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Identification of Hidden Hazard Risks of Coal Mine Gas Accidents based on SNA and Analysis of Action Path

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Abstract

Hidden hazard risks of coal mine gas accidents significantly threaten the safety production of coal mine enterprises. Determining how these hidden hazard risks can be recognized and analyzing their action relations is a problem that the business and academic circles must urgently solve. To determine the action paths among hidden hazard risks of coal mine gas accidents and formulate scientific control measures, typical coal mine gas accidents during 2013–2023 in China were reviewed and analyzed based on the "human-equipment-environment-management" framework by combining the accident-causing theory. Twenty influencing factors were recognized and extracted using the grounded theory. Then, the degree centrality and betweenness centrality were determined for the influencing factors using methods derived from social network analysis. The hierarchy of influence of factors was determined, and the risk propagation mechanism in the system network was disclosed. Results reveal that coal safety management system and implementation, degree of safety standardization, investment in safety technology, and gas concentration have higher relative centrality than others. This finding reveals that these factors have a relatively higher influencing intensity on the risk system of coal mine gas accidents and have strong controls in the accident system. The key risk factors can easily intensify hidden hazard risks and cause the occurrence of accidents. The obtained conclusion provides a new decision-making idea for control coal mine gas risks.

Keywords: Hidden hazard risks; Coal mine; Gas accidents; Influencing factors; SNA

1. Introduction

With China's standardization of the coal mining industry and increasing attention to safety production in recent years, safety management ability and technological level of coal production have achieved considerable progress. However, some gaps in China's standards compared to developed countries that adopt mechanical coal mining can still be observed, particularly in the fatality rate per ton, with the country still ranking at the top in terms of casualties [1]. Concerning mine conditions in China, most of the existing mining shafts are underground wells with complicated geological conditions, multiple hazard types, and extensive distribution areas. China has one of the poorest mining conditions and most serious hazards among the main coal-producing countries in the world [2, 3]. With the increasing exploitation depth in coal mines, geological conditions in deep exploitation become increasingly complicated, exacerbated by the increasing geostress and amount of soft rocks. Deep coal seams are characterized by "high stress, high gas pressure, high gas content, and low permeability". The hidden hazard factors are increasing daily, and the possibility of great hazard occurrence is increasing continuously According to recent data statistics from the Coal Supervision Bureau, Ministry of Emergency Management of the People's Republic of China, hidden hazard factors are the main causes of mine safety accidents and key constraints against normal ordered production of coal mines [4, 5]. Nearly 80% of major mine accidents are related to gob, fault, fold, and other hidden hazard factors and often cause changes or abandonment of mine production and construction projects [6]. Therefore, scientific identification of hidden hazard factors in deep mining and analyzing the mutual relations among these factors are prerequisites to formulating effective guarantee measures for safe coal production.

Nevertheless, existing studies on hidden hazard risk analysis of coal mines mainly focus on statistics of major hazard sources caused by environmental and geological factors, including mine fault, joint, fold, collapse column, and roof collapse, but they hardly focus on the hierarchy of hidden hazard factors and logic of a disaster causes [7, 8]. Hidden hazard factors have the characteristics of invisibility, time-varying, and vulnerability. Although geophysical prospecting, chemical prospecting, drilling, and many other exploration methods have been developed, scientific methods and knowledge on the disaster-causing mechanism of hidden hazard factors are still limited. Because the coal production system is a complicated nonlinear dynamic system, hidden hazard factors and various landform characteristic environments, gas environments, and hydrogeological features all undergo dynamic changes [9]. Identifying and assessing hidden hazard risks in early mine production effectively decrease safety accidents in coal mine enterprises. Therefore, a statistical analysis of typical coal accident cases in China was conducted first. Through the

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classification of major disaster accidents, such as floods, gas disasters, fire disasters, roof disasters, and rock bursts, hidden hazard factors that cause accidents were reviewed comprehensively, and key index factors were screened. Then, a correlation analysis of hidden hazard factors and their action mechanisms was conducted. This study aims to provide decision references to the safety production of mine enterprises and the prevention of hidden hazard risks.

2. State of the Art

The concept of hidden hazard factors in coal mines was proposed for the first time in 2014. Thus far, no complete knowledge system has been formed. Associated studies focus mainly on the concepts, features, types, and exploration technologies of hidden hazard factors. For example, Jing et al. [10] proposed methods and standards to identify and evaluate major risk sources (gas exploration, fire disasters, and coal dust explosion) in coal mines. Fan et al. [11] believed at least 13 types of hidden hazard factors can be found in coal mines, namely, fault, jointing, fold, collapse column, roof collapse, floor confined water, rock burst, gas, spontaneous combustion and fire disaster of coal seams, goaf water, harmful gases in the gob, poor sealing drill holes, and mining separation water. They analyzed the characteristics of hidden hazard factors and disaster-causing mechanisms. The proposed detection technologies of hidden hazard factors include the electromagnetic method, seismic prospecting technique, drilling technique, logging, downhole TV technique, etc. Xu et al. [12] identified hidden hazard factors of flood disasters in local small coal mines based on the classification of mine hydrogeological types and found that hidden hazard factors included water accumulation in old goaf, water-rich characteristics of the aquifer, water diversion structure, mining effect, or artificial water channels. By checking hidden hazards against safe mine production, Han et al. [13] found that fault fractures and collapse columns in shafts pose risks to the safety production of coal mines. They also formulated the corresponding prevention measures according to the screening for hidden hazard factors. Wang et al. [14] believed five major underground geological hazard types could be observed, including gas, coal dust, water, fire, and roof. These disasters can bring serious hazards to the safety production of surrounding coal mines. Moreover, a set of general investigation methods was proposed to explore hidden hazard factors in coal mines. Zhang et al. [15] combined the major types of hidden hazard factors in the coal mine and analyzed exploration techniques for different types of hidden hazard factors. According to existing studies, scholars screen hidden hazard risks of coal mines by using physical indicators, such as gas parameters, hydrogeological parameters, and wind volume, and formulate risk prevention measures through relevant engineering technological means. Nevertheless, the coal mine hazard system is a complicated nonlinear dynamic system, and coupling effects among different hidden hazard factors can be found. Moreover, risk-induced disasters have complicated causes. However, existing research perspectives and methods cannot disclose correlations of hidden hazard factors well.

With respect to the action mechanism of hidden hazard factors in coal mining accidents, existing studies classify causes of major coal mining accidents into two types: (1) human factors (management factors) are fundamental causes, and (2) technological factors are important causes. Lenné et al. [16] analyzed the causes of coal mining accidents in Australia during 2007–2008. Page [17] analyzed the causes of coal mining accidents in the USA from perspectives of organization size and diversified arrangement of organizational operation. Patterson et al. [18] investigated the causes of coal mining accidents in Queensland, USA, from January 2004 to June 2008. Based on the literature review and case study, Saleh et al. [19] summarized the causes of coal mining accidents in the USA from human behaviors, organization management, and technological equipment. They suggested introducing the concept of defense in depth into the coal mining industry. Paul et al. [20] studied workers' behaviors in two Indian mines through a questionnaire survey. The questionnaire analyzed unsafe behavioral causes from perspectives of negative emotion, risk-taking behaviors, job dissatisfaction, and safety performance. Liu analyzed the dynamic features of initiation, occurrence, development, and sudden changes of major accidents by using the system dynamic theory and reported that enough destructive energy releasing, essential environmental conditions, high-density exposed groups and vulnerable positions, and disposition defect or poor control are the four major basic factors in formation and development of major accidents [21]. Guo et al. [22] suggested predicting gas outburst accidents through nine indicators, such as the maximum mining depth and coal seam thickness. According to existing studies, research methods on coal mine gas accidents emphasize mathematical statistics and fuzzy mathematical analysis. They are based on mathematical statistics and simulation of disaster accidents. However, analyses of mutual relations of factors have been rare. The action mechanism of risk factors and the process of inducing the evolution of hidden hazard risks have not been disclosed.

To cope with the deficiencies of the existing studies, this study recognized and reviewed hidden hazard factors of coal gas disasters comprehensively using grounded theory and by combining with case study and questionnaire survey. The hidden hazard factors and the accident causative risks were combined with references to safety system engineering. The influencing factors were extracted and defined based on the "human-equipment-environment-management" model framework. Additionally, the influencing matrix of hidden hazard factors and accident causative risks was established by using social network analysis (SNA). Action intensity of different risk factors was judged through degree centrality. The action path and transmission relations of hidden hazard factors in coal mine gas accidents were recognized, and key causes of the accident were disclosed. This study aims to provide references to managers of coal production enterprises to formulate gas risk control strategies.

Subsequent sections of this study are structured as follows: Section 3 interprets the methods for screening and extracting hidden hazards and causative risks associated with coal mine gas accidents, grounded theory, and construction of the SNA model. Section 4 analyzes and discusses results and discloses the action mechanism of coal mine gas accidents. Section 5 summarizes the conclusions.

3. Methodology

3.1 Extraction Method of Hidden Hazard Risk Factors of Coal Mine Gas Accidents Based on Grounded Theory

At present, rich research data and typical historical cases of gas accidents can be found. This study summarized and encoded original data based on grounded theory to assure the scientificity of hidden hazard factors of coal mine gas accidents. The grounded theory uses three modes of encoding: open encoding, principal axis encoding, and core encoding [23]. Specific steps are introduced as follows.

(1) Open encoding. Open encoding refers to the level-1 code of grounded theory and is represented mainly by the collected coal mine gas accidents in terms of accident state. It is an operation process that breaks up the research data and offers a new concept, then recombines the data in a new way.

(2) Principal axis encoding. Principal axis encoding includes level-2 and associative codes. The main task is to discover and establish associations among conceptual categories of hidden hazard risk factors, such as environmental relationships and causal associations.

(3) Selective encoding. Selective encoding refers to core encoding. It involves choosing the "core category" from the discovered coal-gas hidden hazard risks through systematic analysis and setting up the complete disaster occurrence logic by describing the relations among major factors.

According to the analysis framework of "human-equipment-environment-management", this study implemented conceptual encoding, principal axis encoding, and selective encoding of a hidden hazard and accident causative risks through large-scale search and survey of previous typical coal gas disasters. The conceptual factors of coal mine gas accident triggering and evolution were discovered and summarized from the data. The analysis process is shown in Table 1.

Table 1. Conceptual coding analysis of factors influencing crowd stampede incidents

Coal mine gas accidents	Accident trigger and evolutionary process	Conceptual decoding
Gas exploration of Zuoquan Fusheng Coal Mine Co., Ltd of Shanxi Lu'an Group in 2020	The gas conditions for gas exploration were formed in local areas due to air leaks of the closed walls at two sides of an abandoned cutting hole	Gas concentration
	The roof collapsed suddenly or developed severe deformation.	Chaos of crow direction
	Electrical failure produced sparks.	Electrical failure
Coal and gas outburst accident in Limin Coal Mine of Guizhou Qiangsheng Group Investment Co., Ltd in 2022	The extension lane of the air return inclined shaft advances to the working face to construct shot holes.	Low mechanization degree
	Telephone alarm was used after the gas exceeded the limit.	Inadequate coverage of monitoring devices
	Choose comprehensive anti-burst measures according to standards	Safety management system and implementation
	Geostress was large, and the coal seam burst risks have not been eliminated yet.	Geostress
The remaining 81 typical cases of coal and gas outburst accidents	Immediate causes of accidents.	Risk identification results

Through a large-scale case study, influencing factors of coal-gas hidden hazard risks and accident causative factors were extracted through continuous comparison and screening. Moreover, these influencing factors were screened by combining a questionnaire survey. Then, the set of influencing factors was determined.

3.2 Mechanism Analysis of Coal Mine Gas Accidents Based on SNA

SNA employs matrices and graph theory to analyze the macro structure and specific characteristics of complex networks composed of nodes [24]. During SNA, the hidden hazard factors that influence coal mine gas accidents and accident causative factors are combined. Different factors are viewed as network nodes, and the "uniqueness" of these factors in the SNA network is analyzed through the centrality of nodes, which is expressed by the "degree centrality" of the model calculation method [25]. In this study, data on coal-gas hidden hazard risk factors were associated with and analyzed.

In SNA, the index of centrality includes degree centrality and betweenness centrality. Specifically, the numerical value of the degree centrality of coal-gas hidden hazard risk factors expresses the count of nodes that link to the risk factor within the network structure. Specifically, degree centrality encompasses both absolute and relative forms. The former indicates the count of coal-gas hidden hazard risk factors directly related to other factors. The later refers to the proportion of a factor's absolute centrality to the highest centrality achievable within the network's other risk factors. In the analysis of coal-gas hidden hazard risk factors, a risk factor with the higher degree centrality is easier to combine with other risks to cause gas accidents and is in the centre of the network with greater risks. Betweenness centrality is the sum of probability for the node to locate at two node paths on the network, and it represents the ability of the risk to control other nodes. It can be understood as controlling a factor can restrict worsening of other risks to some extent to prevent coal mine gas accidents. The modelling steps of SNA are introduced outlined below.

3.2.1 Development of a Weighted Impact Matrix

The matrix representing hidden hazard risks of coal mine gas accidents was constructed. The influencing intensity among factors was determined by Delphi method. Influencing relations between any two risks were judged by the "0 or 1" scoring system. Specifically, "1" represents a correlation between two risks, while "0" means no relation between two risks. Coal safety management experts judged whether influencing relations among factors and degree of influences can be observed. According to survey results, the direct influencing matrix $X = (x_{ij})_{n*n}$ was obtained, where x_{ij} represents the direct influencing degree of factor i on j. When $i = j$, $x_{ij} = 0$.

3.2.2 Matrix Symmetrization and Binarization

According to the relationship between influencing factors of hidden hazard risks of coal mine gas accidents expressed by the above direct incidence matrix and the accident causative factor set, the direct influencing matrix was symmetrized and binarized using the UCINET software to lay the foundation for the centrality among risks.

3.2.3 Calculation of Index Centrality

The absolute centrality of coal-gas hidden hazard risk factors was expressed by C_{AD}, while the relative centrality was expressed by $C_{AD}{}'$. The calculation method is as follows:

$$C_{AD}{}' = \frac{C_{AD}}{n-1} \tag{1}$$

Where n represents the network scale, defined as the aggregate count of risk factors.

Betweenness centrality for coal-gas hidden hazard risk factors was denoted by C_{ABi}. The calculation formula was as follows:

$$C_{ABi} = \sum_{j}^{n}\sum_{k}^{n} b_{jk}(i) = \sum_{j}^{n}\sum_{k}^{n} \frac{g_{jk}(i)}{g_{jk}}, j \neq k \neq I, j \prec k \tag{2}$$

Where $b_{jk}(i)$ represents the control capability of risk i over the interactions between risks j and k. $g_{jk}(i)$ denotes the count of pathways linking risks j and k that traverse through risk i. g_{jk} quantifies the overall pathways connecting risks j and k. The matrix I serves as the identity matrix.

Based on SNA, this study conducts a centrality analysis of the hidden hazard risk factors associated with coal-gas incidents. The occurrence and evolutionary mechanisms of gas accidents are determined from various perspectives, including the network structure of the accidents, the causal relationships between risk factors, and the intensity of indicator effects.

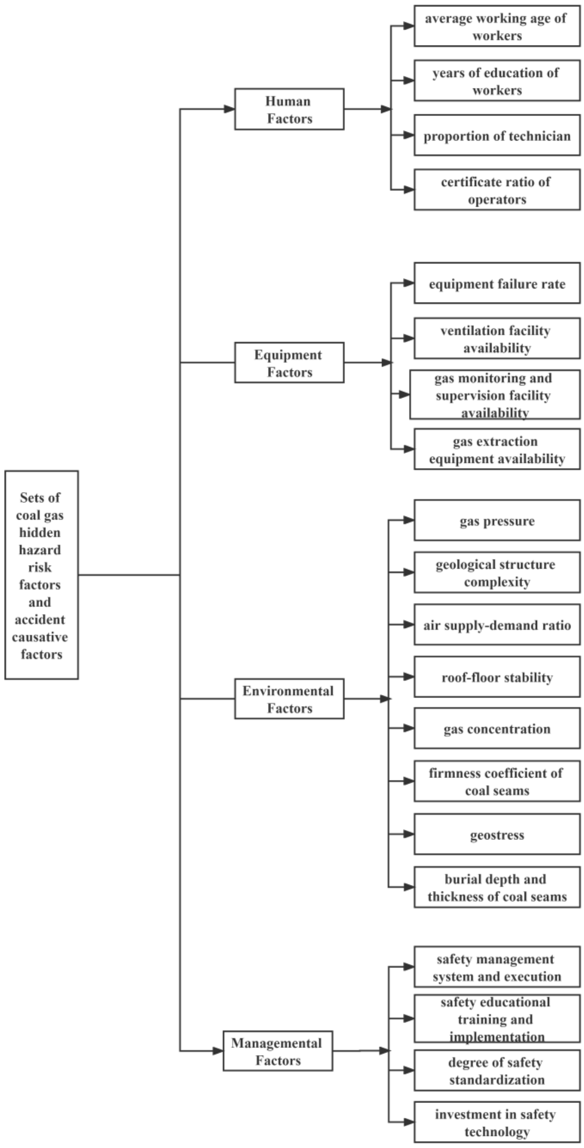

Fig.1. Sets of coal-gas hidden hazard risk factors and accident causative factors

4. Results Analysis and Discussion

4.1 Influencing Factor Set

By combining and screening the hidden hazard risk factors of coal mine gas accidents by associated scholars, a total of 83 gas incidents in Chinese coal production enterprises in 10 years from 2013 to 2023 were collected and reviewed. The universal and representative cases that had great social influence and severe causalities were chosen for conceptual encoding of influencing factors. Then, 16 experts in coal safety production management were interviewed through e-mail, telephone, and video conference from May to September 2022 to further optimize and screen influencing factors. According to the review and analysis of interview results, the simplified 20 influencing factors were obtained according to the index division framework of human-equipment-environment-management (Fig.1).

Accident survey reports of chosen cases were reviewed based on the conceptual encoding of influencing factors [26]. Direct and indirect causes of coal mine gas accidents were analyzed based on grounded theory. Because one accident is usually caused by coupling effect of many factors rather than one, the statistical number of influencing factors was higher than 83.

4.2 Centrality Analysis of Coal-Gas Hidden Hazard Factors

4.2.1 Centrality Results of Influencing Factors

Influencing factors of coal mine gas accidents form a complicated system. Causalities are among the factors. Whether influencing relations can be observed among factors is a basic condition of SNA. In this study, influencing relations among factors were determined by Delphi method and collecting opinions of many experts. Experts were interviewed through e-mail, telephone, and video conference from May to September 2022 to further analyze relation intensity among influencing factors. Then, influencing factors were optimized and screened. Interviewees were Chinese scholars engaged in gas control or from middle-level and senior managers of enterprises, including eight from China University of Mining and Technology, five from China Coal Research Institute, five from Northeastern University of China, five from Henan Polytechnic University, and seven from the frontline managers and technicians of coal mines in China. Each valid questionnaire was transformed into 20×20 data square. A total of 30 data squares were averaged to obtain matrix *K*. Data processing was implemented to matrix *K*. If element K_{mn} (Row *m*, column *n*) in matrix *K* is ≥0.5, the value is "1"; otherwise, it is "0". According to a comprehensive analysis of expert opinions, the adjacent matrix of influencing factors among coal-gas accident risk factors was constructed (Table 2).

Table 2. Multi-valued matrix scoring outcomes for risk factors in the hidden hazard risk system

X	**A1**	**A2**	**A3**	**A4**	**B1**	**B2**	**B3**	**B4**	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**D1**	**D2**	**D3**	**D4**
A1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0
A2	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
A3	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1
A4	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1
B1	0	0	0	0	0	1	1	1	0	0	1	1	1	0	0	0	1	0	1	0
B2	0	0	0	0	1	0	0	0	0	0	1	0	1	0	0	0	1	0	1	0
B3	0	0	0	0	1	0	0	0	0	0	1	0	1	0	0	0	1	0	1	0
B4	0	0	0	0	1	0	0	0	0	0	1	0	1	0	0	0	1	0	1	0
C1	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1	0	1	1	1	1
C2	0	0	0	0	0	0	0	0	1	0	0	1	1	1	1	1	1	1	1	1
C3	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	1	1
C4	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	1	1	1	1
C5	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	1	1	1	1
C6	0	0	0	0	0	0	0	0	1	0	0	1	1	0	1	0	1	1	1	1
C7	0	0	0	0	0	0	0	0	1	1	0	1	1	1	0	0	1	1	1	1
C8	0	0	0	0	0	0	0	0	1	1	0	1	1	1	1	0	1	1	1	1
D1	1	1	1	1	1	1	1	1	1	0	1	1	1	0	0	0	0	1	1	1
D2	0	1	1	1	0	0	0	0	1	0	1	1	1	0	0	0	1	0	1	1
D3	1	1	1	1	1	1	1	1	1	0	1	1	1	0	0	0	1	1	0	1
D4	0	0	0	0	1	1	1	1	1	0	1	1	1	0	0	0	1	0	0	0

Before SNA of the above multi-valued matrix, the multi-valued matrix of hidden disaster-induced coal mine gas accidents was symmetrized and binarized. Degree centrality and betweenness centrality of risk factors were calculated by UCINET software, including absolute degree centrality (*Degree*), relative degree centrality (*Nrm Degree*), proportion (*Share*), and betweenness centrality (*Betweenness*). Table 3 presents the results, and Fig. 2 illustrates the betweenness centrality relations among factors.

Table 3. Calculated results of degree centrality of coal-gas hidden hazard risk factors

Influence Factors	Degree	Nrm Degree	Share	Betweenness	nBetweenness
A1	3.000	15.789	0.015	0.000	0.000
A2	5.000	26.316	0.025	0.000	0.000
A3	6.000	31.579	0.030	0.000	0.000
A4	7.000	36.842	0.035	3.917	1.145
B1	9.000	47.368	0.045	6.111	1.787
B2	6.000	31.579	0.030	0.111	0.032
B3	6.000	31.579	0.030	0.111	0.032
B4	6.000	31.579	0.030	0.111	0.032
C1	11.000	57.895	0.054	5.811	4.613
C2	10.000	52.632	0.050	4.272	5.565
C3	10.000	52.632	0.050	2.211	0.647
C4	10.000	52.632	0.050	45.111	13.190
C5	14.000	73.684	0.069	19.033	1.699
C6	10.000	52.632	0.050	1.033	0.302
C7	10.000	52.632	0.050	3.000	0.877

C8	10.000	52.632	0.050	0.000	0.000
D1	19.000	100.000	0.094	61.094	17.864
D2	14.000	73.684	0.069	21.267	6.218
D3	19.000	100.000	0.094	71.700	20.965
D4	17.000	89.474	0.084	23.600	6.901

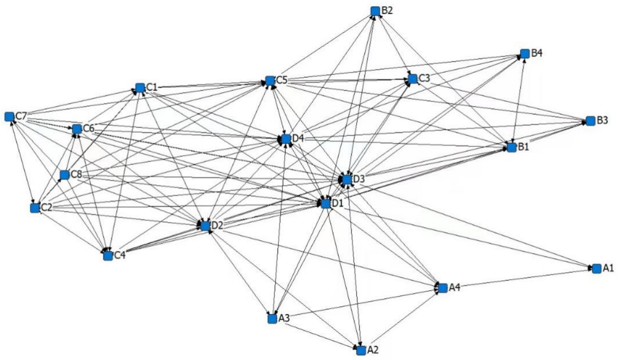

Fig.2. Betweenness centrality analysis of factors under SNA perspective

4.2.2 Centrality results analysis of influencing factors

(1) *Nrm Degree*

The relative degree centrality (*Nrm Degree*) represents the importance of risk factors in the coal mine gas accident network, that is, the central position and influence intensity of factors in the accident. The factor with higher *Nrm Degree* is easier to combine with other factors to cause accidents and has higher risks. Table 3 displays the analysis results for the centrality of influencing factors. Twelve risk factors have high *Nrm Degree* (> 50), including coal safety management system and implementation (D1), degree of safety standardization (D3), investment in safety technology (D4), gas concentration (C5), safety educational training and implementation (D2), gas pressure (C1), wind supply-demand ratio (C3), burial depth and thickness of coal seams (C8), roof and floor stability (C4), geostress (C7), geologic structural complexity (C2), and firmness coefficient of coal seam (C6). Specifically, D1 and D3 have the highest magnitude, reaching 100, which demonstrates that although coal safety management system and implementation and degree of safety standardization are soft constraints of coal mine gas accidents, poor safety management is extremely easy to cause changes of other risk indexes. Among the hidden hazard indices of gas risks, the order of *Nrm Degree* from high to low is as follows: gas concentration (C5) > gas pressure (C1) > wind supply-demand ratio (C3) > burial depth and thickness of coal seams (C8) > roof and floor stability (C4) > geostress (C7) > geologic structural complexity (C2) > firmness coefficient of coal seam (C6). The *Nrm Degree* of all these indices exceeds 50, demonstrating that although hidden hazard factors are direct causes of accidents, they can be easily worsened due to the influence of safety management factors. Coal mine gas accidents occur as a result of the coupling effect of excessively worsening hidden hazard risk factors.

(2) *Betweenness*

Betweenness centrality (*Betweenness*) represents the risk resistance of influencing factors in the coal mine gas accident network. Guo et al. demonstrated that some potential risks may influence other risk factors and an accident occurs as a result of the coupling effect of multiple risks [23]. The factor with higher *Betweenness* can influence other factors more easily and cause coal mine gas accidents. According to the analysis results of Table 3, the risk factors with higher *Betweenness* are D3, D1, C4, D4, D2, and C5. Specifically, the *Betweenness* of D3, D1, and C4 has the highest magnitude, exceeding 45. This outcome indicates that D3, D1, and C4 can readily affect other factors and exert considerable control. Fig. 2 also shows that D3, D1, D4 and D2 are in the core connection positions in the whole network, and are closely related to multiple factors. Hence, management factors play the key role in the occurrence of accidents.

5. Conclusions

To analyze hidden hazard risk factors and accident causative risks of coal mine gas accidents and the mechanism of accident occurrence, a set of influencing factors derived from mathematical statistics is established using SNA. Moreover, an adjacent matrix of risk factors is constructed. The action intensity among factors is analyzed to ascertain their centrality and relative importance. Several conclusions have been drawn from the study:

(1) The mechanism behind gas explosion accidents constitutes a complex and systematic engineering challenge. The analysis index system of coal mine gas accidents based on the “huamn-equipment-environment-management” can depict accident mechanism and logic relations among hidden hazard factors in coal mine environmental factors using the accident causation theory in safety science. From the network analysis perspective, it discloses that gas accident is caused by failures of the risk factor set layer by layer.

(2) Through historical typical case study based on SNA model and grounded theory, key risks of coal mine gas accidents are recognized and screened. Risks, such as coal safety management system and implementation, degree of safety standardization, investment in safety technology, gas concentration, safety educational training and implementation, gas pressure, wind supply-demand ratio, burial depth and thickness of coal seams, roof and floor stability, geostress, geologic structural complexity, and firmness coefficient of coal seam can easily form coupling effect with other factors to cause accidents. Findings from the degree centrality analysis offer directional insights for the control strategies of coal mine gas accidents.

(3) Hierarchy of influences of risk factors and risk transmission paths can be determined accurately through the betweenness centrality analysis of the SNA model. Risks, such as degree of safety standardization, coal safety management system and implementation, roof and floor stability, investment in safety technology, safety educational training and implementation, and excessive gas concentration have strong controls and influences over other relevant risk factors. They amplify the impact of risk factors within a complex network system. Betweenness centrality reveals the significance of safety management measures in gas accident control within coal production enterprises.

Analyzing the influencing factors of hidden hazard risks and accident causative risks of coal mine gas accidents based on SNA can disclose the hierarchy of influence and action mechanism of risk factors and control accident risks better. The proposed problem is the hidden hazard risk factor analysis of coal mine gas accidents based on SNA, which differs from the previous qualitative studies. However, further studies on recognizing and detecting other hidden hazard risks (e.g., flood and gob) under complicated environmental conditions in coal mines are needed. This study has the future research directions..

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