 100mm×100mm, a lap length of 100mm, and a braided pattern for the mesh bars.

① Class I surrounding rock: Plain shotcrete support is adopted, with concrete grade C25 and a support thickness of 50mm.

② Class II surrounding rock: Plain shotcrete support is adopted for drilling connecting roadways with a thickness of 50mm; plain concrete support is adopted for drilling drifts and internal ore drawing connecting roadways of drilling chambers with a thickness of 80mm.

③ Class III surrounding rock: Bolt-mesh-shotcrete support is adopted. The bolt-mesh starts from 1m above the floor. The concrete grade is C25, with a support thickness of 120mm. The bolts are resin bolts (Φ22mm), with a length of 2.5m, arranged in a rhombus pattern with a spacing of 1m×1m; the mesh is made of 6mm diameter steel bars, with a mesh size of 100mm×100mm, a lap length of 100mm, and a braided pattern for the mesh bars.

④ Class IV surrounding rock: Bolt-mesh-shotcrete support is adopted. The bolt-mesh starts from 1m above the floor. The concrete grade is C25, with a support thickness of 150mm. The bolts are resin bolts (Φ22mm), with a length of 2.5m, arranged in a rhombus pattern with a spacing of 1m×1m; the mesh is made of 6mm diameter steel bars, with a mesh size of 100mm×100mm, a lap length of 100mm, and a braided pattern for the mesh bars.

⑤ Class V surrounding rock: A special support scheme is formulated.

Figure 4 Bolt-mesh-shotcrete Support

5. Practice and Optimization of Key Roadway Support Technologies in Metal Mines Applied to Macheng Iron Mine

5.1. Guiding Role of Geological Exploration Technology in Support Design

Macheng Iron Mine is hosted in Proterozoic metamorphic rocks, with complex surrounding rock conditions and well-developed joints/fissures. By comprehensively applying geological radar, drilling, and 3D geological modeling technologies, the research team accurately identified the distribution characteristics of two sets of main joints/fissures and interlayer fractured zones in the mining area. Combined with the Standard for Engineering Rock Mass Classification (GB/T50218-2014), the roadway surrounding rock was classified into Class I to Class V, and the support scheme was dynamically adjusted for different classes. For example, in the crosscut roadway at the -540m level, geological exploration found that there was an "inverted triangular" unstable structure in local areas. By reducing the bolt spacing (from 1.5m×1.5m to 1.0m×1.0m) and adding steel arch frames, the deformation resistance of the support system was significantly improved. This practice shows that refined geological exploration is the foundation for the scientificity of support design, and its results directly determine the rationality of support parameters and engineering safety [10－13].

5.2. Roadway Surrounding Rock Pretreatment and Dynamic Support Optimization

Macheng Iron Mine adopts the "shaft-inclined drift combined development" method, with diverse roadway cross-sectional sizes and different functions. By analyzing the surrounding rock stress distribution under different excavation spans (B=5~10m) through roadway pretreatment, the cross-sectional shape and support sequence were optimized. Roadway pretreatment technology is a pre-requisite technology for roadway support and an important link to ensure the quality of roadway support. During the pretreatment stage of roadway design [14－17], corresponding roadway support measures should be determined by comprehensively considering the geological conditions of the roadway. During roadway excavation, excavation operations should be carried out in accordance with the requirements of the roadway design to ensure the stability and safety of the roadway surrounding rock. For example, for the large-span (B＞10m) ore pass unloading chambers, the "phased excavation + initial shotcrete sealing" process is adopted: after the first phase of excavation, 50mm thick concrete is immediately shotcreted to suppress surrounding rock relaxation; in the second phase, a composite support system is formed by combining anchor cables (Φ21.8mm, 8.6m long) and W steel belts. This case confirms the effectiveness of dynamically adjusting the support sequence and parameters in controlling surrounding rock deformation.

5.3. Innovative Application of Support Materials and Processes

In the optimization of the ore room bottom structure, Macheng Iron Mine introduced low-prestress resin bolts (Φ22mm) and high-strength steel mesh (mesh size 100mm×100mm) to replace traditional cement mortar bolts. At the same time, to address the problem of increased exposed area of the roof of the drilling chambers, the "bolt-mesh-shotcrete + local steel arch frame" combined support is adopted: in the Class III~IV surrounding rock areas, the steel arch frames (36U steel) are welded with bolts to form a rigid frame, and connected with tie rods (Φ25 round steel), which significantly suppresses the expansion of secondary fissures caused by blasting vibration. Such technological innovations not only improve the integrity of the support structure but also reduce long-term maintenance costs.

5.4. Integration of Support Technologies and Future Development Directions

The practice of Macheng Iron Mine shows that roadway support in metal mines needs to realize the technical integration of geological exploration, dynamic design, material innovation, and intelligent monitoring [18]. Future research can be deepened in the following directions: (1) Develop an artificial intelligence-based geological information analysis system to realize automatic recommendation of support schemes; (2) Promote nano-modified shotcrete to improve impermeability and durability; (3) Introduce UAV inspection and 3D laser scanning technologies to construct a digital twin model of roadway deformation. Through technological iteration and interdisciplinary integration, promote the development of mine support towards intelligence and greenization.

6. Conclusions

Aiming at the problem of roadway support in the deep mining of Macheng Iron Mine, by systematically analyzing the failure mechanism of the surrounding rock, an optimization scheme based on the collaborative support theory is proposed, and the following conclusions are obtained:

(1) The support countermeasures for fractured surrounding rock roadways under blasting disturbance in deep metal mines are: phased excavation, initial shotcrete sealing, composite support of resin bolts (anchor cables) and steel belt mesh, and dynamic design of support methods and parameters in a timely manner based on the intelligent monitoring of surrounding rock pressure and deformation.

(2) A dynamic support mechanism combined with geological exploration results is established, and differentiated support designs are carried out for different surrounding rock classes (Class I~V). A hierarchical bolt-mesh-shotcrete + anchor cable + steel arch frame collaborative support system is constructed. By introducing low-prestress resin bolts (anchoring force 180kN), high-density steel mesh (mesh size 100×100mm), and optimizing anchor cable parameters (Φ21.8mm, prestress 250kN), the integrity and deformation resistance of the support structure are significantly improved, effectively ensuring the safety of mining operations.

(3) The "anchor cable + W steel belt" bolt-mesh-shotcrete combined support is adopted to solve the stability problem of large-span open stopes in ore pass unloading chambers. Compared with the original design, the chamber remains stable even when the two-dimensional span is increased by 50%, verifying the scientificity and adaptability of the support parameters.

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