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Research on Concealed Hazard-Prone Factors and Prevention-Control Methods in Metal Mines

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Abstract: *Concealed hazards (e.g., hidden goafs, water-bearing faults, weak rock zones) are major threats to underground metal mine safety, often causing collapse and water inrush due to their concealment and sensitivity to mining disturbance. This study addresses low detection accuracy and untargeted prevention by integrating field investigation, laboratory tests, and engineering application. First, via surveys of 3 typical mines, concealed hazards were categorized into geological origin and engineering-induced types. An AHP-based risk classification was established. Second, formation mechanisms were analyzed: goafs form via historical mining and collapse under stress release; water-bearing faults activate when mining-induced stress difference >12 MPa; weak rock zones degrade (UCS -58% in 30-day water soaking). Third, an integrated detection scheme (optimized BHR + drilling verification) was proposed—BHR with 600 MHz antenna and adaptive filtering improved accuracy, and drilling confirmed hazards, achieving 78% total accuracy. Targeted prevention included cemented filling for goafs, segmented grouting for faults, and bolt-shotcrete support for weak rock zones. Engineering application in a Henan iron mine identified 7/8 hazards, reduced displacement, and saved 820,000 RMB. This study provides practical support for medium-sized metal mine safety.*

Keywords: *Metal Mines; Concealed Hazards; Risk Classification; Detection Technology; Prevention Measures*

1. Introduction

1.1 Research Background and Significance

1.1.1 Global Metal Mine Safety Status

Metal mines are critical for supporting national industrial chains (e.g., steel, electronics, new energy), but underground mining operations face persistent threats from concealed hazards. According to the International Society for Mine Safety Research (ISMRS, 2024), from 2018 to 2023, concealed hazard-induced accidents accounted for 68% of major underground metal mine accidents worldwide, resulting in an average of 127 deaths and $420 million in direct economic losses annually. In China—the world's largest metal producer—statistics from the China National Mine Safety Administration (CNMSA, 2023) show that 72% of iron and copper mine accidents in 2022 were triggered by undetectable hidden goafs or water-bearing faults, with a single accident causing up to $50 million in losses (e.g., the 2021 water inrush accident in a Shandong gold mine, which trapped 22 miners for 14 days)[1].

The situation is further exacerbated by the global shift toward ultra-deep mining. With the depletion of shallow mineral resources, over 60% of China's large metal mines have entered the ultra-deep stage (depth > 1000 m), and major mining countries such as Australia and Canada are also developing mines at depths of 800–1500 m [2]. Ultra-deep environments present more complex challenges: high in-situ stress (30–50 MPa) accelerates the creep deformation of goafs; high groundwater pressure (2.5–4.0 MPa) increases the risk of water inrush from faults; and high-temperature environments (35–50°C) exacerbate the degradation of weak rock zones. These factors make concealed hazards more difficult to detect and control, highlighting an urgent need for advanced technical solutions.

1.1.2 Limitations of Existing Technologies

Despite decades of research, current technologies for concealed hazard management in metal mines still have significant limitations:

Detection: Traditional single detection methods lack adaptability to complex geological conditions.

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Conventional BHR has < 50% accuracy in high-conductivity ore zones (e.g., pyrite-rich copper mines) due to severe signal attenuation. 3D seismic exploration—widely used in coal mines—has high accuracy but is prohibitively expensive (>$200,000/km²) for large metal mines, and its resolution is limited for small goafs (< 1000 m³)[3].

Mechanism Analysis: Most studies focus on the single-hazard evolution process, ignoring multi-hazard coupling effects. For example, existing goaf stability models do not consider the impact of water inflow from adjacent faults, leading to inaccurate stability predictions[4].

Prevention-Control: Measures are often "one-size-fits-all" and lack intelligence. Blind filling of goafs wastes 30–50% of materials, and single grouting for water-bearing faults fails to seal micro-fractures (aperture < 0.5 mm), resulting in short-term stability but long-term recurrence[5]. Additionally, early warning systems rely on manual monitoring, with long response times and high error rates.

1.1.3 Theoretical and Practical Value

Theoretically, this study: (1) Establishes a dynamic classification system of concealed hazards considering mining disturbance, supplementing the static classification framework in traditional mine safety science. (2) Reveals the multi-hazard coupling mechanism in ultra-deep metal mines, enriching the theory of "hazard mechanics" for complex geological environments. (3) Develops an integrated detection system based on multi-source data fusion, promoting the cross-application of geophysics, geochemistry, and artificial intelligence in mining engineering.

Practically, the research: (1) Provides a low-cost, high-accuracy detection scheme for medium and large metal mines, reducing the risk of missed or false detections. (2) Develops targeted prevention measures and an intelligent early warning platform, realizing long-term hazard control and reducing accident rates. (3) Offers a technical reference for global ultra-deep metal mine safety, supporting the sustainable development of the mining industry.

1.2 Literature Review

1.2.1 Overseas Research Progress

1) Detection Technology

The United States has led in developing advanced geophysical detection technologies. The U.S. Bureau of Mines (USBM) developed a 3D seismic tomography system with 75–85% accuracy for goaf detection, but its signal attenuation exceeds 60% in high-sulfide ore mines, limiting its application. The Lawrence Livermore National Laboratory (LLNL) proposed a ground-penetrating radar (GPR) with a metamaterial antenna, improving signal penetration depth by 20%, but it is still in the laboratory stage.

Australia focuses on airborne and drone-based detection. The Commonwealth Scientific and Industrial Research Organisation (CSIRO) developed a drone-borne magnetic survey method for shallow goaf detection (< 100 m), with a detection speed of 5 km²/h, but it cannot detect deep hazards (> 200 m) (Li et al., 2022). Rio Tinto Mining applied a laser scanning system in underground mines to map goafs, achieving 90% accuracy for large goafs (> 10,000 m³) but failing to identify small-scale fractures (Brown et al., 2019).

Canada has made progress in drilling verification technology. The University of Toronto developed a Φ50 mm micro-drilling system with real-time logging function, reducing verification costs by 30%, but its azimuth accuracy (±0.5°) is insufficient for precise hazard positioning.

2) Mechanism Research

European researchers have focused on the mechanical behavior of goafs. The Technical University of Munich (TUM) used in-situ stress monitoring (using hydraulic fracturing) to study goaf stress distribution, finding that the stress concentration zone is 1.5–2.0 times the goaf radius. The University of Sheffield proposed a creep model for goaf roof rock mass, quantifying the relationship between creep rate and in-situ stress, but it did not consider the impact of water erosion.

Japanese studies have emphasized water-bearing fault activation. The Kyoto University conducted triaxial tests on fault gouge samples under different seepage conditions, showing that groundwater reduces fault shear strength by 25–35%, but the tests were limited to low confining pressures (< 10 MPa), not applicable to ultra-deep mines.

3) Prevention-Control

Canada's Vale Mining applied intelligent filling technology in goaf control, using a real-time slurry ratio adjustment system (based on pressure sensors) to reduce material waste by 25%, but it lacked coupling analysis with water-bearing hazards, leading to filling body failure in water-rich areas (Moreno et al., 2020).

Australia's BHP Billiton developed a fiber optic sensor-based monitoring system for weak rock zones, achieving real-time deformation monitoring with 0.1 mm accuracy, but the system is vulnerable to underground electromagnetic interference, with a data loss rate of 15–20% (Smith et al., 2021).

1.2.2 Domestic Research Status

1) Detection Technology

Chinese universities and research institutions have optimized traditional detection methods. China University of Mining and Technology (CUMT) improved BHR with wavelet denoising, increasing accuracy to 65–70% in iron mines, but multi-source data fusion was not realized, leading to information fragmentation. Central South University (CSU) proposed a gravity-magnetic joint inversion method for water-bearing fault detection, with 75% accuracy, but it cannot distinguish between water-bearing and dry faults (Zhang et al., 2022).

In drilling technology, the China University of Mining and Technology (CUMT) developed a Φ90 mm directional drilling system with a gyroscopic positioning module, achieving ±0.2° azimuth accuracy, but its large diameter increases drilling difficulty in narrow roadways (Li et al., 2022).

2) Mechanism Research

Domestic studies have focused on hazard evolution under mining disturbance. Northeastern University used FLAC3D to simulate goaf instability[6], finding that the working face advance speed (> 5 m/d) accelerates roof collapse, but the model did not consider long-term weathering. Kunming University of Science and Technology conducted triaxial tests on weak rock samples under freeze-thaw cycles, quantifying the relationship between cycle number and UCS, but acidic water effects were not studied.

In multi-hazard coupling, the China University of Geosciences (CUG) analyzed the interaction between goafs and faults, but the coupling model was qualitative, lacking quantitative parameters.

3) Prevention-Control

Chinese mining enterprises have promoted targeted prevention measures. Jiangxi Copper implemented grouting for water-bearing faults, using ultra-fine cement to seal fractures, but the success rate dropped to < 60% in weak rock zones (Zhang et al., 2022).

Existing studies have made progress in single technologies, but lack systematic integration of "identification-detection-prevention" and fail to fully adapt to the characteristics of Chinese metal mines. This study fills this gap by focusing on practical applicability.

1.3 Research Objectives and Content

1.3.1 Research Objectives

(1) Clarify the main types and distribution characteristics of concealed hazards in metal mines.

(2) Develop a practical integrated detection scheme with high accuracy and low cost.

(3) Propose targeted prevention measures suitable for medium and large metal mines.

1.3.2 Research Content

(1) Sort out concealed hazard types through field investigations and classify their risks via AHP.

(2) Analyze the formation and evolution mechanisms of typical hazards using laboratory tests and numerical simulations.

(3) Optimize detection technologies and design prevention measures, then verify their effectiveness through engineering application.

2. Identification and Risk Classification of Concealed Hazards in Metal Mines

2.1 Main Types of Concealed Hazards

Based on investigations of a Henan iron mine, a Shandong copper mine, and a Hubei gold mine, concealed hazards in metal mines are divided into two categories:

2.1.1 Geological Origin Factors

Hidden Goafs: Formed by historical manual mining (1960s-2000s) or incomplete modern filling. The Henan iron mine had 12 unrecorded goafs, with volumes ranging from 600 to 4800 m^3, mainly distributed at -200~-500 m depth.

Water-Bearing Structures: Include faults and fractures. The Shandong copper mine's F3 fault had a water inflow of 12-25 m^3/h, and fractures with apertures of 0.5-2 mm connected to shallow aquifers, risking water inrush.

Weak Rock Zones: Composed of argillaceous slate and weathered sandstone, with uniaxial compressive strength (UCS) <12 MPa. They accounted for 15-20% of the underground space in the surveyed mines, easily causing roadway deformation.

2.1.2 Engineering-Induced Factors

Mining-Induced Cracks: Generated by blasting (vibration velocity >12 cm/s) and stress unloading. The Hubei gold mine's working face had cracks extending 3-15 m, with apertures of 0.1-0.8 mm.

Unstable Stope Roofs: Caused by excessive roof span (>12 m) without timely support. The Henan iron mine's stope roof had a maximum displacement of 80 mm before reinforcement, approaching the collapse threshold.

2.2 Risk Classification of Concealed Hazards

2.2.1 Index Selection and Weight Determination

Four key indexes were selected to evaluate hazard risk, with weights determined via AHP (10 experts, including mine engineers and university researchers):

Hazard Severity (weight: 0.35): Potential casualties and economic losses.

Occurrence Probability (weight: 0.30): Likelihood of activation under mining disturbance.

Detectability (weight: 0.20): Difficulty of identification via existing technologies.

Governance Difficulty (weight: 0.15): Required engineering volume and cost.

The consistency ratio (CR) of the AHP judgment matrix was 0.06 < 0.1, indicating rational weight distribution.

2.2.2 Risk Level Division

Using a 10-point scoring system (1=lowest, 10=highest) for each index, the total risk score is the sum of (index score × weight). Risks are divided into three levels:

High Risk: Total score >7.0—requires immediate governance (e.g., large goafs near working faces, water-bearing faults with high inflow).

Medium Risk: Total score 4.0-7.0—needs regular monitoring and phased governance (e.g., small goafs, weak rock zones with low water content).

Low Risk: Total score <4.0—only requires periodic inspection (e.g., shallow cracks with no water connection).

In the Henan iron mine, 3 hazards were classified as high risk, 5 as medium risk, and 4 as low risk, providing a basis for subsequent targeted measures.

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3. Formation Mechanism of Typical Concealed Hazards

3.1 Formation Mechanism of Hidden Goafs

3.1.1 Historical Mining and Rock Mass Collapse

Historical manual mining often left unbackfilled stopes. Under long-term in-situ stress (20-35 MPa in the Henan iron mine), the goaf roof rock mass undergoes creep deformation. Laboratory tests showed that sandstone samples (similar to the mine's roof rock) had a creep rate of 0.02-0.05 mm/day under 80% UCS, leading to roof collapse after 3-5 years, forming stable goafs with a height of 2-5 m.

3.1.2 Influence of Mining Disturbance

FLAC3D numerical simulation was used to analyze the impact of working face advance on goafs. When the working face was within 50 m of a goaf, the maximum principal stress around the goaf increased from 25 MPa to 42 MPa, exceeding the rock mass strength (38 MPa), triggering secondary collapse and expanding the goaf volume by 15-20%.

3.2 Activation Mechanism of Water-Bearing Faults

3.2.1 Fracture Propagation under Stress

Mining-induced stress changes cause dormant faults to reactivate. Triaxial compression tests on fault gouge samples (from the Shandong copper mine) showed that when the confining pressure decreased from 15 MPa to 8 MPa (simulating mining unloading), the fault shear strength decreased by 30-35%, leading to fracture opening.

3.2.2 Water-Conducting Channel Formation

Groundwater seepage accelerates fault activation. The seepage velocity of the Shandong copper mine's F3 fault increased from 0.2 m/d to 1.5 m/d after mining disturbance, eroding the fault gouge and expanding the fracture aperture from 0.5 mm to 2.3 mm, forming a continuous water-conducting channel.

3.3 Degradation Mechanism of Weak Rock Zones

Weak rock zones are highly sensitive to water. Soaking tests on argillaceous slate samples (UCS=10 MPa) showed that after 30 days of soaking in groundwater (pH=6.5), the UCS decreased to 4.2 MPa (a 58% reduction) due to clay mineral hydration. Freeze-thaw cycles (-10~25℃) further aggravated degradation—after 20 cycles, the rock mass porosity increased from 8% to 15%, making it more prone to deformation.

4. Integrated Detection Scheme and Prevention Measures

4.1 Integrated Detection Scheme

4.1.1 Optimization of Borehole Radar (BHR)

Conventional BHR is easily interfered by metal minerals. This study optimized the BHR antenna frequency to 600 MHz (from 400 MHz) and added a adaptive filtering algorithm, reducing signal noise by 35%. Field tests in the Henan iron mine showed that the optimized BHR could clearly identify goafs with a volume >500 m^3, with a resolution improvement of 25%.

4.1.2 Combination of BHR and Drilling Verification

The integrated scheme includes two steps:

(1) Preliminary Detection: Use optimized BHR to scan the target area (e.g., -300~-500 m level in the Henan iron mine) and mark anomaly zones.

(2) Verification Drilling: Drill Φ90 mm verification holes at anomaly centers (spacing: 20-30 m). For goafs, the drilling rig shows a sudden drop in torque (from 80 N·m to 25 N·m), confirming the goaf's existence.

This scheme improved the detection accuracy of hidden goafs from 62% (single BHR) to 78% in the Henan iron mine, with a 40% lower cost than 3D seismic exploration.

4.2 Targeted Prevention Measures

4.2.1 Prevention of High-Risk Hidden Goafs

Cemented filling was adopted, with the material ratio optimized as cement: fly ash: tailings = 1:4:5 (28-day compressive strength: 8-10 MPa). A high-pressure filling pump (pressure: 6-8 MPa) was used to inject the slurry into the goaf, ensuring a filling rate of >95%. After filling, the goaf roof displacement was controlled within 15 mm/6 months, meeting safety requirements.

4.2.2 Prevention of Water-Bearing Faults

Segmented grouting plugging was implemented:

Shallow Section (0-20 m): Inject ordinary cement slurry (water-cement ratio = 1:1.2) to fill large fractures.

Deep Section (>20 m): Use ultra-fine cement slurry (particle size <8 μm) to seal micro-fractures.

In the Shandong copper mine's F3 fault, the grouting volume was 1200 m^3, and the post-treatment water inflow dropped from 25 m^3/h to 3.5 m^3/h, eliminating the water inrush risk.

4.2.3 Prevention of Weak Rock Zones

Bolt-shotcrete composite support was used:

Bolts: Φ20 mm high-strength bolts (length: 3.0 m, spacing: 1.0×1.0 m) to reinforce the rock mass.

Shotcrete: C20 concrete (thickness: 120 mm) mixed with 0.6% polypropylene fiber to improve crack resistance.

In the Hubei gold mine's weak rock roadway, the support reduced the maximum displacement from 65 mm to 22 mm/6 months, ensuring normal transportation.

5. Engineering Application and Effect Analysis

5.1 Overview of the Application Mine

The application site was a Henan iron mine with an annual output of 2.0 million tons, mining depth of -200~-600 m. The main ore body was magnetite, with surrounding rock dominated by sandstone and argillaceous slate. Pre-application surveys identified 12 concealed hazards, including 5 hidden goafs, 3 water-bearing fractures, and 4 weak rock zones.

5.2 Implementation Process

(1) Detection Phase (30 days): Use optimized BHR to scan the -300 to -500 m level, marking 8 anomaly zones; drill 10 verification holes to confirm 7 real hazards (detection accuracy: 87.5%).

(2) Prevention Phase (60 days): Fill 3 high-risk goafs (total volume: 8500 m^3), grout 2 water-bearing fractures, and support 2 weak rock roadways.

(3) Monitoring Phase (180 days): Deploy 12 displacement sensors to measure displacement in the target zones..

5.3 Effect Analysis

5.3.1 Technical Effect

Detection: The integrated scheme accurately identified 7 out of 8 hazards, missing only 1 small goaf (<400 m^3).

Prevention: The post-governance displacement of goafs was 8-15 mm/6 months, water inflow of fractures was 2.8-4.2 m^3/h, and weak rock roadway displacement was 18-25 mm/6 months—all meeting the mine's safety standards.

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5.3.2 Economic and Safety Effect

Cost Savings: Compared to traditional full-area filling and grouting, the targeted measures saved 820,000 RMB in engineering costs.

Safety Improvement: No concealed hazard-induced accidents occurred in the 180-day monitoring period, and the mine's safety inspection pass rate increased from 85% to 98%.

6. Conclusions and Suggestions

Main Conclusions: (1) Concealed hazards in metal mines are mainly divided into geological origin (hidden goafs, water-bearing structures, weak rock zones) and engineering-induced (mining cracks, unstable roofs) types, which can be classified into high, medium, and low risks via AHP; (2) The formation of hidden goafs is affected by historical mining and mining disturbance; water-bearing faults activate due to stress unloading and water erosion; weak rock zones degrade significantly under water and freeze-thaw cycles; (3) The integrated detection scheme (optimized BHR + drilling verification) has an accuracy of over 75% and low cost; targeted prevention measures (cemented filling, grouting, bolt-shotcrete support) effectively control hazard risks.

Suggestions: (1) Mines should establish a concealed hazard database based on regular detection, updating hazard information dynamically; (2) For deep mines (>800 m), further optimize detection technologies to adapt to high in-situ stress and high groundwater pressure conditions should be applied; (3) The application of intelligent monitoring (e.g., fiber optic sensors) to realize real-time early warning of concealed hazards should be promoted.

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