Research on Dynamic Evaluation of Outburst Hazard Risk Level in Coal Mine Working Face

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Abstract

To achieve accurate prediction and dynamic evaluation of coal and gas outburst hazards in coal mine working faces, this study takes the No. 9 coal seam in the I11 and I13 mining areas of Linhuan Coal Mine, Huaibei Mining Group as the research object. A dynamic evaluation index system covering four major categories-gas, geology, stress and outburst prevention measures-with fourteen sub-items has been constructed. A dynamic evaluation system for outburst hazards in coal mine working faces has been developed, and the outburst risk levels at different stages of the 9111 and 9134 working faces have been evaluated and analyzed. The research results indicate that the developed dynamic evaluation system enables intelligent generation and dynamic updating of outburst hazard evaluation maps. The highest outburst risk is observed near the open-off cut during the design phase of the 9111 working face, while the central part of the 9134 working face exhibits a relatively high outburst risk during the preparation phase due to the influence of faults. The research findings provide a scientific basis and technical support for gas prevention in the outburst-prone coal seam working faces of Linhuan Coal Mine and also offer a reference for dynamic evaluation of outburst hazards in working faces of similar outburst-prone mines.

Keywords

Coal and gas outburst; risk level evaluation; dynamic evaluation system; outburst hazard.

1. Introduction

Coal and gas outburst is one of the severe natural disasters in coal mines, posing a significant threat to the safety of coal mine production and the lives of personnel [1]. As the mining depth increases, the risk of outburst further escalates, along with an enhancement in the complexity and uncertainty of outburst disasters [2]. Linhuan Coal Mine, a large outburst-prone mine in the Huaibei Coalfield, primarily mines the No. 7, No. 9 (No. 8), and No. 10 coal seams, all of which are outburst-prone. The mine's absolute gas emission rate reaches 36.47 m^3/min, with a relative gas emission rate of 8.03 m^3/t. The geological structure is complex, characterized by well-developed faults and tectonic fractures, and significant intrusion of magmatic rocks, which significantly affects the gas occurrence in the coal seams, presenting immense challenges for the prediction and prevention of outburst hazards in working faces [3-4].

Currently, the evaluation of outburst hazards in coal mine working faces in China is predominantly static, making it difficult to adapt to the dynamic changes in gas parameters, geological conditions, stress states, and other factors during the mining process of working faces. This leads to discrepancies between the evaluation results and on-site realities, preventing timely and accurate support for the formulation and adjustment of outburst prevention measures [5-9]. However, notable differences exist in the geological conditions and

gas occurrence characteristics among different mines, rendering existing evaluation methods and systems difficult to directly apply to the complex geological conditions and outburst characteristics of Linhuan Coal Mine. Therefore, based on this context, this paper takes the No. 9 coal seam in the I11 and I13 mining areas of Linhuan Coal Mine as the research object. Through the analysis of outburst-causing factors, the construction of an evaluation index system, the establishment of a prediction model, and the development of an evaluation system, this study conducts a stage analysis and dynamic evaluation of the outburst hazard risk level in working faces. The aim is to address issues such as insufficient prediction accuracy and evaluation lag for outburst hazards in the mine's working faces, providing a scientific basis for gas prevention and control in the mine while offering technical references for similar outburst-prone mines.

2. Engineering Geology and Gas Overview

Linhuan Coal Mine is located in Huaibei City, Anhui Province. It commenced production in December 1985 with a designed production capacity of 1.8 million tons per annum (t/a). In 2013, its production capacity was approved to be increased to 2.8 million t/a. The mine adopts a shaft-multi-level-partition-cross-cut development method and employs a diagonal mixed ventilation system. It currently has multiple production, preparation, and development mining areas. The coal-bearing strata in the mine are of Carboniferous-Permian age, containing 28 coal seams. Among them, the No. 9 coal seam is the focus of this study, with an average thickness of 2.27 m and a relatively simple structure. The coal types are predominantly fat coal and coking coal. The mine field has a complex geological structure with well-developed faults. Magmatic intrusions mainly affect the strata above the No. 4 and No. 10 coal seams, with relatively minor impacts on the No. 9 coal seam. The hydrogeological conditions are complex. The main mined coal seams, namely the No. 7, No. 9 (No. 8), and No. 10 coal seams, are all outburst-prone. Gas occurrence is significantly influenced by factors such as burial depth and geological structures. The maximum measured relative gas pressure in the No. 9(8) coal seam underground is 1.52 MPa, with a gas content of 8.97 m^3/t.

3. Stage Analysis Method for Outburst Hazard Risk Level in Working Faces

3.1. Patterns and Causal Factors of Coal and Gas Outbursts

Based on statistical analysis of outburst incidents in major outburst-prone mining areas in China and at Linhuan Coal Mine, coal and gas outbursts exhibit the following patterns:

(1) Correlation between mining depth and outburst hazard: As mining depth increases, low-gas mines may transform into outburst-prone mines, and the severity of outbursts intensifies. In the same mining area and coal seam, gas pressure and gas content increase approximately linearly with burial depth.

(2) Significant impact of geological structures on outbursts: In stress concentration zones such as fold axes and fault fracture zones, gas tends to accumulate, forming "gas pockets," resulting in significantly higher outburst hazards compared to other areas. In contrast, open structural zones facilitate gas dissipation, reducing outburst risks.

(3) Influence of coal seam occurrence conditions on outbursts: Areas with significant variations in coal seam thickness, steep dip angles, and thick soft layers exhibit low coal strength and poor permeability, hindering gas dissipation and increasing outburst hazards. In regions affected by magmatic intrusions, coal metamorphism increases, gas content rises, and outburst risks escalate.

(4) Distinct temporal and spatial distribution characteristics of outbursts: During working face development and extraction, disturbance operations such as blasting and coal cutting are prone

to triggering outbursts. Outbursts predominantly occur in stress concentration zones such as the working face heading and mid-coal wall.

Coal and gas outbursts result from the coupled effects of multiple factors, including gas, geology, stress, and outburst prevention measures [10]. Based on the actual conditions at Linhuan Coal Mine, the primary causal factors are categorized into four major groups:

(1) Gas-related factors: These include gas pressure, gas content, abnormal gas emissions, and outburst precursors. Higher gas pressure and content increase the driving force for outbursts. Sudden changes in gas emission rates and coal wall gas ejection serve as critical indicators of impending outbursts.

(2) Geological factors: These encompass variations in coal seam thickness, soft layer thickness, parting extinction points, faults, collapse columns, magmatic intrusions, and the properties and thickness of surrounding rocks. Geological structures disrupt coal body integrity, reduce coal strength, and influence gas occurrence and migration.

(3) Stress-related factors: Primarily reflected in the coal's firmness coefficient, lower coal strength corresponds to weaker resistance to failure. Under the combined effects of gas pressure and in-situ stress, coal is prone to fragmentation, triggering outbursts.

(4) Outburst prevention measure factors: These include the protective range of protective coal seams, implementation of gas drainage measures, and execution of local outburst prevention measures. Inadequate or ineffective outburst prevention measures fail to effectively reduce outburst hazards.

3.2.   Dynamic Evaluation Index System for Outburst Hazard Risk

Based on the analysis of outburst causal factors, combined with the characteristics of outburst-prone coal seams at Linhuan Coal Mine and the requirements of regulations such as the Coal Mine Safety Regulations and the Specification for Identification of Coal and Gas Outburst Hazards, a dynamic evaluation index system for outburst hazard risk in working faces has been established, encompassing four major categories and fourteen sub-items. Specifically, the gas-related category includes five items: abnormal regional effectiveness testing indicators, abnormal regional verification indicators, abnormal daily prediction indicators, abnormal gas emissions, and the impact of outburst precursors. The geological category comprises seven items: the variation rate of coal seam thickness, soft layer thickness, parting extinction points, the influence range of faults, the influence range of collapse columns, the invasion range of igneous rocks, and the properties and thickness of surrounding rocks. The stress category includes one item: the coal's firmness coefficient. The outburst prevention measure category consists of three items: the protective range of protective coal seams, the implementation status of gas drainage measures, and the implementation status of local outburst prevention measures. Additionally, evaluation criteria and weights for each index have been clearly defined to ensure the scientific and targeted nature of the evaluation. The specific index system is presented in Table 1.

Table 1 Dynamic Evaluation Index System for Outburst Hazard Risk in Working Faces at Linhuan Coal Mine

Primary Indicators	Secondary Indicators	Evaluation Criteria	Weight
Gas-related (0.35)	Regional Effectiveness Testing Indicator Anomalies	Indicators exceeding critical values are considered abnormal; otherwise, they are normal.	0.08
	Regional Verification Indicator Anomalies	Verification indicators exceeding critical values are considered abnormal; otherwise, they are normal.	0.07
	Daily Prediction Indicator	Prediction indicators exceeding critical values	0.08

	Anomalies	are considered abnormal; otherwise, they are normal.	
	Abnormal Gas Emissions	Sudden changes in gas emission volume (increase ≥ 50%) are considered abnormal; otherwise, they are normal.	0.06
	Impact of Outburst Precursors	The presence of precursors such as coal ejection or drill bit jamming is considered a severe impact; otherwise, there is no impact.	0.06
Geological-related (0.30)	Coal Seam Thickness Variation Rate	A variation rate ≥ 20% indicates high risk, 10%–20% indicates medium risk, and < 10% indicates low risk.	0.05
	Soft Layer Thickness	A thickness ≥ 0.5 m indicates high risk, 0.3–0.5 m indicates medium risk, and < 0.3 m indicates low risk.	0.04
	Parting Extinction Points	The presence of parting extinction points indicates high risk; otherwise, it indicates low risk.	0.03
	Fault Influence Range	A fault throw ≥ 5 m indicates high risk, 1–5 m indicates medium risk, and < 1 m indicates low risk.	0.06
	Collapse Column Influence Range	The presence of a collapse column indicates high risk; otherwise, it indicates low risk.	0.03
	Igneous Rock Intrusion Range	The presence of magmatic intrusion indicates high risk; otherwise, it indicates low risk.	0.04
	Surrounding Rock Properties and Thickness	Fractured surrounding rock with a thickness < 5 m indicates high risk; otherwise, it indicates low risk.	0.05
Stress-related (0.15)	Coal Firmness Coefficient	A coefficient < 0.5 indicates high risk, 0.5–1.0 indicates medium risk, and > 1.0 indicates low risk.	0.15
Outburst Prevention Measure-related (0.20)	Protective Layer Coverage	Failure to cover the working face indicates high risk, partial coverage indicates medium risk, and complete coverage indicates low risk.	0.07
	Gas Drainage Measure Implementation	Failure to implement as required indicates high risk, partial implementation indicates medium risk, and complete implementation indicates low risk.	0.07
	Local Measure Implementation	Failure to implement as required indicates high risk, partial implementation indicates medium risk, and complete implementation indicates low risk.	0.06

3.3. Evaluation Method for Outburst Hazard Risk Level

The fuzzy comprehensive evaluation method is employed to assess the outburst hazard risk level of working faces, with the Analytic Hierarchy Process (AHP) utilized to determine the weights of each indicator. The specific steps are as follows:

Establish an Evaluation Factor Set: The four major categories with fourteen sub-items of indicators are considered as evaluation factors, forming the evaluation factor set U = {U₁ (Gas-related), U₂ (Geological-related), U₃ (Stress-related), U₄ (Outburst Prevention Measure-

related)}, where U_i = {U_{i1}, U_{i2}, ..., U_{in}} (i = 1, 2, 3, 4; n represents the number of secondary indicators under each primary indicator).

Establish an Evaluation Grade Set: Based on the degree of outburst hazard, the evaluation grades are classified into three levels: high risk, medium risk, and low risk, forming the evaluation grade set V = {V_1 (High Risk), V_2 (Medium Risk), V_3 (Low Risk)}.

Determine the Weight Set: Using the AHP, combined with the outburst characteristics of Linhuan Coal Mine and expert opinions, the weights of each primary and secondary indicator are determined, forming the weight set W = {W_1, W_2, W_3, W_4}, where W_i = {W_{i1}, W_{i2}, ..., W_{in}}.

Construct a Fuzzy Evaluation Matrix: Through on-site measurements and data analysis, the membership degrees of each evaluation factor to different evaluation grades are determined, and a fuzzy evaluation matrix R is constructed.

Fuzzy Comprehensive Evaluation: The comprehensive evaluation result B is calculated using matrix multiplication as B = W × R. Based on the principle of maximum membership degree, the outburst hazard risk level of the working face is determined.

3.4. Development of the Dynamic Evaluation System

Based on the aforementioned evaluation methods, a dynamic evaluation system for outburst hazard risk in the working faces of Linhuan Coal Mine has been developed. The system utilizes MapGIS technology and employs an SD file database for map data storage to manage working face data. Its primary functions include:

Data Management Functionality: The system establishes a database for gas-geological information and outburst hazard risk data specific to the working faces, enabling the input, query, modification, and deletion of data related to gas parameters, geological structures, and outburst prevention measures.

Dynamic Evaluation Functionality: By inputting evaluation indicator data, the system automatically calculates the outburst hazard risk level, facilitating real-time evaluation of outburst hazards in the working faces.

Map Generation Functionality: The system automatically generates evaluation maps for outburst hazards in the working faces, supports the import of CAD base maps, and enables intelligent generation, automatic correction, and printout of evaluation maps.

Early Warning Functionality: When the evaluation result indicates a high risk level, the system automatically issues an early warning alert, prompting on-site personnel to take targeted outburst prevention measures.

This system can adapt to the dynamic changes in various evaluation indicators during the mining process of the working face, enabling dynamic updates of the outburst hazard evaluation maps. It provides a fundamental basis and auxiliary decision-making support for predicting and warning against outburst hazards in the working faces.

4. Field Engineering Applications

The aforementioned staged analysis method for outburst hazard risk and the dynamic evaluation system were applied to the 9111 working face (design phase) and the 9134 working face (preparation phase) at Linhuan Coal Mine. By integrating on-site measured data and geological information, an analysis of outburst hazard risk was conducted to validate the effectiveness of the method and system.

4.1. Outburst Hazard Risk in the Design Phase of the 9111 Working Face

The 9111 working face is located in the I11 mining district, primarily mining the No. 9 coal seam. The working face has a strike length of 1,200 m and a dip length of 180 m, with a coal seam thickness ranging from 1.8 to 2.5 m (average 2.2 m), a coal seam dip angle of 12° to 18° (average

15°), and a soft layer thickness of 0.3 to 0.6 m (average 0.45 m). During the design phase, geological exploration data, gas parameters from adjacent working faces, and geological structure information were collected. Combining these with the measured original gas pressure results (0.40–1.30 MPa) in the No. 9 coal seam of the I11 mining district, the established dynamic evaluation index system and fuzzy comprehensive evaluation method were employed to assess the outburst hazard risk.

The evaluation results indicated that the overall outburst hazard risk in the design phase of the 9111 working face exhibited a distribution characteristic of "higher at both ends and lower in the middle." The area near the open-off cut had the highest risk level, classified as high risk, primarily due to a coal seam thickness variation rate of 22%, a soft layer thickness of 0.5~0.6 m, proximity to a fault fracture zone, significant stress concentration, and easy gas accumulation. The central area of the working face had stable coal seam thickness with no significant geological structure influence, classified as low risk. The areas near the conveyor roadway and return airway were classified as medium risk, mainly affected by roadway construction disturbances and localized abnormal gas emissions. For the high-risk area, the design phase proposed optimizing the open-off cut layout to avoid the fault fracture zone, constructing a bottom gas drainage roadway in advance for gas pre-drainage, and reducing the outburst risk.

4.2. Outburst Hazard Risk in the Preparation Phase of the 9134 Working Face

The 9134 working face is located in the I13 mining district, primarily mining the No. 9 coal seam. The working face has a strike length of 1,050 m and a dip length of 160 m, with a coal seam thickness ranging from 1.7 to 2.4 m (average 2.1 m), a coal seam dip angle of 10° to 16° (average 13°), and a soft layer thickness of 0.2 to 0.5 m (average 0.35 m). During the preparation phase, some roadway construction had been completed, and on-site measured residual gas pressure (0.12~0.23 MPa), residual gas content (3.30~4.10 m^3/t), and geological structure data were collected. The dynamic evaluation system was used for real-time evaluation.

The evaluation results showed that the overall outburst hazard risk in the preparation phase of the 9134 working face was medium to low. The central area of the working face, affected by the F12 fault (with a throw of 3~5 m), was classified as high risk due to coal fragmentation, a gas content of 3.90~4.10 m^3/t, a coal firmness coefficient of 0.45~0.50, and significant stress concentration. The areas at both ends of the working face and away from the fault were classified as low risk, with low residual gas pressure and content and no significant outburst precursors. Based on the evaluation results, enhanced gas drainage measures were implemented in the high-risk central area, including increasing the density of drainage boreholes and extending the drainage time, while strengthening on-site monitoring, focusing on gas emission volume and coal wall conditions. After a secondary evaluation, the outburst hazard risk in this area was reduced to medium risk, meeting the safety requirements for preparation phase construction.

4.3. Validation of Application Effectiveness

Through the evaluation of outburst hazard risk and the implementation of targeted outburst prevention measures at different stages of the 9111 and 9134 working faces, no coal and gas outburst accidents occurred during subsequent construction. Gas emissions remained stable with no significant outburst precursors, validating the scientific and effective nature of the staged analysis method for outburst hazard risk and the dynamic evaluation system established in this study. Specifically, the optimization plan proposed during the design phase of the 9111 working face effectively controlled the outburst risk in the open-off cut area, improving construction efficiency by 15%. The enhanced drainage measures taken in the high-risk area during the preparation phase of the 9134 working face reduced the average gas content by 0.35

m^3/t and the average gas pressure by 0.04 MPa, ensuring safe and orderly progress of preparation work.

5. Conclusion

(1) A dynamic evaluation index system for outburst hazard risk in working faces has been established, covering four major categories and fourteen sub-items related to gas, geology, stress, and outburst prevention measures. Combining fuzzy comprehensive evaluation and the Analytic Hierarchy Process (AHP), it enables scientific evaluation of outburst hazard risk in working faces, with evaluation results highly consistent with on-site conditions.

(2) The developed dynamic evaluation system for outburst hazard risk in working faces can realize functions such as data management, dynamic evaluation, map generation, and early warning. It can adapt to the dynamic changes in indicators during the mining process of working faces, providing intelligent support for outburst risk management and control.

(3) Engineering applications have demonstrated that the area near the open-off cut in the design phase of the 9111 working face has the highest outburst hazard risk, while the central area in the preparation phase of the 9134 working face has a higher risk due to fault influence. The implementation of targeted outburst prevention measures can effectively reduce the outburst risk and ensure the safety of working face construction.

Acknowledgments

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