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ORIGINAL PAPER

Research progress of disaster factors and a prevention alarm index of coal and gas outbursts

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Abstract

Coal and gas outbursts are one of the most serious disasters in coal mining, and disaster prediction and prevention alarms are key technologies to prevent coal and gas outbursts. This paper summarizes the progress of research on outburst prevention alarm indicators and prevention alarm technology for mines; the mechanism of coal and gas outbursts; the relationship between the coal seam geological environment and outbursts; and the relationship between coal seam gas drainage, roadway excavation and mine working face (DEM) operations and outbursts. Prevention alarm indicators are key to effective prevention alarms. The analysis proposes that from the perspective of understanding the relevant theoretical research and the effectiveness, timeliness and comprehensiveness of the prevention alarms, there are still some deficiencies, and establishing preventive alarm indicators and preventive alarm models is difficult. Assuming the reasonable management of coal seam DEM, the coal seam geological environment is established as a secondary indicator. Production, gas drainage, ventilation, monitoring and control, auxiliary production and other systems are the third-level indicators. Catastrophic parameters such as safety distance, pre-extraction time, mining procedures and DEM replacement are used as fourth-level indicators for the outburst disaster risk assessment index system, which provides a basis for understanding mine risk decision-making and disaster prevention and alarms.

Keywords Coal and gas outburst · Preventive alarm index · Production system · Coal seam gas drainage, roadway excavation, mine working face deployment · Geological environment

Introduction

Coal is the basis for ensuring the world's energy security, stability and economic development. Attaching great importance to safe coal production is a prerequisite for ensuring the sustained, stable and healthy development of the coal industry. Figure 1 shows the number of gas accidents and deaths in China from 2008 to 2017 according to monthly statistics. As shown in Fig. 2, the number of coal mine gas accidents in China and the number of deaths from gas accidents basically follow the same pattern, basically maintaining around 25% and 10%. The proportion of gas accident deaths to the total death toll has declined, but the proportion is relatively high, close to 35% in 2013. The proportion of gas accidents in total accidents has shown an increasing trend after 2014. It can be seen that gas accidents have always been a major factor in coal mine safety production, and its prevention and control are particularly important (Karacan et al. 2011).

The high casualty rate and high damage rate of gas accidents have resulted in large losses to the world's economy and energy industry and seriously threaten the lives of miners (Gao and Liu 2009). Coal and gas outbursts are extremely complex dynamic phenomena (Ruilin and Lowndes 2010) and are common accidents in coal mines. The mechanical action process of coal and gas outburst is shown in Fig. 3. Gas outbursts can suddenly eject gas and coals from coal seams into roadways or stopes in a short period of time. A large amount of gas and broken coal form a special shape of

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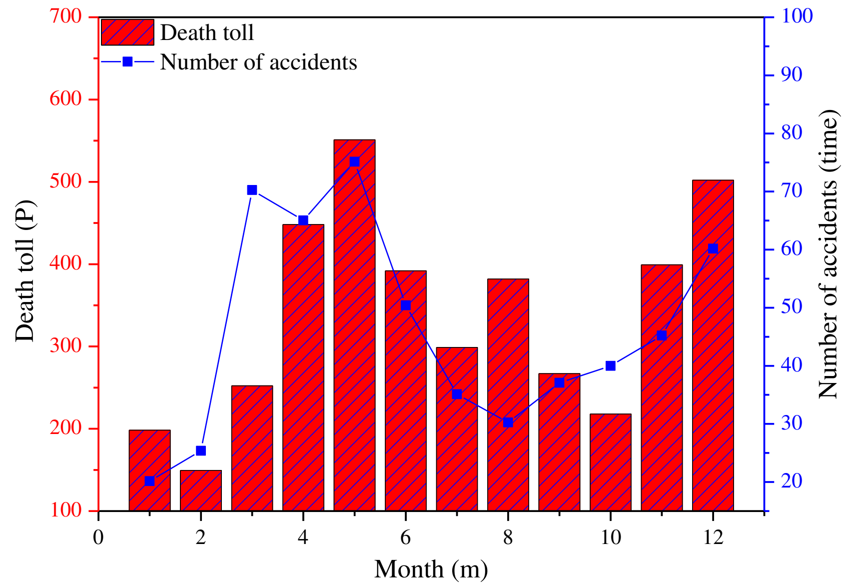
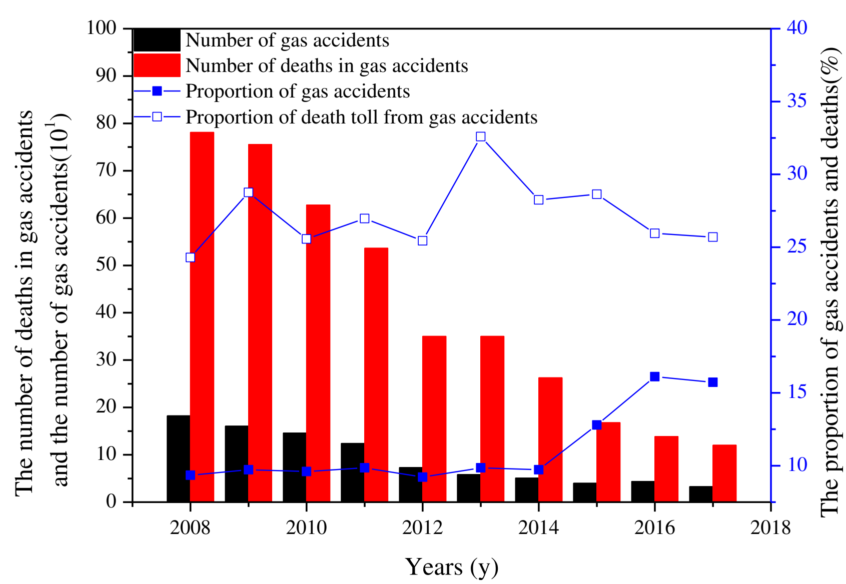
Fig. 1 The number of gas accidents and deaths by month



voids in the coal body and create a certain dynamic effect. It is likely that the pulverized coal can fill hundreds of metres of roadway.

A disaster alarm is the key technology to prevent coal mine accidents. Research on prevention warning theory began at the end of the nineteenth century, but research that has a direct impact on modern prevention warning systems began in the 1950s (Gao and Liu 2009). In the mid- to late 1990s, the research results of single-operation prevention alarms and cost-effective prevention alarms began to appear. After several decades of development, relatively mature critical alarm and state alarm have basically been formed. From the perspective of the system, a mine is predominantly a large system composed of people, machines and the environment. The system is spatially distributed in three dimensions and dynamically developed in time, which makes the mine system have a significant correlation with the occurrence of an outburst (Ruilin and Lowndes 2010). Therefore, an outburst prevention alarm based on disaster-causing factors in the mine not only requires a state alarm or critical alarm but also needs to make risk assessments from the perspective of the system and incorporate dynamic system trend information. This requires finding a scientific and reasonable alarm indicator based on the overall perspective. This paper describes and summarizes the progress of research on coal mine outburst disasters, analyses the existing shortcomings, discusses the development direction of disaster prediction and prevention alarms and proposes a prevention alarm index system based on the rationality of the production system, considering the balance of coal seam gas drainage, roadway excavation and

Fig. 2 The number of gas accidents and the number of deaths and their proportions by year



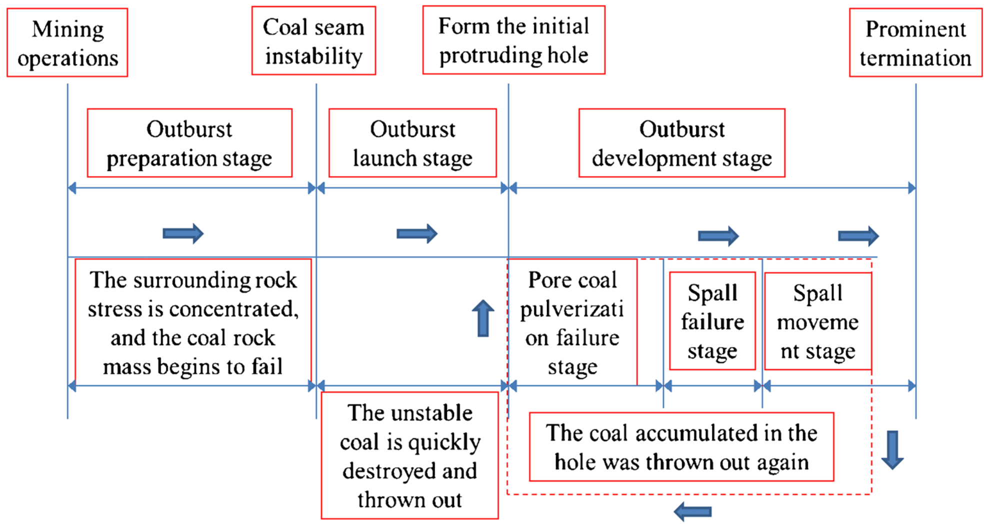


Fig. 3 The mechanical action process of coal and gas outburst

the mine working face (DEM) to prevent and control of gas disasters. In addition, this study provides guidance for prevention alarm technology.

Outburst disaster alarm indicators and prevention alarm techniques

The application of prevention alarm theory in the coal industry started late. Due to the relatively high level of coal mine safety management in developed countries, the accident rate in coal mines is lower than that in other production industries. For instance, the accident rate in coal mines in the USA is much lower than that in 20 other industries, so there is no in-depth research in this area. China began to study prevention alarm theory in the late 1980s. In recent years, coal and gas outburst prevention alarm technology has made significant progress in terms of both software and hardware. For example, Wen et al. (Wen et al. 2011) established an outburst prevention alarm information platform, realizing real-time intelligent prevention alarms for dangerous roadway excavation and mine working faces.

The key to prevention alarms is to establish a scientific, systematic and practical prevention alarm indicator system. Currently, the more mature coal and gas outburst alarm indicators are based on technical indicators, such as gas pressure, gas emission and gas concentration. Zhou et al. (Miao et al. 2020) proposed a preliminary prevention alarm indicator system that includes three parts: underground gas monitoring, ground gas monitoring and external environmental monitoring. Wu and Yang (Wu and Yang 2007) initially established a prevention alarm indicator system for gas explosions and coal and gas outbursts. Guo et al. (Guo et al. 2016) used the method of directly measuring the gas content of coal seams to predict coal outbursts. Wei et al. (Wei et al. 2017) selected four parameters as the characteristic indicators of outburst prediction: downhole gas emission peak, gas rise gradient, gas overrun time and gas fall gradient. Ji et al. (Ji et al. 2016) developed a set of new technologies and equipment for predicting coal and gas outbursts based on gas content, which extends the prediction depth of the roadway excavation and mine working face from less than 10 m currently to 65 m and shortens the prediction time by 50%.

In addition to gas parameters, scholars have proposed using microseismic, acoustic emission, electromagnetic radiation and other methods to make outburst predictions and have vigorously developed technology and hardware. Lu et al. (Lu et al. 2014) developed a microseismic monitoring coal and gas outburst positioning system. Li et al. (Li et al. 2006) proposed a standardization process based on the geographic information system (GIS) for coal and gas outburst alarms, as shown in Fig. 4. Nie et al. (He et al. 2007) developed a non-contact electromagnetic radiation monitoring and prevention alarm technology and equipment for dynamic coal and rock disasters. Qin and Lu (Qin and Lu 2019) concluded that the prediction of coal and gas outburst areas can be achieved based on the seismic AVO (amplitude variation with offset) response characteristics at the outburst points. Zhang et al. (Zhang et al. 2011) carried out microseismic monitoring of coal-rock damage on a fully mechanized mine working face, monitoring of mine pressure and actual measurement of gas emission in roadway excavation and at mine working faces.

A multi-indicator and multifactor outburst prevention alarm indicator system is also gradually being developed and realized, as shown in Fig. 5. For instance, Sun et al. (Sun et al. 2006) proposed 15 indicators, such as mining depth and coal seam thickness. Zhang et al. (Zhang et al. 2017) proposed using 9 indicators, such as maximum mining depth and coal seam thickness, for outburst prediction. Hou et al. (Hou et al. 2014) established a comprehensive prediction and prevention alarm indicator system for coal and gas outbursts based on three aspects: the objective hazards of the working

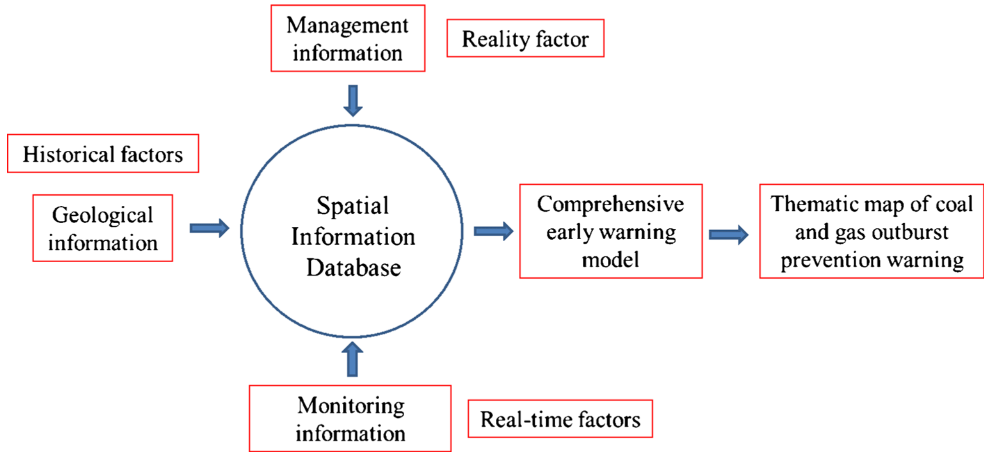


Fig. 4 Schematic diagram of research scheme based on GIS

face, the major defects of anti-burst measures and the major hidden dangers of safety management. Neilan et al. (Neilan et al. 2013) identified prevention alarm indicators as basic indicators for prevention alarms and related indicators and classified prevention alarm levels.

First, due to the nonlinear physical and mechanical properties of coal, the complexity of gas occurrence and migration processes and the similarity of the dynamic characteristics of dynamic phenomena, the study of outburst mechanisms is complicated, and there is a lack of a quantitative and unified theoretical system. Second, there is a lack of systematic research on the geological environment and extractive mining deployment as a unified whole, so the role of the geological environment and extractive mining deployment in outbursts is unclear. Third, there are problems such as imperfect monitoring and early warning indicators for coal and gas outburst disasters, insufficient self-analysis capabilities of early warning models and low levels of early warning system automation.

Research progress on the causes of coal and gas outbursts

Based on the perspective of understanding disaster prediction and prevention alarm indicators, this paper describes the progress of research related to outburst mechanisms, coal seam geological environments and outbursts and coal mine production systems and outbursts and analyses the supporting roles of various aspects of research on prevention alarm indicators and prevention alarm technology.

Research progress on coal and gas outburst mechanisms

In the 1950s, Soviet scholars made major breakthroughs in the study of outburst mechanisms and successively proposed a number of hypotheses that still have a great influence. These hypotheses are considered to be the result of the combined effects of multiple factors, which can be collectively referred to as the comprehensive mechanism of action hypothesis. For example, the energy hypothesis is that an outburst is caused by the deformation potential of the coal and the gas internal energy. When the stress state of the coal seam suddenly changes, the potential release causes the coal seam to be broken at a high speed, and the gas is desorbed and emerges from the broken coal to form a gas flow, throwing the broken coal into the mining space. The smashing wave hypothesis describes the physical phenomena that occur during a continuous outburst process and better explains the delamination that occurs during that process. The comprehensive hypothesis suggests that outburst occurrences are the result of a combination of many factors, including geostress, gas in the coal, the physical and mechanical properties of coal, the microscopic and macroscopic structures of coal seams and coal seam gravity.

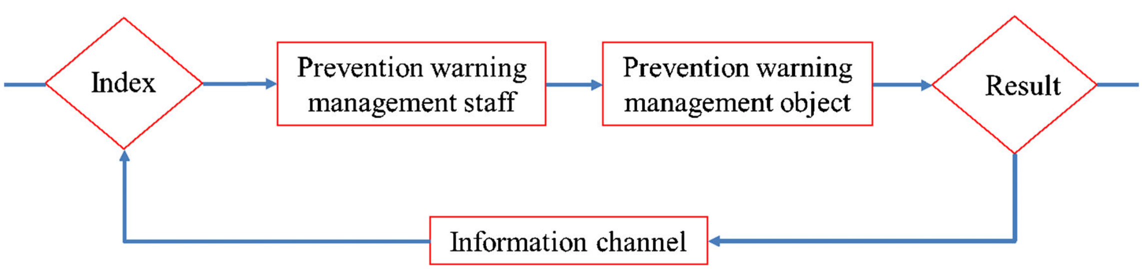


Fig. 5 Basic principle diagram of prevention warning management

The comprehensive action hypothesis indicates that the process is indeed affected by many factors, but there are still some phenomena that cannot be explained, such as the regional distribution of accidents, the delay of outburst accidents, the strong intensity when passing the coal gate, the gas discharge exceeding the coal seam gas content and other phenomena. In recent years, there have been new developments in the study of coal and gas outburst mechanisms, including the rheological hypothesis (Sun et al. 2019), the spherical shell instability hypothesis (Miao et al. 2020), the two-phase fluid hypothesis (Sun et al. 2020), the critical layer-stress wall hypothesis (Wang et al. 2018a), the sticky slip hypothesis (Li et al. 2018), and the solid-flow coupling instability hypothesis (Li et al. 2019). Song and Zhang (Song and Zhang 2013) used the theory of mechanics to explore coal and gas outburst disasters and used dimensional analysis to obtain the one-dimensional flow solution and starting criterion for coal and gas outbursts. Choi and Wold (Choi and Wold 2004) used mechanics theory to describe the various stages of coal and gas outbursts in detail and analysed the coal and gas outburst process under mechanical action.

There are many hypotheses about the causes and conditions of outbursts, and the understanding of the outburst mechanism gradually develops from a single factor to many factors. After long-term observation and research on the outburst phenomenon in a large number of mines, the causes, conditions and processes of outbursts have basically been mastered. It is clear that the coal, rock, gas and stress fields involved in outbursts are a unified system. The radial stress and gas pressure distribution of the cavity wall during the development of coal and gas outburst is shown in Fig. 6. Based on this idea, to understand disaster prevention and forecasting and prevention alarms, parameters such as stress monitoring, gas pressure tests and coal mechanics characteristics were selected as prevention alarm indicators.

Influence of the coal seam geological environment on mine outburst disasters

The coal seam geological environment is generally considered to be the inherent background of coal mine production. However, due to the complexity of coal seam occurrence, this element can also be considered as dynamic, which can provide indicators for disaster alarms. The geological structure plays a significant role in the control of coal and gas outbursts (Ni et al. 2014). The geological structure not only changes the original structure of the coal body but also causes the thickness of the coal seam to vary, the structural stress distribution to be uneven, the local stress to be concentrated and the coal structure to be severely damaged. The coal body strength is low, the ability to resist compression is reduced, and the gas distribution is uneven, resulting in a large gas pressure gradient.

As a part of the geological environment, gas occurrence characteristics in coal seams are also important for disaster prevention and alarms. Wei et al. (Liang et al. 2018) proposed a physical explosion model of coal and gas outbursts and analysed the relationship between the prediction index and gas expansion energy. Jacek (Sun et al. 2019; Sobczyk 2014) analysed the effect of adsorption processes on coal and gas outbursts caused by gas pressure under laboratory conditions. He and Zhang (He and Zhang 2000) considered that vibration is an important factor in inducing coal and gas outbursts and discussed the mechanism of vibration-induced coal and gas outbursts. Yin et al. (Yin et al. 2011) concluded that as the stress level in the stress concentration region increases, the experimental absolute compressive strength and relative compressive strength also increase. Wang et al. (Wang et al. 2017) systematically studied the whole process of crack initiation, expansion, penetration, throwing, development and termination of gas-bearing coal-rock failure–induced extrusion, outburst and composite dynamic phenomena. Kuroiwa and Tashiro (Kuroiwa and Tashiro 1960)

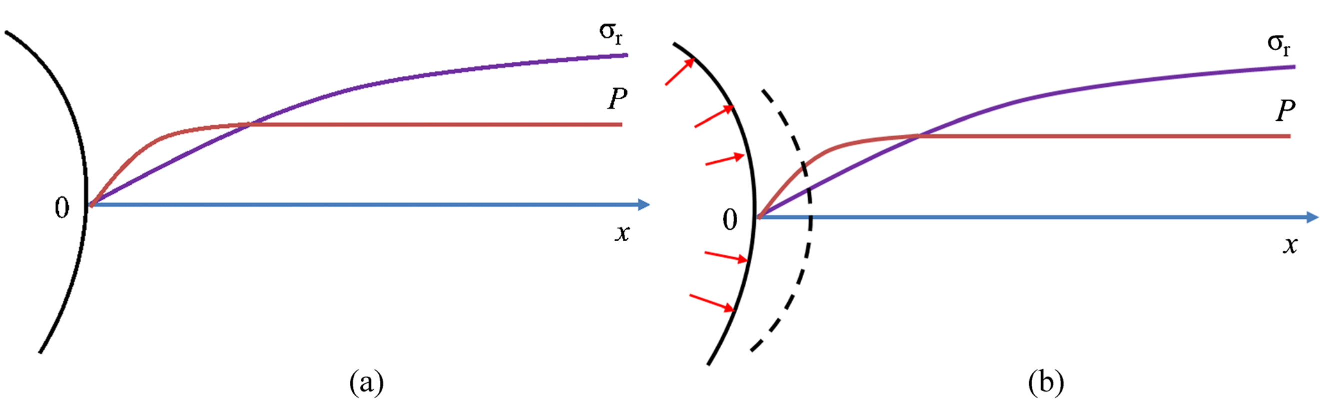


Fig. 6 The radial stress and gas pressure distribution of the cavity wall during the development of coal and gas outburst. Here, σ_r is the in situ stress of coal, characterizing coal strength, Mpa; P is the coal seam gas pressure, Mpa. **a** Coal pulverization stage. **b** Coal seam fracture stage. (a) Coal pulverization stage, (b) Coal seam fracture stage

established an experimental system for simulating coal and gas outbursts under different gas pressures, stresses and coal conditions and determined the outburst conditions. Cao et al. (Cao et al. 2014) found that the risk of coal and gas outbursts increased when the thickness of soft coal suddenly increased or the thickness continued to be greater than 0.8 m.

The research of gas geology has greatly promoted the close relationship between gas disaster prediction and the geological environment, and its research results have been promoted and applied (Judd et al. 2002). Palodkar et al. (Palodkar and Jana 2019; Fu et al. 2012) proposed a set of geological indicators of coal and gas outburst danger zones and divided the geological factors of coal and gas outbursts into two aspects: geological conditions affecting gas occurrence and geological conditions affecting coal and gas outbursts. The proposal includes geological indicators such as mine geological structure, coal thickness and variability and coal structure. Figure 7 shows the geological index system of coal and gas outburst. Ruilin and Lowndes (Ruilin and Lowndes 2010) used the gas geological unit method to select some gas geological parameters to identify the gas outburst zones of coal seams. Yang and Guo (Zhang et al. 2009) proposed that geological structures control coal and gas outbursts by controlling the physical environment.

Influence of coal mine production systems on mine outburst disasters

Coal mine production systems that mainly refer to production activities, such as mine development, excavation and mining, are closely related to coal and gas outburst accidents. Gas drainage is a fundamental measure to eliminate coal and gas outburst disasters. The safe production policy has increasingly higher requirements for gas drainage, which prompts an early production mode based on coal production to gradually investigate the development of gas drainage. There is a balance problem that needs to consider the production relationship of the DEM.

Wu et al. (Wu et al. 2020) proposed the concept of DEM balance and believed that the extraction and balance relationship is that the three processes of DEM production maintain a strict sequence and balance in time and space distribution. The method for determining the time required for gas drainage is shown in Fig. 8. Kumar et al. (Kumar et al. 2018) proposed a method for rationally determining gas drainage and extraction systems for mines with coal and gas outbursts. Wang et al. (Wang et al. 2008) first proposed the concept of a safe coal volume, which laid a theoretical foundation for establishing a DEM balance. Tang et al. (Tang et al. 2020) proposed a method to determine the outburst extraction capacity of outburst coal seams. Kong (Sun et al. 2020) used statistical analysis of the actual extraction engineering method of the mine and established a prediction model for the outburst time of the mine. To better realize the coordinated and efficient development of coal and gas and ensure the safety and efficiency of coal production, Shanxi Jincheng Anthracite Mining Group Co., Ltd. adopted the joint technology of surface drilling and drainage, combined ground and underground drainage and underground drainage to form the planning area, preparation area and production area. The "three-zone linkage" regional progressive three-dimensional extraction model (Wang et al. 2018b) lays the foundation for the DEM balance.

The DEM balance is reflected in time and space. Currently, mines are mostly guided by the "three super-front" mining deployment guidelines; that is, roadway excavation is ahead of extraction, gas drainage is ahead of protective layer mining, and protective layer mining is ahead of the protected layer. In space, it is necessary to consider the stress concentration caused by the layout of the roadway and the order of coal seam mining, which is closely related to the occurrence of outbursts (Yang et al. 2012). For mines with outburst coal seams, determining their reasonable DEM is an important part of the prevention and control of coal and gas outbursts and other gas dynamic phenomena, as well as effective management of gas emissions. Currently, there are relatively few studies on how to establish a DEM balance evaluation model.

Discussion

The selection of outburst prevention alarm indicators and the establishment of an indicator system are related to the limited nature of disaster alarms. Previous research provides a good foundation for understanding the prevention and control of disasters, and the occurrence of outburst disasters in engineering applications has been suppressed to a certain extent. However, the author believes that there are still some shortcomings in understanding the validity, timeliness and

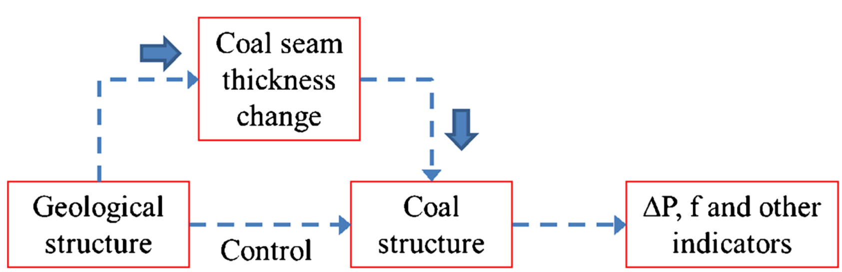


Fig. 7 Geological index system of coal and gas outburst. Here, ΔP is the initial gas diffusion velocity of coal, mmHg; f is the coal hardiness coefficient, dimensionless

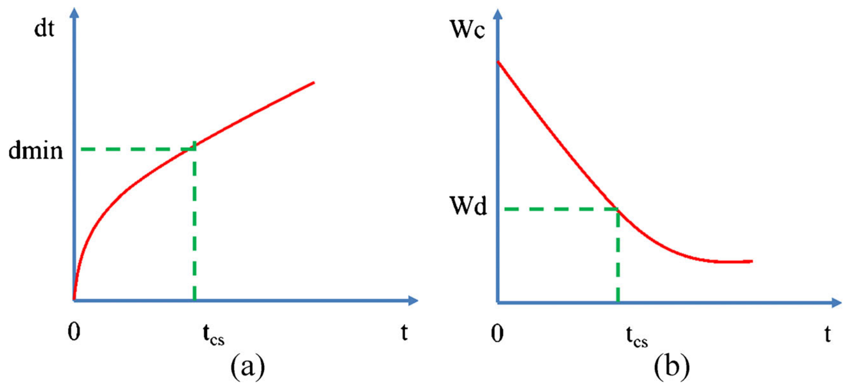


Fig. 8 Method for determining the time required for gas drainage. Here, t_{cs} is the time required for the gas drainage rate to meet the minimum requirement dmin; dmin is the minimum requirements for gas drainage rate; dt is the gas drainage rate at different times; Wc periodically determines the residual gas content in coal seams at different times during the drainage process; Wd is the highest allowable coal seam gas content obtained by inverse calculation of the lowest drainage rate. **a** Determine tcs by using the relationship between draining rate and draining time; **b** determine tcs by using the safety value of coal seam gas content. (a) Determine t_{cs} by using the relationship between draining rate and draining time; (b) Determine t_{cs} by using the safety value of coal seam gas content.

comprehensiveness of relevant theoretical research and prevention alarms. The difficulty in establishing prevention alarm indicators and prevention alarm models is mainly reflected in the following:

(1) In terms of the outburst mechanism, the comprehensive effect hypothesis explains the outburst mechanism to a certain extent, but most hypotheses qualitatively describe the phenomenon of coal and gas outbursts. The physical and mechanical properties of coal and rock that affect coal and gas outbursts are nonlinear. The failure modes of coal and rock masses are diverse, the process of gas occurrence and migration is complex, and the dynamic characteristics of dynamic phenomena are similar. The failure modes are impossible to distinguish from a quantitative point of view, which leads to the complexity of the research on the mechanism of disaster prevention and the lack of quantitative and unified theoretical systems. Hypotheses other than the comprehensive hypothesis are based on a certain indicator. The proposed prevention alarm indicators are based on this lack of universality and practicality.
(2) Lack of overall consideration. A mine is a large system integrating production and safety. It includes working face mining, roadway excavation, mine ventilation, monitoring and control and auxiliary production systems. It has certain impacts on disaster prevention and disaster reduction. Prevention alarm technology has gradually realized the investigation of multiple indicators and multiple factors, but there are few studies on the role of production systems in outbursts. The mechanisms of disasters caused by various factors are not clear, and the theoretical support is not sufficient, so prevention alarm technology cannot fully consider the overall situation.
(3) Insufficient research on the space-time synergy among DEM. As the depth of mining continues to increase, the geological environment of coal seams is becoming increasingly complex. The increase in mining depth is extremely important for mine development, coal seam mining procedures and DEM replacement. When the coal mine cannot be properly operated in the time and space of the production system, safe production is facing hidden dangers. How to judge the rationality of the production system through prevention alarm technology becomes even more important.
(4) The indicator system is confusing, which is not conducive to finding the root cause of disasters. Currently, there are many classification criteria for indicators. When the index system is established, it aims to be comprehensive, but it does not provide index classification, leading to the indicators lack of comparability, and consequently, the disaster assessment results are not reliable. In addition, the prevention alarm indicators are complicated and inconsistent, there are many indicators for qualitative description, and there are few indicators that can be quantified. In addition, most of the indicators are not computerized and can only be manually assessed; the outburst prevention alarm indicators of the mine production system are not concise, and the single evaluation method is not compatible with big data systems.

Based on the above analysis, this paper proposes that to improve the application effectiveness of prevention alarm technology, in-depth research is necessary to understand the disaster-causing factors, find the main controlling factors of outburst disasters and select technically feasible and theoretically reasonable forecasting indicators. The basic principles are as follows:

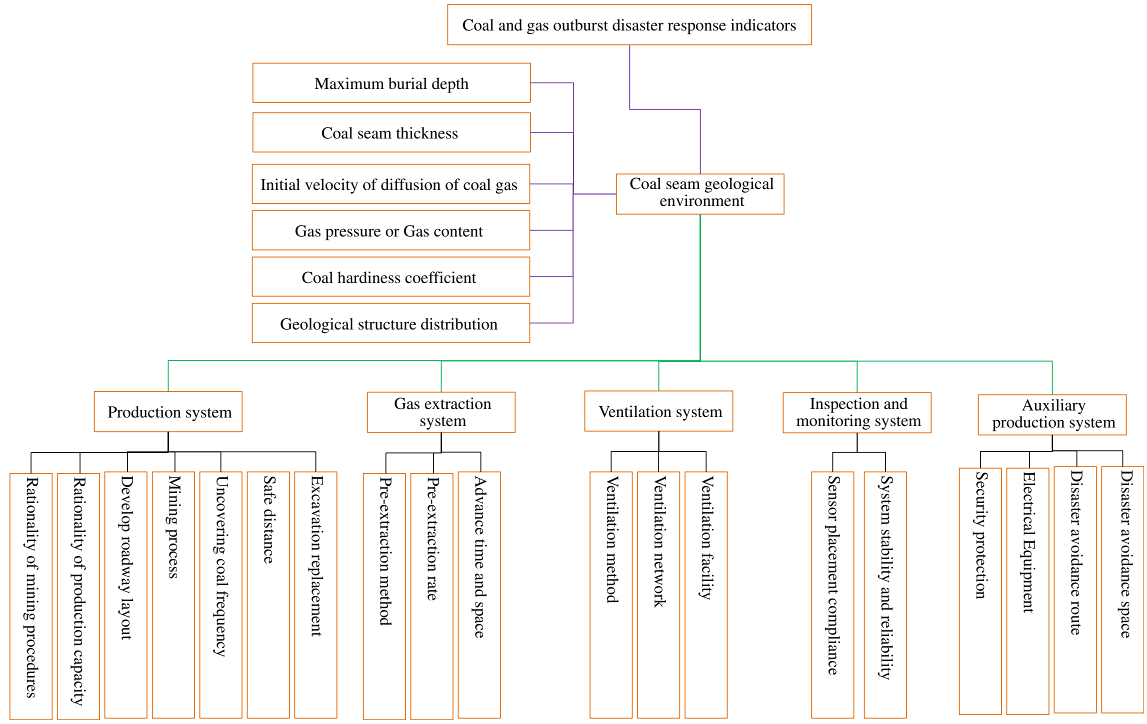


Fig. 9 Index system of disasters and disaster prevention for coal and gas outbursts in coal mines

(1) Improve the geological environment level of coal seams and use this as a background to examine the rationality of mining activities, ventilation systems, monitoring and monitoring systems. Comprehensively analyse the disaster-causing factors of coal and gas outbursts, establish a concise and clear alarm indicator system, and construct an outburst risk identification method and prevention alarm model for multisource data fusion.

(2) Pay attention to the DEM balance and investigate the deployment of the lead time and space stress between the three aspects. Further refine the DEM index and carry out characterization and investigation through parameters such as lead time, lead space and mining procedure so that the establishment of the prevention alarm model contains sufficient parameters to promote the effectiveness of the prevention alarm, guide engineering practice and realize the DEM balance.

Based on the above principles, by analysing the hazard factors of the mine production system, the coal seam geological environment is set as the secondary indicator, and the production system, gas drainage, ventilation system, monitoring and control, auxiliary production and other systems are the third-level indicators. The risk evaluation index system further refines the third-level indicators and selects quantifiable parameters such as safety distance, pre-extraction time, mining procedure and mining and replacement as the fourth-level index, as shown in Fig. 9. The indicator system has obvious advantages in understanding risk assessment, establishing a prevention alarm model and quantifying the mining index. On this basis, the prevention alarm model of multisource data fusion is constructed to judge the possibility of coal and gas outburst accidents and the severity of the consequences, which provides a basis for understanding mine risk decisions and disaster alarms.

Conclusions

(1) This study summarized the progress of research on mine prevention alarm indicators and prevention alarm technology, coal and gas outburst mechanisms, coal seam geological environments and outbursts and DEM deployment and importance, highlighting that prevention alarm indicators are the key to effective prevention alarms. According to the analysis, from the aspects of understanding the relevant theoretical research and prevention alarm effectiveness, timeliness and comprehensiveness, there are still some shortcomings, and the support for prevention alarm indicators and prevention alarm models is weak. To this end, we should conduct in-depth research to understand the disaster-causing factors, find the main factors controlling outburst disasters and select predictive indicators that are technically feasible and theoretically reasonable.

(2) Based on the perspective of outburst risk assessment, prevention alarm models and index quantification, emphasizing the rational deployment of DEM, analysing

and understanding the hazard factors in mines, establishing a coalbed geological environment as a secondary indicator to production systems, gas drainage, ventilation systems, monitoring and control, auxiliary production and other systems are the third-level indicators of the outburst disaster risk assessment index system. Quantifiable parameters such as safety error distance, pre-extraction time, mining procedures, extraction and replacement are selected as the fourth-level indicators. The indicator system has obvious advantages in facilitating risk assessment, establishing prevention alarm models and quantifying the mining index to construct a prevention alarm model that fuses multisource data, judge the possibility of coal and gas outburst accidents and the severity of the consequences and provide a basis for understanding mine risk decisions and disaster alarms.

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Declarations

Conflict of interest The authors declare no competing interests.

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