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Modeling the dynamics of disaster evolution along causality networks with cycle chains

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HIGHLIGHTS

- A model for describing disasters evolution along cycle chains is developed.
- A phase transition is revealed when varying CPL or self-recovery coefficient.
- Increasing delay time cannot stop disaster system with cycle chain from collapse.
- Assigning more resources to nodes in cycle chains has high repairing efficiency.

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ABSTRACT

A model for describing the evolution process of disasters, especially for disaster causality networks with cycle chains, has been developed. In the model, the impacts from the causative nodes, self-recovery behaviors, repair by government, internal noise and impacts outside the system have been taken into consideration. In particular, the cumulative effect of the inducing relationship between the causative node and its son node, due to cycle chain, has been quantified by the new model. Based on the proposed model, a parametric study, covering a range of conditional probability of directed inducing links, delay coefficient for disaster evolution and self-recovery coefficient during the recovery process, has been conducted by means of simulations. The results of these simulations point towards a phase transition of the disaster system with cycle chains when increasing conditional probability of directed inducing links or self-recovery coefficient. Particularly, we observe a critical conditional probability of directed inducing links and a critical self-recovery coefficient, beyond which, the whole system may be out of control after certain evolution time, regardless of the fact that the initial disturbance has disappeared. In addition, it is interesting to find that increasing delay coefficient cannot suppress the disaster evolution completely, for a disaster system that is potentially out of control due to the self-reinforce of cycle chains. Of course, the disaster evolution velocity drops when increasing delay coefficient, and this has a positive significance on disaster rescue. Further, it also illustrates that it is a bad strategy to arrange the total rescue resources uniformly during the disaster rescue process, while the strategy that disseminating more resources on the nodes in cycle chains and arranging the rescue resources in line with the potential maximum deviation of nodes, will have higher efficiency. With our model, it is possible for people to get an insight of disaster evolution mechanism along cycle chains and then improve preparedness and anticipative disaster response managements.

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1. Introduction

Disastrous events have occurred since the earliest times, and despite the development of science and technology, they still cause many victims and losses each year [1]. According to the United Nations, about 300 million people are affected by natural disasters world-wide each year and three billion people live in endangered areas. In the recent years, the economic impact, and also the number and size of disasters seem to grow [2]. In 2011, disasters caused about 30,000 victims and a damage of more than 380 billion US Dollars all around the world. Today, a disaster can easily result in billions of loss and thousands of casualties. For example, the Indian Ocean tsunami, which was caused when the Indian Plate was subducted by the Burma Plate, triggered a series of devastating tsunamis along the coasts of most landmasses bordering the Indian Ocean, killing over 230,000 people in fourteen countries in 2004 [3]. Also, the losses due to the earthquake in Japan in March 2011 amounted to more than 30 billion US Dollars and more than 15,000 casualties. Besides, the earthquake has caused the nuclear accidents, primarily the level 7 meltdowns at three reactors in the Fukushima Daiichi Nuclear Power Plant complex, and the associated evacuation zones affecting hundreds of thousands of residents [4].

One common feature of the disastrous events is the so-called domino or avalanche effect. It means that one critical situation triggers another one and so on, so that the situation worsens even more [1]. Hence, even if a very small disturbance may result in enormous loss because of the propagation, coupling and enhancement of different critical situations. For this reason, it is really of great significance to model the disaster evolution behavior.

However, an experimental study of disasters under real world conditions is almost impossible and therefore mathematical and computer models are often very helpful tools to extend human knowledge. Furthermore, the complexity of systems struck by disasters does not allow one to model the interactions of all involved entities and processes in detail. Therefore, we have to capture them by an appropriate generic [5].

Consequently, various models were developed to mimic the disaster evolution and spreading (especially along the infrastructure networks) in the recent years [1,2,5–10]. Among which, Helbing et al. introduced a versatile method for the investigation of interaction networks and showed how to use it to assess effects of indirect interactions and feedback loops [1]. They also discussed why disasters occur more frequently and are more serious than expected according to a normal distribution, and they identified further fields where network theory could help to improve disaster response management [2].

As Helbing et al. indicated, networks theory plays a vital role in investigating disaster spreading and evolution in recent years. Buzna et al. [11] presented a model which combines network nodes as active, bistable elements and delayed interactions along directed links, for the dynamic spreading of failures in networked systems. By means of simulations, they explored the time-dependent spreading and cascade failures in different network topologies. Simonsen et al. [12] studied cascading failures in networks using a dynamics flow model based on simple conservation and distribution laws. Wu et al. [13] investigated the onset and spreading of cascading failure on weighted heterogeneous networks by adopting a local weighted flow redistribution rule. Guo et al. [14] investigated the dynamics of disaster spreading in community networks with Buzna et al.'s model.

To suppress disaster spreading and evolution, emergency response will be crucial, and this response needs a mobilization of external resources, which are limited. How to effectively allocate these resources to fight disasters best has also been investigated. Buzna et al. [5] studied the effectiveness of recovery strategies for a dynamic model of failure spreading network. Ouyang et al. [15,16] specifically considered emergency response to disaster-struck scale-free networks when some nodes in the network have redundant systems, via a new model, which is constructed based on the disaster spreading model originally proposed by Buzna et al.. Chen et al. [17] proposed a new model for describing evolution and control of disaster system including instantaneous and continuous actions. In his model, impact from causative disaster events, stochastic noise of disaster node and self-healing function are taken into consideration, and some key parameters, namely link appearance probability, retardation coefficient, ultimate repair capacity of government, dynamical modes considering different disaster evolving chains, and the positions of link with specific performance in disaster network system are involved.

The above models have been relatively adequate modeling the disaster dynamics and emergency response. However, during the disaster evolution, cycle chains may be formed, which are crucial in these disaster causality networks, since the amplification of the negative effects through the chains may considerably deteriorate the situation. Such loops are sometimes called "vicious circles" [5]. For instance, in a catastrophe event (e.g. earthquake), people may suffer a slight short of goods and materials temporarily, but the rumor that goods are in extremely short supply may come into being afterwards. As a result, people may rush to purchase, though most of them are not lack of that, which will in turn result in serious short of goods and materials. Hence, it is of great necessity and significance to understand how disaster propagates and evolves along the cycle chains. This is particularly important in disaster reduction. However, the existing models have not considered the influences of cycle chains, and maybe they are insufficient to mimic the dynamics of disaster evolution along cycle chains. For this reason, the existing models should be improved to be suitable to simulate disaster dynamics with cycle chains, and this is what this paper emphasize.

Our paper is organized as follows. The construction principles of disaster causality network will be presented in Section 2. In Section 3, we will propose our mathematical model of disaster evolution along the causality network, especially along the cycle chains. Then in Section 4, the studied case of this paper will be introduced, as well as the default parameter settings. Next in Section 5, we will present the results of computer simulations based on the proposed model. The evolution behaviors

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