Spreading mechanism of underground mine fire based on the complex network

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Abstract

Underground mine fire system often refers to an open and dissipative system with complex structure and behavior features. The purpose of this study is to investigate fundamental questions of structure, connectivity, information exchange and causality by complex networks to built system model and network model of underground mine fire. The complex network theory is employed to analyze model of underground mine fire network including the whole and individual attributes. The former consists of density, average degree, clustering coefficient and distance, while the latter contains degree centrality, betweenness centrality and closeness centrality. The relationship between nodes and disaster is gained, which has a great influence on fire network. The degree distribution of function is used to test and determine whether underground mine fire network has a small-world effect of complex network as well as scale-free property and network centrality to verify the underground mine fire system as a kind of complex network. Therefore, the topological structures of complex networks and changes of key parameters are applied to study evolution and spread dynamics of fire network.

Keywords: underground mine fire network, complex network, degree distribution, topological structure

1 Introduction

Fire disasters occur mostly unexpected, which is found that many of them show characteristic scenarios [1,2]. Fire strong initial event triggers an avalanche of failure, which spreads in a cascade-like manner within a network and finally has impact on large parts of the system [3]. The study of complex networks is an interdisciplinary field which deals with general structural properties in biological, neural, physical, chemical, social and technical network structures [4-7]. Complex networks, can be used to study any complex system, as the general abstract and description way of large and complex system as well as abstract structure form of system. It focuses on the topology of system structure so that it can understand deeply system structure and the evolution of structure [8-13].

The essence of using complex network theory to study underground mine fire spread is to focus on the changes of network structure and characteristics caused by the network node and edge changes. The purpose of this study is to establish network model based on complex underground mine fire network, to study the overall structure properties of the fire network and to judge whether it has small-world effect [14] and scale-free property [15]. It is helpful to understand the path, way, phase characteristics and the affective factors of the fire spread. This study analyzes the general rule, the interaction mechanism of the event activities of evolution under unconventional underground mine fire. Besides, this study lays a solid theoretical foundation to build fire evolutionary model and simulation and provides guiding principles to construct warning management mode of underground mine fire event.

This article is divided into the following parts. In part two, underground mine fire network is constructed, and the framework of fire spread is transformed into fire network model. In part three, the authoritative data of underground mines fire cases is collected and sorted to extract relationship between disaster factors and node, which has great influence on fire network. Complex network theory is used to analyze underground mine fire network model including overall properties such as density, average degree, clustering coefficient and distance and individual properties like degree centrality, betweenness centrality and closeness centrality. The relationship between disaster factors and node is gained, which has great influence on the fire network. In part four, the degree distribution of function is applied to test and determine whether underground mine fire network has a small-world effect of complex network as well as scale-free and network center property to verify the underground mine fire system as a kind of complex network.

2 Establishing network system of underground mine fire

It is necessary to establish a basic model of mathematical transformation when underground mine fire system transforms into fire network. Based on systematic principle and the definition of underground mine fire, it can be learned that disaster system is made up of a series of disasters, including disaster environment, disaster drivers and disaster bearers [16]. The underground mine

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fire system is defined as five factors, $UFS = [E, D, B, M_{ed}, M_{db}]$. E represents collection of hazard inducing environment; D represents disaster-causing factors; B represents disaster-affected bodies, M_{ed} represents the mapping relation between hazard inducing environment and disaster-causing factors; M_{db} represents the mapping relationship between disaster factor and disaster bearers. Where:

1) Set E is defined as $E = \{e_1, e_2, e_3, ..., e_m\}$, which is made up of m factors.

2) Set D is defined as $D = \{d_1, d_2, d_3, ..., d_n\}$, which is made up of n disaster factors.

3) Set B is defined as $B = \{b_1, b_2, b_3\}$, where b_1 refers to damage and deaths of human, b_2 refers to damage of facilities and b_3 refers to the damage of environment.

4) Set M_{ed} of the mapping relation between pregnant disaster environment and disaster factors is presented. The mapping relation is defined as certain pregnant disaster environment causing the emergence of disaster factors, which can show matrix, When e_m leads to d_n, $e_m d_n = 0$, *Med* is (0,1) matrix.

5) Set M_{db} of the mapping relationship between disaster factors and disaster-causing factors is stated: If there are disaster factors, the influence degree of disaster bearers is 1, otherwise it is 0. M_{db} is (0, 1) matrix.

The model can comprehensively reflect the system of coal mine disasters. Through this model, if we extract the disaster factors and final outcome after disaster happened, we can draw the reason of trigger disasters and its development process under the connection of two relations. We call these factors involved in this logical process as disaster factors so that the underground mine fire system is transform into disaster factors as the nodes and the fire network of trigger relationship as edges.

Based on the theory of network analysis, elements of UFS are extracted. G can be defined as a tetrad, namely, $G=(V,P,W,R)$, where V represents the disaster nodes set; P represents the collection of edges of disaster nodes; W represents the set of weight of two connecting points and edges; R represents the set of update rules of fire network.
1) The nodes collection of underground mine fire V: the collection of disaster nodes is made up of disaster factors D and disastrous situation $(M_{ed} + M_{db})$, namely $V = D + (M_{ed} + M_{db})$.
2) P edge collection of fire nodes: trigger logic relationship between disaster factors and disastrous situation are abstracted as edges. Because there is causal relationship between hazard factors, the edge of underground mine fire network is directed edge.

2.1 IDENTIFYING NETWORK NODES

In complex networks, identifying influential nodes is very important part of reliability analysis, which has been a key issue in analyzing the structural organization of a network [17]. Node importance is a basic measure in characterizing the structure and dynamics of complex networks [18-23]. Hence, identifying influential nodes has been an open issue and a critical research task in complex networks. Various centrality measures have been proposed over the years to rank the nodes of a graph according to their topological importance [24]. When influential nodes are identified, the related disaster factors are searched for and the main disaster nodes are analyzed one by one, which are combined at last. After the cases are carefully classified and analyzed, network nodes of underground mine fire are identified finally. The matrix method is used for network modeling. Therefore, identifying network relationship mainly shows to determine the node relationship matrix. When network relations are defined, the methods of mature accident tree analysis and disaster chain analysis are employed, which are commonly used in current disaster accident analysis of underground mine. Then the method of system engineering is applied to identify step by step. The network of underground mine fire is established: $G = (V, P, W, R)$.

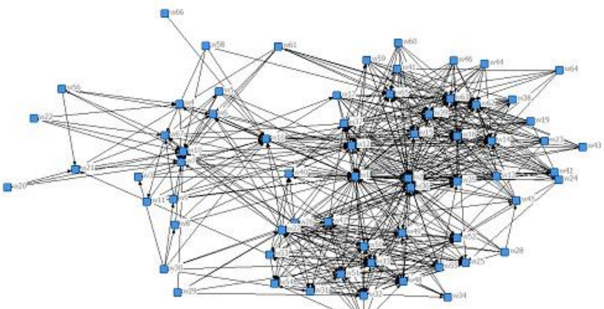


FIGURE 1 Network topology of UMFN

3 The complex network attributes of underground mine fire

In this section, the whole attributes and characteristics of underground mine fire are analyzed including density, average degree, clustering coefficient and distance.

3.1 OVERALL STRUCTURE ATTRIBUTES ANALYSIS OF UNDERGROUND MINE FIRE NETWORK

The structure attributes of underground mine fire network mainly includes the nodes, the number of edges, density, average node degree, clustering coefficient, the longest path and average distance. Based on the relevant formula of description of a complex network statistics and the calculation of Ucinet software, the structural index of each item of underground mine fire network as is shown in Table 1. In Figure1, the network topology of underground mine fire network is shown.

TABLE 1 Structure attributes of UMFN

Index	Data	Index	Data
Nodes	67	Arcs	610
Density	0.1379	Clustering coefficient	0.442
Average distance	2.392	Maximum distance	6

Compared with random network of the same scale, the density of underground mine fire network is 0.1379, which has high closeness. Cluster coefficient is 0.442 > 0.100, which reflects that disaster factors in the fire system have higher node collectivization tendency, and proves the chain coupling ability in part conditions between the disaster factors. The average distance is 2.392, which indicates that one disaster factor in the fire system changes by 2.392 steps and can cause other disaster factors to change and shows that disaster path of underground mine fire is shorter.

3.2 ANALYSIS OF INDIVIDUAL CENTRICITY OF UMFN

Complex network theory is used to analyze underground mine fire network model individual properties like degree centrality, betweenness centrality and closeness centrality.

3.2.1 Analysis of node centricity

Node centricity of individual disaster factor directly reflects its position in fire network and shows that the individual factor has the centricity role to influence other disaster factors. The descriptive statistics of node centricity is calculated. Average degree is 5.911, which means that each disaster factor will affect the average 5.911 of other disaster factors. In-degree centralization is larger than out-degree centralization, which is more diffuse. Based on the standard variance, standard deviation of in-degree centralization is greater than the mean, while standard deviation of out-degree centralization is less than the mean.

According to in-degree and out-degree centralization, the out-network nodes are more concentrated, and most disaster factors point to small part of disaster factors. While in-network is more dispersed, which illustrates the mine fire system has many dispersed sources of dangers, few of which can eventually lead to disaster and is concentrated.

3.2.2 Analysis of betweenness centrality

According to the definition of betweenness centrality, it can be known that the statistics of spacing centricity of underground mine fire network is shown. The average spacing centricity of underground mine fire network is 66.821. The maximum value is 843.188, and the minimum value is 0. The standard variance of betweenness centrality is 124.405. The data shows that betweenness centrality of underground mine network has a very large heterogeneity. The maximum average value is 12.6 times than average value, while standard deviation is 1.86 times than average value.

3.2.3 Analysis of closeness centrality

Network node centricity reflects the direct influence of one disaster factor on the network and describes the "leadership" of disaster factor, while closeness centrality reflects pivotal role of disaster factor for other disaster factors, and describes its role of "mediation" for other disasters. Closeness centricity shows the difficulty of disaster influence on other disaster factors. We define that if one disaster factor in the fire network less depends on other disaster factors, the closeness centrality of disaster factor will be higher, and its ability affecting the state change of other disaster factors will be weaker.

4 Degree distribution function tests

Complex network is an abstract description of complex system. It is a kind of network with self-organization, self-similarity, small-world and scale-free characteristics. Underground mine fire network is established by abstracting elements in the underground mine fire system to the network nodes. The underground mine fire system has typical characteristics of complex network. However, it is necessary to be further confirmed whether it can be considered as complex networks. If the underground mine fire system is a kind of complex network, the underground mine fire system is a complex system in a certain sense. Only underground mine fire is confirmed a kind of complex network, can some research method on the complex network be applied to the study and analysis of underground mine fire network. In this case, the evolution of the fire network dynamics research can be carried out. This chapter inspects whether the underground mine fire systems have complex systems through distribution function. If the network is a random or regular network, this dynamics study has no value and significance. In this section, degree distribution function is used to test whether underground mine fire system has a series of characteristics of complex systems.

4.1 SMALL WORLD EFFECT TESTS

According to the theory of small world effect, a small world network has the shorter average path length and high clustering coefficient. According to the statistical properties of small world network model, the clustering coefficient of WS small-world networks [25] is $C(\rho)=\frac{3(\mathrm{k}-2)}{4(\mathrm{k}-1)}(1-\rho)^3$. The average path length of small world model is $L(\rho)=\frac{2N}{K}f\left(\frac{NK\rho}{2}\right)$. N is the network node; k is the average degree; ρ is random reconnection probability. When the network clustering coefficient is $C(\rho)>0.1$, average path length will be $L(\rho)<10$. The network is called the small world network. The network underground mine fire in this study is $L(\rho)=2.392<10$, $C(\rho)=0.442>0.1$ and therefore it has the characteristics of small world effect. Underground mine fire is a kind of small world network.

4.2 SCALE-FREE EFFECT TESTS

Complex network has a small world effect and scale-free property. The scale-free property reflects that few influential nodes control and most of the nodes influencing the others with nodes of a large number of connections are called distributed nodes. It reflects the extreme imbalance between the network nodes, and this imbalance is the characteristics of complex networks. The type of network is judged by degree distribution character. The degree distribution of rule network is function δ. The random network is normal distribution. These two network nodes follow certain rules of the distribution, which is called the scale network.

Power-law distribution can reflect the extreme imbalance of function so that the judgment of scale-free property of network can be based on whether it satisfies the power-law distribution characteristics or not. Exponential distribution has the same as characteristics with the power-law distribution. It can reflect high aggregation and is close to 1 area with the characteristics of a fast decline, but it is much slower than a power-law distribution is close to 0. Exponential distribution is applied to a small number of nodes, and complex network analysis of the node floating larger changes. This section judges if underground mine fire network is complex network according to the principle that whether the degree distribution is subject to exponential distribution or not.

Underground mine fire network is directed network. The in-degree and out-degree are analyzed. According to the definition of degree distribution, the vertical axis adopts occurrence frequency of the node *P*(*k*), and the horizontal axis is the node value *k* of linear coordinate. Figure 3 is out-degree distribution, and Figure 2a is the index distribution. Figure 2b is degree distribution of single logarithmic coordinates. Figure 3a is in-degree distribution. Figure 3b is the in-degree distribution in single logarithmic coordinates.

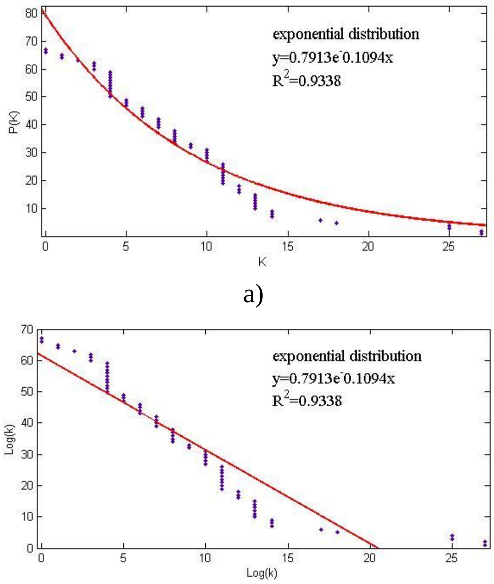
1) Distribution functions of the underground mine fire network is $y = \lambda e^{-\lambda x} = 0.7913e^{-0.109x}$ .The fitting line slope in single logarithmic coordinates is 0.109, and linear fitting is $R^2 = 0.9348$.

$$P(\mathrm{K} > \mathrm{k}) \sim e^{-0.109}, (0 < \mathrm{k} \le 27), \quad (1)$$

2) Exponential function of underground mine fire network is $y = 0.542e^{-0.019x}$. The fitting line slope in single logarithmic coordinates is –0.073 and linear fitting is $R^2 = 0.9348$.

$$P(\mathrm{K} > \mathrm{k}) \sim e^{-0.073}, (0 < \mathrm{k} \le 40.299), \quad (2)$$

Through the analysis and curve fitting, it is found that frequency distribution of in-degree and out-degree obeys the exponential distribution well. The straight slope of out-degree distribution λ is 0.109, fitting line slope of in-degree distribution is –0.073. In-degree and out-degree of underground mine fire network obey exponential distribution, and therefore it can prove that the underground mine fire network is scale-free networks with the scale-free characteristic.

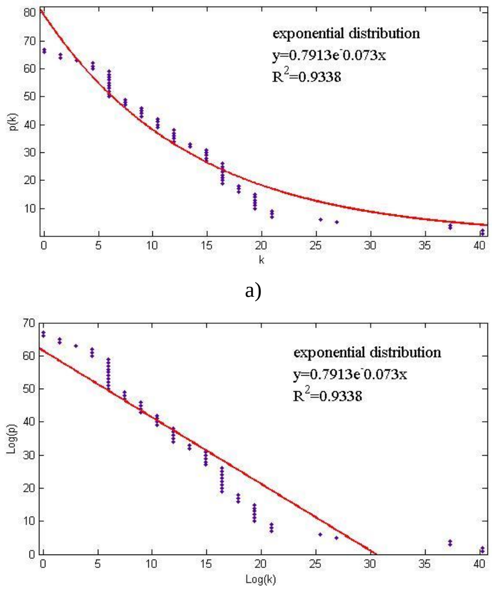


a)

b)

FIGURE 2 OutDegree Centrality Distribution of UMFN

(Obey exponential distribution and Fitting line slope is –0.109)



a)

b)

FIGURE 3 InDegree Centrality Distribution of UMFN

(Obey exponential distribution and Fitting line slope is –0.073)

Underground mine fire network is scale-free network, which indicates that few degree values in fire system are greater than distributed nodes of other nodes in the network. These distributed nodes can dominate and control structure and composition of the fire network, which shows that these distributed nodes control underground mine fire network system. When this kind of disaster factors appears, their damages are much larger than other disaster factors, such as gas explosion with maximum average values of in-degree and our-degree. Therefore, removing few nodes with maximum value in fire system or cutting off connection with adjacent nodes with larger degree value will have great effect on the whole network connectivity. Besides, it can effectively inhibit the proliferation and spread of emergency.

Based on the above research, the underground mine fire network is complex network with 'small world effect' and 'scale-free property'. The underground mine fire system has the characteristics of complex systems. Judging the characteristics of complex system of the underground mine fire system will be helpful to research the development and evolution of the fire from the perspective of complex system.

4.3 THE TESTING OF BETWEENNESS CENTRALITY FUNCTION DISTRIBUTION

The exponential function of betweenness centrality of underground mine fire network is $y = 0.542e^{-0.019x}$. In Figure 4, it can be seen that the distribution of betweenness centrality of underground mine fire network obeys better the exponential distribution $R^2 = 0.9224$. When betweenness centrality is near 200, an inflection point happens (the betweenness centrality of more than 200 is only seven). Most of the node betweenness centrality is in small value area. Seven disaster factors of the betweenness centrality of more than 200 have large values of in-degree and our-degree. It shows that these disaster factors in the network have great individual influence and play a strong bridge intermediary role. In the prevention and control of underground mine fire, disaster factors of large betweenness centrality can be moved out based on listed order of betweenness centrality. Based on path displayed by the network topology structure, disaster factors can be controlled or eliminated to reduce the intermediation role of disaster factors and overall network connectivity, and make fire events be controlled in the certain scope and improve safety of underground mine system.

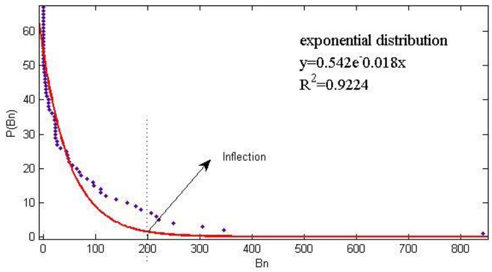


FIGURE 4 Betweeness centrality distribution of UMFN

5 Conclusions

Based on underground mine safety engineering, system engineering theory and computer simulation, complex network theory is employed to systematically explore topological property of underground mine fire network and internal mechanism from empirical observation to theory construction. The conclusion is drawn as follows:

1) According to the complex evolution and coupling relationship of underground mine fire, systematic model and network model of underground mine fire network are set up. In addition, underground mine fire network is analyzed from two aspects of the whole and individual attributes.

2) In term of the whole attributes, the density of underground mine fire network is 0.138. It has high closeness degree compared with random network with the same scale. Its cluster coefficient is 0.442, which reflects that disaster factors in the fire system has higher node collectivization tendency and illustrates that the underground mine fire system higher clustering has high clustering phenomenon. Besides, it also shows that there is strong chain coupling among disaster factors under the local condition. The average path length is 2.392, which indicates that the change of one disaster factor in a fire system only has 2.392 steps to cause possibly the change of adjacent disasters factors. It reflects that causing disaster path of underground mine fire is shorter.

3) According the analysis of individual attributes, it can be found that the in-degree of heterogeneity is stronger. The variation range of in-degree is greater than the variation range of out-degree, which reflects that the dangerous sources of underground mine fire system are more and scattered, but factors causing the fire is relatively few and concentrated. Large in-degree of value can cause serious disasters. The analysis of betweenness centrality shows that the network has few disaster factors playing great medium role. The analysis of space centrality shows that disaster driver with high mediation exist in the network. In term of closeness centrality, a great deal of disaster factors has high closeness, which results the distance between disaster drivers in the entire network to become small. Major disaster factors of in-closeness centrality are caused by human factors, which shows that closeness between personnel irregularities and status change of disaster factors is very high. In safety management control system of the underground mine fire, disaster nodes of the greater in-degree values should be controlled strictly and carefully, as well as the nodes of large betweenness centrality and smaller closeness centrality to some extent reduce the possibility of preventing underground mine fires.

4) Based on testing the distribution function of degree, the underground mine fire system is further verified as a kind of complex network. According to topology structure of complex network and the performance index, it is possible to do dynamic study on the fire network evolution.

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