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Monitoring Earthquake Network Measures in Aftershock Sequences in Greece

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Abstract

Strong earthquakes ($M \geq 6.0$) may be followed by numerous aftershocks, which steadily decrease in frequency according to Omori law. The stronger aftershock usually causes catastrophic consequences as the strong earthquake that preceded has reduced the durability of buildings. The identification of certain occurrence patterns of strong aftershocks is then of both scientific and societal significance and effective tools are seeking for this scope. The monitoring of complex earthquake networks that are formed from Greek seismicity, based on the evolution of their measures, such as global efficiency, betweenness centrality and clustering coefficient is performed, aiming to identify when these networks exhibit distinct evolution between the main shock and strongest aftershocks occurrence. As network nodes the 2D seismic cells in which the study area was appropriately divided are considered and their connections among the nodes are given by the succession of earthquakes. The data are taken from a seismic catalog comprising crustal earthquakes (focal depth less than 50 km) of magnitude $M \geq 3.0$ that occurred in the territory of Greece in between 1999-2017. During this period twenty two (22) main shocks of $M \geq 6.0$ occurred, and is examined the evolution of network measures on earthquake networks before the strongest aftershocks. The earthquake networks are formed on sliding windows of a few days for monitoring the network measures variation. To assess whether the values of network measures are statistically significant the construction of randomized networks is required, and the same network measures are calculated for comparison purposes. The monitoring of network measures revealed that their values were found statistically significantly different from the corresponding values of the randomized networks shortly before the strongest aftershocks.

Objectives

- The investigation of the complex seismicity behaviour constitutes a major scientific challenge and an indispensable component in improving our knowledge concerning seismogenesis and earthquake forecasting.
- One approach for investigating the spatial and temporal complexity of seismicity is effected through the construction of earthquake networks, given that graph theory provides a framework to investigate the structure and dynamics of a complex system.
- The examination of basic network measures, such as global efficiency and clustering coefficient, will unveil properties of spatio-temporal seismicity structure and give a new perspective for the seismic hazard assessment.
- The scope of this work is the monitoring of evolution of eight (8) basic network measures for six (6) of 22 aftershock sequences that occurred during 1999-2017 in Greek territory by strong earthquakes with $M \geq 6.0$, and the identification of potential patterns in the distinct evolution of the earthquake networks structure before the strongest aftershock. We study six (6) of them for which the interevent period was sufficiently long for the network measures to be robustly computed.

Method

- The construction of earthquake networks is based on the Abe and Suzuki (2004a). The study area is divided into $2D$ cells that are considered as nodes of the earthquake networks inside which the earthquakes occurred, and the connections are given by the succession of earthquakes.
- For the monitoring of earthquake network structure for aftershock sequences that examined, the eight (8) different network measures that are considered and computed, are: clustering coefficient, characteristic path length, global efficiency, betweenness centrality, eigenvector centrality, assortativity, eccentricity and diameter.
- The investigation of evolution of these network measures values for aftershock sequences, requires checking of statistical significance of these values in each time interval (sliding window per day) after comparing them with the corresponding values of randomized networks.
- A randomization setting requires the preservation of the degree of each node in the original network based on the shuffling of the connections of the original network and is called RNnoddeg (Maslov and Sneppen 2002). In a different approach, the random network is not formed by randomizing the connections of the original network, but it is built according to the Erdős and Rényi (1959) model with preset probability of connections as in the original network, which essentially corresponds to the preservation of the average degree and is called RNpoisson.

Randomization significance test

- Since the asymptotic null distribution of each statistics is not known, meaning each one of the (eight) 8 network measures, a randomization significance test is applied and the empirical null distributions for each statistics is formed from the values of the statistics computed on the B randomized networks (for any of the 2 approaches for network randomization which are used).

- The null hypothesis H_0 that the network measure values of both the original and randomized networks are similar (i.e. $p - value > 0.05$, see eq. (1)) is considered. To establish the statistical significance of the network measures values the test should reject the null hypothesis H_0 (i.e. $p - value < 0.05$, see eq. (1)).
- The p-value is calculated, and the test decision is reached at the significance level $\alpha = 0.05$. Denoting q_0 the test statistics computed for the original network, and $q_1, \dots, q_B$ for the B randomized ones (in the computations we set $B = 100$), the p-value is

$$p=\begin{cases} \frac{2r_0}{B+1}, \text{ if } r_0 \leq \frac{B+1}{2} \\ \frac{2(1-r_0)}{B+1}, \text{ if } r_0 > \frac{B+1}{2} \end{cases} \quad (1)$$

where r_0 is the rank of q_0 in the ordered list of $q_0, q_1, \dots, q_B$.

Results

- The percentages of rejection of H_0 are computed from the average of the corresponding rejections of H_0 that are derived for each one of the 6 examined cases in each non-overlapping time window (Figure 1).
- It was found that the values of most of the network measures are different than the corresponding values of the randomized networks in the last time window, with higher percentages of rejection of H_0 than in the other time intervals, before the upcoming strongest aftershocks.

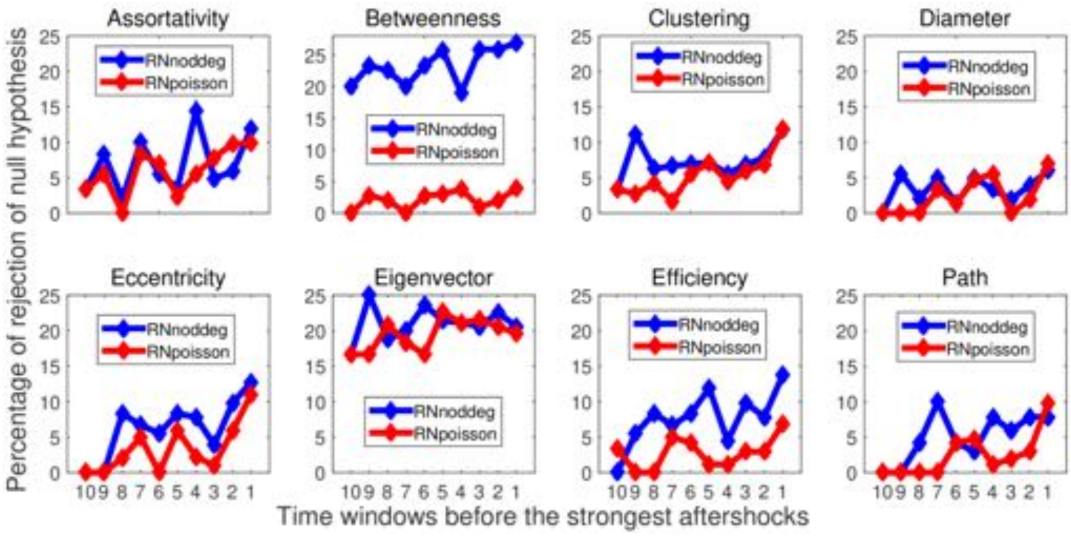

Figure 1. The percentage of rejection of H_0, that the values for each of the 8 network measures and the 2 randomization approaches of original and randomized networks are similar, based on all the 6 strongest aftershocks which are considered.

Conclusions

- The evolution of network measures revealed that the values for the original earthquake networks are different, i.e. there is statistical significance, from the corresponding values for randomized networks in the last time interval before the aftershocks.
- The application of the network theory is found to be a powerful tool for the investigation of complex phenomena, such as seismic activity as the changes in the network structure can reveal certain seismicity behavior a few days before an aftershock occurrence.

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