Physica A 407 (2014) 175–184

Contents lists available at ScienceDirect

Physica A

journal homepage: www.elsevier.com/locate/physa

Earthquake networks based on space–time influence domain

Xuan He *, Hai Zhao, Wei Cai, Zheng Liu, Shuai-Zong Si

College of Information Science and Engineering, Northeastern University, Shenyang, 110819, China

HIGHLIGHTS

- A new earthquake network construction method based on space–time influence domain is proposed.
- The influence domain is determined by the magnitude of each event in the catalog.
- The earthquake network constructed by our method is proved to be scale-free.
- The earthquake network constructed by our method is proved to be small-world.
- The Omori Law for aftershocks emerges as a result of our analysis.

ARTICLE INFO

Article history:
Received 15 January 2014
Received in revised form 7 March 2014
Available online 3 April 2014

Keywords:
Earthquake networks
Complex networks
Space–time influence domain
Scale-free
Small-world
Omori law

ABSTRACT

A new construction method of earthquake networks based on the theory of complex networks is presented in this paper. We propose a space–time influence domain for each earthquake to quantify the subsequence of earthquakes which are directly influenced by the former earthquake. The size of the domain is according to the magnitude of earthquake. In this way, the seismic data in the region of California are mapped to a topology of earthquake network. It is discovered that the earthquake networks in different time spans behave as scale-free networks. This result can be interpreted in terms of the Gutenberg–Richter law. Discovery of small-world characteristic is also reported on the earthquake network constructed by our method. The Omori law emerges as a feature of seismicity for the out-going links of the network. These characteristics highlight a novel aspect of seismicity as a complex phenomenon and will help us to reveal the internal mechanism of seismic system.

1. Introduction

Earthquakes occur as a result of global plate motion [1]. However, the earthquakes are only appearances in the earth's crust as we can detect. Behind the appearances, complex interaction and correlation exist in the internal of seismic system [2–4]. On the other hand, an earthquake can release a huge amount of energy which is propagated by the seismic wave. Sequences of earthquakes often appear related to main shocks of large magnitude, which are followed in time by nearby smaller events. Sometimes, the main shock is also preceded by a few intermediate or smaller precursor shocks [5]. It is actually presenting a dynamical behavior of networks [6].

Complex network theory is a powerful method for describing the complexity of systems [7]. It helps us to comprehend the internal structure of a complex network so that scientists can understand, model, predict and control many complex systems. In recent years, significant contributions have been given to many natural and man-made systems based on

* Corresponding author. Tel.: +86 15909830688.
E-mail address: hexuan19860627@hotmail.com (X. He).

http://dx.doi.org/10.1016/j.physa.2014.03.093

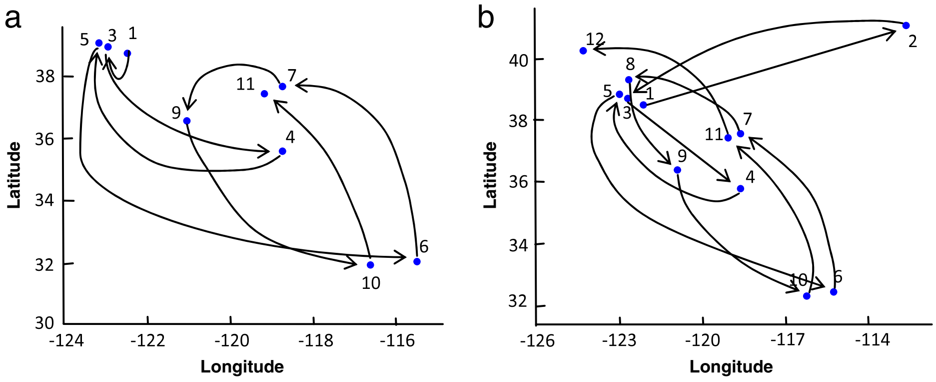

Fig. 1. Network topologies generated by the data in Tables 1 and 2 and using Abe's method. (a) The topology generated by the data in Table 1, (b) the topology generated by the data in Table 2.

complex networks, such as social networks [8,9], software networks [10,11], Internet topology [12,13], and transportation networks [14]. And it proves to be an effective method to study complex system.

Few researchers have already introduced the complex network theory into the seismic study and found that the seismology is characterized by several features of complex networks [3,15–17]. The first step for quantifying the complexity of the earthquake phenomena is the process of constructing the network. An earthquake network construction method based on time series has been first introduced into seismic study in 2004 by Abe and Suzuki [15]. In their work, nodes representing the grid cells in geographically were linked when successive earthquakes occurred in them. And the characteristics of such networks have been found in a series of their papers [15,17–20]. The scale-free [15] and small-world [18] nature of the earthquake networks were found by them. And the networks were discovered to be hierarchically organized and assortatively mixed [19]. Xie Zhou-min presented a weighted earthquake network model [6] on the former work of Abe et al. He has also demonstrated scale-free statistics of earthquake network and analyzed the evolution law of the network structure entropy.

Baiesi and Paczuski [3] constructed an earthquake network by introducing a metric to quantify correlations between earthquakes that take into account the time interval and spatial distance between any two events. And the pairs of events are marked as linked nodes. Their work, which appeared just after Ref. [15], is guided by the work in Ref. [2] that has collected a great attention. However, in 2005, Carbone et al. [21] have found that the unified scaling law claimed in Ref. [2] for waiting times is not universal and depends on datasets to be employed. That explains why one cannot see universal properties of the network proposed in Ref. [3]. On the other hand, Abe and Suzuki [22] have shown that their method certainly has its firm basis on the universal scaling law for waiting internal times. Therefore, we start our work with the method of Abe and Suzuki, not with that of Ref. [3].

Earthquakes exhibit complex correlations in space, time, as well as magnitude [2–5,23,24]. It is may be not appropriate to construct an earthquake network only considered by time series. In this paper, we propose an intuitive construction method considering time, space and magnitude. We employ a space–time influence domain according to the magnitude for every earthquake. The domain represents a direct effect range on the related earthquakes within it. After processing all the events in the earthquake catalog, a new earthquake network topology is produced. In this paper, we also analyze the characteristics of the networks constructed by our approach.

The rest of this paper is organized as follows. In Section 2, the earthquake networks construction method based on time series is introduced briefly in order to present our idea. Section 3 is devoted to describe our method to construct the earthquake network. In Section 4, necessary data and parameters employed in this study are illustrated. And we analyze the characteristics of the network in three respects in Section 5. In Section 6, we discuss the universality of our method. Finally, in Section 7, the conclusions of this paper are presented.

2. Earthquake networks based on time series

The earthquake network construction method based on time series by Abe and Suzuki [15] is described briefly as follows.

The network associated with a particular geographical region is simply constructed by dividing the region into small equal-sized cubes or squares (cells). Each cell was regarded as a node if any earthquake occurred within. Two successive earthquakes defined an edge from former to latter between two nodes. In this way, the complex event–event correlation was replaced by the edge. If two successive earthquakes occurred in the same cell, they formed a self-loop. This approach allowed one to map seismic data to a growing random network once the cells were set.

In order to analyze the above method, we first obtain a set of data from the earthquake catalog made available by the Incorporated Research Institutions for Seismology (IRIS: http://service.iris.edu/fdsnws/event/docs/1/builder/) as shown in Table 1 covering the region 30° N–39° N latitude and 111° W–124° W longitude in the period between January 1, 2014 and January 2, 2014. And we apply the data to generate related network topology as shown in Fig. 1(a). Then, we extend the