Earthquake disaster chain model based on complex networks for urban engineering systems

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Abstract: According to news reports on severe earthquakes since 2008, a total of 51 cases with magnitudes of 6. 0 or above were analyzed, and 14 frequently occurring secondary disasters were identified. A disaster chain model was developed using principles from complex network theory. The vulnerability and risk level of each edge in this model were calculated, and high-risk edges and disaster chains were identified. The analysis reveals that the edge "floods → building collapses" has the highest vulnerability. Implementing measures to mitigate this edge is crucial for delaying the spread of secondary disasters. The highest risk is associated with the edge "building collapses → casualties," and increased risks are also identified for chains such as "earthquake→building collapses→casualties," "earthquake→landslides and debris flows→dammed lakes," and "dammed lakes → floods → building collapses." Following an earthquake, the prompt implementation of measures is crucial to effectively disrupt these chains and minimize the damage from secondary disasters.

Key words: earthquake; disaster chain; seismic resilience; secondary disaster; complex network; vulnerability; risk level

DOI: 10.3969/j. issn. 1003 – 7985. 2024. 03. 002

G iven its expansive landmass and intricate geographical features, China faces a significant geographical challenge: over two-thirds of its provincial capitals and more than half of its county-level urban areas are situated in regions with a seismic design intensity of 7 degrees or higher. Consequently, building structures in China are under considerable threat from seismic disasters[1–2]. The rapid pace of urbanization, along with increased human activities, has intensified the occurrence of various disaster-inducing factors. The growing complexity of infrastructure and lifeline networks further amplifies the vulnerability of urban engineering systems. Consequently, various disaster events have occurred frequently in recent years. Primary natural disasters often trigger a series of secondary disasters, expanding the scope of the impact both in time and space and posing significant threats to modern cities. Historical data confirm the clustering characteristic inherent in natural disasters[3]. Consequently, there is a pressing need for a thorough analysis of potential disasters within urban engineering systems and an imperative to enhance their capacities to effectively manage such crises.

To describe the evolution process of secondary disasters, scholars have primarily introduced tools such as co-occurrence analysis[4], multi-agent modeling[5], Petri nets[6], Bayesian networks[7–13], and complex networks[14]. Most research focuses on the construction, expression, and study of network structures. These network structures can visually display the current state of disaster events, predict future development trends, and analyze the key factors influencing event progression as well as the forces driving these factors[15]. For example, Ma et al. [8] utilized the Bayesian network toolbox for dynamic analysis of disaster networks to examine the vulnerability of urban earthquake-induced secondary disaster networks. Wang et al. [9] compiled 23 common earthquake disaster chains and used Bayesian networks to assess these chains, identifying the critical links that lead to loss of life. Liu[14] analyzed the chain effects of four typical urban disasters. By employing Bayesian networks, joint probability distributions of disaster levels for each node were obtained, and a risk assessment model for urban natural disaster chains was constructed. Tang et al. [16] developed a directed network model to represent the interconnections among seismic secondary disasters and their cascading effects in urban regions. According to this, disaster mitigation strategies addressing seismic cascading effects at the urban regional level were developed from a systemic perspective. However, these studies typically focus on a limited number of cases, regions, and types of disasters. They analyze the factors influencing the propagation effects of disaster consequences and presuppose network structures based on only a few instances. Additionally, the method of extracting key seismic damage data from news reports for constructing network structure models has not received sufficient attention in existing research. Consequently, the applicability and practicality of these research results

are likely to be subject to certain limitations.

This paper establishes an analysis model based on the principles of complex networks[16−20] for earthquake-induced secondary disasters in urban engineering systems. The model aims to uncover the mechanisms governing disaster diffusion and evolution, delineate the structure of the disaster network, assess the risk level for each edge, and propose mitigation measures for edges with higher risk levels.

1　Acquisition of Earthquake Cases for Urban Engineering System

The prerequisite for identifying relationships among earthquake-induced secondary disasters is the availability of damage data. Currently, the China Earthquake Networks Center website provides basic data on historical strong ground motion records. This comprehensive database includes detailed information such as the date and time of occurrence, magnitude, and geographic coordinates for each earthquake event. Additionally, news re-

ports, which are characterized by openness, authenticity, and timeliness, also focus on disasters and serve as valuable sources of data[21]. By extracting and analyzing information from news reports, the basic details and evolution patterns of secondary disasters can be understood. Therefore, in this paper, causal relationships about disasters are identified and extracted from news texts, and a disaster chain model is constructed. This enables the analysis of significant nodes in the evolution of disasters, providing crucial foundations for disaster mitigation.

All earthquake cases in this paper are extracted from the historical records of the China Earthquake Networks Center and historical news from China News. A search using the keyword "earthquake" on China News yielded over 10 000 domestic earthquake event news reports from January 1, 2008, to February 28, 2023. After filtering out irrelevant reports, more than 3 000 news reports related to earthquake-induced secondary disasters were obtained. Among these, 51 earthquakes with a magnitude of 6.0 or above are listed in Table 1.

Table 1　Summary of earthquakes with a magnitude of 6.0 or higher

No.	Time	Epicenter location	Magnitude	No.	Time	Epicenter location	Magnitude
1	2023-02-06	Turkey	7.8	27	2017-08-09	Jiuzhaigou, Sichuan	7.0
2	2023-01-30	Shaya, Xinjiang	6.1	28	2016-12-08	Hutubi, Xinjiang	6.2
3	2022-09-18	Hualien, Taiwan, China	6.9	29	2016-11-25	Aketao, Xinjiang	6.7
4	2022-09-05	Luding, Sichuan	6.8	30	2016-10-17	Zadoi, Qinghai	6.2
5	2022-06-10	Barkam, Sichuan	6.0	31	2016-05-12	Yilan, Taiwan, China	6.0
6	2022-06-01	Lushan, Sichuan	6.1	32	2016-02-06	Kaohsiung, Taiwan, China	6.7
7	2022-03-26	Delingha, Qinghai	6.0	33	2016-01-21	Menyuan, Qinghai	6.4
8	2022-03-23	Taitung, Taiwan, China	6.6	34	2016-01-02	Linkou, Heilongjiang	6.4
9	2022-01-08	Menyuan, Qinghai	6.9	35	2015-07-03	Pishan, Xinjiang	6.5
10	2021-10-24	Yilan, Taiwan, China	6.3	36	2015-04-25	Nepal	8.1
11	2021-09-16	Lu County, Sichuan	6.0	37	2014-11-22	Kangding, Sichuan	6.3
12	2021-05-22	Maduo, Qinghai	6.4	38	2014-10-07	Jinggu, Yunnan	6.6
13	2021-05-21	Yangbi, Yunnan	6.4	39	2014-08-03	Ludian, Yunnan	6.5
14	2021-04-18	Hualien, Taiwan, China	6.1	40	2014-05-30	Yingjiang, Yunnan	6.1
15	2021-03-19	Biru, Tibet	6.1	41	2014-02-12	Yutian, Xinjiang	7.3
16	2020-07-23	Nyima, Tibet	6.6	42	2013-10-31	Hualien, Taiwan, China	6.3
17	2020-06-26	Yutian, Xinjiang	6.4	43	2013-08-12	Qamdo, Tibet	6.1
18	2020-01-19	Jiashi, Xinjiang	6.4	44	2013-07-22	Min County, Gansu	6.6
19	2019-08-08	Yilan, Taiwan, China	6.4	45	2013-06-03	Nantou, Taiwan, China	6.7
20	2019-06-17	Changning, Sichuan	6.0	46	2013-04-20	Lushan, Sichuan	7.0
21	2019-04-24	Mêdog, Tibet	6.3	47	2013-03-27	Nantou, Taiwan, China	6.5
22	2019-04-18	Hualien, Taiwan, China	6.7	48	2011-03-11	Japan	9.0
23	2018-11-26	Taiwan strait, China	6.2	49	2010-01-12	Haiti	7.0
24	2018-02-04	Hualien, Taiwan, China	6.5	50	2010-04-14	Yushu, Qinghai	7.1
25	2017-11-18	Mainling, Tibet	6.9	51	2008-05-12	Wenchuan, Sichuan	8.0
26	2017-08-09	Jinghe, Xinjiang	6.6				

2　Analysis of Earthquake-Induced Secondary Disasters

2.1　Construction of disaster chain network

Numerous intricate systems in the world manifest as network structures, including interpersonal networks, collaboration networks, and food chain networks. A typical

network comprises nodes and edges connecting these nodes, where nodes represent different entities in a system and edges symbolize relationships between these entities. The study of complex networks can reveal the formation mechanisms and evolutionary rules underlying the topological structures of networks. In this paper, earthquake-induced secondary disasters are regarded as nodes, while the connections between these disasters are repre-

sented as edges within a complex network.

Upon reviewing the news reports related to the 51 earthquake cases listed in Table 1, 14 secondary disasters with high frequency can be summarized. These include earthquakes, building collapses, disruptions to power and water supply systems, impacts on livelihoods, leakage of hazardous materials, fires, casualties, landslides and debris flows, damage to transportation lines, dam failures, floods, dammed lakes, tsunamis, and epidemics. Each of these events is assigned a corresponding node number, as presented in Table 2.

Table 2   Earthquake-induced secondary disasters

Node	Secondary disaster
V_1	Earthquake
V_2	Building collapses
V_3	Disruptions to power and water supply systems
V_4	Impact on livelihoods
V_5	Leakage of hazardous materials
V_6	Fires
V_7	Casualties
V_8	Landslides and debris flows
V_9	Damage to transportation lines
V_{10}	Dam failures
V_{11}	Floods
V_{12}	Dammed lakes
V_{13}	Tsunamis
V_{14}	Epidemics

Constructing the edges of a complex network for secondary disasters involves extracting causal relationships from disaster news reports. The prevalence of expressions indicating causality within earthquake news reports can shed light on the progression of secondary disasters. For example, a report on the 6.5-magnitude earthquake in Ludian, Yunnan, in 2014 detailed that "an earthquake-induced landslide at the Niulanjiang power station dam resulted in the formation of a dammed lake, prompting the evacuation of over 200 residents from more than 40 homes in the reservoir area, with those in threatened zones urgently relocating." This account encompasses a chain of disasters: earthquake, landslides and debris flows, dammed lake formation, and subsequent floods, delineating a sequence "earthquake→landslides and debris flows→dammed lake→floods." By employing this approach, the causal links between secondary disasters can be represented as edges connecting disaster nodes within the complex network model.

This method identifies and extracts causal relationships among disasters from news reports, providing substantial empirical support for subsequent research. By analyzing the evolutionary process of secondary hazards in earthquake cases, connecting edges can be extracted and utilized to construct an earthquake disaster chain network. The resulting network diagram is illustrated in Fig. 1.
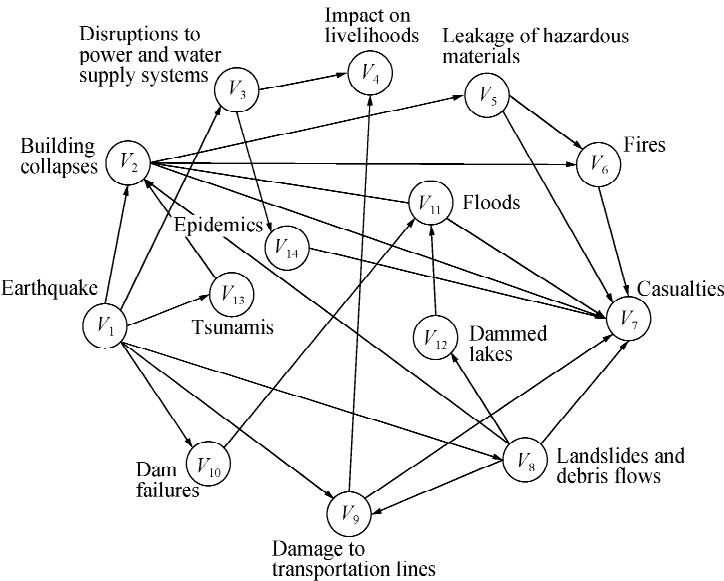

Fig. 1   Diagram of earthquake disaster chain network

2.2   Vulnerability analysis of disaster chain

2.2.1   Edge betweenness

The edge betweenness refers to the sum of the shortest paths between any two nodes that pass through a particular edge in the disaster chain network. This measure is defined as follows:

$$B_i = \sum_{j,k \in v} n_{jk}(i) \qquad (1)$$

where B_i denotes the betweenness of edge i; v represents all nodes in the disaster chain network; node j represents any arbitrary starting point, and node k represents any arbitrary endpoint in the network structure; n_{jk} denotes the number of shortest paths between node j and k passing through edge i, and the typical values for n_{jk} are 0

or 1. The edge betweenness of edges in the disaster chain network is calculated using Eq. (1), as presented in Table 3.

Table 3 Betweenness of edges in the disaster chain network

Edge	Edge betweenness	Edge	Edge betweenness
$V_1 \rightarrow V_2$	4	$V_6 \rightarrow V_7$	1
$V_1 \rightarrow V_3$	3	$V_8 \rightarrow V_2$	3
$V_1 \rightarrow V_8$	2	$V_8 \rightarrow V_7$	1
$V_1 \rightarrow V_9$	1	$V_8 \rightarrow V_9$	2
$V_1 \rightarrow V_{10}$	2	$V_8 \rightarrow V_{12}$	3
$V_1 \rightarrow V_{13}$	1	$V_9 \rightarrow V_4$	2
$V_2 \rightarrow V_5$	7	$V_9 \rightarrow V_7$	1
$V_2 \rightarrow V_6$	7	$V_{10} \rightarrow V_{11}$	6
$V_2 \rightarrow V_7$	3	$V_{11} \rightarrow V_2$	9
$V_3 \rightarrow V_4$	2	$V_{11} \rightarrow V_7$	3
$V_3 \rightarrow V_{14}$	3	$V_{12} \rightarrow V_{11}$	6
$V_5 \rightarrow V_6$	1	$V_{13} \rightarrow V_2$	4
$V_5 \rightarrow V_7$	1	$V_{14} \rightarrow V_7$	2

2.2.2 Average path length

The average path length refers to the average shortest path length between the initial node and other nodes in the network after removing a specific edge. The equation is given as follows:

$$L_i = \frac{1}{N-1} \sum_{t \neq k \in v} d_{tk} \qquad (2)$$

where L_i denotes the average path length of the network after the removal of edge i; N represents the total number of nodes in the network; d_{tk} represents the shortest path length from initial node t to node k. The average path length after the removal of each edge in the disaster chain network is calculated using Eq. (2), as presented in Table 4.

Table 4 Average path length of the disaster chain network after the removal of each edge

Removed edge	Average path length	Removed edge	Average path length
$V_1 \rightarrow V_2$	1.77	$V_6 \rightarrow V_7$	1.54
$V_1 \rightarrow V_3$	1.55	$V_8 \rightarrow V_2$	1.54
$V_1 \rightarrow V_8$	1.55	$V_8 \rightarrow V_7$	1.54
$V_1 \rightarrow V_9$	1.62	$V_8 \rightarrow V_9$	1.54
$V_1 \rightarrow V_{10}$	1.67	$V_8 \rightarrow V_{12}$	1.50
$V_1 \rightarrow V_{13}$	1.58	$V_9 \rightarrow V_4$	1.54
$V_2 \rightarrow V_5$	1.50	$V_9 \rightarrow V_7$	1.54
$V_2 \rightarrow V_6$	1.62	$V_{10} \rightarrow V_{11}$	1.62
$V_2 \rightarrow V_7$	1.54	$V_{11} \rightarrow V_2$	1.54
$V_3 \rightarrow V_4$	1.54	$V_{11} \rightarrow V_7$	1.54
$V_3 \rightarrow V_{14}$	1.50	$V_{12} \rightarrow V_{11}$	1.54
$V_5 \rightarrow V_6$	1.54	$V_{13} \rightarrow V_2$	1.54
$V_5 \rightarrow V_7$	1.54	$V_{14} \rightarrow V_7$	1.54

2.2.3 Connectivity

Connectivity refers to the ratio of the number of nodes that remain connected after removing a specific edge to the total number of nodes in the network. The equation is given by

$$H_i = \frac{N_i}{N} \qquad (3)$$

where H_i represents the connectivity of the network after edge i is removed; N_i is the number of nodes that remain connected after edge i is removed. The connectivity after removing each edge in the disaster chain network is calculated using Eq. (3), as presented in Table 5.

Table 5 Connectivity of the disaster chain network after removing each edge

Removed edge	Connectivity	Removed edge	Connectivity
$V_1 \rightarrow V_2$	1.00	$V_6 \rightarrow V_7$	1.00
$V_1 \rightarrow V_3$	1.00	$V_8 \rightarrow V_2$	1.00
$V_1 \rightarrow V_8$	1.00	$V_8 \rightarrow V_7$	1.00
$V_1 \rightarrow V_9$	1.00	$V_8 \rightarrow V_9$	1.00
$V_1 \rightarrow V_{10}$	1.00	$V_8 \rightarrow V_{12}$	1.00
$V_1 \rightarrow V_{13}$	1.00	$V_9 \rightarrow V_4$	1.00
$V_2 \rightarrow V_5$	1.00	$V_9 \rightarrow V_7$	1.00
$V_2 \rightarrow V_6$	1.00	$V_{10} \rightarrow V_{11}$	1.00
$V_2 \rightarrow V_7$	1.00	$V_{11} \rightarrow V_2$	1.00
$V_3 \rightarrow V_4$	1.00	$V_{11} \rightarrow V_7$	1.00
$V_3 \rightarrow V_{14}$	1.00	$V_{12} \rightarrow V_{11}$	1.00
$V_5 \rightarrow V_6$	1.00	$V_{13} \rightarrow V_2$	1.00
$V_5 \rightarrow V_7$	1.00	$V_{14} \rightarrow V_7$	1.00

2.2.4 Edge vulnerability

Edge vulnerability indicates the impact on the network after removing a specific edge from the complex network[14]. Generally, edges with higher vulnerability tend to pose greater risks to the network. The equation is given by

$$V_k = \frac{B_k L_k}{H_k} \qquad (4)$$

where V_k represents the vulnerability of edge k; B_k signifies the betweenness of edge k; L_k denotes the average path length of the network after edge k is removed; H_k represents the connectivity of the network after edge k is removed.

In Eq. (4), edge betweenness serves as a metric to evaluate the importance of a network edge, with higher betweenness indicating a larger flow load at the edge. The average path length and connectivity act as indicators of a network's dispersion and robustness. A higher average path length or lower connectivity suggests reduced connectivity in the newly formed network after edge removal, indicating a more substantial impact on the network's integrity.

Therefore, in a complex network, a higher vulnerability of an edge indicates a greater impact on the network after the removal of that specific edge. This suggests that the edge is more susceptible to damage and signifies its importance within the entire complex network. According

to the results from Tables 3, 4, and 5, the vulnerability of each edge in the earthquake disaster chain network is calculated and presented in Table 6.

Table 6 Vulnerability of each edge of disaster chain networks

Edge	Edge vulnerability	Edge	Edge vulnerability
$V_1 \rightarrow V_2$	7.08	$V_6 \rightarrow V_7$	1.54
$V_1 \rightarrow V_3$	4.64	$V_8 \rightarrow V_2$	4.62
$V_1 \rightarrow V_8$	3.09	$V_8 \rightarrow V_7$	1.54
$V_1 \rightarrow V_9$	1.62	$V_8 \rightarrow V_9$	3.08
$V_1 \rightarrow V_{10}$	3.33	$V_8 \rightarrow V_{12}$	4.50
$V_1 \rightarrow V_{13}$	1.58	$V_9 \rightarrow V_4$	3.08
$V_2 \rightarrow V_5$	10.50	$V_9 \rightarrow V_7$	1.54
$V_2 \rightarrow V_6$	11.31	$V_{10} \rightarrow V_{11}$	9.69
$V_2 \rightarrow V_7$	4.62	$V_{11} \rightarrow V_2$	13.85
$V_3 \rightarrow V_4$	3.08	$V_{11} \rightarrow V_7$	4.62
$V_3 \rightarrow V_{14}$	4.50	$V_{12} \rightarrow V_{11}$	9.23
$V_5 \rightarrow V_6$	1.54	$V_{13} \rightarrow V_2$	6.15
$V_5 \rightarrow V_7$	1.54	$V_{14} \rightarrow V_7$	3.08

Table 6 highlights that the edge "floods→building collapses" has the highest vulnerability, indicating that preventing this hazard is crucial for minimizing damage to the overall disaster network. Disrupting this disaster chain requires implementing appropriate measures to enhance building safety and understanding local flooding history and characteristics before an earthquake strikes. Actions such as river dredging, embankment reinforcement, and cleaning drainage systems are essential. Furthermore, old buildings should be reinforced and renovated to ensure structural stability. Additionally, edges such as "building collapses→leakage of hazardous materials" and "building collapses→fires" also show significant vulnerability, underscoring the importance of timely preventive measures for mitigating earthquake-induced secondary disasters.

3 Risk Analysis of Disaster Chain in Urban Engineering System

3.1 Node loss of disasters

The impact of a disaster event within a complex network can be quantified by the total degree of a node, which is the sum of the node's in-degree and out-degree. In directed networks, the out-degree represents the number of edges originating from a node, while the in-degree indicates the number of edges directed towards it. A higher out-degree suggests that the disaster leads to more subsequent disasters, whereas a higher in-degree implies more contributing factors leading to the disaster occurrence. Nodes with a higher total degree play a more critical role in the entire network and potentially cause greater losses[22]. Therefore, the total degree of nodes is used to gauge the magnitude of node loss for the disaster chain network. The node loss in the disaster chain network is presented in Table 7.

Table 7 Node loss of disaster chain networks

Node	Node loss	Node	Node loss
V_1	6	V_8	5
V_2	7	V_9	4
V_3	3	V_{10}	2
V_4	2	V_{11}	4
V_5	3	V_{12}	2
V_6	3	V_{13}	2
V_7	7	V_{14}	2

3.2 Causation rate of disasters

In the evolutionary progression of a disaster chain, the likelihood of a disaster's occurrence is often related to the preceding event connected to it within the disaster chain network. The causation rate is used as the probability for calculating the risk level. To quantify the causation rate, the Jaccard index is introduced and modified. The original expression is commonly used to analyze the correlation between events and is as follows:

$$J_{ab} = \frac{C_{ab}}{C_a + C_b - C_{ab}} \tag{5}$$

where J_{ab} represents the co-occurrence rate of events a and b; C_a and C_b represents the frequencies of events a and b; C_{ab} represents the co-occurrence frequencies of events a and b.

In this study, the causation rate of disaster a leading to disaster b can be expressed using the following modified Jaccard index:

$$J'_{ab} = \frac{C'_{ab}}{C_a + C_b - C'_{ab}} \tag{6}$$

In Eq. (6), J'_{ab} represents the causation rate of disaster a triggering disaster b, and $0 \leqslant J'_{ab} \leqslant 1$; C'_{ab} is defined as the frequency of disaster a causing disaster b. The results of causation rates between earthquake secondary disasters, as calculated using Eq. (6), are presented in Table 8.

Table 8 Causation rates between earthquake secondary disasters

Edge	J'_{ab}	Edge	J'_{ab}
$V_1 \rightarrow V_2$	0.647	$V_6 \rightarrow V_7$	0.028
$V_1 \rightarrow V_3$	0.471	$V_8 \rightarrow V_2$	0.556
$V_1 \rightarrow V_8$	0.480	$V_8 \rightarrow V_7$	0.556
$V_1 \rightarrow V_9$	0.490	$V_8 \rightarrow V_9$	0.778
$V_1 \rightarrow V_{10}$	0.137	$V_8 \rightarrow V_{12}$	0.217
$V_1 \rightarrow V_{13}$	0.020	$V_9 \rightarrow V_4$	0.889
$V_2 \rightarrow V_5$	0.121	$V_9 \rightarrow V_7$	0.208
$V_2 \rightarrow V_6$	0.121	$V_{10} \rightarrow V_{11}$	0.571
$V_2 \rightarrow V_7$	1.000	$V_{11} \rightarrow V_2$	0.121
$V_3 \rightarrow V_4$	0.852	$V_{11} \rightarrow V_7$	0.057
$V_3 \rightarrow V_{14}$	0.042	$V_{12} \rightarrow V_{11}$	0.500
$V_5 \rightarrow V_6$	0.143	$V_{13} \rightarrow V_2$	0.030
$V_5 \rightarrow V_7$	0.057	$V_{14} \rightarrow V_7$	0.030

3.3 Risk level of disaster chain

In the disaster chain network, the risk level of an edge is equal to the product of the probability of that edge, the node loss, and the vulnerability of that edge. The equation is expressed as

$$R_{ab} = J'_{ab} K_b V_{ab} \qquad (7)$$

where R_{ab} represents the risk level of edge ab; K_b denotes total degree associated with node b (see Table 7); V_{ab} signifies the vulnerability of the edge ab. According to results from Tables 6, 7, and 8, the risk level of edges in the disaster chain network is calculated using Eq. (7). The resulting risk levels for each edge in the single chain are presented in Table 9.

According to Eq. (7), the risk level of a composite disaster chain in the network is expressed as

$$R = J'_a K_a V_a + J'_{ab} K_b V_{ab} + \ldots + J'_{mn} K_n V_{mn} \qquad (8)$$

where R represents the risk level of a composite disaster

Table 9 Risk level of edges of disaster chain networks

Edge	Risk level of edge	Edge	Risk level of edge
$V_1 \rightarrow V_2$	32.054	$V_6 \rightarrow V_7$	0.299
$V_1 \rightarrow V_3$	6.545	$V_8 \rightarrow V_2$	17.949
$V_1 \rightarrow V_8$	7.418	$V_8 \rightarrow V_7$	5.983
$V_1 \rightarrow V_9$	3.167	$V_8 \rightarrow V_9$	9.573
$V_1 \rightarrow V_{10}$	0.915	$V_8 \rightarrow V_{12}$	1.957
$V_1 \rightarrow V_{13}$	0.062	$V_9 \rightarrow V_4$	5.470
$V_2 \rightarrow V_5$	3.818	$V_9 \rightarrow V_7$	2.244
$V_2 \rightarrow V_6$	4.112	$V_{10} \rightarrow V_{11}$	22.154
$V_2 \rightarrow V_7$	32.308	$V_{11} \rightarrow V_2$	11.748
$V_3 \rightarrow V_4$	5.242	$V_{11} \rightarrow V_7$	1.846
$V_3 \rightarrow V_{14}$	0.375	$V_{12} \rightarrow V_{11}$	18.462
$V_5 \rightarrow V_6$	0.659	$V_{13} \rightarrow V_2$	1.305
$V_5 \rightarrow V_7$	0.615	$V_{14} \rightarrow V_7$	0.653

chain. For primary disaster events, $J'_a = 1$, and V_a denotes the maximum vulnerability value among all edges within the network. The results of the risk levels for various disaster chains in the seismic disaster chain network of urban engineering systems are organized as presented in Table 10.

Table 10 Risk level of disaster chains in the chain network

No.	Disaster chain	Expression	Risk level
1	$V_1 \rightarrow V_8 \rightarrow V_{12} \rightarrow V_{11} \rightarrow V_2 \rightarrow V_7$	Earthquake→landslides and debris flows→dammed lakes→floods→building collapses →casualties	155.0
2	$V_1 \rightarrow V_{10} \rightarrow V_{11} \rightarrow V_2 \rightarrow V_7$	Earthquake→dam failures→floods→building collapses→casualties	150.2
3	$V_1 \rightarrow V_2 \rightarrow V_7$	Earthquake→building collapses→casualties	147.4
4	$V_1 \rightarrow V_8 \rightarrow V_2 \rightarrow V_7$	Earthquake→landslides and debris flows→building collapses→casualties	140.8
5	$V_1 \rightarrow V_8 \rightarrow V_{12} \rightarrow V_{11} \rightarrow V_2 \rightarrow V_5 \rightarrow V_6 \rightarrow V_7$	Earthquake→landslides and debris flows→dammed lakes→floods →building collapses →leakage of hazardous materials→fires→casualties	127.4
6	$V_1 \rightarrow V_8 \rightarrow V_{12} \rightarrow V_{11} \rightarrow V_2 \rightarrow V_5 \rightarrow V_6$	Earthquake→landslides and debris flows→dammed lakes→floods →building collapses →leakage of hazardous materials→fires	127.1
7	$V_1 \rightarrow V_8 \rightarrow V_{12} \rightarrow V_{11} \rightarrow V_2 \rightarrow V_5 \rightarrow V_7$	Earthquake→landslides and debris flows→dammed lakes→floods →building collapses →leakage of hazardous materials→casualties	127.1
8	$V_1 \rightarrow V_8 \rightarrow V_{12} \rightarrow V_{11} \rightarrow V_2 \rightarrow V_6 \rightarrow V_7$	Earthquake→landslides and debris flows→dammed lakes→floods →building collapses →fires→casualties	127.1
9	$V_1 \rightarrow V_8 \rightarrow V_{12} \rightarrow V_{11} \rightarrow V_2 \rightarrow V_6$	Earthquake→landslides and debris flows→dammed lakes→floods →building collapses →fires	126.8
10	$V_1 \rightarrow V_8 \rightarrow V_{12} \rightarrow V_{11} \rightarrow V_2 \rightarrow V_5$	Earthquake→landslides and debris flows→dammed lakes→floods →building collapses →leakage of hazardous materials	126.5

Table 9 illustrates notable differences in the risk levels among various edges in the disaster chain network. The highest risk level is associated with the edge "building collapses→casualties," followed by "earthquake→building collapses." Table 10 reveals that the chains "earthquake→building collapses→casualties," "earthquake→landslides and debris flows → dammed lakes," and "dammed lakes → floods → building collapses" are frequently encountered among the top 10 disaster chains with the highest risk levels. During the Wenchuan earthquake, intense main and aftershocks triggered numerous secondary disasters, such as building collapses, landslides, mudslides, and debris flows in the affected area. Massive landslides blocked rivers, creating 256 barrier lakes that persisted for more than 14 d[23]. This observation is con-

sistent with the findings of our research.

Additionally, earthquake disaster chains often demonstrate long-chain effects in urban engineering systems. Disaster chains with more than three links are typically referred to as long chains. As presented in Table 10, among the 10 disaster chains with higher risk levels, there exist three chains with five links and three with six links; the longest disaster chain encompasses seven links, and it is considered an ultralong chain. A significant characteristic of a long chain is that even if the initial part of the chain is disrupted, subsequent events may still unfold, posing challenges for halting secondary disasters. The main reason for the formation of long disaster chains is the inherent complexity of urban engineering systems, which are highly prone to triggering cascading failures when natural

disasters occur, thereby causing the disaster chain to continuously lengthen.

Therefore, in post-earthquake measures, it is crucial to proactively address these high-risk edges of the disaster chain, promptly implement strategies to disrupt the chain, and effectively reduce the occurrence of earthquake-induced secondary disasters. A summary of interventions for high-risk edges is presented in Table 11.

Table 11   Measures for chain breaking on edges with higher risk levels

Disaster chain	Examples of mitigation measures
Earthquake → building collapses→casualties	Promote seismic isolation technology and energy dissipation techniques to reduce or prevent damage to buildings; enhance seismic design standards for buildings in seismic zones, especially critical facilities such as schools and hospitals; conduct comprehensive safety assessments for existing buildings and carry out timely seismic retrofitting[24]
Earthquake → landslides and debris flows →dammed lakes	Conduct comprehensive geological hazard identification and risk assessment; avoid earthquake fault zones and geological hazard-prone areas during the selection of sites for major projects; implement measures such as vegetation coverage and slope protection in high-risk geological hazard areas to prevent landslides and collapses
Dammed lakes → floods → building collapses	Conduct safety assessments and inspections and establish long-term monitoring systems for dammed lakes; form spillways through natural erosion or manual excavation to lower water levels and mitigate downstream flood risks if necessary[25]

4   Conclusions

1) According to news reports on domestic earthquakes from the past decade, covering 51 earthquakes with magnitudes of $\geqslant 6.0$ and associated secondary disaster incidents, 14 representative and frequently occurring secondary disasters are identified as nodes. Causal relationships between these disasters are extracted from the news reports to construct a network depicting the evolution of earthquake-induced secondary disasters using complex network theory.

2) Through vulnerability analysis of the complex network, the vulnerability of each edge is calculated. The edge "floods→building collapses" shows the highest vulnerability, highlighting an increased associated risk. Effective preventive measures should be promptly implemented to mitigate this risk.

3) Analysis of the disaster chain in urban engineering systems reveals that the highest risk is associated with "building collapses→casualties," and other high-risk edges include "earthquake→building collapses." The chains "earthquake → building collapses → casualties," "earthquake→landslides and debris flows→dammed lakes," and "dammed lakes→floods→building collapses" are frequently among the top 10 disaster chains with the highest risk levels.

4) Earthquake disaster chains often display long-chain effects in urban engineering systems. Among the top 10 disaster chains with higher risk levels, seven consist of five or more links; the longest chain comprises seven links. The primary reason for the formation of long disaster chains is the inherent complexity of urban engineering systems, which are susceptible to triggering cascading failures during natural disasters, thereby extending the disaster chain continuously. Prompt implementation of measures to disrupt high-risk edges in disaster chains is essential following an earthquake.

5) One limitation of this study is the exclusion of secondary disaster intensity levels, which could affect the comprehensiveness of the analysis. Future research should more precisely investigate the specific impacts of these intensity levels on the overall disaster scenario.

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基于复杂网络的城市工程系统地震灾害链模型

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摘要：通过收集 2008 年以来重大地震事件的新闻报道，分析 51 起震级大于等于 6.0 级的地震，总结出 14 个出现频次较高、具有代表性的地震次生灾害事件. 然后基于复杂网络理论构建灾害网络拓扑结构模型，对该模型的各边分别进行脆弱度和风险度的计算，最终确定风险度较高的连接边和灾害链. 结果表明："洪灾→建筑倒塌"的脆弱度最高，从防范地震次生灾害的角度对其事前采取断链措施有利于最大程度延缓次生灾害的传播；"建筑倒塌→人员伤亡"的风险度最大，同时灾害链当中"地震→建筑物倒塌→人员伤亡""地震→山体滑坡和泥石流→堰塞湖"和"堰塞湖→洪水→建筑物倒塌"等链的风险也较高. 在地震灾害发生后应及时对这些风险度较大的边采取断链措施，从而有效减少地震次生灾害的危害.

关键词：地震；灾害链；抗震韧性；次生灾害；复杂网络；脆弱度；风险度

中图分类号：TU312