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Research on Safety Evaluation and Early Warning of Emergency Management Capability for Major Disaster Accidents in Coal Mines Based on Complexity System Theory in the Context of Digitization

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Abstract: *Based on the study of the five aspects of preventive measures, emergency preparedness quality rapid response capability, recovery capability, and lesson summary evaluation in three states before, during, and after the occurrence of accidents, the relationships among these five aspects were analyzed. According to the process of selecting safety evaluation indicators for the emergency management capacity of major coal mine disasters, the theoretical hypothesis of the relationship between evaluation indicators was proposed; the data obtained were analyzed for reliability and validity using SPSS, and the structural equation model was constructed for factor analysis and path analysis using AMOS software to validate the proposed hypothesis, and the validation results showed that each evaluation indicator had different effects on the emergency response capacity of major coal mine disasters. The validation results show that each evaluation index has different effects on the emergency management capacity of major coal mine disasters. The results show that each evaluation index has diverse ways and degrees of influence on the emergency management capacity of major coal mine disasters, and that a reasonable safety evaluation method can be used to propose better safety measures and improve the emergency management capacity of major coal mine disasters.*

Keywords: *Coal Mine Major Disaster; Emergency Management Capability; Structural Equation Modeling; Complexity System Theory; SPSS; AMOS*

1. Introduction

The coal mining industry is an important energy industry in China, providing important basic support for economic development. However, coal mining production faces various major disaster risks, such as gas explosions, mine water inrush, roof collapse, etc. These disasters not only seriously threaten the safety of miners, but also bring huge economic losses and social impacts to enterprises. Therefore, strengthening the early warning and risk assessment of major disasters in coal mines is particularly important. The generation and occurrence conditions of coal seams in China are complex, and most coal mines are mined by underground workers, which also determines the frequent occurrence of coal mine disasters in China. Disasters such as gas, water, fire, roof, and rock burst are the main types of disasters in China's coal mines, especially coal and gas outburst, water inrush, fire, rock burst, gas and coal dust explosion, which can easily cause group deaths and injuries. They are key prevention and control targets for coal mine safety production in China. Moreover, with the increasing depth and intensity of coal mining, problems such as high gas content, high stress, high water pressure, and high temperature are becoming increasingly prominent. Various disasters are becoming increasingly serious, and multiple types of disasters are coupled, exacerbating the difficulty of coal mine disaster management and bringing greater challenges to China's coal mine safety work. The research on early warning and risk assessment of major disasters in coal mines is an important topic in the field of mine safety. With the continuous expansion of coal mining scale and the increase in depth and complexity of mines, the risk of major disasters in coal mines is also increasing. In order to effectively prevent and control the occurrence of major disasters in coal mines and improve the level of mine safety production, the country has introduced a series of policy measures to vigorously promote the early warning and risk assessment of major disasters in coal mines.

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Coal mine disaster early warning technology can assess the possibility and harmfulness of disasters based on the obtained hidden dangers and precursor information before they occur, and send warning signals to relevant departments or personnel to remind them to take timely prevention and control measures to avoid the occurrence of disasters. Early warning can achieve early identification and source control of safety risks, and mitigate disasters in their early stages. Early warning is an important technical means for disaster prevention and reduction in today's society. Coal mines, as a key area of concern for safety production in China, have been vigorously developed in recent years under the guidance of national policies. Major disaster warning technologies in coal mines have been applied on-site and have played a significant role in preventing coal mine accidents.

Although some progress has been made in the early warning and risk assessment of major disasters in coal mines, there are still some problems that need to be addressed urgently. For example, existing warning models and methods often target specific types of disasters and cannot achieve comprehensive warning for multiple disasters; In addition, the risk assessment process did not fully consider the factors causing various disasters, resulting in inaccurate assessment results. Therefore, this study aims to address the shortcomings of existing technologies and develop a system that can comprehensively warn of major disasters in coal mines and accurately assess their risks.

2. Overview of emergency management capabilities for major coal mine disasters

The emergence of mega-accidents is why the concept of emergency management was introduced. Emergency management is a necessary measure adopted by decision makers to analyze the three processes in the early, middle and late stages of the development of emergencies, applying science and technology and management planning tools to protect the lives and property of the public, promoting the development of a harmonious and civilized society and healthy activities[1]. The occurrence of coal mine disasters is characterized by suddenness, uncertainty, catastrophism and succession, so we need to evaluate the emergency management capabilities of the five major coal mine disasters and consider these characteristics in the process of evaluation[2]. According to the "Coal Mine Accident Emergency Rescue Plan," the coal mine is susceptible to five types of disasters: roof collapse, gas leaks, water damage, fires, and coal dust hazards.

2.1. Roofing accident

Roofing is mainly the phenomenon of collapse of the upper rock layer in the mine during the mining process. In the process of mining under the mine, with the increasing depth of mining, some of the rock layers may be affected by the fault, then the roof of the shaft will be deformed, the rock layer will fall or cracks, and then there will be a roofing accident.[3]

2.2. Gas accidents

Gas explosions are essentially violent combustion reactions. The process of this type of reaction is extremely complex. The gas absorbs enough heat, causing the chain of gas molecules to immediately break and dissociate into multiple free radicals.[4]

2.3. Water damage in coal min

Water damage in mines mainly refers to mine permeability. During the construction and production of a mine, surface water and groundwater gush into the mine through various channels, causing mine flooding when the mine gushes water beyond its normal drainage capacity.[5]

2.4. Coal mine fires

Fire is one of the most important disasters that seriously threaten the safety of coal production and can easily cause mass death and injury. China has abundant coal resources, many coal-forming periods, diverse types of coal fields, mining coal seams with diverse geological characteristics, and mining areas prone to spontaneous combustion and spontaneous combustion coal seams are widely distributed. First, it is easy to natural, natural coal seams are widely distributed, and the risk of natural shipping is high. Second, the difficulty of exogenous fire prevention, major accidents occur from time to time. Third, coal mine fires cause serious secondary disaster accidents.

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2.5. Coal dust disaster

Coal dust is the tiny coal rock particles produced by crushing coal and rock during coal mining production. Coal dust flying in the roadway during coal mining. Coal dust pollutes the air and affects the health of miners, and when it reaches a certain concentration in the air, it can cause explosions and disasters when it meets fire. The factors affecting coal mine dust explosions are quite extensive, such as the concentration of oxygen and the concentration of dust.[6]

3. Evaluation indicators for emergency management capacity of major coal mine disasters

3.1. Preventive measures

It is an organization's awareness of a risk factor and the measures it takes to address that factor. The main measures are the following:

(1) Safety production risk assessment report

Risk assessment of production safety accidents is an important component of managing production safety accident emergency planning. It involves the application of principles and methods from safety system engineering and safety control theory.[7]

(2) Coal Mine Emergency Drills

The main purpose of emergency drills in coal mines is to familiarize miners and managers with emergency procedures and methods, and to improve emergency response and organization and coordination skills in the event of an emergency through simulated emergencies.

(3) Plan review and update

Plan review and update is an important part of coal mine safety management, the main purpose of which is to evaluate and optimize the implementation of coal mine safety production plans, prevent accidents and ensure the effectiveness of coal mine safety measures.

3.2. Quality of emergency preparedness

The quality of emergency preparedness refers to the degree and effectiveness of emergency preparedness of organizations or individuals in case of emergencies, such as natural disasters, man-made accidents and other emergencies. Its quality is related to the ability and effectiveness of disposal after an emergency.

(1) Emergency plan implementation

The implementation of the emergency plan refers to whether the organization or individual of the coal mine can take action to dispose of the situation in a timely and effective manner in accordance with the requirements of the plan after the occurrence of an emergency.[8]

(2) Emergency personnel training

The implementation of the emergency plan refers to whether the organization or individual of the coal mine can take action to dispose of the situation in a timely and effective manner in accordance with the requirements of the plan after the occurrence of an emergency. It is directly related to the effectiveness of the disposal of emergencies and the safety of employees' lives and property.

(3) Emergency supplies stockpile and emergency communication equipment

The situation of emergency material reserves and emergency communication equipment is the key to guarantee the response to emergencies. Government departments and enterprises and institutions have corresponding emergency plans, and have carried out emergency material reserves and emergency communication equipment configuration.

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4. Evaluation model of emergency management capability of major coal mine disasters and accidents

4.1. Establishment of Structural Equation Modeling

Structural equation model is a statistical method to analyze the relationship between variables based on the covariance matrix of variables, and it is an important tool for multivariate data analysis. Structural equation analysis can handle multiple dependent variables simultaneously, allowing both independent and dependent variables to contain measurement errors. Simultaneous estimation of factor structure and factor relationships, it allows for a more flexible measurement model, estimating the fit of the entire model[9].

The structural equation model includes two parts: measurement equation and structural equation. The structural equation describes the relationship between latent variables as shown in equation (1), and the measurement equation describes the relationship between latent variables and explicit variables as shown in equations (2) and (3).

$$\textbf{structural equation}\ \ \boldsymbol{\eta} = \boldsymbol{\beta\eta} + \boldsymbol{\Gamma\xi} + \boldsymbol{\zeta} \tag{1}$$

$$\textbf{measurement equation}\ \ \mathbf{Y} = \boldsymbol{\Lambda_y \eta} + \boldsymbol{\varepsilon} \tag{2}$$

$$\textbf{measurement equation}\ \ \mathbf{X} = \boldsymbol{\Lambda_x \xi} + \boldsymbol{\delta} \tag{3}$$

In the equation, $\boldsymbol{\xi}$ is the matrix of potential exogenous variables (potential independent variables); $\boldsymbol{\eta}$ is the matrix of potential endogenous variables (latent dependent variables); Y is the measurement variable matrix; X is the structure coefficient matrix; $\boldsymbol{\beta}$ is the residual matrix of the structural equation; $\boldsymbol{\delta}$ is the measurement coefficient matrix; $\boldsymbol{\varepsilon}$ is the latent endogenous variable (latent dependent variable) matrix; $\boldsymbol{\zeta}$ is the residual matrix of the measurement equation[10]. A preliminary model of the full path structural equation affecting the risk warning of major disaster accidents in coal mines was constructed. As shown in Figure 1

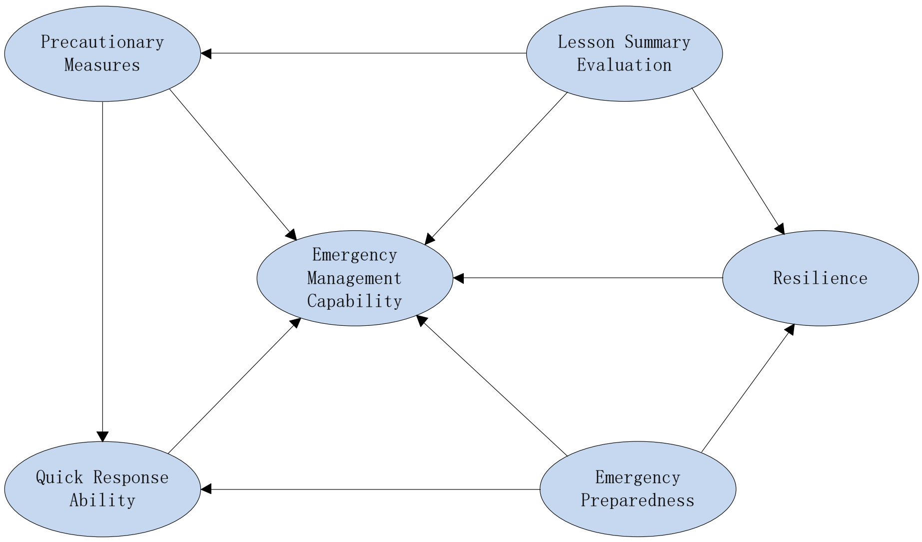

Figure 1: A preliminary model of full-path structural equations affecting the early warning of risk of major disaster accidents in coal mines.

4.2. Survey questionnaire design

The quality of the questionnaire design will directly affect the scientific validity and reliability of the results. Designing a questionnaire with high reliability and validity is a prerequisite to ensure the quality of the study. In this paper, 184 questionnaires were distributed through Questionnaire Star, of which a total of 160 were valid. According to the evaluation purpose and practical needs, after referring to the literature and information, after analyzing the 20 variables randomly surveyed for five aspects of prevention measures, quality of emergency preparedness, rapid response capability, recovery capability, and lesson summary evaluation, questions were prepared according to a 5-point Likert scale, with 1~5 indicating strongly disagree, disagree, relatively agree, agree, and strongly agree, respectively. The results are shown in Table 1.

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Table 1 Questionnaire results

Observable Variable	Question	Vertex mean	Total mean
Preventive measure	Risk assessment report	4.59	4.3400
	Plan and review and update	4.29	
	Emergency drill	4.14	
Emergency preparedness work quality	Emergency plan implementation	3.19	4.0078
	Emergency personnel training	4.34	
	Emergency supplies reserves	4.25	
	Emergency communications equipment	4.25	
Rapid response ability	Start the emergency response mechanism	4.38	4.0913
	Process control the speed and effect	4.31	
	The transparency of information release and timeliness	3.93	
	On-site command and collaboration	3.68	
	To eliminate a hazard	4.16	
Recovery capability	Clean up the work completion	3.64	4.0172
	Infrastructure repair rate	4.06	
	Infrastructure recovery rate	4.21	
	Resident resettlement quality	4.15	
Lesson summary evaluation	Lessons summary	4.28	3.9104
	Risk assessment report	3.73	
	Hazard identification and analysis	3.72	

4.3. Reliability test

SPSS software was used to calculate the data obtained from the questionnaire, and the size of Cronbach's alpha coefficient was used to test the credibility of the questionnaire, and the test results are shown in Table 2.

Table 2 Alpha coefficient range

Alpha coefficient range	Is the reliability ideal?
>0.9	Reliability is excellent
0.8-0.9	Reliability is ideal
0.7-0.8	High reliability
0.6-0.7	Reliability is also ideal
<0.6	The reliability is not ideal, delete the item

It is known from domestic and international studies that Cronbach a reliability is judged by the alpha coefficient, if this value is higher than 0.8, it means that this value has high reliability; if this value is between 0.7 and 08, it means that the reliability is good; if this value is between 0.6 and 07, it means that the reliability is acceptable; if this value is less than 0.6, it means that the reliability is poor. From Table 2, α=0.933, which is greater than 0.9, indicating high reliability of the data.[8]

4.4. Validity test

(1)KMO and Bartlett sphericity test

As can be seen in Table 3, the KMO measure value is 0.851, which is greater than 0.8, indicating that the design scale data are well suited for factor analysis, and the Bartlett sphericity test approximate chi-square value is 2541.517 with 171 degrees of freedom and a p-value of 0.000, which is less than 0.01, passing the significance test at the 1% level of significance.[9]

Table 3 KMO and Bartlett's

KMO Sampling Suitability Quantity	**0.851**	
Bartlett's sphericity test	approximate chi-square	2542.517
	degrees of freedom	171
	salience	0.000

(2)Principal Component Extraction

The statistical table of the extracted principal components of the 19 topics of the emergency management capability scale, the cumulative explained variance is 78.377%. This indicates that the five factors extracted from the 19 questions have a relatively good degree of explanation for the original data.

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The eigenvalue of factor 1 is 8.811, explaining 46.375% of the variance, the eigenvalue of factor 2 is 2.218, explaining 11.672% of the variance, the eigenvalue of factor 3 is 1.812, explaining 9.538% of the variance, the eigenvalue of factor 4 is 1.155, explaining 6.078% of the variance, and the eigenvalue of factor 5 is 0.895, explaining 4.713% of the variance percentage.

(3)Rotation matrix diagram

Using the rotation method to make the silver variable more interpretable, this paper uses the maximum variance rotation method for rotation, and the rotated silver loadings are shown in Table 4.

Table 4 Total Variance Explained

Rotated component matrix [a]					
	Composition				
	1	2	3	4	5
YF1					0.888
YF2					0.595
YF3					0.536
ZB1			0.684		
ZB2			0.788		
ZB3			0.720		
ZB4			0.819		
XY1	0.872				
XY2	0.856				
XY3	0.910				
XY4	0.709				
XY5	0.823				
HF1		0.879			
HF2		0.652			
HF3		0.787			
HF4		0.744			
PJ1				0.860	
PJ2				0.648	
PJ3				0.695	

Extraction method: principal component analysis method.
Transfer method: Caesar normalized maximum variance method.

4.5. Analysis of model results

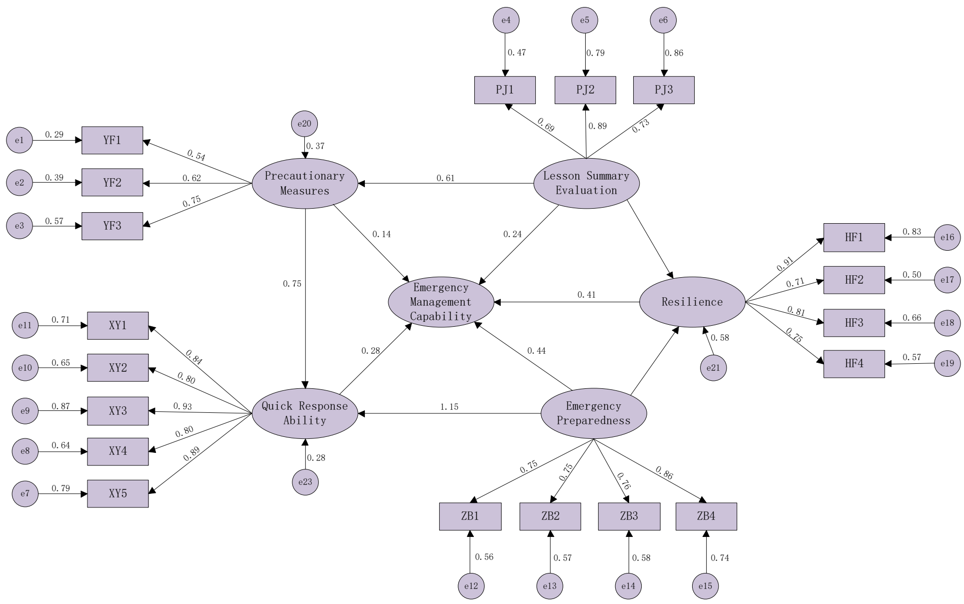

Figure 2 Analysis of model results

According to Figure 2. For the "preventive measures", it can be seen that all the significant variables are positively correlated with the latent variables and the correlations are relatively high. Among them, the standardized regression coefficients between safety production risk assessment report, plan review and update, and emergency drill and preventive measures are 0.54, 0.62, and 0.75, respectively. It can be seen that emergency drills have a great impact on the implementation of emergency prevention measures.

For the "summary evaluation of lessons learned", it can be seen that each explicit variable is positively correlated with the latent variable. Among them, the standardized regression coefficients between lesson summary, risk assessment report, hazard identification and analysis and lesson summary evaluation are 0.69, 0.89 and 0.93, respectively. Therefore, the risk assessment report and hazard identification and analysis are the top priorities in the summary evaluation of lessons learned.

For "resilience", it can be seen that all the significant variables are positively correlated with the latent variables. Among them, the standardized regression coefficients between the completion rate of cleanup work, the rate of facility repair, the rate of infrastructure restoration, and the quality of resettlement of residents and emergency recovery capacity were 0.91, 0.71, 0.81, and 0.75, respectively. It is clear that the completion rate of cleanup is critical to emergency recovery capabilities.

For "emergency preparedness", it can be seen that all explicit variables are positively correlated with latent variables. The standardized regression coefficients between the implementation of emergency plans, emergency personnel training, emergency supplies stockpiling, and emergency communication equipment and the quality of emergency preparedness are 0.75, 0.75, 0.76, and 0.86, respectively. So, in emergency preparedness, emergency communication equipment is the top priority.

For the "quick response job", it is known that each explicit variable is positively correlated with the latent variable. Among them, the standardized regression coefficients of whether the emergency response mechanism is activated after an incident, the speed and effectiveness of process control, the transparency and timeliness of information release, the smoothness of on-site command and collaboration, and the elimination of accident hazards to restore social stability and rapid response work are 0.71, 0.65, 0.87, 0.64, and 0.79, respectively. The activation of emergency response after an incident is very important for rapid response efforts.[10]

5. Conclusion

(1) We mainly establish the data structure and use SPSS for reliability and validity analysis, and then use AMOS software to construct structural equation models and elaborate on the theory of emergency management.

(2) The five major categories of coal mine disasters are identified in the 14th Five-Year Plan, People's Daily, the 2022 Coal Industry Development Annual Report, and related domestic literature.The data were derived from the statistics of articles published by China Coal Association and others and analyzed the background and purpose of the study.

(3) The emergency management capability of major coal mine disasters is then roughly divided into five areas: preventive measures, quality of emergency preparedness, rapid response capability, recovery capability, and lesson summary evaluation, and then each area is analyzed one by one.

(4) After determining the structural equation model and designing the questionnaire, the data derived from the questionnaire were calculated using SPSS software, and then analyzed after building the structural equation model to draw conclusions in each of the five areas.

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