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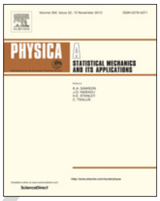

Visibility graph analysis of 2002–2011 Pannonian seismicity

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HIGHLIGHTS

- The Visibility Graph properties of Pannonian seismicity are analysed.
- The slope of the *k*–*M* plot is related with the Gutenberg–Richter *b*-value.
- Such a relationship is in agreement with that found for other seismic areas.
- The universal character of such a relationship is shown.

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ABSTRACT

The Visibility Graph (VG) properties of the seismic sequence which occurred in Pannonia from 2002 to 2011 have been put in a relationship with the seismic parameter *b*-value derived from the Gutenberg–Richter law; this law, which is the frequency–magnitude distribution, represents the main characteristic of a seismic sequence. It is found that between the *b*-value of the Pannonian seismicity and the slope of the least square fitting line of the *k*–*M* plot (which is the relationship between the magnitude *M* of each event and its connectivity degree *k*) there exists a close relationship. The relationship is valid for two depth classes of events, shallow (depth less than 40 km) and deep (depth larger than 70 km), for which different mechanisms of earthquake generation exist. These results confirm similar findings already obtained for the seismicity in different areas of Mexico (Telesca et al., 2013), suggesting the existence of a universal law.

1. Introduction

Lacasa et al. [1] developed the visibility graph (VG) method, by which the investigation of a time series is performed through the mapping on networks or graphs. By means of such a mapping, the dynamical properties of time series are converted into the topological properties of networks, and, vice versa, the characteristics and features of time series can be inferred from those of networks. Q2

In the VG approach a segment connects any two values of the series that can be seen by each other, meaning that such a segment is not broken by any other intermediate value of the series. In terms of graph theory, each value of the time series represents a node, and two nodes are connected if there exists visibility between them. The mathematical definition of the visibility criterion [1] can be given as follows: two arbitrary data values (t_a, y_a) and (t_b, y_b) are visible to each other if any other data (t_c, y_c) placed between them fulfils the following constrain:

$$y_c < y_b + (y_a - y_b)\frac{t_b - t_c}{t_b - t_a}. \tag{1}$$

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Let us indicate with k_i the connectivity degree, which is the number of connections of each node i. The following properties always hold [1]: (1) connection: each node is visible at least to its nearest neighbours (left and right); (2) absence of directionality: no direction is defined in the links; (3) invariance under affine transformations (rescaling of both axes and Q3 horizontal and vertical translations) of the time series.

It was shown that the graph developed using the VG method transforms periodic, random and fractal time series into regular, random and scale-free networks respectively [1–3].

The VG method was mainly applied to investigate the dynamical properties of continuous signals. Pierini et al. [4] analysed by using the VG method the time series of hourly means of wind speed recorded at two wind stations in central Argentina (one inland and the other coastal) finding that the topological properties of the two series are similar and do not depend on the characteristics of the two sites. The analysis of the v–k (sample value–connectivity degree) plots also suggested that higher values of a series are not necessarily "hubs", that is values characterized by large connectivity. Telesca et al. [5] analysed by the VG method ocean tide records in central Argentina and discriminated local (linked with the coastal conditions) from global (linked to more general and common atmospheric forcing and ocean current conditions) effects just analysing the properties of the connectivity degree distribution curve.

Recently the VG method was applied also to point processes (sequence of events randomly occurring in time). Telesca and Lovallo [5] applied the VG method to the seismicity of the whole Italy, finding the presence of power-law behaviour in the distribution of the connectivity degree independent of the time-clustering structure and of the increase of the magnitude threshold. Telesca et al. [6] performed the VG analysis of the sequences of earthquakes which occurred in the sub-duction zone of Mexico and found that the k–M plots (which is the relationship between the magnitude M of each event and its connectivity degree k) were characterized by increasing trend of k with the increase of M, revealing, thus, the property of hub as typical of the higher magnitude events. Furthermore, they found an empirical direct relationship between the slope of Q4 the line fitting in a least square manner the k–M plot and the b-value of the Gutenberg–Richter law. Such a finding suggested that the VG properties of seismicity can incorporate the seismological ones in a more general sense because the VG method takes into account not only the magnitudes of the events (as the Gutenberg–Richter law does) but also their time occurrence.

In the present paper, we investigate the relationship between the b-value of the Gutenberg–Richter law and the slope of the k–M plot as obtained by the VG method for the seismicity which occurred in Pannonia from 2002 to 2011. This area is characterized by two depth classes of events: shallow (depth less than 40 km) and deep (depth larger than 70 km). Our aim is to investigate the VG properties of these two different depth classes of seismicity (and their relationship with the b-value) and their variation through time.

2. Seismicity data

The Pannonian Basin and surrounding orogens (referred to as the "Pannonian Region") are located in the northern sector of the central Mediterranean region. The Pannonian Basin is bounded on the north to the east by the Carpathian mountain belt, on the south by the Dinarides mountain belt and on the west by the Eastern Alps. The area is tectonically rather complicated and has been studied intensively over the last decades [7].

Seismicity in the Pannonian Basin is more moderate compared to the peripheral areas; however the distribution of the total seismic energy release indicates current deformation in the basin area as well. Shallow hypocental depth within the top 30–40 km of the earth's crust is principal in the entire region except for the Vrancea zone where intermediate depth seismicity (from 70 to 160 km) is governing (see Fig. 1). Focal mechanism solutions show that strike-slip and thrust faulting are almost exclusive in the Southern Alps and in the Dinarides. In the Eastern Alps and Western Carpathians focal mechanism solutions present exclusively strike-slip character. In the Pannonian Basin, thrust and strike-slip faulting seem to be dominant, while earthquakes in the Vrancea area occur in a compressive regime with thrust tectonics [8].

A comprehensive earthquake catalogue has been compiled, listing historical and instrumentally recorded earthquakes throughout the Pannonian Region bounded by 44.0–50.0 N latitude and 13.0–28.0 E longitude with the primary aim of seismic hazard assessment of nuclear power plant sites. Different magnitude scales were converted to Mw magnitude resulting in a "quasi homogeneous" earthquake database. The catalogue contains more than 20 000 events ranging in date from 1501 to 2011. After declustering the catalogue [9], some 15 600 "independent" events remained and the list is considered to be complete for earthquakes larger than M 6.0 since 1500, for earthquakes larger than M 5.8 since 1601, for earthquakes larger than M 5.3 since 1701, for earthquakes larger than M 4.7 since 1801 and for magnitudes greater than 3.5 since 1881. In combination with the stress data derived from focal mechanism solutions for individual earthquakes these data provide a relatively strong basis for evaluating seismic sources and seismotectonic models both within and surrounding the Pannonian Basin [10].

3. Results

We analysed the seismicity of Pannonia area (Fig. 1) which occurred from 2002 to 2011 (http://www.georisk.hu/References/GR-PSHA_44-50_13-28_2001-2011.txt). This seismicity is characterized by two well-separated depth classes, the shallow events (depth less than 40 km) and deep events (depth larger than 70 km) (Fig. 2). Therefore, we analysed both the two sets of events. Preliminarily we determined the magnitude of completeness. Fig. 3 shows the cumulative (square) and the unbinned (triangle) frequency–magnitude distribution (Gutenberg–Richter law) for both the series. From

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