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Editorial

Theory and Technology for the Prevention of Mine Water Disasters

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1. Introduction

The complex hydrogeological conditions in deep mining areas, coupled with large-scale and high-intensity mining activities, have triggered a series of mine water disasters and significant resource waste issues [1,2]. Mine water disaster prevention is crucial for the safe operation of mines. Studying the occurrence mechanism of water disasters, advanced detection, and disaster prevention can provide a theoretical basis and effective solutions for mine water treatment [3,4]. By studying fundamental mechanical theories of water-bearing coal rocks, technologies for the resource utilization of mine water, the mechanisms of surrounding rock, and advanced technologies for early warning and prevention of mine water disasters, accurate prediction and rapid response to mine water hazards can be achieved. This can minimize the losses caused by mine water disasters [5]. To ensure mine safety production, modern technological approaches are playing an increasingly vital role in both mine safety production and water resource management [6,7].

To address these challenges, scholars have made breakthroughs in various fields by leveraging modern technological approaches [8]. For example, they have employed a combination of methods to detect concealed water-bearing fractures and conducted in-depth studies on the geochemical characteristics of groundwater and mine water, providing technical support for a more accurate understanding of mine hydrogeological conditions and preventing water inrush [9]. Simultaneously, the application of advanced monitoring technologies and machine learning has enabled the identification of drainage tunnel intrusions and the prediction of water-bearing fracture expansions under thick, hard-roof conditions, providing effective means for timely detection and early warning in regard to mine safety disasters [10]. Research into the matching relationship between explosives and rock has improved blasting efficiency, reduced safety risks, and enhanced mine resource extraction efficiency [11,12]. In the Loess Plateau region, scholars have studied monitoring and assessment methods for landslides and debris flows, providing scientific theoretical guidance for disaster prevention and mitigation in the area [13]. By establishing coal mine water disaster risk assessment methods and researching the deformation and destruction characteristics and acoustic properties of sandstone at different water immersion depths, scholars have provided theoretical foundations for more precise identification and evaluation of mine water hazard risks and predicting the stability of water-inundated roadways, laying the groundwork for the development of effective prevention and control measures [14].

This Special Issue research explores the application of modern technology to enhance mine safety and promote the utilization of mine water resources from multiple perspectives. It provides critical theoretical foundations and technical support for ensuring mine safety and promoting sustainable development in the mining industry. The achievements will not only provide important theoretical support and technical backing for ensuring safe mine production but also offer powerful technological strength to promote sustainable development in the mining industry and to aid in building green mines.

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2. An Overview of Published Articles

The incubation process, scientific evaluation, and efficient prevention of mine water disasters are of great significance for the safe and efficient mining of Chinese coal mines. Implementing efficient water detection, revealing the evolution mechanism of water disasters, and accurately evaluating the risk of water disasters are the essential technologies in regard to efficient prevention of water disasters. Ten papers in this Special Issue cover topics relevant to this subject.

Lu et al. proposed a geophysical–drilling–hydrochemical coupled method for the accurate detection of concealed water-conducting faults in coal mines. This method combines integrated mining geophysical exploration, hydrogeological drilling, and hydrochemical exploration (GDH). It conducts a thorough analysis of the background geological data obtained through surface exploration, enabling the prediction of potentially concealed water-conducting structures. Then, the seismic reflection method (SRM) and mine transient electromagnetic method (MTEM) are combined to detect the location and water-bearing properties of the target structures. Subsequently, the target drilling areas are defined by the anomalies detected by the integrated mine geophysical technique. Considering the hydrogeological information of water-conducting structures obtained through drilling methods, the hydrogeological information of water-conducting structures can be directly acquired. Through hydrochemical analysis, inrush water sources and their runoff conditions can be identified, and the spatial relationship between the source aquifers and mining space can be determined. Thus, the properties, scale, and configuration of the water-conducting structures can finally be evaluated. This multiple-method solution can accurately detect concealed water-conducting structures and help prevent water inrush disasters.

Yuan et al. developed a monitoring system to simulate intrusions in drainage tunnels based on distributed acoustic sensing (DAS) and the obtained typical characteristics of events such as rockfall events and water release. On this basis, an identification method for drainage tunnel intrusion events using principal component analysis (PCA) and neural networks was proposed. PCA reveals that amplitude-related parameters—amplitude, mean amplitude, and energy—significantly contribute to the classification of DAS signals, reducing the dimension of feature parameters by 54.8%. The accuracy of intrusion event classification is improved with PCA-processed data compared to unprocessed data, with overall accuracy rates of 79.1% for rockfall events and 72.7% for water release events. Additionally, the artificial neural network model outperforms the Bayesian and logistic regression models, demonstrating that an ANN has advantages in handling complex models for intrusion event classification.

Bai et al. investigated the initiation mechanism of landslide and debris flow disasters and collected their spreading patterns. Historical satellite images in the Laolang gully were used to generate three-dimensional topographic and geomorphological maps. Typical landslides were selected for measuring landslide thickness using a standard penetrometer and high-density electrical method. Numerical models were established to simulate the occurrence and development of landslides under different working conditions and to evaluate the spreading range based on the propagation algorithm and friction law. The results provide scientific and theoretical guidance for the prevention and control of rainfall-induced landslide and debris flow disasters in the Loess Plateau area.

Wang et al. examined the hydrogeochemical characteristics and evolution of Ordovician groundwater in the Zhuozishan coal mine in the northwest region of China. A total of 34 groundwater samples were collected for hydrogeochemical analyses and investigation of their evolution processes with the help of a piper trilinear diagram, a Gibbs diagram, and an ion ratio diagram. The author analyzed the runoff changes by analyzing the variation in characteristic ion concentrations, including sodium (Na^+), potassium (K^+), bicarbonate (HCO_3^-), chloride (Cl^-), sulfate (SO_4^{2-}), calcium (Ca^{2+}), and magnesium (Mg^{2+}), from the supply area to the discharge area. It was indicated that the northern part of the coalfield is characterized by a geological structure that creates a retention area for groundwater, resulting in an unordered runoff process with a complex formation mechanism. The middle region is free from geological constraints that would alter the flow direction, thus simplifying the process of groundwater formation. In contrast, the southern area experiences an increase in strata depth and fault blocking, which creates a retention zone, thereby making the groundwater formation process more complex. This research contributes to the effective management of groundwater resources in this coalfield and other mining sites.

Wang et al. developed a prediction model of water-conduction fracture zones based on a back propagation (BP) neural network by integrating theoretical analysis, field measurements, and algorithmic advancements. Firstly, they determined the height index system of the water-conducting fracture zone through an overburden migration analysis and correlation tests. This system includes mining height, buried depth, dip angle, working face width, and overburden rock lithology, and it features five groups of characteristic parameters. Then, the 35 pairs of minefield-measured data were collected to establish the measured height data set of the water-conducting fracture zone. Secondly, a BP neural network prediction model and a traditional support vector regression (SVR) prediction model were constructed based on a Pytorch framework, and the models were trained and tested by selecting data sets. Thirdly, the optimal prediction model was determined by comparing the model with the empirical model and the multiple regression model of mining regulations for coal pillar maintenance and pressure in buildings, water bodies, railways, and main shafts. Finally, a typical mine was selected for application to verify the suitability of the optimal model. The research results provide technical guidance for similar fragile coal seams.

Yang et al. analyzed the hydrochemical characteristics of highly mineralized coal mine water in semi-arid regions in Northwest China and revealed the formation mechanism of the water. Their research collected a total of 38 groundwater and mine water samples to examine the hydrogeochemical characteristics of high-salinity mine water using Piper diagrams and Gibbs diagrams, as well as isotope analyses and ion ratio coefficients. Additionally, they put forward corresponding mine water treatment recommendations. This study concludes that the TDS content of groundwater increases with hydrographic depth. The average TDS concentration of Quaternary, Luohe, and Anding groundwater is 336.87, 308.67, and 556.29 mg/L, respectively. However, the TDS concentration of Zhi Luo groundwater and mine water is 2768.57 and 3826.40 mg/L, respectively, which matches with high-salinity water. The hydrochemical type of Quaternary, Luohe, and Anding groundwater is predominantly the HCO_3-Ca type, while the hydrochemical type of Zhiluo groundwater and mine water is predominantly the SO_4-Na type. Furthermore, there are minimal differences observed in regard to δD and $\delta^{18}O$ values among these waters. It can be inferred that the Zhiluo formation in groundwater serves as the primary source of mine water supply, primarily influenced by the concentration processes caused by evaporation. The high salinity of mine water is closely related to the high salinity of Zhiluo groundwater. The high salinity of groundwater has gradually evolved under the control of the concentration caused by evaporation and rock-weathering processes. The dissolution of salt rock, gypsum, and other minerals serves as the material basis for the formation of high-salinity groundwater. In addition, the evolution of major ions is also affected by cation exchange.

Wei et al. take the 2102 fully mechanized mining face in the Balasu coal mine as the research background. By combining numerical simulation with physical simulation, the fracture evolution and strata movement characteristics in thick and hard overlying strata are simulated and analyzed and the formation mechanism of a water-conducting fracture in the overlying strata is revealed. It is further verified by field measurements of the development height of "two zones". The results show that the number and development height of fractures undergo the change–growth process of "slow–rapid–uniform". The water-conducting cracks in overlying strata show a dynamic expansion process of "local micro-cracks–jumping cracks–through cracks–water-conducting cracks". The fracture between the caving zone and fracture zone presents obvious layered characteristics. The overall shape of the water-conducting fracture zone is "saddle-shaped", and the maximum development height lags behind the coal mining face by about 180 m. This research provides theoretical guidance and a scientific basis for coal mine water disaster prevention under similar geological conditions.

Liu et al. studied the characteristics of deformation and damage as well as acoustic properties of sandstone in circular tunnel morphology under different inundation depths. In this study, the TAW-2000 press and static strain system was employed to investigate the mechanical properties, crack evolution, and deformation field distribution of sandstone with round holes at different immersion depths. Additionally, the study analyzed the impact of immersion depth on the characteristic parameters of acoustic emission. The results show that immersion depth is negatively correlated with the compressive strength and the modulus of elasticity of sandstone. As immersion depth increases, the duration of the compression and yield phases of the rock samples also increases, while the duration of the elastic phase remains relatively unchanged. These research findings have significant reference value for addressing issues related to water immersion and the degree of water saturation in roadways within rock engineering.

Zhu et al. studied the matching of explosives and rocks based on the hydrophysical properties of rocks. Firstly, they derived the theoretical solutions for crushing-zone energy, fragmentation energy, and fragment-throwing energy. Subsequently, concrete blocks with four types of cement–sand ratios were prepared and four types of emulsion explosives were used to conduct single-hole blasting tests. In these tests, a high-speed camera was employed to capture the trajectory of the blasting fragments, which were later collected. Finally, the crushing energy, fracturing energy, and fragment-throwing energy were calculated according to the test results and the basic parameters of the used explosives and concrete models. The results indicate that the size and distribution pattern of blasting blocks are significantly influenced by the hydrophysical properties of concrete and explosive properties. The higher the energy consumption in the rupture zone, the smaller the size of the fragments and the more uniform the distribution.

Xu et al. evaluated coal mine water hazard risk based on the combination of extension theory, game theory, and the Dempster–Shafer evidence theory. Firstly, they established a hierarchical water hazard risk evaluation index system. Then, matter–element theory in extension theory was used to establish a matter–element model for coal mine water hazard risk. The membership relationship between various evaluation indexes and risk grades of coal mine water hazard risk was quantified using correlation functions of the extension set theory, and the quantitative results were normalized to obtain basic belief assignments (BBAs) of risk grades for each index. Subsequently, the subjective weights of evaluation indexes were calculated using the order relation analysis (G1) method and the objective weights of evaluation indexes were calculated using the entropy weight (EW) method. The improved combination weighting method of game theory (ICWMGT) was introduced to determine the combination weight of each evaluation index, which was used to correct the BBAs of risk grades for each index. Finally, a fusion of the DS evidence theory, based on a matrix analysis, was used to fuse the BBAs, and the rating with the highest belief in the fusion result was taken as the final evaluation result. The evaluation model was applied to a water hazard risk evaluation of the Sangbei coal mine. The evaluation result was the II grade water hazard risk, which was in line with the actual engineering situation. The evaluation result was compared with the evaluation results of three methods, namely the expert scoring method, the fuzzy comprehensive evaluation method, and the extension method. Through this comparison, the scientificity and reliability of the method adopted in this paper were verified.

3. Conclusions

The research on the domains of geology and mining encompasses multiple facets, including rock mechanics, hydrogeology, and mining disaster prevention. By analyzing and synthesizing diverse research outcomes, a more lucid understanding of the overall developmental trends and crucial information in this field can be attained, providing a robust reference for subsequent research and engineering practices. The following is a summary of the conclusions from ten relevant articles.

(1) Uniaxial compressive tests on rock samples with circular holes demonstrate that, as the immersion depth increases, the uniaxial compressive strength and elastic modulus of sandstone notably decline, while the peak strain gradually rises. With a greater immersion depth, both the rapid decrease in uniaxial compressive strength and the increase in peak strain are more pronounced. When pressure is applied to rock samples at different immersion depths, water seepage leads to deviations in strain monitoring and the crack propagation and tensile failure points vary with the immersion depth.
(2) A numerical model is established to simulate the occurrence, development, and propagation range of debris flows under different working conditions. An appropriate DEM data resolution can reasonably assess debris flow risk, and a lower critical slope threshold results in more loose material flow, leading to wider and further landslide dispersion, which can simulate landslide movement under various conditions.
(3) Functional expressions for energy in various parts are derived based on principles like mass conservation. Different types of explosives and the physical conditions of water lead to different fragment sizes and distributions after an explosion, which provides important references for research on the matching of explosives with rocks in hydraulic engineering.
(4) Layers within the mining impact area exhibit a directional deflection in the stress chain, forming strong chain arches. Tensile stress concentration regions initially develop tensile cracks, and water-conducting fractures form through a specific process, reaching an approximate height of 108 m. The predictive model for extremely thin coal seams effectively forecasts the height of water-conducting fracture zones, while methods like BP neural networks can enhance predictive accuracy.
(5) High-salinity mine water can be treated using reverse osmosis combined processing techniques. The hydrogeochemical characteristics of Ordovician limestone groundwater are closely related to the flow direction, with three distinct hydrogeochemical regions being formed based on different flow mechanisms. Moreover, research on groundwater in mining areas indicates that a geophysical–drilling–hydrochemical coupled approach can accurately detect concealed water-conducting structures and that combining multiple methods can overcome the limitations of individual approaches, thus enhancing detection methods.
(6) Establishing a monitoring system based on DAS can capture typical event characteristics. The principal component analysis indicates significant correlations among feature parameters, showing higher classification accuracy after PCA processing, while artificial neural network models are excellent in handling complex models for classifying intrusion events.
(7) The risk assessment method based on extension theory, game theory, and DS evidence theory is proposed. An evaluation index system and risk assessment levels are established, optimizing the weighting result combinations to determine risk control factors and key prevention indicators. The assessment results are in good agreement with actual conditions and are scientifically reasonable, making them valuable for promotion and application.

In conclusion, these ten articles conduct in-depth research in the fields of geology and mining, covering rock properties, geological disasters, hydrogeology, and risk assessment. They reveal the changing patterns of rock mechanical properties under different conditions and the impact of explosions on rocks. Research on debris flows and landslides provides a foundation for disaster prevention and modeling, while groundwater studies present valuable information for treating high-salinity mine water and analyzing groundwater chemistry. The study of concealed water-conducting structure detection methods aids in enhancing safety in coal mining, and the proposed risk assessment approaches provide a sound decision-making basis for managing water hazards. These research findings not only enrich our theoretical knowledge on geology and mining but also offer practical engineering applications and methodological guidance.

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