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ORIGINAL PAPER

Study on chain relationship and risk assessment model of coal mine geological disasters

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Abstract

Geological disasters are mostly located in the mined area of the mine, which mainly shows the characteristics of suddenness, mass occurrence, induction, regional, diversity, and great harm. Mine geological disasters often bring heavy casualties and property losses, and their social impact is huge. This paper studied the characteristics and inducing factors of typical geological disasters in mines, pertinently studied the inducing internal and external factors of geological disasters, analyzed the chain relationship and main characteristics of mine geological disasters, and studied the close relationship between the breeding, inducing, and formation of different geological disasters and environmental geology in mining areas. These disasters will have cumulative effects over time; the interaction between disasters is likely to form a chain reaction and have a serious impact on the mining area and surrounding areas. Using the analytic hierarchy process, a risk assessment system of mine geological disasters with 10 indexes is constructed from three aspects: geological conditions, natural conditions, and human activities. The analytic hierarchy process (AHP) structure model was established, and the comprehensive evaluation model of mine geological disaster risk was established through the research of AHP research. A comprehensive analysis of mine geological disaster risk in the recent 10 years was conducted to study the changing trend of different evaluation indicators. The key indicators affecting geological disasters were obtained, which provided theoretical support for mine geological disaster prediction.

Keywords Coal mine geological disasters · Geological disaster chain relationship · Analytic hierarchy process (AHP) · Disaster risk assessment model

Introduction

Coal is the main energy resource in China, and its output exceeds 1/3 of the world's total output (Xu et al. 2018). With coal mining gradually entering the deep mining stage, the hydrogeological conditions of the mining become more complex (Zhang et al. 2009). The original in situ stress balance will be destroyed in the process of coal mining (Jin et al. 2019), resulting in geological disasters under the coupling action of mining disturbance and complex stress, forming a complex geological disaster chain (Shao 2019). Mine geological disasters not only seriously affect the safety of mining and cause great economic losses (Wang et al. 2021; Yan et al. 2020a), but also the consequences of heavy casualties caused by mine geological disasters will have a bad social impact.

Mine geological disasters generally do not occur in isolation, and the disasters are interconnected to form a complex disaster system or disaster chain (Xiao et al. 2014). A disaster chain is used to describe the chain effect caused by geological disasters or other incentives (Peili and Wei 2018). It can be divided into the causal chain, homologous chain, mutually exclusive chain, and even-exclusive chain. Chain is a universal law between things and phenomena in nature (Tan and Qiao 2020). Its causal relationship exists objectively in the movement and change of the material world, reflecting the phenomena of "cause without effect"

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and "result without cause" that do not appear in the material world. A generalized disaster chain is a phenomenon in which a generalized disaster (initiating damage ring) starts another one or more generalized disasters (passive damage ring), and a generalized disaster group is a collection of two or more generalized disasters (Liu et al. 2020). For the disaster chain system, the chain generation mode and environment of the disaster chain determine the final destruction energy of the disaster. The mine geological disaster chain is mainly caused by coal mining (Yao et al. 2012). The structure of the mine geological disaster chain belongs to the dendritic disaster chain. With the acceleration of mining activities, mine geological disasters will show a trend of further aggravation. There are many types of geological disasters in coal mines (Chen 2020). It is necessary to study the disaster mechanism of geological disasters (Zhu et al. 2017), analyze the chain relationship of different geological disasters, put forward disaster identification standards, carry out monitoring and early warning of geological disasters in mines (Chu and Muradian 2016), and take effective measures to prevent the occurrence of geological disasters.

Coal mine geological disasters and types of disaster chains

Types of mine geological disasters

With the increase of mining depth, the mining hydrogeological environment is becoming worse and worse. At present, the common geological disasters mainly include coal and gas outbursts, mine roof collapse, mine water inrush, landslide, and debris flow caused by underground mining. These mine geological disasters are associated with the evolution process and are caused by mining. To study the mine geological disaster chain, it is necessary to first understand the characteristics of typical mine geological disasters (Cheng et al. 2021; Yan et al. 2020b).

Coal and gas outburst

In the process of mining coal resources, not only do coal resources exist in the coal and rock bodies but also a certain amount of gas exists in the surface of coal resources and the gaps between the coal seams. In the process of coal mining, the free gas in the coal seam is released, resulting in high gas concentration in the mine. The main component of gas is alkanes. Under normal conditions, the density of the gas is 0.716 kg/m^3 and the permeability is 1.6 times that of air. When the gas concentration exceeds the limit, people will be suffocated, and it is very easy to cause explosion accidents in case of open fire or sparks, which will cause great harm to mine staff and equipment. The main reason for exceeding the standard of gas concentration is that the mine ventilation equipment can not meet the needs of production. It is necessary to further improve the ventilation system and strengthen the gas extraction according to the monitoring indicators of gas concentration in mining.

Mine roof collapse

In the process of mining, the stability of rock mass under the disturbance of mining is insufficient, the stress balance in goaf is difficult to maintain in large-scale mining, and the stress of surrounding rock is redistributed to achieve a new stress balance. In the process of stress redistribution, there will be stress concentration, which will induce large-scale mine rock mass cracking and affect the stability of rock masses. Typical mine roof accidents mainly include the following: (1) Local roof fall accidents are prone to occur at locations with many cracks in the rock mass and broken roofs; (2) Roof fall accidents caused by changes in geological conditions near faults and collapse pillars; (3) When the strength of mine support materials does not meet the requirements of regulations or the support method can not meet the requirements of the mine mining area, local roof fall accidents will also occur (Fig. 1).

The main causes of mine roof collapse accidents are untimely mine monitoring and early warning, unreasonable mine support schemes, and insufficient strength of support materials. When encountering faults and collapse columns, the support needs to be strengthened; otherwise, the roof collapse accident will occur under the action of structural stress and mining stress, which will pose a great threat to the life safety of mining workers.

Mine water inrush

With the deepening of the mining process, the hydrogeological conditions of the mine become more complex. Surface water, underground aquifer, karst water, and old kiln water are ubiquitous. Karst collapse column, water diversion fault, and plugging effect of water discharge hole are very easy to form a through water diversion channel, which leads to mine water inrush disaster. Mining will also affect the overall layout of groundwater. When the hydraulic distribution changes, it will lead to a large area of funnel risk, causing water infiltration and water gushing accidents in coal mines. When there is a large influx of groundwater in the process of mining, it will not only affect the efficiency of mining, but also threaten the life and property safety of underground workers, and seriously affect the economic benefits and development level of mining enterprises.

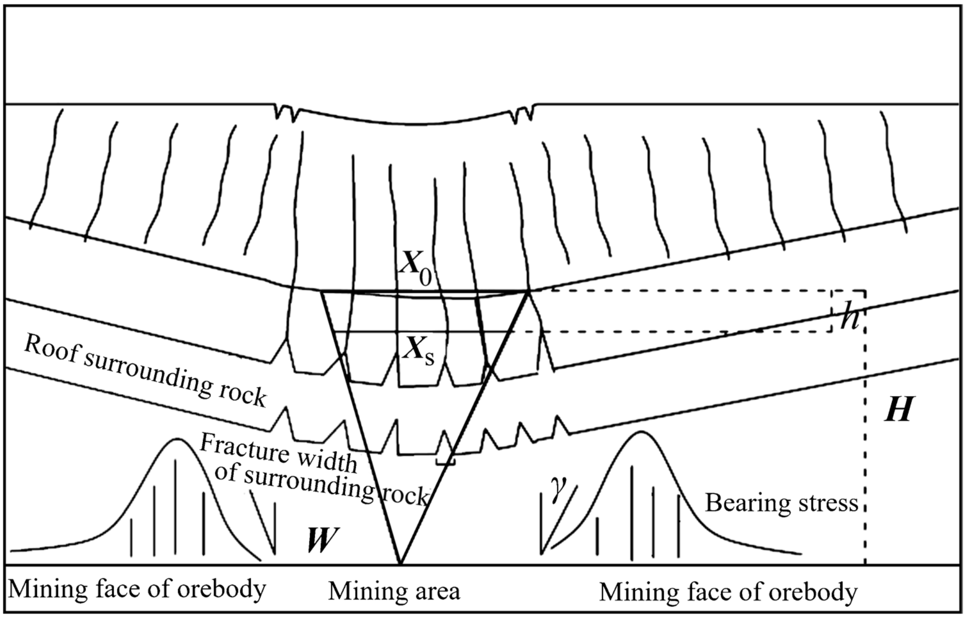


Fig. 1 Diagram of roof collapse

Landslide and debris flow

When geological disasters such as roof instability and mine water inrush occur in underground mines, the initial geological structure stress balance state of aboveground rock mass is broken, and surface cracks, landslides, and debris flows are very easy to occur. Under the disturbance of mining, the steep tensile fracture surface of rock mass is easy to fall off and move vertically, which poses a great threat to the safety of surrounding residential houses, ground facilities, and personnel. When continuous rainfall occurs, landslides and debris flows occur under the action of stress and water.

Types of mine geological disaster chain

The complexity of the internal structure of the mine geological disaster chain and the complex relationship between different disasters lead to the randomness, difference, and diversity of the mine geological disaster chain. To study the occurrence mechanism and evolution law of mine geological disaster chain, it is necessary to first analyze the basic types and attributes of mine geological disaster chain, and classify mine geological disasters from the aspects of causality, disaster cause, and disaster mechanism in combination with the start-up and evolution characteristics, disaster transformation causality, and temporal and spatial distribution characteristics of geological disasters, as shown in Table 1.

According to the causality of geological disasters, the mine geological disaster chain can be divided into associated geological disaster chain and derived geological disaster chain (Hu et al. 2012). The chain of associated geological disasters in mines refers to different geological disasters induced by the same factor. There is no inevitable connection between each geological disaster. The disaster types show the characteristics of parallel distribution in a different time and spaces. The time interval between different disasters is short, forming a spatial disaster chain. Although there is no inevitable connection between different types of geological disasters in the associated geological disaster chain, these geological disasters coexist at the same time,

Table 1 Classification of mine geological disaster chain types

Number	Classification	Disaster chain type
1	Causality	Associated mine geological disaster chain Derived loess geological disaster chain
2	Cause of formation	External power mine geological disaster chain Internal dynamic mine geological disaster chain Man-made mine geological disaster chain Complex dynamic mine geological disaster chain
3	Catastrophe mechanism	Water source mine geological disaster chain Water-mechanic source mine geological disaster chain Focal mine geological disaster chain

and the inducing factors are consistent, such as a large number of geological disasters such as land subsidence, landslide, debris flow, and ground fissures induced by seism. The mine-derived geological disaster chain refers to the causal geological disaster chain in the mine. The occurrence of one type of geological disaster causes subsequent different types of geological disasters. The occurrence of different geological disasters has obvious causality and time sequence, which can be described by main disasters and secondary disasters. For example, the roof collapses after the instability of the surrounding rock in the mine, and the expansion of the surrounding rock fissures forms a water inrush disaster that leads to the aquifer, which in turn induces landslides in the surface rock mass, and debris flow disaster under the influence of precipitation. Different types of geological disasters in this disaster chain show obvious causality, and different disasters in the geological disaster chain occur one after another (Fig. 2).

According to the causes of geological disasters, the mine geological disaster chain can be divided into internal dynamic geological disaster chain, external dynamic geological disaster chain, man-made geological disaster chain, and complex dynamic geological disaster chain. The dynamic geological disaster chain in the mine represents the geological disaster chain composed of different types of mine geological disasters induced by the internal dynamic geological process. The mine endogenous geological disaster chain is mainly caused by collapse, ground fissure, landslide, and other geological disasters caused by fault active zone and strong seism. The dynamic geological disaster chain outside the mine is a surface geological disaster chain such as landslide, debris flow, and barrier lake caused by heavy rainfall and freeze–thaw. The influence range of this geological disaster chain is relatively large. The man-made geological disaster chain in mines refers to the geological disaster induced by the stress balance of rock mass destroyed by human mining work. The threat of geological disasters in mine production is mainly caused by mining disturbance. The main driving force of geological disasters such as rock fracture expansion, surrounding rock instability, and mine water inrush in the process of rock mass stress redistribution is human mining activities. The complex dynamic geological disaster chain of mines mainly refers to the compound geological disaster chain induced by the coupling of internal power, external power, and human mining activities in the process of mine production.

According to the catastrophe mechanism of geological disasters, the mine geological disaster chain can be divided into water source geological disaster chain, hydro-mechanical geological disaster chain, and focal geological disaster chain. Mine water-sourced geological disaster refers to the water inrush accident induced by the expansion and evolution of cracks in the surrounding rock of the mine under the driving action of groundwater to form water-conducting channels that connect underground aquifers and induce mine water inrush accidents. The hydraulic-mechanical geological disaster chain is a geological disaster induced by the joint action of water and force. The mechanical properties of the surrounding rock of the mine will change greatly under the coupled action of water and force, and mine roof collapse and mine water inrush accidents are very likely to occur. Mine focal type geological disaster chain is a geological disaster chain driven by seism.

Main characteristics of mine geological disasters and geological disaster chain

The occurrence of mine geological disasters not only threatens the safety of mine staff and underground equipment, but also brings great economic losses to the mine (Tao et al. 2016). Different types of geological disasters often occur in

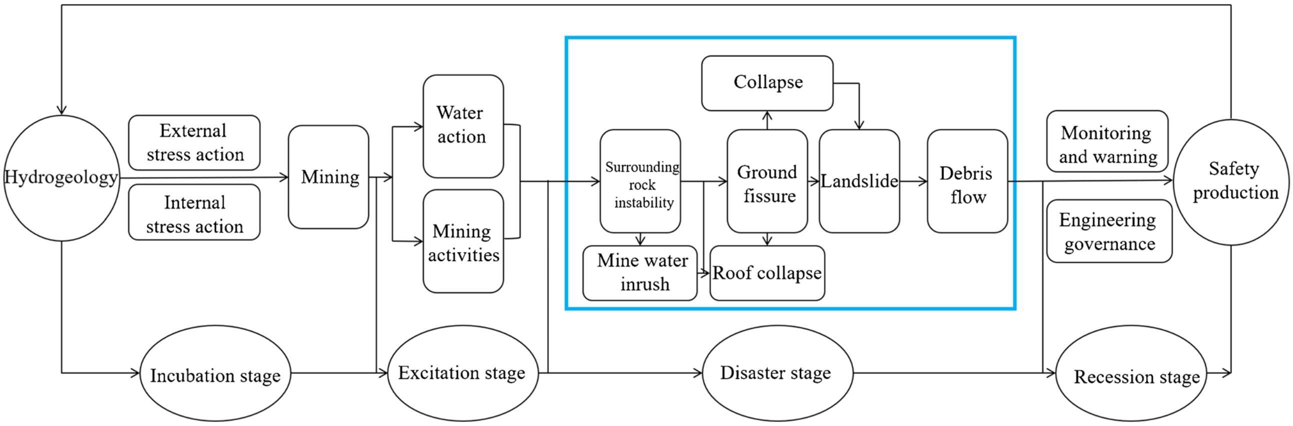


Fig. 2 Mine geological disaster chain and disaster development process

the process of coal mining, so it is necessary to comprehensively analyze the characteristics of different geological disasters and the characteristics of the geological disaster chain.

Characteristics of mine geological disasters

Mass occurrence and secondary

There are various types of geological disasters in the process of mining. Geological disasters show the characteristics of mass occurrence, which is the most prominent feature of mine geological disasters. Mining destroys the original in situ stress equilibrium state of rock mass, changes the original stable internal stress, and redistributes the stress, which destroys the stability of the rock mass. With the deepening of mining depth, the geological structure, hydrogeological conditions, and stress conditions inside the mine will become more complex. Mining will not only affect the internal stress of rock stratum but also affect the stability of surrounding rock stratum structure, resulting in large-scale and continuous geological structure damage. Mine geological disasters not only show the characteristics of mass occurrence but also show the characteristics of secondary. In the process of coal mining, geological disasters will occur repeatedly at different time and spaces. When the disaster is large, it will have a serious impact on the surrounding rock mass and surrounding environment.

Induction and derivation

Another obvious feature of mine geological disasters is induction. The occurrence of a single geological disaster will induce other different types of geological disasters, which will bring significant security threats, loss of life, and property to mine production. The mine water inrush disaster in the process of mine production will cause a large number of groundwater to flow into the mining face. In the continuous infiltration process, it will induce the instability of stratum structure, induce different degrees of settlement and cracking of the ground, and finally lead to the instability of surface rock mass structure to form landslide disaster. These geological disasters will further affect the rock strata, soil strata, and surrounding water bodies, which will lead to more new geological disasters, affect the normal production work of the mine, disrupt the original mining progress, and cause huge property losses to the mine.

Diversity

The types of geological disasters faced in mining are characterized by diversity, and the duration of actual damage caused by different types of geological disasters is also quite different. Some geological disasters occur slowly and last for a long time, while others occur suddenly and last for a short time. The duration of geological disasters such as rock mass structure damage, rock mass cracking, and surface collapse in mine geological disasters is relatively long, while geological disasters such as landslides, gas explosions, roof damage, and mine water inrush have a short occurrence time but great disaster harm. Therefore, the mine needs to carry out geological disaster monitoring and early warning and formulate corresponding geological disaster prevention and control systems according to different disaster types and incentives.

Suddenness

There are many types of mine geological disasters, most of which are sudden, and the occurrence time is sudden, which will cause great damage in a short time, such as gas explosion and mine water inrush. Geological disasters rapidly intensify from multi-end to catastrophic, and cracks in rock mass expand to sudden destruction, causing major sudden geological disasters.

Regional

Mine geological disasters have obvious regional characteristics. In areas with complex stress conditions and hydrogeological conditions in the mining area, it is relatively difficult to mine the ore body, and it is also more prone to geological disasters. In the fault fracture zone, collapse column, and other areas where the mine is located, the performance of geological disasters is more complex, and the governance of geological disasters is further more difficult.

Characteristics of mine geological disaster chain

Complexity and variability

The genesis and transformation process of the mine geological disaster chain are complex and changeable. The evolution effect of the disaster chain shows strong concealment and lag, which will lead to a wider and more destructive impact of disasters. The complexity and variability of the mine geological disaster chain are mainly reflected in the diversity of factors in the disaster excitation stage, the complexity of the regularity of the disaster chain, the fuzziness of the critical state of transformation between disasters, and the complexity of critical conditions.

The influencing factors of the excitation stage of the mine geological disaster chain include not only the drive of internal and external power but also the influence of man-made mining activities. Under the influence of these factors, different geological disaster chains and different geological disaster chains will appear. Due to the different stress conditions and hydrogeological conditions, there are great differences in the influence degree of geological disaster chain in different locations of the mine. In the disaster-causing stage, the coupling effect of a single factor and multiple factors will continue to develop, resulting in the phenomenon of mutual integration and derivation, and the phenomenon of disaster causality.

Due to the complexity of hydrogeological and stress conditions in which the mine is located, there are great differences in mine geological disaster chains, and the inducements and evolution laws of different disaster chains are different. It is difficult to accurately analyze the chain evolution relationship of regional geological disaster chains. The study of mine geological disaster chain involves the analysis of the dynamic transformation process between geological disasters, energy transformation, crack evolution, and stress change process. Under the action of groundwater, complex multi-field coupling of thermal–hydraulic–mechanical–chemical will occur, which has a great impact on the physical and mechanical properties and constitutive model of rock masses. In the process of analyzing the evolution of mine water inrush and inducing other geological disasters, it is necessary to study the evolution process and disaster mechanism of the mine geological disaster chain in combination with the knowledge of fluid mechanics and continuum mechanics.

There is some fuzziness in the relationship between different mine geological disasters, so it is difficult to analyze and study the critical state and critical conditions of disaster transformation in the mine geological disaster chain. The continuous change of physical and mechanical properties of rock mass under complex conditions induces different types of geological disasters with the advancement of the fracture evolution process.

Periodicity and timeliness

The evolution process of the mine geological disaster chain is divided into four stages: incubation stage, excitation stage, disaster stage, and recession stage, as shown in the figure, which has obvious periodicity and timeliness (Ma 2020). The chain relationship between geological disasters is shown in Fig. 3. A single geological disaster will induce a variety of different geological disasters, and there are some differences in the evolution process of the geological disaster chain. In the incubation stage of mine geological disasters, the energy of rock mass accumulates, and the cracks initiate and evolve until the energy reaches a stable peak, which stimulates the occurrence of geological disasters. In the disaster stage of geological disasters, different types of geological disasters will appear continuously, and there is a chain relationship between different disasters. With the use of on-site monitoring, early warning technology, and emergency response mechanism, corresponding measures are taken to prevent the occurrence of geological disasters or prevent the further development of geological disasters, and the mine geological disaster chain has entered the recession stage.

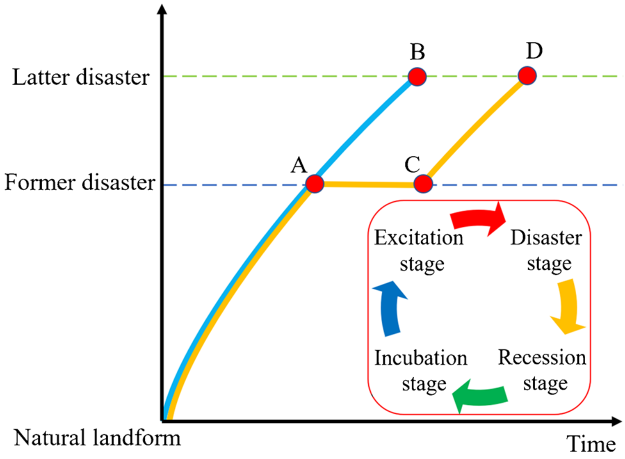


Fig. 3 Timeliness and periodicity of mine geological disaster chain

Amplification effect and attenuation effect

During the evolution of the mine geological disaster chain, the transformation between different disaster types and the difference of disaster mechanisms lead to the amplification effect and attenuation effect of the scale of the mine geological disaster chain as shown in Fig. 4. During the development of geological disasters in mines, with the accumulation and transformation of rock mass-energy, the disaster rate

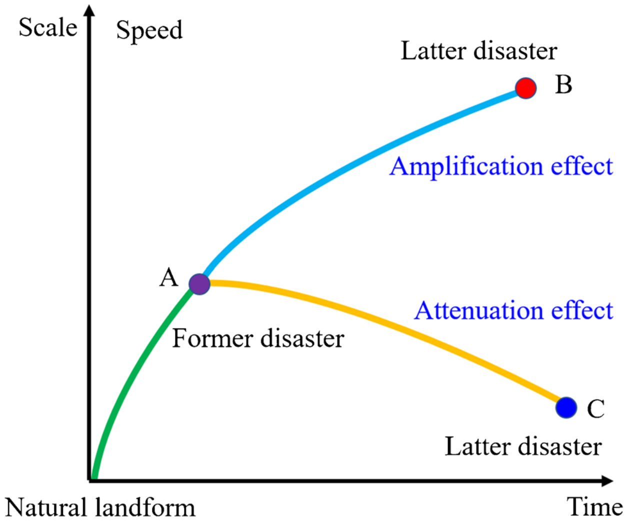


Fig. 4 Amplification effect and attenuation effect

of the disaster source body will gradually increase without sudden change of dissipated energy. With the evolution of the mine geological disaster chain and the stimulation of new geological disasters, the impact scale of the disaster source will gradually expand, which is the amplification effect of the mine geological disaster chain. The attenuation effect of the mine geological disaster chain refers to the gradual dissipation of the energy of the disaster source during the evolution and catastrophe of the disaster chain, and the impact scale and evolution speed of the disaster will gradually decrease. In the chain evolution process of mine geological disaster chain, the chain structure is closely related to the amplification effect and attenuation effect of the disaster chain. The amplification effect of the geological disaster chain mostly exists in the chain structure of multiple disasters, while the attenuation effect is common in the chain structure of single disasters.

Risk assessment of mine geological disasters

Mine surrounding rock stability evaluation and geological disaster risk assessments are one of the main methods to predict geological disasters and chain disasters in mining areas. Through on-site investigation and the layout of monitoring and early warning system, the disaster-causing factors of mine geological disasters are obtained, the weight coefficient is assigned, and the evaluation index system and evaluation model of mine geological disasters are established (Mu et al. 2013).

The commonly used methods in mine geological disaster risk assessment are the subjective judgment method and objective analysis method. The analytic hierarchy process (AHP), expert scoring method, and fuzzy mathematics method are subjective judgment methods, and information method, entropy method, and evidence weight method are objective analysis methods (Zhang 2020). The subjective analysis method needs to assign the weights of the evaluation factors subjectively, and its accuracy is closely related to the engineering experience and knowledge reserves of experts. The objective analysis method determines the proportion of each evaluation factor according to the objective information of the influencing factors, and its accuracy is limited by the weight setting of the evaluation factors, ignoring the influence of engineering experience and professional knowledge.

Selection of risk assessment factors for mine geological disasters

The selection of risk assessment factors is the key to establishing a risk assessment model for mine geological disasters. According to the analysis of the relationship between mine geological disasters and disaster chain, the selection of geological disaster assessment factors is shown in Fig. 5.

Analytical hierarchy process calculation

Analytic hierarchy process steps

The analytic hierarchy process compares every two factors in the multi-factors, gives the comparison coefficient according to their importance, and then obtains the judgment matrix

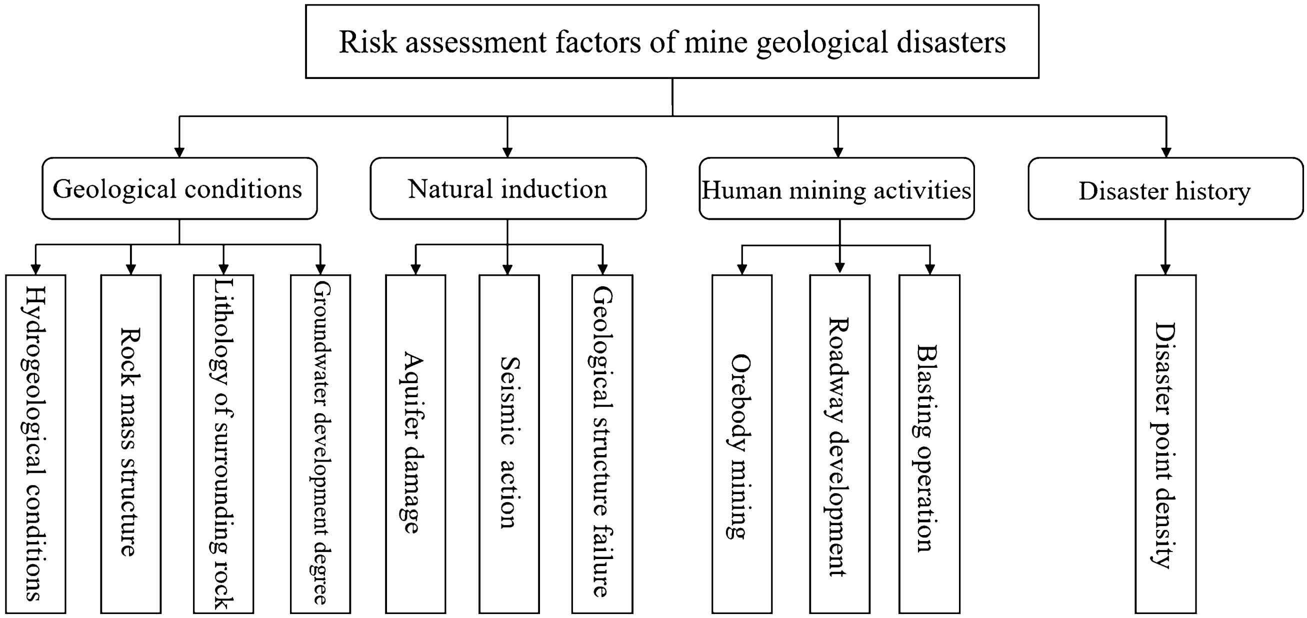


Fig. 5 Hierarchy structure of mine geological disaster risk assessment

(Nong et al. 2014). Through the operation of the matrix, the important proportion of each influencing factor of complex events is obtained, and the complex problem is simplified. The specific steps of the analytic hierarchy process are shown in Fig. 6.

1) Establish a hierarchical model. To decide on a problem by using the analytic hierarchy process, it is necessary to deal with it hierarchically. According to the nature of the problem and the overall goal to be achieved, the problem is divided into different constituent elements. According to the relationship between the elements, the decision-making objectives, factors to be considered, and decision-making objects are divided into the highest level, the middle level, and the lowest level according to the relationship, and a hierarchical structure diagram is drawn to form a multi-level analysis structure model.
2) Construct judgment matrix. Using the theory of fuzzy mathematics, let experienced experts compare and score the importance of each factor. In the process of comparing various elements, linguistic description is not conducive to quantitatively depicting a decision-making problem, and some scholars found that using the 9-level proportional scale is convenient for the transformation from qualitative to quantitative (Zhang and Yang 2018).
3) Calculate the element weight vector.

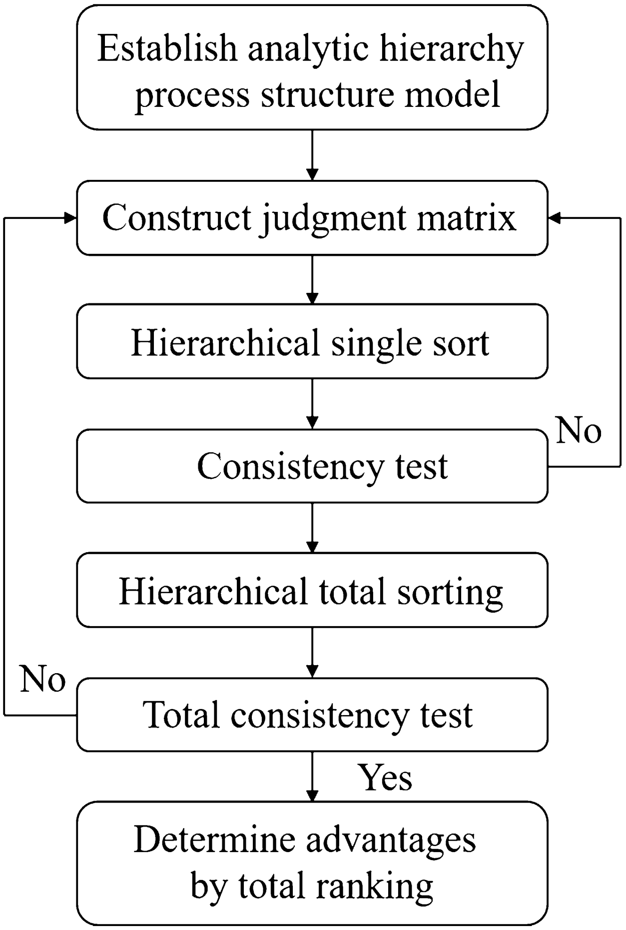


Fig. 6 Steps of analytic hierarchy process

Research methods of analytic hierarchy process

The analytic hierarchy process needs to determine the judgment matrix. It is assumed that the set a is composed of n parts greater than 0, and a_{ij} $(1 \le i \le n,\ 1 \le j \le n)$ is used to represent the multiple of part i which is more important than the part j relative to the whole, to construct the judgment matrix D:

$$D = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix} \tag{1}$$

where $a_{ij} > 0$, $a_{ij} = 1/\,a_{ij}$, $a_{ii} = 1$.

a_{ij} indicates that different scaling principles are determined. In the research, the exponential scaling principle is used to determine the value of each element in the D. The exponential scale can more accurately reflect the relative importance of each part than the traditional 1 ~ 9 scale. The scale value of the index scale and its meaning are shown in Table 2.

Since it is difficult to calculate the eigenvalues and eigenvectors of the matrix by conventional methods, the following formula can be used to calculate the eigenvectors of matrix D.

① Each column vector of the matrix D is normalized W_{ij}, normalizing the columns of the judgment matrix.

$$W_{ij} = \frac{a_{ij}}{\sum_{1}^{n} a_{ij}} \tag{2}$$

② According to the following formula, the normalized matrix is obtained by adding rows W_i:

Table 2 Scale value of index scale and its meaning

Category	Scale value
a_i as important as a_j	$e^{0/4}$
a_i slightly more important than a_j	$e^{2/4}$
a_i more important than a_j	$e^{4/4}$
a_i strongly more important than a_j	$e^{6/4}$
a_i extremely more important than a_j	$e^{8/4}$
The importance of ratio lies between a_i and a_j	$e^{1/4}$ 、$e^{3/4}$ 、$e^{5/4}$ 、$e^{7/4}$
a_i unimportant description than a_j	Reciprocal of the corresponding scale value

$$w_i = \sum_{j=1}^{n} w_{ij} \quad (3)$$

③ Pair vector w_i is normalized to obtain the eigenvector W_i:

$$W_i = \frac{w_i}{\sum_1^n w_i} \quad (4)$$

$W=(W_1,\ W_2,\cdots,\ W_i)^{\ T}$ is the approximate eigenvector, and each component represents the weight of each part.

④ Calculate the maximum eigenvalue of the vector λ_{max}:

$$\lambda_{max} = \sum_{i=1}^{n} \frac{(DW)_i}{nw_i} \quad (5)$$

where $(DW)_i$ is the i component of the eigenvector DW.

⑤ Conformance inspection:

Consistency test is to test the contradiction between various scores caused by artificial scoring, to correct the judgment matrix deviating from consistency (Karimnia and Bagloo 2015). Generally, it is determined according to the consistency index CI and random consistency ratio CR. When $CR < 0.1$, it is considered that the judgment matrix has a good degree of consistency, the assignment is reasonable, and the test is passed. Otherwise, the judgment matrix needs to be reconstructed. The specific calculation formula is as follows:

$$\lambda_{max} = \sum_{i=1}^{n} \frac{(DW)_i}{nw_i} CR = \frac{CI}{RI} = \frac{\left(\lambda_{max} - n\right)/(n-1)}{RI} \quad (6)$$

where CI is the consistency index, RI is the average random consistency index, and RI has its specific value. See Table 3 for details. λ_{max} is the maximum eigenvalue and n is the order of the above matrix.

If $CR < 0.1$, the matrix D meets the consistency requirements.

Risk assessment model of mine geological disasters

Comprehensive evaluation hierarchy model

The 10 main indicators of the 11 indicators of geological disaster risk assessment are divided into three aspects. See the comprehensive evaluation model shown in Table 4. From top to bottom, they are as follows: the target layer (A) is mine geological disaster; Criterion layer (B) is natural condition (B_1), geological condition (B_2) and human activity (B_3); Index layer (C) is aquifer (C_1), seismic action (C_2), geological structure (C_3) corresponding to natural condition (B_1), hydrogeological condition (C_4), rock mass structure (C_5), surrounding rock lithology (C_6), groundwater development degree (C_7) corresponding to geological condition (B_2), mine mining (C_8), roadway development (C_9), and blasting operation (C_{10}) corresponding to human activity (B_3).

Weight analysis

Based on the geological disaster investigation results of a coal mine in Shanxi, the judgment matrix D of the target layer (a) is determined according to the index scale value of each index, and the characteristic vector corresponding to the maximum eigenvalue of the target layer matrix, i.e., the weight vector, is calculated, as shown in Table 5.

According to the weight of criterion layer B relative to target layer a and index layer C relative to criterion layer

Table 3 Random consistency ratio of index scale

Matrix order	1	2	3	4	5	6	7	8	9	10	11	12	13
RI	0	0	0.35	0.60	0.76	0.79	0.84	0.92	0.96	0.98	1.02	1.04	1.07

Table 4 Mine geological disaster risk comprehensive evaluation model

Target layer A	Criterion layer B	Index layer C
Mine geological disaster	Natural conditions B_1	Aquifer damage C_1
		Seismic action C_2
		Geological structure failure C_3
	Geological conditions B_2	Hydrogeological conditions C_4
		Rock mass structure C_5
		The lithology of surrounding rock C_6
		Groundwater development degree C_7
	Human activity B_3	Orebody mining C_8
		Roadway development C_9
		Blasting operation C_{10}

Table 5 Judgment matrix of target layer A and its index weights

A	B_1	B_2	B_3	Weigh(W)
B_1	1	$1/e^{3/4}$	$1/e^{4/4}$	0.5167
B_2	$1/e^{3/4}$	1	$1/e^{2/4}$	0.2454
B_3	$1/e^{4/4}$	$1/e^{2/4}$	1	0.2379

B, the comprehensive weight of each index layer C can be determined. See Table 6 for the comprehensive weight of each index.

Comprehensive evaluation of geological disaster risk

According to the survey results of coal mine geological disasters in recent 10 years, the indexes of each index layer are scored, the comprehensive score is calculated according to its weight value, and the comprehensive risk score is obtained, as shown in Fig. 7.

Table 6 Comprehensive weight of indicator layer C

Target layer A	Criterion layer B	Index layer C
Mine geological disaster	B_1 (0.5167)	C_1 (0.1279)
		C_2 (0.2757)
		C_3 (0.1131)
	B_2 (0.2454)	C_4 (0.1167)
		C_5 (0.0531)
		C_6 (0.0642)
		C_7 (0.0114)
	B_3 (0.2379)	C_8 (0.1034)
		C_9 (0.0714)
		C_{10} (0.0631)

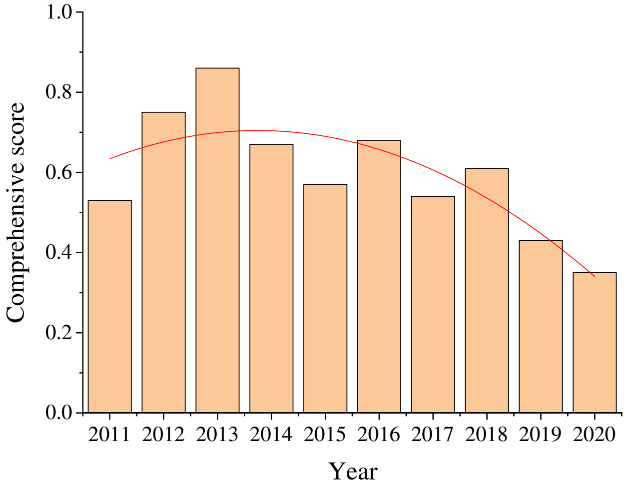


Fig. 7 Comprehensive score of coal mine geological disaster risk in recent 10 years

Table 7 Risk classification of mine geological disasters

Number	Comprehensive score range	State
1	$0 \leq Y < 0.3$	Low risk
2	$0.3 \leq Y \leq 0.6$	Medium risk
4	$0.6 < Y \leq 1$	High risk

The calculation formula of the comprehensive score is:

$$Y = \sum W_i X_i \tag{7}$$

where W_i represents the weight of each indicator, and X_i indicates the score value of each indicator.

The geological disaster survey results of a mine in Shanxi from 2011 to 2020 are normalized and the comprehensive weight of various indicators is assigned. The calculated results are shown in Fig. 7. It can be seen intuitively from the figure that there are obvious differences in mine geological disasters in different years, but they generally show a downward trend in fluctuation.

According to the comprehensive score of mine geological disaster risk, the risk level is divided into low risk ($0 \leq y < 0.3$), medium risk ($0.3 \leq y \leq 0.6$), and high risk ($0.6 < y \leq 1$), as shown in Table 7.

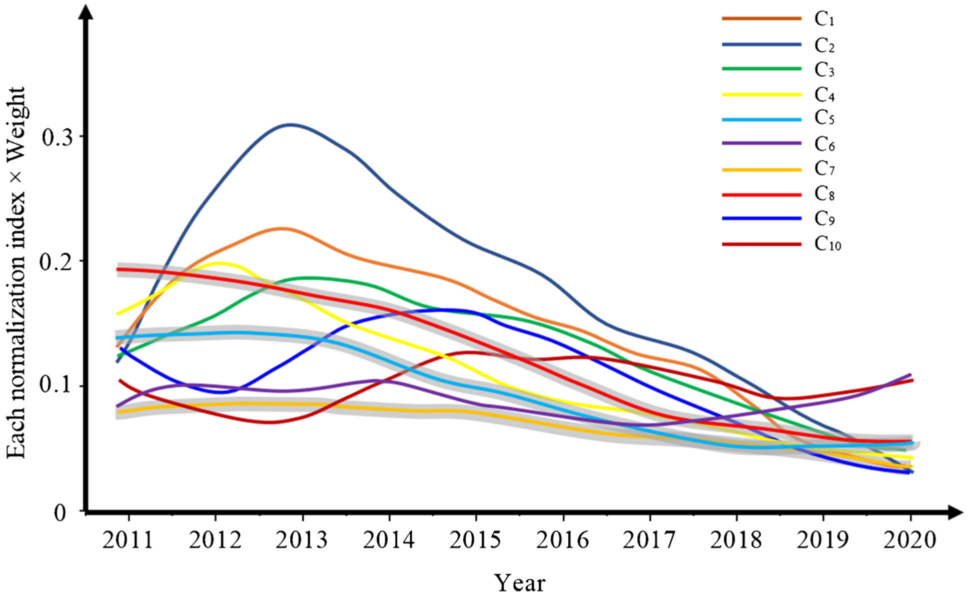
To further analyze the main factors of the change of mine geological disasters, the trend line shown in Fig. 8 is drawn for a comprehensive analysis of normalized indicators and weights. It can be concluded from the figure that seismic action, aquifer damage, hydrogeological conditions, and geological structure have the greatest impact on mine geological disasters, in which the changing trend of seismic action and aquifer damage increases first and then decreases.

With the implementation and management improvement of mine prevention and control measures in recent years, the impact of ore body mining, rock mass structure, and groundwater development on mine geological disasters decreases year by year, as shown in the shaded curve in Fig. 8. Therefore, the risk level of mine geological disasters shows a downward trend year by year, and other indicators show fluctuating changes, causing local fluctuation of mine geological disaster risk grade.

Conclusion

The locations of geological disasters are mostly located in the areas where the mines have been mined, which mainly show the characteristics of suddenness, mass occurrence, induction, regional, diversity, and great harm. Mine geological disasters often bring heavy casualties and property losses, and their social impact is huge. Therefore, it is very important for the protection of mine geology and ecological

Fig. 8 Variation trend of normalized indexes multiplied by the weight



environment to deeply analyze the characteristics and causes of mine geological disasters, to put forward the geological disaster evaluation model.

(1) The types and basic characteristics of typical mine geological disasters are investigated and analyzed. Mine geological disasters mainly include coal and gas outburst, mine roof collapse, mine water inrush, landslide, and debris flow, showing obvious characteristics of mass occurrence and secondary, induction, derivation, diversity, and regional.

(2) The types and main characteristics of the mine geological disaster chain are deeply analyzed. According to the causality, causes, and catastrophe mechanism of mine geological disaster chain, the mine geological disaster chain is divided into associated mine geological disaster chain and derived loess geological disaster chain; external power mine geological disaster chain, internal power mine geological disaster chain, man-made mine geological disaster chain, and complex power mine geological disaster chain; water source mine geological disaster chain, force water source mine geological disaster chain, and focal mine geological disaster chain. Mine geological disaster chain shows the main characteristics of complexity, variability, periodicity and timeliness, amplification effect, and attenuation effect.

(3) Through the field geological disaster investigation of the mine, the analytic hierarchy process is used to study the evaluation model of mine geological disaster. According to the analysis of the relationship between mine geological disasters and disaster chain, the risk assessment factors of mine geological disasters are selected. Establish the analytic hierarchy process structure model, establish the comprehensive evaluation model of mine geological disaster risk through the research of analytic hierarchy process. Conduct the comprehensive analysis of mine geological disaster risk in recent 10 years, study the changing trend of different evaluation indicators, and obtain the key indicators affecting geological disasters, to provide theoretical support for mine geological disaster prediction.

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Declarations

Conflict of interest The authors declare no competing interests.

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