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Weighted network analysis of earthquake seismic data

Abhijit Chakraborty [a], G. Mukherjee [b], S.S. Manna [a,*]

[a] *Satyendra Nath Bose National Centre for Basic Sciences, Block-JD, Sector-III, Salt Lake, Kolkata- 700098, India*
[b] *Bidhan Chandra College, Asansol 713304, Dt. Burdwan, West Bengal, India*

HIGHLIGHTS

- For the first time the seismic data has been used to construct a weighted network.
- Link weights are found to be highly heterogeneous and in fact, power law distributed.
- The weighted version reflects the absence of hierarchy i.e., assortative mixing.
- Strong rich-club ordering effect is observed.

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ABSTRACT

Three different earthquake seismic data sets are used to construct the earthquake networks following the prescriptions of Abe and Suzuki (2004). It has been observed that different links of this network appear with highly different strengths. This prompted us to extend the study of earthquake networks by considering it as the weighted network. Different properties of such weighted network have been found to be quite different from those of their un-weighted counterparts.

1. Introduction

Earthquake is probably one of the most important natural phenomena affecting human life and property, hence its study and quest of a preventive mechanism have a long history. Different laws have been formulated from empirical observations e.g., the Gutenberg–Richter law [1] relates the frequency of tremors of a given magnitude and the Omori law [2] describes the temporal rate of decay of aftershocks corresponding to a main shock. More recently Physicists have tried to explain the earthquake dynamics as a scale invariant process. Correlation among different shocks as well as the recurrence time distributions [3–6] have been studied. The spatial positions of earthquake epicenters have been claimed to form fractal sets [7,8]. A number of models have been proposed and studied. For example, the well known Burridge–Knopoff model describes the slow creeping of the continental plates along the fault lines as a stick–slip process [9]. Very importantly Bak et al. suggested that the phenomenon of earthquakes may be looked upon as a Self-Organized Critical process which spontaneously generates long range spatio-temporal correlations or scale-invariance [10,11]. However the actual mechanism of the underlying dynamics or efficient forecasting of this complex phenomenon has not been possible yet.

Recently the time sequence of occurrence of different tremors and the positions of their epicenters in different earthquake catalogs have been studied using the tools of complex network theory. Baiesi and Paczuski considered different tremor events as the nodes of a network where a pair of nodes is linked if the correlation between them exceeds a certain threshold

* Corresponding author.
E-mail address: manna@bose.res.in (S.S. Manna).

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Table 1
All angles are measured in degrees. **SC**: Southern California Earthquake Data Center, http://www.data.scec.org/ **JU**: Japan University Network Earthquake Catalog, http://wwweic.eri.u-tokyo.ac.jp/db/junec/ **CAN**: Canada's National Earthquake Database, http://earthquake.usgs.gov/earthquakes/eqarchives/.

Region Period	SC 1973–2011	JU 1985–1998	CAN 1950–1992
θ_{min}	32	25.73	0
θ_{max}	37	47.964	87.75
ϕ_{min}	−122	126.43	−99.86
ϕ_{max}	−114	148.0	177.1
n	572601	200910	25970
$(L_{lat}L_{lon})^{1/2}$	638.33 km	2178.01 km	14715.41 km

value [12,13]. In another method, Abe and Suzuki considered a link between every pair of successive tremor events [14–21]. Both groups suggested that the earthquake network has scale-free structures with small-world properties. In addition, there are other studies which deal with correlations, recurrence times and modeling of earthquakes [22–25].

To construct the earthquake network, Abe and Suzuki digitized the entire earthquake region into a rectangular grid, using the lattice constant as a tunable parameter [14]. Here, a cell is considered as a node if at least one tremor has its epicenter within this cell. A pair of nodes is defined to be connected by a link if and only if at least one pair of successive seismic events occurs whose epicenters are located within these two cells. It has been observed that the associated network is hierarchical, it has the assortative property and its clustering co-efficient follows a scaling relation with cell size as well as the size of the earthquake network. It is to be noted that, in this network analysis of earthquakes, all links are treated on identical footing irrespective of (i) the strengths of the tremors and (ii) the number of successive pair of events that correspond to a particular link which implies that the network introduced by Abe and Suzuki is an unweighted network.

On the other hand, a more detailed analysis reveals that roles played by different links have different importance—which demands the introduction of a new variable called 'weight' associated with a link. In many networks link weights represent the strength of ties between nodes which are not similar and in fact quite often they are highly heterogeneous. There are several well known examples. For example, the passenger traffic between a pair of airports in airport networks [26,27], strength of the pair-interaction between two species in ecological network [28], the volume of trade between two countries in the international trade network [29,30] etc. A number of new properties of these networks have come to light when they are analyzed considering the link weights.

The method of Baiesi and Paczuski is crucially based on the work of Bak et al. in Ref. [3]. However, careful examinations of Ref. [3] have revealed that their work ambiguously contains several artificial assumptions regarding e.g., precision of time separation for detecting events etc. Later, it has been found that the unified scaling law in Ref. [3] for waiting times fails to hold for data sets other than the Californian one [31]. This is the reason why one cannot see universal properties in networks of the Baiesi–Paczuski type. On the other hand, the method of Abe and Suzuki is certainly associated with a universal law [32].

In this paper, we study the earthquake network as a weighted network to gain better insights about the structural properties and correlations present in the network. In Section 2, we define the weighted network and describe the quantities observed. In Section 3, we present the results and their analysis. In Section 4, we describe the rich-club analysis. The paper is summarized in Section 5.

2. The weighted earthquake network

Given the time sequence of occurrence of seismic events in a particular earthquake catalog, the network is constructed following Abe and Suzuki in Ref. [14]. We define the weight w associated with a specific link as the total number of successive events between its two end nodes. It is observed that these weights are not similar at all, in fact they vary over a wide range.

Three different earthquake catalogs have been analyzed, namely, the Southern California Earthquake Data Center catalog (SC), Japan University Network Earthquake catalog (JU) and Canada's National Earthquake Database catalog (CAN). Different specifications of these catalogs are given in Table 1. Each catalog contains the data for every seismic event within a specified period: geographical positions of the epicenters described by their latitudes (θ) and longitudes (ϕ) and the precise times of occurrence. During the period from 1932 to 1972 the number of events in the SC data is very small compared to rest of the period. Therefore we have analyzed the SC data for the period from 1973 to 2011 containing a total of 572601 events. The Japan University catalog has the total of 200910 seismic events between 1985 and 1998, whereas the Canadian catalog has the record of 25970 seismic events within the interval between 1950 and 1992.

These epicenters are extended over a region which we refer as the 'earthquake region'. The earthquake region corresponding to a particular earthquake catalog is characterized by the minimum and the maximum values of these coordinates, i.e., $(\theta_{min}, \theta_{max})$ and (ϕ_{min}, ϕ_{max}). Following the method in Ref. [14] the earthquake regions have been digitized into different grids to analyze the data. The main difference is we have used two dimensional cells on the surface of the earth and ignored the depth coordinate of the epicenter, whereas Abe and Suzuki mainly used three dimensional cells. Therefore all the tremor events that occur within cells of different depths, situated on the same column of cells, are clubbed together into the tremor events of only one cell in our method. Consequently, the number of nodes in Abe et al.'s network is