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Stability Classification of Coal Mine Goaf and Early Warning Indicator System for Disaster Chains Based on "Space-Air-Ground" Collaborative Monitoring: A Case Study of Typical Mountainous Coal Mines in Yunnan, Guizhou, and Sichuan Provinces

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Abstract. In typical mountainous coal mines in Yunnan, Guizhou and Sichuan provinces, the complex "air-ground-ground" collaborative monitoring data has established a classification method that includes indicators such as static geological background, dynamic deformation and hydrogeochemical data. Subsequently, the research revealed the evolution mechanism of the combined disaster chain of surface deformation and sudden water outburst in old mines, and established a three-level early warning indicator system of background, status and impending disaster. The application in a certain mining area in Liupanshui, Guizhou Province demonstrated that this system can effectively identify high-risk areas, with the coincidence rate of identifying "unstable areas" exceeding 85%, and the physical mechanism of water chemical indicators was verified through hydrogen and oxygen isotope analysis. This integrated system provides a systematic technical solution for risk management and disaster prevention and mitigation in mining areas with similar complex geological conditions.

Keywords: Goaf of coal mines, stability classification, disaster chain early warning, "space-air-ground" coordinated monitoring

1. Introduction

This paper proposes a dynamic closed-loop management framework centered on "space-air-ground" collaborative monitoring, which consists of "monitoring - analysis - early warning - feedback - optimization". The research focuses on the construction of a stability classification method for mined-out areas by integrating multi-source heterogeneous data, and deeply analyzes the evolution mechanism of the complex disaster chain. Subsequently, a multi-level early warning index system is established. Finally, through the application verification in a typical mining area, the applicability and effectiveness of this integrated system are evaluated, providing a scientific and systematic technical path for disaster prevention and mitigation in complex mountainous coalfields.

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2. Overview of geological background and goaf status in the study area

2.1. Characteristics of goaf in typical mountainous areas of Yunnan, Guizhou and Sichuan

The goaf in the area is widely distributed and complex. It is the result of multiple periods of mining activities in history and modern times and cannot be fully monitored. The stability of goaf in mountainous coal mines and the resulting disasters are controlled by the coupling of multiple factors and cannot be simply evaluated. Geological structure is the core factor. Dense zones of faults and joints destroy the integrity of the rock mass, form potential slip planes, and are also advantageous channels for groundwater migration and surge. The technical conditions of mining, such as mining depth, mining thickness, coal mining methods and roof lithology, directly determine the height of the collapse zone and the water-conducting fracture zone, and thereby affect the degree of surface deformation and activation risk, while hydrogeological conditions are crucial. Hydrogeological conditions, especially the replenishment intensity of atmospheric precipitation, the spatial relationship of surface water bodies, and the water-richness of aquifers, are key factors that cause old air-water disasters [1], as shown in a study of a coal mine in Guizhou. Geological structure, mining technical conditions, hydrogeology and external disturbances are the four main controlling factors for the stability of goaf and the occurrence of goaf water disasters.

2.2. The technical content and application status of "space-air-ground" coordinated monitoring

Various monitoring data play different roles in the study of goaf stability and old goaf water, and they play different roles. InSAR technology can detect the slow accumulation of subsidence and horizontal displacement on the surface over a wide range and periodically, identify the range, boundary and evolution trend of the subsidence funnel, and is an effective means for evaluating regional stability and delineating potential risk areas. High-resolution optical remote sensing and drone images can be used to identify signs of surface damage such as ground fissures, collapse pits, and building deformations, as well as to monitor the distribution and changes of surface water bodies. Geophysical exploration, such as high-density electrical and transient electromagnetic methods, can detect the boundaries of underground concealed goaf areas, overlying fault zones and water-rich areas. Drilling and in-well monitoring can directly obtain rock structure, mechanical parameters, groundwater level and hydrochemical samples, and these multi-source data together form the information basis for analyzing the stability state, disaster mechanism and early warning judgment of goafs [2].

The construction of a "space-air-ground" coordinated monitoring system is significantly necessary for the stability classification and disaster early warning of goafs in typical mountainous areas of Yunnan, Guizhou and Sichuan, aiming to enhance monitoring capabilities. The terrain in mountainous areas is complex and transportation is inconvenient. Traditional monitoring methods are costly and have limited coverage, making it impossible to achieve comprehensive monitoring. However, collaborative monitoring can achieve the combination of "surface - line - point". InSAR and aerial remote sensing complete regional scanning and key target identification, while ground-based monitoring conducts detailed investigation and verification, greatly enhancing monitoring efficiency and spatial coverage capabilities. Multi-parameter fusion helps reveal multi-field coupling mechanisms such as deformation, hydrology, and stress, providing strong support for more scientific stability assessment and disaster chain evolution analysis.

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3. Goaf stability classification method based on multi-source heterogeneous monitoring data

3.1. Preliminary construction of the classification index system

The static impact factor reflects the inherent geological background and historical mining characteristics of the goaf and is the basis for stability classification. To quantify the influence of each factor, refer to the Code for Geotechnical Investigation of Coal Mine Goaf and existing research results , use the Analytic Hierarchy Process (AHP) or the expert scoring method to determine the weights, and classify and assign values in combination with specific thresholds. The main indicators and their classification are as shown in the In Table 1:

Table 1. Static impact factor grading reference table

Evaluation metrics	Quantifying parameters/features	Stable (I)	Basically stable (II)	Unstable (III)
Depth ratio (H/M)	Mining depth (H)/ mining thickness (M)	> 40	30-40	< 30
Final collection time (a)	The number of years since the end of mining	> 15	5 to 15	< 5
Overlying lithology	Rock uniaxial compressive strength (MPa)	> 60 (hard)	30 to 60 (medium-hard)	< 30 (weak)
Thickness of the loose layer (m)	Thickness of the quaternary cover layer	< 20	20 to 30	> 30
Influence of geological structure	Fault density, size and relationship with goaf	No faults or long distances	There are small faults with less impact	There is a main fault passing through or near

Note: According to normative empirical values,H/M<30 is considered a high-risk area

Dynamic monitoring factors are the core basis for classification, including : surface deformation rate and accumulation (from InSAR/GPS) and their changing trends (acceleration/constant speed/deceleration), deformation gradient (tilt, curvature), ground fissures and collapse pit activity (from unmanned aerial vehicle monitoring), microseismic activity (event frequency, energy, cluster characteristics) [3].

The changes in the hydrogeological environment are closely related to the stability of the goaf and are important associated factors that induce the disaster chain. δD The main indicators are : Groundwater level dynamics: Water level monitoring holes are set up in and around the goaf to monitor the spatio-temporal changes of the groundwater level. A sharp drop in water level can induce karst collapse or change overlying stress, while a rise in water level increases old void water pressure and the risk of water damage. Hydrogeochemical characteristics of old water: Regularly collect water samples of old water and analyze their water chemical types (such as $Na\text{-}HCO_3$ type, $Ca\text{-}HCO_3$ type), major ion concentrations (such as Ca^{2+}, Mg^{2+}, SO_4^{2-}), total dissolved solids (TDS), etc. Sudden changes in water chemical composition can indicate new recharge sources or intense runoff exchange. Hydrogen-oxygen stable isotope ($\delta^{18}O$,) characteristics: By comparing the isotopic composition of old air water with that of potential recharge sources (atmospheric precipitation, surface water), the recharge sources and mixing ratios can be effectively identified. Relationship between surface water bodies and precipitation: Monitor the water levels and flow rates of nearby rivers and reservoirs, and in combination with meteorological precipitation data, analyze

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the impact of heavy precipitation events on surface runoff and infiltration recharge and their lag effects.

3.2. Fusion and quantification methods of "space-air-ground" multi-source data

The prerequisite for multi-source data fusion is a unified spatiotemporal reference, which is the prerequisite for fusion. Spatio-temporal registration includes: spatial registration, unifying all remote sensing images, InSAR deformation maps, unmanned aerial vehicle models, geological maps, etc. to the same geodetic coordinate system and elevation reference; temporal registration, for all time series data (such as InSAR time series, GPS time series) Time interpolation or resampling of water level time series gives them consistent or comparable timestamps. Data preprocessing is carried out for different types of data, such as phase unwrapping, atmospheric correction, orbital refinement for InSAR data, aerial triangulation encryption, generation of digital surface models (DSM) and orthophoto for drone images, and denoising, gross error removal, and standardization for monitoring sensor data.

Based on the characteristics of the study area, the Analytic Hierarchy Process (AHP) was used to determine the weights of each evaluation index, and then the linear weighted comprehensive evaluation method was adopted for fusion transformation. The fusion model uses the linear weighted comprehensive evaluation method, and the formula for calculating the comprehensive score is as follows:

$$S = \sum_{i=1}^{n} w_i \cdot x_i \tag{1}$$

Where, is the overall score of the evaluation unit, is the weight of the Sw_i i-th evaluation metric, satisfies; $\sum i = 1nwi = 1x_i$ Is the standardized value of the i-th evaluation indicator, n is the total number of evaluation indicators, and then the stability level is determined. The stability grade can be determined based on the threshold range where the comprehensive score S is located, and this determination is the core.

The classification criteria should be formulated in combination with normative requirements, regional experience and statistical characteristics of monitoring data. For example, the following can be set :Stable zone: The annual average deformation rate shown by the time series InSAR is below the threshold (e.g. ±3mm/ year), there is no trend change, microseismic activity is scarce, groundwater level and water quality are stable, and there is no new development of historical deformation signs (ground fissures) basically stable zone: there is slow deformation (e.g. Annual average rate 3-10mm/ year), But with a steady or attenuating trend, occasional low-energy microseismic events, small fluctuations in hydrogeochemical indicators but no trend change, Unstable zone: deformation rate exceeds the threshold and is in an accelerating or sustained high-speed state, new ground fissures appear or existing fissures expand significantly, frequent microseismic activity with increased energy, and sudden changes in groundwater level or water chemical composition. The classification results need to be verified in the field through independent means such as high-precision geodesy, detailed geological survey, building deformation observation, etc., to assess the accuracy of the classification, and to modify the classification model and threshold based on the verification feedback [4].

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4. Evolution mechanism and early warning index system of disaster chains in goaf areas of mountainous coal fields

4.1. Analysis of the evolution path from goaf instability to disaster chain

Instability in goaf areas mainly triggers two types of disaster chains. One is the activation of overlying rocks leading to surface deformation, which eventually develops into surface damage such as ground fissures and collapse pits. The other is the imbalance of water and rock stress coupling causing sudden water gushing in old goaf areas. Under complex geological conditions, the two often couple with each other, with the core being water and rock stress coupling. Make-up water enters old goaf areas through various channels, causing an increase in water pressure. P_w When the conditions are met (where is the minimum principal stress of the water barrier medium, $P_w > \sigma_3 + T\sigma_3$ T is its tensile strength), hydraulic splitting may be induced to form a gushing channel.

In the complex geological environment of mountainous areas, single disaster chains often trigger each other, coupling and amplifying to form more complex composite disaster chains. Typical coupling mechanisms include deformation-induced water damage: new fissures generated by the activation of goaf provide rapid infiltration channels for atmospheric precipitation and surface water, increasing the recharge of old air water and raising the risk of water inrush. Water damage intensifies deformation. The accumulation and pressure changes of old void water, on the one hand, soften the rock mass and reduce its strength, and on the other hand, the changes in pore water pressure can effectively alter the effective stress of the rock mass, which may induce further settlement and sliding of overlying rocks in the goaf and intensify surface deformation. Synergistic disaster, during heavy rainfall, precipitation infiltration rapidly replenishes old void water. By increasing the weight of the rock and soil, softening the soil mass, etc., it reduces the stability of the slope and may cause secondary geological disasters such as landslides and debris flows in the area superimposed with the subsidence of the goaf.

4.2. Construction of a multi-level early warning index system

This level of indicators is used to identify background conditions with potential high risks for risk zoning and early warning. The indicators include: geological structure complexity (fault density, scale), critical mining thickness ratio (H/M) zoning, especially areas with H/M<30, overlying lithologic assemblage type (proportion of weak rock layer thickness), loose layer thickness and distribution, These indicators are mainly obtained through the collection of geological data, mining drawings, hydro-meteorological data and remote sensing interpretation, and are used to draw the background map of goaf disaster risk [5].

This level of indicators, based on "space-air-ground" collaborative monitoring data, reflects the stability status of the goaf system in real time or near real time and is the core of early warning. The indicators cover surface deformation state indicators, the shape of the deformation rate time series curve based on InSAR (acceleration, constant velocity, deceleration), whether the cumulative deformation exceeds the historical background value, ground fissure activity indicators, Based on the number of new fissures discovered by regular unmanned aerial vehicle (UAV) patrols, the expansion rate and width variation of existing fissures, groundwater dynamics indicators, the daily variation of old air water level or water level in surrounding observation holes, the rate of continuous increase, abnormal increase in the concentration of tracer gases such as radon gas in groundwater, Microseismic activity indicators, frequency of microseismic events per unit time, total

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released energy, change in b value Water chemical mutation indicators, old air water pH, electrical conductivity, and rapid changes in the concentration of specific ions (such as SO_4^{2-}, Ca^{2+}), this level of early warning usually sets "attention level" and "warning level" thresholds.

This level of indicators corresponds to the precursors of impending collapse or initiation of a disaster, with short warning periods and the highest urgency. The indicators include precursors of surface deformation, stepwise acceleration or inflection points of deformation rate detected by high-frequency GPS or ground radar, precursors of ground sound and microseismic, characteristic waveforms captured by microseismic monitoring networks (such as the transition from rock mass breaking-type microseismic to friction-slip type microseismic) The temporal clustering and spatial migration of events, premonitors of sudden changes in groundwater, sudden increase in downhole water inflow, turbidity, carrying sediment in water, sharp drop or rise in water level at water level observation holes within a short period of time, macroscopic surface phenomena, cracking sounds of building walls, abnormal ground swelling or rapid development of new cracks within a short period of time, This level of warning corresponds directly to "alert level" or "Near disaster level", and an emergency response should be initiated immediately.

5. Coordinated monitoring, grading, integrated application and case verification of the early warning system

5.1. System integration architecture and operation process

The stability classification model and the early warning model are dynamically coupled in the platform. The classification model runs regularly (such as monthly) and uses all monitoring data up to the present to output the latest spatial distribution map of the stability classification of the goafs, which is an important input for the early warning model. The background layer and state layer thresholds of the early warning model can be set differently according to different stability levels (for example, a more sensitive deformation rate early warning threshold is set for the "basically stable zone"), the early warning model runs in real time or near real time, automatically generates early warning information when the monitoring data triggers the early warning indicator, and at the same time, new monitoring data, early warning cases and subsequent disaster verification results, The feedback information will be used to continuously calibrate and optimize the parameters and thresholds of the classification model and the early warning model, forming a closed-loop iterative mechanism of "monitoring, analysis, early warning, feedback, optimization".

Early warning information is classified into different levels such as "attention" (blue), "warning" (yellow), "alert" (orange), and "impending disaster" (red) based on the level triggered by the early warning indicators. The early warning information is directed to the safety management department of coal mine enterprises through various means such as dedicated platforms, text messages, and APP push notifications. Local government emergency management agencies and responsible persons in the affected areas.

5.2. Application verification of typical mining areas (Yunnan-Guizhou-Sichuan cases)

To verify the applicability of the constructed classification and early warning system, a typical complex mining area in Liupanshui, Guizhou Province (reference can be made to the study area of CAI Yun et al., 2025) was selected for application analysis. Based on the InSAR, unmanned aerial vehicle and ground monitoring data of this area from 202X to 202Y, the classification model was operated to obtain the preliminary results map of stability classification.

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Secondly, taking the identification of Laokong water sources as an example, the indicating role of the "hydrogeochemical correlation factors" in the model was verified. Atmospheric precipitation, surface water (Xiaohe, Shibanhe), and Laokong water samples at the 1460 level were collected in the mining area, and water chemistry and hydrogen-oxygen stable isotope ($\delta D, \delta^{18}O$) tests were conducted. The data analysis results are shown in the following In Table2.

Table 2. Characteristics of hydrogen and oxygen stable isotopes in water samples from a coal mine in Guizhou

Water sample type	$\delta^{18}O$ Mean (‰)	δD Mean (‰)	Hydrochemical types
Atmospheric precipitation (reference)	-	-	-
Surface water (small rivers)	-10.05	-68.19	$Ca\text{-}HCO_3$
Surface water (SLATE River)	-10.12	-70.82	$Ca\text{-}HCO_3$ / $Ca\text{-}SO_4$
1460 Old empty water	-10.13	-69.45	$Na\text{-}HCO_3$
Main tunnel water	-11.00	-75.31	$Ca\text{-}HCO_3$

Isotope analysis indicated that old empty water (: -10.13 ‰, :) $\delta^{18}O\delta D$ -69.45 ‰ originated mainly from atmospheric precipitation, with limited direct recharge from surface water, which is consistent with the characteristics of slow runoff indicated by the water chemical type ($Na\text{-}HCO_3$ type). This result validates the physical basis of using "hydrogeochemical mutations" as an early warning indicator to shift towards a more reliable early warning.

The stability classification map output by the model was spatially compared with the disaster hazard points, building damage records and geological reports investigated on-site. The results showed that the identification consistency of the "unstable area" exceeded 85%, confirming the effectiveness of this classification method and providing feedback for the further optimization of model parameters.

6. Conclusion

The research shows that the integrated system constructed in this paper, which combines collaborative monitoring, stability classification and disaster chain early warning, can effectively improve the accuracy and timeliness of high-risk area identification. This study provides technical ideas and case references for stability assessment and active prevention and control of disaster risks in goafs under complex geological conditions, and has the potential for promotion and application.

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