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A scenario-based model for earthquake emergency management effectiveness evaluation

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ABSTRACT

Earthquakes usually produce a complex disaster chain including fires, landslides, floods, plague, and social panic, which eventually leads to disastrous consequences. In such situations, earthquake emergency management is vital for reducing the risks and the disastrous consequences. Scenario-based methods have often been used by decision makers in different fields as an instrument to manage the uncertainty of the effects of earthquakes. This paper adopts a scenario-based model to evaluate the effectiveness of earthquake emergency management. The model extracts the key elements of earthquake emergency management, simulates possible earthquake disaster scenarios, and obtains an evaluation according to the real situation. It is verified by comparing it with the real situation of the Wenchuan earthquake in China through scenario deduction and simulation. It shows that the scenario-based model can be used to reproduce the development process of an earthquake, identify the key factors which can effectively reduce earthquake losses and then help policy makers to have a better understanding of the earthquake disaster from which to put forward practical measures for emergency management.

1. Introduction

Among natural disasters, earthquakes represent one of the most unpredictable, lethal and devastating phenomena from an economic and social standpoint. Besides the collapse of a large number of buildings and mass damage to critical lifeline engineering infrastructure, an earthquake usually also triggers a series of secondary derivative disasters such as landslides, fires, floods, plague, and social unrest. There is a strong possibility that it will cause serious casualties, huge economic losses and other catastrophic consequences. Since earthquakes disaster is a great threat to human lives, economic development and social system, immense effort has been made to control risks and mitigate losses. Most of the studies have been limited to single earthquakes disaster. But the emergency strategies for single disaster may be less effective when there are other unexpected secondary events (Kumasaki et al., 2016). For the reliable effective emergency management of earthquakes, secondary disasters should be taken into account in management strategies. However, the occurrence of each specific secondary event depends on the local geological conditions, economic development, cultural identity, political factors and so on. The secondary disasters chain is a complex system which is difficult to predict accurately.

The scenario method, aimed at developing alternative visions of the future, is well known as an approach to studying situations that can lead to vital changes and in which it is difficult to create explicit relationships among events. Moreover, the scenario model can be integrated with other predictive models which enable diverse flexible approaches to face uncertain issues (Bañuls et al., 2013; Carpenter et al., 2006; De Lattre-Gasquet, 2006; Yang et al., 2017). It can help decision makers analyze a variety of the possible future trends, identify the key factors and make the best decisions. Several researchers from different domains of knowledge have already contributed different approaches to scenario-generation techniques. In this paper, a scenario-based model is proposed to estimate possible evolutions of earthquakes. This model aims to evaluate earthquake emergency management effectiveness.

The high death of the Wenchuan earthquake makes this issue a focus in China. The model is applied to the Wenchuan 8.0 earthquake occurred in Sichuan, China on May 12, 2008. The epicenter was located in Yingxiu Town, Wenchuan County. > 100,000 km^2 of land were damaged. Apart from the collapse of a large number of buildings and serious damage to the critical infrastructure, this devastating earthquake also caused a series of secondary disasters, including aftershocks, landslides, debris flows, etc. According to statistics, the Wenchuan

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earthquake killed > 69,000 killed people, with > 37 million injured, and nearly 18,000 missing. Direct economic losses totaled > 840 billion RMB. Significantly, more than one third of the casualties and economic losses were caused by the various types of secondary disasters and other emergencies triggered by the earthquake.

The rest of the paper is organized as follows. The relevant literature on earthquakes, scenario methods and emergency management are reviewed in Section 2. Section 3 outlines the methodology adopted by the study. A scenario-based model is constructed by considering the whole process of earthquake emergency management. The other purpose of Section 3 is to identify the key factors in earthquake emergency management through a sensitivity analysis. In Section 4, the model is applied to the Wenchuan earthquake for scenario deduction and simulation, and is followed by results. Section 5 discusses the implications of the model for emergency management decision-makers. And the study is compared with other related researches. Section 6 is the conclusion and is focused on presenting specific recommendations for the goal of improving earthquake emergency management.

2. Literature review

The research on earthquakes has focused on seismic fragility assessment, earthquake loss evaluation and seismic secondary derivative disasters. Del Gaudio and Ricci (2016) believed that the consequences in terms of casualties and direct or indirect damage to the structures and infrastructures are related to the quality and type of constructions. They use a simplified analytical method for a seismic fragility assessment of reinforced concrete buildings on a large scale. The US Federal Emergency Management Agency and the US National Institute of Architecture jointly developed a model called HAZUS for assessing the loss caused by an earthquake, and with further improvements, the model can make basic loss estimates, detailed regional loss estimates and more specific loss estimates of buildings (Wang, 2014). Wang (2005) confirmed that the method of predicting casualties caused by earthquakes with GDP and population density as parameters is applicable to small areas. The research on seismic loss assessment is developing rapidly, and various evaluation methods are becoming more mature. Most of this research is focused on casualties and direct economic losses, but there is a lack of research on secondary derivative disaster losses and indirect economic losses from the impact of the secondary disaster chain. The disasters triggered by earthquakes have been highlighted as the initial earthquake disaster is compounded by those secondary events (Kumasaki et al., 2016). The study of earthquake secondary derivative disaster chains is mainly confined to earthquake-induced fires, poison gas leaks, and explosion disasters. Longinow et al. (1990) considered the failure of the gas and electrical systems during earthquakes and constructed a risk model of secondary fire disasters. Antonioni et al. (2007) analyzed the secondary hazards induced by earthquakes such as the leakage of hazardous substances and fire. Ji et al. (2008) used cellular automata to study the risk assessment method of the earthquake disaster chain and included social factors such as population density and sensitivity to provide a scientific basis for the emergency response to the disaster chain. Baiocchi et al. (2017) identified possible urban microclimate changes in a city after a seismic event. Contreras et al. (2017) analyzed spatial resilience in the recovery process in L'Aquila. They concluded that the allocation of facilities was oriented to supply basic services but neglected other needs of the community which reduces its resilience. Human have an emotion that is quite prevalent in response to a sudden natural disaster. The study calls this emotion panic. The consequences of panic for earthquake response behavior are complex. Social unrest is a kind of group response behavior (Nardulli et al., 2015; Khaldun et al., 2016; Lavin et al., 2017). Goltz and Bourque (2017) suggested that behavior during a rapid onset disaster is diverse, varies with social context, and is largely rational, adaptive and consistent with norms and role performance. They also mentioned that fear, this study calls it panic, proved to be a very interesting variable and a component in motivating certain behaviors. The above research on the earthquake disaster chain is generally focused on a specific secondary derivative hazard caused by an earthquake. As to a more integrated earthquake secondary disaster chain, there is qualitative and descriptive analysis, but a lack of quantitative analysis.

Postma and Liebl (2005) indicated several methods of scenario construction in order to enhance the practicality of scenario analysis in decision management. Mahmoud et al. (2009) put forward a formal framework for scenario development in support of environment-based decision-making. Pomerol (2001) addressed the question of how decision-makers manage the combinatorial explosion in scenario development under uncertainty and suggested some ideas for scenario management. Alizadeh et al. (2016) presented a scenario-building framework to help energy industries develop more resilient conservation policies when faced with uncertainties. Fink and Schlake (2000) explained how CI professionals can develop corporate, industry, market and global scenarios, and described the integration of these scenarios into the processes of competitive intelligence and strategic management. Chang et al. (2007) relied on scenario analysis to develop a decision-making tool that can be used by government agencies in planning for flood emergency logistics. Jenkins (2000) studied how to select one or two of the most informative scenarios for environmental disaster planning for disasters like the release of thousands of tons of crude oil or chemicals in large quantities. Bañuls et al. (2010) proposed a step-by-step model for clustering scenarios via cross-impact and added tools for detecting critical events. Scenario-based methods were also combined with other methods to solve specific problems based on the real situation, see Alizadeh et al. (2016), and Banuls and Salmeron (2007).

Government-led disaster emergency management is currently adopted by most countries. It is important for reducing risks and protecting people and property. Some studies have been made about the assessment of earthquake emergency management. Wex et al. (2014) came up with a decision support model to help solve the rescue unit assignment scheduling problem which is one of the key issues in emergency management. Avvenuti et al. (2014) used Social Media to gather updated information about earthquakes in order to improve earthquake emergency management. Ren et al. (2016) assessed earthquake emergency plan implementation by evaluating 30 indicators in terms of operational mechanism, emergency response, and emergency safeguards. David (2005) offered some suggestions, guidelines, and models for the assessment of emergency plans. Vu and Noy (2015) summarized that the Chinese government was fairly effective at distributing resources across its extensive reach after large natural disasters and could mitigate some of the indirect adverse impacts. Cole et al. (2017) examined the impact of pre-disaster planning and post-disaster aid on firms recover after a natural disaster. They found that pre-disaster policies such as having alternative transport arrangements and a diversified supplier network positively affect post-disaster sales. And the post-disaster aid from banks and trading partners also has a positive influence. Evaluating and improving emergency management capabilities by taking into account possible future disaster scenarios under the current emergency preparations and possible emergency response scenarios is a new idea. There is no integrated model of earthquake emergency management effectiveness evaluation. However, it is believed that the scenario method can be one of the solutions.

3. Methodology

3.1. Scenario-based assessment model construction

A scenario-based model is proposed to make a comprehensive evaluation of the effectiveness of earthquake management work. This tool is a combination of the Delphi Method, Cross-impact Method (CIA) and Interpretive Structural Modeling (ISM). By means of the Delphi Method and CIA, the correlation among events related to an earthquake can be understood clearly. This model aims to make a scenario analysis and deductions about the development of earthquakes, in order to put forward some useful proposals for decision makers and improve earthquake emergency management work.

3.1.1. Event set creation

Event set creation is a straightforward process based on observing and studying historical cases of earthquakes. It is important to get a comprehensive set of possible events; 30 related events are selected in this work. According to the nature of the events, they are classified according to three categories:

Initial Conditions (IC_i): Initial conditions are assumptions, a-priori or source events that have already occurred before an earthquake or which have a probability of being true or false at the time of an earthquake. They are chosen to reflect the status of earthquake emergency management and other critical events which may potentially have a major influence on subsequent events. All such initial conditions are assumed to have 0.5 probability which means the conditions will occur or not occur with the same probability.

IC1: The earthquake happens during work time in the daytime.
IC2: The earthquake happens during rest time in the night.
IC3: The earthquake happens during the peak electricity-using period.
IC4: The population density in the disaster area is high.
IC5: Most of the buildings in the disaster area have poor seismic performances.
IC6: The lifeline system and infrastructure have poor seismic performances.
IC7: The government has perfect emergency plans.
IC8: The key enterprises and factories have emergency plans, strong aseismic and earthquake disaster reduction consciousness.
IC9: The government has regularly carried out large-scale emergency drills and the public has strong aseismic and earthquake disaster reduction consciousness.
IC10: The disaster prevention project and emergency material reserves meet the requirements.

Dynamic Events (DE_i): Dynamic events are related events after an earthquake happens. They are chosen to reflect the possible secondary disasters caused by an earthquake, the possible emergency rescue measures taken by the government and the public, and other possible situations. Like the initial conditions, all such dynamic events are initially assumed to have a 0.5 probability.

DE1: Aftershocks of magnitude 6 happen several times.
DE2: A large number of buildings collapse.
DE3: Large-scale fires happen several times.
DE4: The earthquake causes landslides.
DE5: Dams or dammed lakes burst causing flooding.
DE6: Hazardous gas, bacteria or other dangerous radioactive substance leak and diffuse.
DE7: Water supply, electricity supply and gas supply are destroyed.
DE8: The communication network is interrupted.
DE9: The traffic system is paralyzed.
DE10: The health situation in the living environment in the disaster area deteriorates resulting in the outbreak of infectious diseases.
DE11: Looting, robbery and other social unrest are caused.
DE12: Professional emergency rescue teams undertake efficient rescue task.
DE13: Humanitarian aid can be delivered to the population in need.
DE14: The emergency shelter can provide shelter, emergency medical care and basic living facilities for victims and establish rescue command sites.
DE15: The government can call upon and organize enterprises, nonprofit organizations and volunteers to join in the rescue.
DE16: The government can guide public opinion and defuse public discontent effectively.

Outcome Events (OE_i): Outcome events refer to the results of the earthquake. Three typical negative outcomes are listed. These are also assumed to be 0.5 as an initial probability.

OE1: The earthquake causes heavy casualties.
OE2: The earthquake causes huge economic losses.
OE3: The poor emergency rescue work causes public resentment and leads to social panic.

3.1.2. The Delphi Method application process

It is a highly time-consuming process to get the causal relationship estimates between every two events in the event set. A total of 18 experts in the field of emergency management, as well as specialists engaged in front-line rescue have been invited to comprise the expert panel. The Delphi Method is based on anonymous communication with feedback. This process is designed and implemented through the following steps:

(1) Soliciting estimates about the relationships among these three types of components (initial conditions, dynamic events and outcome events). An initial probability of 0.5 is assumed for the occurrence of each event as mentioned before. Due to the different nature of each event, there are 478 causal relationship estimates that must be made by the panel, see Fig. 1.

(2) Each expert is told to indicate either a probability estimate change of the event i (E_i) (i = 1, 2, …, 30) from 0.5, given that the event j (E_j) (j = 1, 2, …, 30) is supposed to occur. The estimate of the impact that the occurrence of E_j may have on the occurrence of E_i depends on the following rules in Table 1 that is the score table.

(3) The Delphi Method is a cyclical process. It should finish with a consensus estimate about the direction and degree of the impact. It is considered to have reached an agreement when no less than two-thirds of the estimated values for a single interaction are all in one of these four intervals: between 0.01 and 0.3, between 0.2 and 0.5, between 0.5 and 0.8, or between 0.7 and 0.99.

(4) Once there is an agreement on the direction and degree of the relationship between any two events, the arithmetic mean of the estimates is used as the final estimated value. The estimation matrix can serve as the input for the cross-impact process (for this see Table A.1 in the Supplementary materials). The cells in the matrix are the impact estimations R_{ij} (representing the impact that the occurrence of E_j may have on the occurrence of E_i), the diagonal cells are the overall probabilities (OPV).

3.1.3. The cross-impact analysis process

By using the process described above, the estimation matrix is obtained as the input for the cross-impact process. Based on the cross-impact formula as Eqs. (1), (2), the cross-impact matrix can be built (see Table A.2 in the Supplementary materials). The cells in the matrix are the influence factors C_{ij} (representing the influence coefficient of E_j on E_i), the diagonal cells are the overall probabilities (OPV), G_i represents the impact of external events which are not included in the model on

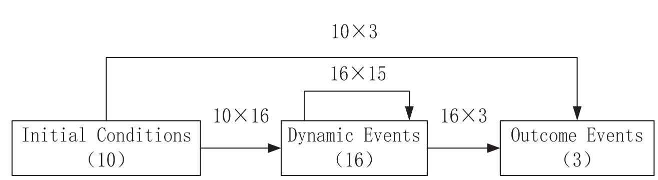


Fig. 1. Influence diagram with the number of events and the number of estimates needed.

Table 1
Score table.

Number	Explanation
0.99	Significant positive impact.
0.9	Obvious positive impact.
0.8	Great positive impact.
0.7	A certain positive impact.
0.6	Slight positive impact.
0.5	No impact.
0.4	Slight negative impact.
0.3	A certain negative impact.
0.2	Great negative impact.
0.1	Obvious negative impact.
0.01	Significant negative impact.

each event. A positive value of C_{ij} means the occurrence of E_j can push the occurrence of E_i and a negative one obstructs the occurrence. In this context, the words “positive” and “negative” denote the direction of the impact (+ or-).

$$C_{ij} = \frac{1}{1-P_j}\left\{\left[\ln\frac{R_{ij}}{(1-R_{ij})}\right]-\left[\ln\frac{P_i}{(1-P_i)}\right]\right\} \quad (1)$$

where:

i, j represents an event, respectively
R_{ij} represents the impact that the occurrence of E_j may have on the occurrence of E_i
$P_{i,j}$ represents the probability for the occurrence of $E_{i,j}$

$$P_i = \frac{1}{1+\exp\left(-G_i-\sum_{k\neq i}^{N} C_{ik}P_k\right)} \quad (2)$$

where:

$P_{i,k}$ represents the prediction probability of $E_{i,k}$
G_i represents the impact of external events on E_i

In order to assess the rationality of the event set, the following sums of the factors are examined from Table A.2.

$$|\text{Internal events impacts}| = \sum |C_{ij}| = 719.09$$

$$|\text{External events impacts}| = \sum |G_i| = 136.24$$

$$|\text{Total impacts}| = \sum |C_{ij}| + \sum |G_i| = 855.32$$

$$|\text{Internal events impacts}|/|\text{Total events impacts}| = 84.07\%$$

$$|\text{External events impacts}|/|\text{Total events impacts}| = 15.93\%$$

As can be seen, 84.07% of the total impacts are explained by the events explicitly included in the model and 15.93% are due to the events which are not included. It means the event set is to some degree comprehensive and the model is feasible. Once the cross-impact matrix is obtained, a limit value can be set to extract the most critical events in the event set as the inputs for the Interpretive Structural Modeling (ISM). From Fig. 2, that of the histogram of cross-impact factors, the limit value is $|C_{ij}| = 1.75$ when the most significant impacts of the first 30% need to be extracted.

3.1.4. The interpretive structural modeling application process

This scenario-based model can be graphically expressed by the Interpretive Structural Modeling (ISM). The starting point of ISM methodology is a collection of events.

$$S = \{S_1, S_2, S_3, \ldots, S_n\} \quad (3)$$

The relationship between the elements in set S are binary and the adjacency matrix A can be calculated from these binary relationships, defined as a binary n × n matrix. The cells in the matrix are a_{ij} which can be calculated.

$$a_{ij} = \begin{cases} 1, & S_i R S_j \\ 0, & S_i \overline{R} S_J \end{cases} \quad (4)$$

where:

1 represents the direct connection from node S_i to node S_j
0 represents no direct connection from node S_i to node S_j

With matrix A, the reachability matrix R that is a square, transitive, reflexive, and binary matrix can be obtained.

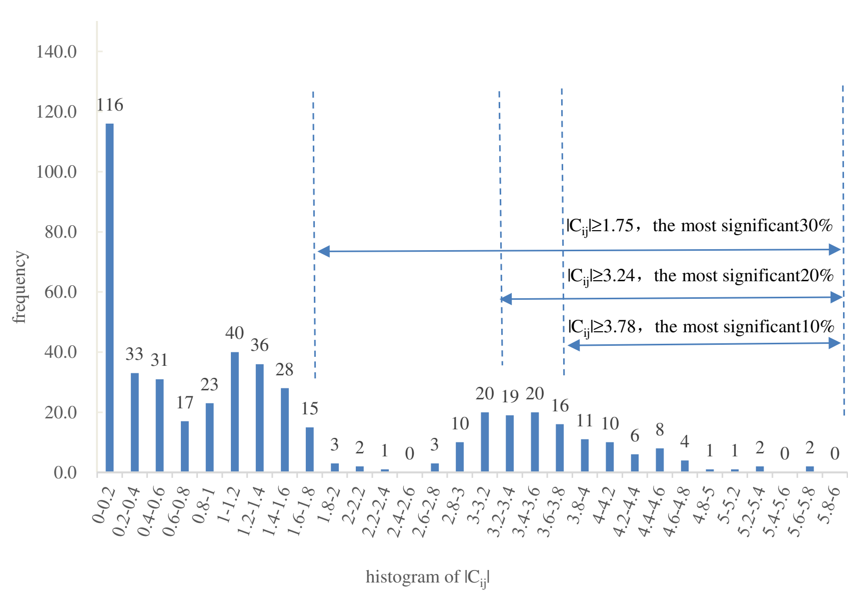
$$R = (A+I)^m = (A+I)^{m-1} \neq (A+I)^{m-2} m = 1, 2, 3\ldots \quad (5)$$

where:

I is the identity matrix

The cells in the matrix are r_{ij} can be calculated.

Fig. 2. Histogram of cross-impact factors.



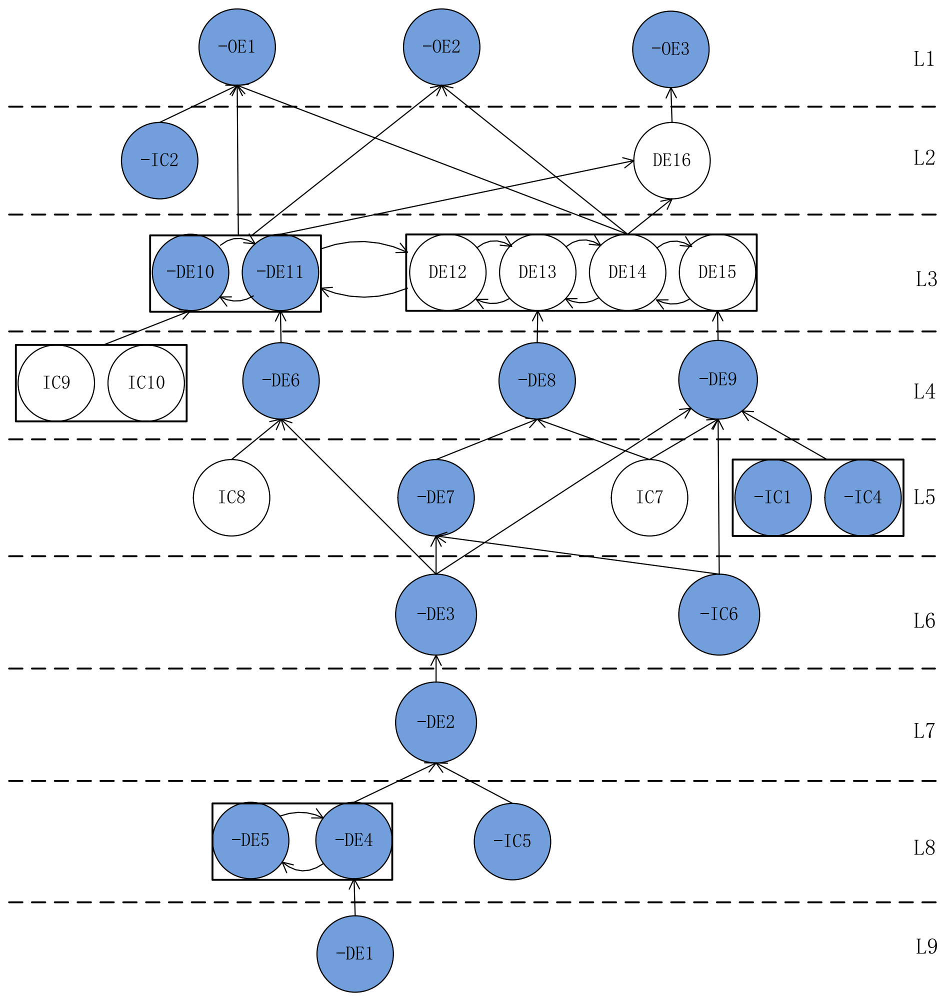


Fig. 3. Digraph for the limit value $|C_{ij}| = 1.75$ – with 30%.

$$r_{ij} = \begin{cases} 1, & \text{node } S_i \text{ can reach node } S_j \\ 0, & \text{node } S_i \text{ cannot reach node } S_j \end{cases} \tag{6}$$

Then, the nodes are divided into two sets: antecedents (Ant) and succedents (Suc). Ant (S_i) is constructed with all of the elements which can reach S_i, and Suc (S_i) is constructed with all of the elements which S_i can reach. And a collection set C = Ant∩Suc can be got. If $C(S_i) = Ant(S_i)$, the element S_i is divided into the high level, and moves on like this until all the elements are divided into different levels. By means of partitioning and extracting from the matrix model, a multi-level digraph can be obtained.

This process aims to obtain the structure of the strong relationships portrayed in a digraph model. If the value of $|C_{ij}|$ is greater than or equal to the limit value, it means that there is a direct connection from node S_j to node S_i. Matrix A should be square, positive and binary. The cross-impact matrix is not a positive one, so it needs to be transformed into a positive matrix with all its elements greater than or equal to zero. If $C_{ij} < 0$, the occurring event $E_{i,j}$ needs to be transferred to the non-occurring event - $E_{i,j}$.

By applying the ISM approach, the forecasted scenario can be represented in scenario digraphs which can show the direction and the degree of the impact between the events. Figs. 3 and 4 are the digraphs for the limit value $|C_{ij}| = 1.75$ – with 30% and $|C_{ij}| = 3.78$ – with 10%, respectively. In the figures, the different colors represent the different directions of the impacts. A relationship between two events of the same color represents a positive impact, while those with different colors are negative impacts. In Fig. 3, there is no IC3 because of its weaker relationship with other events ($|C_{ij}| < 1.75$). The interaction between DE10 and DE11 is the strongest in all secondary derivative disasters. It means the outbreak of infectious diseases is most likely to cause social panic compared with other secondary disasters. DE12, 13, 14, and 15 constitute a micro set which means they have positive impacts on each other and usually happen together. IC9 and IC10 have a direct negative impact on DE10 and DE11, which means that public disaster prevention consciousness, a disaster prevention project and emergency material reserves can almost certainly avoid the outbreak of infectious diseases and social panic. DE8 and DE9 have a direct negative impact on the rescue work, which should be covered in government emergency plans (IC7). A large number of buildings collapsing (DE2) at the lower level is a precursor to the emergence of other secondary derivative disasters.

In Fig. 4, the top 10% strong relationships are selected to construct the scenario digraph. Compared with Fig. 3, the relationships among the events are further refined. IC1, 2, and 8 disappear because of their weak relationships with the other events ($|Cij| < 3.78$). The micro scene set (DE12, 13, 14, and 15) is separated into three levels. The interactions among them and the disaster events are refined. In all emergency response work, the professional rescue team's quick action (DE12) has a direct and important impact on reducing casualties (OE1) and controlling social panic (OE3). The government's effort to guide public opinion (DE16) makes a considerable contribution to controlling social panic (OE3). In all secondary derivative disasters, fires (DE3) have a direct and significant impact on casualties (OE1) and economic losses (OE2). The guidance given by the emergency preparations (IC7, 9, and 10) to the rescue work (DE13, 14, 15, and 16) is clarified. In all emergency preparation work, IC5 and IC6 are at the lowest level, which

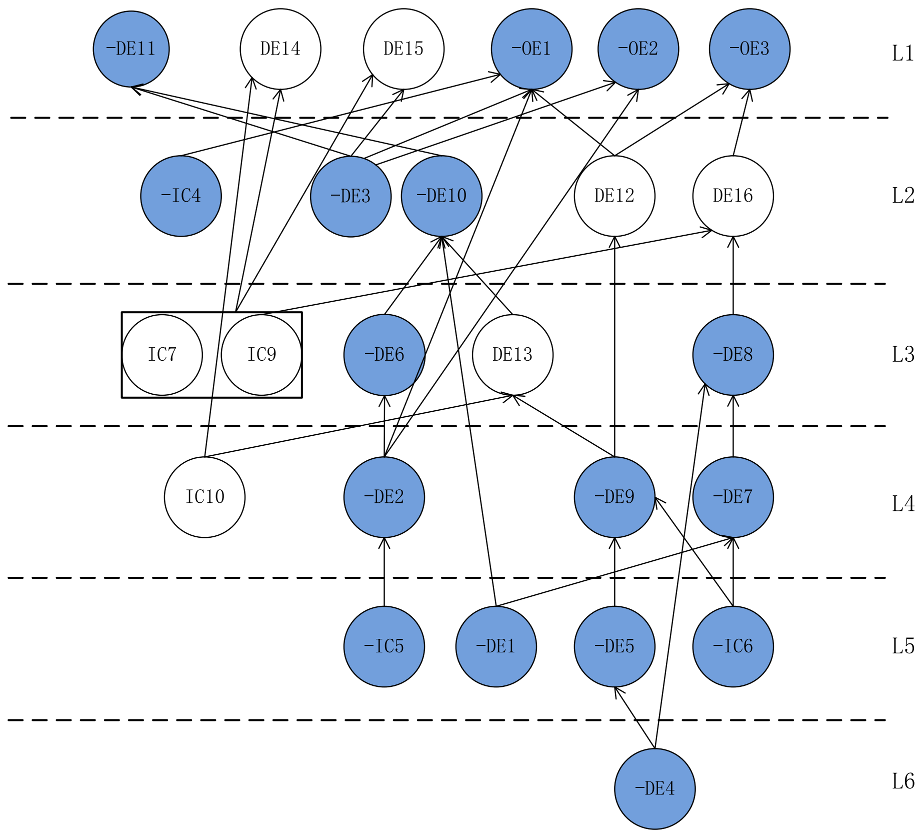


Fig. 4. Digraph for the limit value $|C_{ij}| = 3.78$ – with 10%.

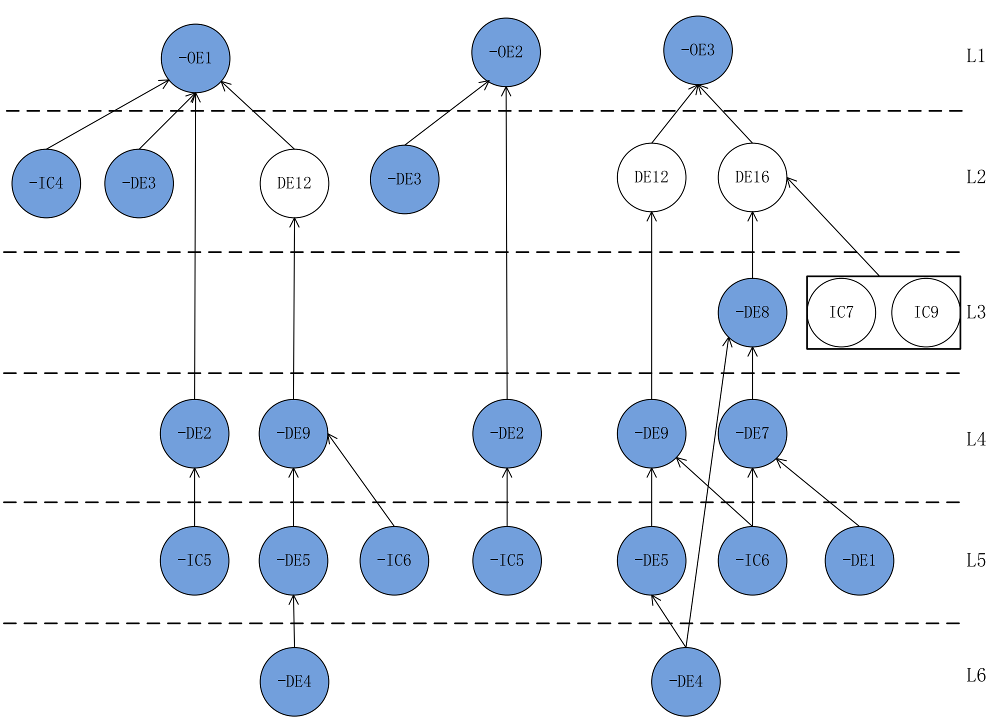


Fig. 5. Digraph for the three outcome events for the limit value $|C_{ij}| = 3.78$ – with 10%.

means the seismic performance of buildings and infrastructure is the fundamental point of concern for emergency preparations.

Fig. 5is the digraph for the three outcome events for the limit value $|Cij| = 3.78$ – with 10%. In it, three mini-scenarios related to the three outcome events are created in order to focus on the losses from the earthquake. IC7, IC9, DE12, and DE16 are still in the scenario digraph, which means they are the pivotal events in earthquake emergency management.

3.2. Earthquake scenario analysis and deduction

The output of the Interpretive Structural Modeling combined with

Table 2
Prediction probabilities of the other events in initial conditions analysis.

	S0	S1	S2	S3	S4	S5
IC1	0.5	0.5	0.5	0.5	0.5	0.5
IC2	0.5	0.5	0.5	0.5	0.5	0.5
IC3	0.5	0.5	0.5	0.5	0.5	0.5
IC4	0.5	0.5	0.5	0.5	0.5	0.5
IC5	0.5	0.5	0.5	0.5	0.5	0.5
IC6	0.5	0.5	0.5	0.5	0.5	0.5
IC7	0	1	0	0	0	1
IC8	0	0	1	0	0	1
IC9	0	0	0	1	0	1
IC10	0	0	0	0	1	1
DE1	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000
DE2	0.6015	0.5361	0.5439	0.6015	0.5227	0.3985
DE3	0.8577	0.7670	0.5796	0.6978	0.7760	0.1423
DE4	0.5118	0.5118	0.5118	0.5118	0.4882	0.4882
DE5	0.5869	0.5288	0.5652	0.5869	0.4934	0.4131
DE6	0.9285	0.7683	0.3642	0.8882	0.9179	0.0715
DE7	0.8488	0.7138	0.5076	0.8308	0.7138	0.1512
DE8	0.9422	0.5066	0.8331	0.9011	0.8505	0.0578
DE9	0.9018	0.6138	0.8033	0.7611	0.8033	0.0982
DE10	0.9868	0.7268	0.9737	0.9471	0.7597	0.0132
DE11	0.9958	0.9059	0.9918	0.8907	0.8540	0.0042
DE12	0.0576	0.6438	0.1208	0.1088	0.1096	0.9424
DE13	0.0094	0.2556	0.0189	0.0297	0.3058	0.9906
DE14	0.0017	0.0841	0.0032	0.0841	0.0985	0.9983
DE15	0.0013	0.1426	0.0172	0.0889	0.0059	0.9987
DE16	0.0067	0.3889	0.0111	0.2550	0.0185	0.9933
OE1	0.9911	0.9536	0.9709	0.8413	0.7748	0.0089
OE2	0.9776	0.9010	0.5736	0.9269	0.9249	0.0224
OE3	0.9956	0.8587	0.9907	0.9122	0.8847	0.0044

the Cross-Impact Analysis results is the basis of the scenario analysis. This article aims to create a model for earthquake emergency management effectiveness evaluation, so those related events should be chosen to conduct a sensitivity analysis. In this way, the influence of the key factors can be tested by changing the initial probability. Based on the nature of the related events, those key factors are extracted from the initial conditions and dynamic events.

3.2.1. Initial conditions analysis

In initial conditions, IC7, 8, 9, and 10 are the events related to emergency management. The influence of these four key factors can be tested by changing the initial probability to analyze the consequences for the other events, especially for the outcome events. There are six scenario forecasts in which events IC7, 8, 9, and 10 are supposed to apply to the cases where none occur, only one occurs, and all occur. The initial probability of the other events remains 0.5. Based on the cross-impact formula of Eq. (2), the probability of the other events under those six scenario forecasts can be observed in Table 2.

From these results, the impact on the outcome event heavy casualties (OE1) from high to low are events IC10, IC9, IC7, IC8. The disaster prevention project and emergency material reserves (IC10) are important in reducing the casualties. The government should regularly carry out large-scale emergency drills and focus on emergency education (IC9) in order to cultivate an aseismic and earthquake disaster reduction consciousness in the public. Compared with the other three events, IC8 has a significant role in the reduction of economic losses (OE2). The vast majority of these losses always come from business losses. So it's essential that the key enterprises and factories should have emergency plans and a strong disaster reduction consciousness (IC8). A perfect emergency plan (IC7) plays a crucial role in stabilizing public sentiment (OE3). Four initial conditions working together can reduce the losses to a considerable degree, which means that comprehensive emergency preparation is necessary to reduce the risk and the losses from earthquakes.

3.2.2. Dynamic events analysis

The dynamic events related to emergency management are DE12, 13, 14, 15, and 16. The impact of these key factors can be tested in the same way and give the results shown in Table 3. This displays the probabilities of the other events in a dynamic events analysis.

S2 in Table 3 shows that professional emergency rescue teams' quick action (DE12) is significant for reducing casualties (OE1) compared with other dynamic events. Enterprises, non-profit organizations and volunteers' participation in the rescue (DE15) can restore the economic losses (OE2). However, none of these six dynamic events has a notable impact on the three outcome events alone, but the combination of them does. So several scenarios (S7, 8, 9, and 10) are considered. In S7, the probability of the dynamic events DE12 = DE13 = 1, DE14 = DE15 = DE16 = 0 are used. It represents the situation where the rescue task is efficient and humanitarian aid can be delivered in time. Under this scenario, the casualties (OE1) can be reduced by a considerable degree and the economic losses (OE2) can also be reduced slightly. It means that effective rescue work in an earthquake area is the key factor not only for reducing the casualties and economic losses, but to also for easing social panic. However, the government's effective work in guiding public opinion and defusing public disconnect (DE16) has a more obvious impact on easing social panic (OE3) than the other events. So S9 and S10 are conducted. In S9, DE15 = DE16 = 1, DE12 = DE13 = DE14 = 0. In S10, DE14 = DE15 = DE16 = 1, DE12 = DE13 = 0. As can be seen, under S9, there is a clear reduction in economic losses (OE2), but there is only a slight effect on the casualties (OE1) and social panic (OE3). And under S10, there is a significant reduction in economic losses (OE2) and social panic (OE3), and casualties (OE1) also have a noticeable decline.

4. Application and results

4.1. Scenario deduction for the Wenchuan earthquake in China

4.1.1. Scenario deduction setting

Based on the real situation, the timeline of the critical rescue events after the Wenchuan earthquake can be got, see Table 4.

The Wenchuan earthquake occurred in the daytime, so IC1 = 1, and IC2 = IC3 = 0. According to official statistics, the population density of Wenchuan County was not high, so IC4 = 0. Most of the structures in the County were built in the 1990s with a poor seismic capacity which could not withstand such a large earthquake. So IC5 = IC6 = 1. As the central government attached vital importance to emergency management, thus IC7 = 1. The local government did not carry out regular emergency drills, and so the disaster prevention preparations were insufficient and the workers in the key enterprises and factories had poor aseismic and disaster reduction consciousness, so IC8 = IC9 = IC10 = 0.

It is difficult to determine the probability of the dynamic events. In this article, once a dynamic event has happened, its probability is 1. The aftershocks of magnitude 6, landslides and debris flow happened soon after the earthquake. At the same time, a large number of buildings collapsed. So DE1 = DE2 = DE4 = 1. However, the situation of the other secondary disasters was not clear, so they remain at their initial probabilities 0.5. Based on the timeline of critical rescue events, DE12 = DE13 = DE14 = DE15 = DE16 = 1 are set chronologically in the following steps.

Working from the timeline in Table 4, seven steps are used to deduce the rescue scenario over the 4 days after the Wenchuan earthquake in Table 5.

4.1.2. Deduction results analysis

Based on the cross-impact formula of Eq. (2), the probabilities of the other events under each scenario can be obtained in Table 6, and the trend of the probabilities of three outcome events can be found in Fig. 6.

Table 3
Prediction probabilities of the other events in dynamic events analysis.

	S0	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
IC1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
IC2	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
IC3	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
IC4	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
IC5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
IC6	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
IC7	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
IC8	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
IC9	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
IC10	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
DE1	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000
DE2	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000
DE3	0.5889	0.4769	0.5889	0.5889	0.5231	0.5889	0.4111	0.4769	0.5889	0.5231	0.5231
DE4	0.4944	0.4944	0.4944	0.4944	0.4944	0.5056	0.5056	0.4944	0.5056	0.5056	0.5056
DE5	0.5222	0.5000	0.5222	0.5222	0.5000	0.5222	0.4778	0.5000	0.5222	0.5000	0.5000
DE6	0.6358	0.5052	0.6150	0.6044	0.5937	0.5937	0.3642	0.4830	0.5612	0.5502	0.5170
DE7	0.6556	0.5068	0.6455	0.6556	0.5155	0.6455	0.3444	0.4957	0.6455	0.5043	0.5043
DE8	0.7464	0.5547	0.7292	0.6733	0.5781	0.7292	0.2536	0.5326	0.6534	0.5562	0.4674
DE9	0.7098	0.4606	0.6718	0.7098	0.6152	0.6816	0.2902	0.4168	0.6816	0.5832	0.5832
DE10	0.9967	0.9325	0.8364	0.9708	0.9842	0.9946	0.0033	0.1911	0.9531	0.9744	0.8089
DE11	0.9961	0.9792	0.9262	0.9375	0.9724	0.9817	0.0039	0.6974	0.7592	0.8809	0.3026
DE12	0	1	0	0	0	0	1	1	0	0	0
DE13	0	0	1	0	0	0	1	1	0	0	0
DE14	0	0	0	1	0	0	1	0	1	0	1
DE15	0	0	0	0	1	0	1	0	0	1	1
DE16	0	0	0	0	0	1	1	0	1	1	1
OE1	0.9959	0.8457	0.9348	0.9780	0.9804	0.9878	0.0041	0.2449	0.9372	0.9438	0.7551
OE2	0.9697	0.8935	0.9006	0.9120	0.8392	0.8891	0.0303	0.7033	0.7215	0.5661	0.2967
OE3	0.9999	0.9923	0.9965	0.9966	0.9972	0.9904	0.0001	0.8339	0.8037	0.8333	0.1661

Table 4
The timeline of the critical rescue events after the Wenchuan earthquake.

Time	Event
May, 12	
14:28	An earthquake measuring 8.0 on the Richter scale occurred in Sichuan.
15:00	Local garrison and armed police forces started rescue.
18:49	6000 officers and soldiers rushed to the disaster area.
In the evening	The central government fully deployed disaster relief work.
	4000 soldiers rushed to the disaster area carrying disaster relief equipment.
	Emergency medical team rushed to the disaster area.
May, 13	
2:00	The first group of 1100 firemen rushed to the disaster.
6:30	> 16,000 soldiers had become involved in relief work.
21:00	Part of the rescue force got into the epicenter of the disaster area.
May, 14	
20:00	Relief supplies had been dropped into the disaster area.
22:00	Some roads reopened unimpeded.
May, 15	
9:00	> 2000 medical personnel arrived in the disaster area.
10:00	There were 5000 medical personnel implementing medical assistance.
12:00	The giant disaster relief machinery could get into the disaster area successfully
May, 16	
In the daytime	International rescue teams arrived in the disaster area.
In the evening	The roads leading to the disaster area reopened unimpeded.

Table 5
Scenario deduction setting of the Wenchuan earthquake.

Step	Scenario
Step 0	IC1 = IC5 = IC6 = IC7 = 1, IC2 = IC3 = IC4 = IC8 = IC9 = IC10 = 0
Step 1	DE1 = DE2 = DE4 = 1
Step 2	DE12 = 1
Step 3	DE16 = 1
Step 4	DE13 = DE14 = 1
Step 5	DE15 = 1

In order to verify the scenario-based model, the prediction results obtained by the model are compared with the real situation of the Wenchuan earthquake. The earthquake caused 69,227 deaths, 374,643 people injured, and 17,923 people missing. During the life rescue phase, the rescue team searched for > 27,000 people who were buried of which 3338 were survivors, and also rescued and transferred 1.4 million people to safe areas. The number of casualties was reduced thanks to the quick rescue work. As can be seen in Fig. 6, shortly after the earthquake, the probability of heavy casualties (OE1) increased from 90% to nearly 100%. There was then a downward trend as the rescue work was carried out which was consistent with the real situation described in the statistical report. The earthquake also caused huge direct economic losses of about 845.1 billion RMB. Although the government raised about 80 billion RMB in donations and materials, it had little effect on recovering the huge losses. In Fig. 6, the probability of the economic losses (OE2) always remained at nearly 100% with no significant fluctuation which was also consistent with the real situation. The emergency response measures after the earthquake had little effect on preventing the economic losses, but the emergency preparation work should be given more serious attention as a way to reduce the risk. The emergency response after the earthquake was highly commended. The central government responded quickly, deploying soldiers to the area within 1 h of the earthquake. The government departments spared no efforts to collect and approve useful data and information, and the State Council Information Office issued updates on the latest situation to the public. The timely release of authoritative information soothed public panic and anxiety to a considerable extent, something which was highly praised at home and abroad. “The large-scale disaster relief efforts and the transparency of the Chinese government in responding to the disaster have won the appreciation of the world,” the Financial Times (Ge, 2010) said in its report. As to the social panic (OE3) in Fig. 6, it

Table 6
Prediction probabilities of the other events under each scenario.

	S0	S1	S2	S3	S4	S5
IC1	1	1	1	1	1	1
IC2	0	0	0	0	0	0
IC3	0	0	0	0	0	0
IC4	0	0	0	0	0	0
IC5	1	1	1	1	1	1
IC6	1	1	1	1	1	1
IC7	1	1	1	1	1	1
IC8	0	0	0	0	0	0
IC9	0	0	0	0	0	0
IC10	0	0	0	0	0	0
DE1	0.5000	1	1	1	1	1
DE2	0.9514	1	1	1	1	1
DE3	0.8678	0.9962	0.9952	0.9952	0.9952	0.9945
DE4	0.5173	1	1	1	1	1
DE5	0.5757	0.9885	0.9880	0.9880	0.9880	0.9874
DE6	0.8835	0.9985	0.9981	0.9979	0.9977	0.9974
DE7	0.9880	0.9999	0.9999	0.9999	0.9999	0.9999
DE8	0.9759	0.9999	0.9998	0.9998	0.9998	0.9997
DE9	0.9627	0.9998	0.9997	0.9997	0.9997	0.9996
DE10	0.8918	0.9994	0.9973	0.9965	0.9252	0.8495
DE11	0.9745	0.9986	0.9966	0.9927	0.8795	0.7303
DE12	0.3472	0.0042	1	1	1	1
DE13	0.1231	0.0006	0.0030	0.0034	1	1
DE14	0.3227	0.0846	0.1825	0.2874	1	1
DE15	0.3934	0.1299	0.2637	0.4552	0.7829	1
DE16	0.4659	0.1585	0.2677	1	1	1
OE1	0.9283	0.9999	0.9994	0.9989	0.9897	0.9777
OE2	0.9894	1.0000	1.0000	1.0000	0.9999	0.9997
OE3	0.8278	0.9965	0.9738	0.8140	0.1469	0.0366

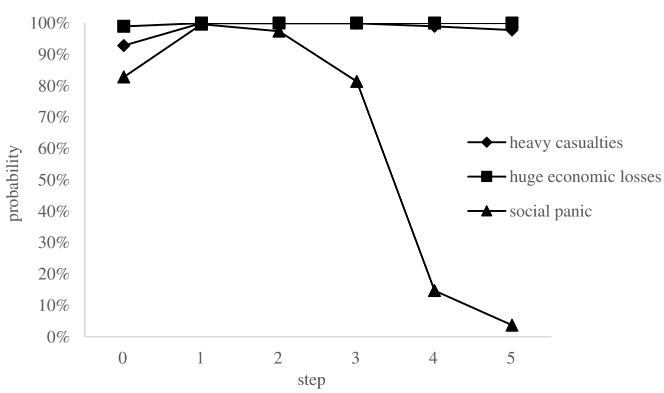


Fig. 6. The trend of the prediction probabilities of three outcome events.

probability increased to nearly 100% after the earthquake which corresponded with the real situation. Once the government began to carry out the relief work, social panic moved onto a slightly decreasing trend. When the government guided public opinion and defused public discontent effectively, social panic was noticeably alleviated. When the rescue teams and supplies arrived in the disaster area, its probability experienced a significant decline. It showed that the government played an active role in appeasing public panic, and that the effective relief work was the key factor. However, in the initial scene (step 0), the probability of three outcome events had already reached a very high value which meant the poor emergency preparation work had a significant impact on the consequences of the serious losses.

The simulation results are consistent with the real situation. In general, the emergency response work after the Wenchuan earthquake was quick and effective. However, due to the poor emergency preparation work, the earthquake still caused heavy casualties and huge economic losses.

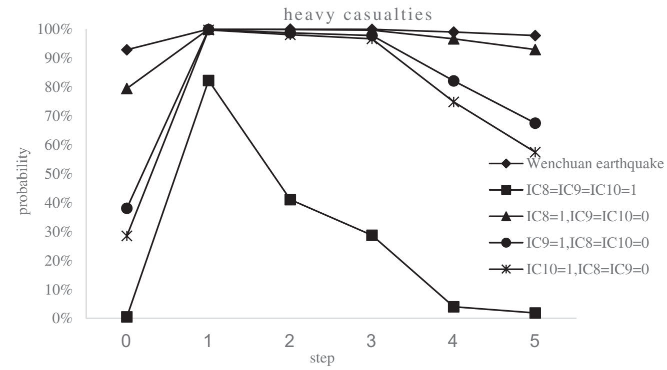


Fig. 7. Heavy casualties.

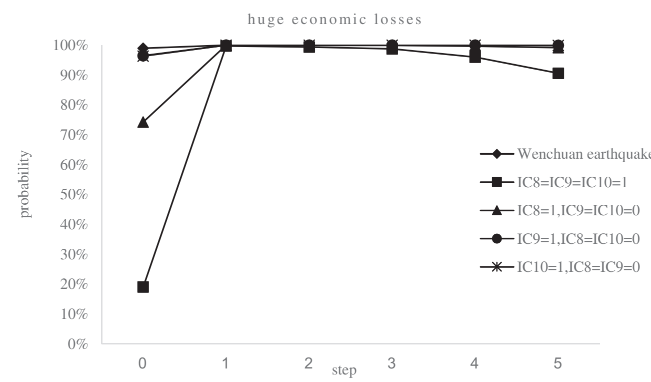


Fig. 8. Huge economic losses.

4.2. Scenario simulation for the Wenchuan earthquake in China

Due to the poor emergency preparation, the Wenchuan earthquake caused heavy casualties and huge economic losses. A scenario simulation of the emergency preparation work has been conducted to provide some effective suggestions for future earthquake emergency management. The simulation contains four scenes: IC8 = 1, IC9 = IC10 = 0; IC9 = 1, IC8 = IC10 = 0; IC10 = 1, IC8 = IC9 = 0; IC8 = IC9 = IC10 = 1. The others remain the same as they were in the Wenchuan earthquake. In different scenarios, the probabilities of the three outcome events, i.e. heavy casualties, huge economic losses and social panic are shown in Figs. 7, 8, 9 respectively.

In Fig. 7, perfect disaster prevention project construction and adequate material reserves (IC10) have a great effect on reducing casualties. Public awareness of disaster prevention and daily large-scale emergency drills (IC9) also has the same positive effect. However, the aftershocks, the collapse of large numbers of buildings and other

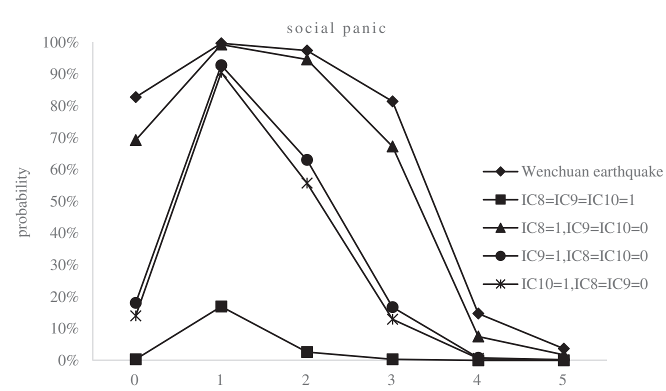


Fig. 9. Social panic.

secondary derivative disasters can significantly increase the likelihood of casualties (step 2). As can be seen in Fig. 8, the emergency plan and management of the key enterprises and factories (IC8) have a positive effect on reducing economic losses to some degree. However, once an earthquake had caused huge economic losses, they are difficult to restore. In Fig. 9, perfect disaster prevention project construction, adequate material reserves (IC10) and the experience of large-scale emergency drills (IC9) can help the public to face the earthquake disaster calmly. Nevertheless, a worsening of the disaster situation will considerably increase the likelihood of social panic (step 2). Even so, it is easy to control public panic due to the perfect emergency preparation work.

Some suggestions can be put forward from the simulations analyzed above. The emergency preparation work plays a key role in guiding the government and the public to deal positively with an earthquake disaster. It is also necessary to reduce the risk and losses from an earthquake. A large number of collapsed buildings may increase casualties and economic losses, so the seismic performance of buildings should also be considered in earthquake emergency management. Moreover, the government should pay more attention to the secondary derivative disasters. In this case, it is necessary to establish the corresponding emergency plans and carry out sufficient publicity and education. Rescue work and relief supplies are the key to saving lives. In this respect, perfect emergency management makes it easier to carry out relief work, and guarantee adequate and efficient relief supplies. The economic losses caused by an earthquake are hard to restore. Thus, the seismic performance of buildings and the disaster prevention work of factories are particularly critical. Lastly, for social panic, the positive public opinion guidance and timely and effective rescue work are equally important and complementary.

5. Discussion

Based on historical seismic cases, earthquake-related events are selected to form an events set. Most of the events are related to the earthquake, seismic secondary disasters and emergency management. And the casual relationship estimates between every two events are given by the Delphi Method. Experts in the field of emergency management and specialists engaged in front-line rescue are invited to comprise the expert panel in order to get consensus estimate results. The estimation matrix is the input for the cross-impact process. Based on the Cross-impact Method (CIA), the cross-impact matrix can be built. The most significant impacts of the first 10% and 30% are extracted. This scenario-based method is graphically expressed by the Interpretive Structural Modeling (ISM). Based on scenario deduction for the Wenchuan earthquake in China, it has been proved that this scenario-model can be a tool for analyzing and evaluating earthquake emergency effectiveness. The model is capable of forecasting possible secondary disasters, filtering key emergency response measures and identifying the correlation between events.

Most studies have considered the association between earthquakes and single secondary disasters (Barranco et al., 2017; Mazza, 2017; Romeo et al., 2017; Shi et al., 2017; Wu et al., 2017). However, in reality, earthquakes usually trigger disaster chains, involving a series of secondary disasters. And there are always chain reactions between secondary disasters. Most of the research on earthquake emergency management is only concerned with one point: evacuation, transportation network, resilience of emergency departments and so on (Bernardini et al., 2017; Davies et al., 2017; Zanini et al., 2017). This study conducts several possible earthquake disaster scenarios. The scenarios include seismic elements, possible secondary disasters, emergency management factors and disaster losses. The study conducts a comprehensive seismic assessment model. This model clarifies the critical relationship between all events. The probability changes of secondary disasters can provide specific recommendations for emergency response. Based on the predicted probabilities of losses, the model can be used to assess the effectiveness of emergency preparedness and response work.

6. Conclusions

In this paper, Cross-Impact Analysis and Interpretive Structural Modeling (CIA-SIM) have been combined with the Delphi method to build a scenario-based model for earthquake emergency management effectiveness evaluation. The CIA-SIM process helps to deal with conflict resolution, obtain consensus and increase the quantity of information. Through the whole process of scenario awareness, construction and deduction, the effectiveness of earthquake emergency management can be evaluated. Based on the results, useful suggestions can be provided for emergency management work.

A series of hypothetical earthquake emergency scenarios have been developed based on the real cases in which the potential implications of critical events for other events, especially for the outcome events, are analyzed. The relationship between events can be explicitly expressed in digraph. The promotion impacts of secondary disasters are clearly revealed. Aftershocks, building collapse, landslides and floods are usually the causes of other secondary disasters. The guidance given by the emergency preparations to the rescue work is also clarified. And all emergency rescue works can constitute a micro set. It means they have inter positive impacts on each other. They can also be separated to clarify respective impacts on secondary disasters and losses. The critical factors affecting earthquake losses can be extracted. Population density has a direct impact on casualties. In emergency preparations, the disaster prevention project and emergency material reserves are the most important for avoiding heavy casualties. The seismic performance of buildings and infrastructure has a significant negative impact. Most secondary disasters have a significant negative impact on casualties. Efficient rescue task can effectively reduce casualties. As for economic losses, poor seismic performance of buildings is a key cause of massive economic losses. Compared with other secondary disasters, large-scale fires will cause more obvious economic losses. And there is no emergency measures that can effectively restore economic losses. The huge economic losses from an earthquake are hard to recover. A perfect emergency plan plays a vital role in stabilizing public sentiment. Aseismic and reduction consciousness can help the public to deal calmly with the disaster. However, the destruction of the lifeline system and the occurrence of disaster chain will aggravate public panic. Efficient rescue task and the government's positive guidance on public opinion can greatly ease panic. The results show that the emergency preparation work is necessary to avoid the serious losses and adverse social impact caused by an earthquake. In the emergency rescue phase, all the rescue measures need to cooperate with each other in order to achieve the desired results. As can be seen from the results of the analysis, the probabilities of the earthquake losses decrease substantially when several rescue measures are carried out effectively.

This scenario-based model is verified by a scenario deduction and simulation for the Wenchuan earthquake. The prediction of the scenario is consistent with the real situation. Through this model, the key factors in earthquake emergency management can be identified. According to the real disaster situation and scenario simulation results, it can help to propose specific response measures and identify the key points in the subsequent rescue work. Also, several specific recommendations to reduce disaster losses can be provided to improve emergency management in the future.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.techfore.2017.12.001.

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