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Investigating the time dynamics of seismicity by using the visibility graph approach: Application to seismicity of Mexican subduction zone

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HIGHLIGHTS

- The visibility graph method was applied to the seismicity of the Mexican subduction zone.
- The visibility graph method allows us to discriminate among seismic areas with different tectonic settings.
- The properties of the visibility graph can be linked with the seismological characteristics of the Gutenberg–Richter law.

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ABSTRACT

By using the method of the visibility graph (VG), five magnitude time series extracted from the seismic catalog of the Mexican subduction zone were investigated. The five seismic sequences represent the seismicity which occurred between 2005 and 2012 in five seismic areas: Guerrero, Chiapas, Oaxaca, Jalisco and Michoacán. Among the five seismic sequences, the Jalisco sequence shows VG properties significantly different from those shown by the other four. Such a difference could be inherent in the different tectonic settings of Jalisco with respect to those characterizing the other four areas. The VG properties of the seismic sequences have been put in relationship with the more typical seismological characteristics (b-value and a-value of the Gutenberg–Richter law).

1. Introduction

The visibility graph (VG) approach to the investigation of time series was developed and presented in the seminal paper by Lacasa et al. [1]. Such a method maps time series into networks or graphs, converting the dynamical properties of time series into topological properties of networks; vice versa, it is also possible to get information about the time series just by analyzing the features of networks.

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: indicating with the couple (t_i, y_i) the generic datum y_i which occurred at time

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t_i, 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 fulfills the following constraint:

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

The following properties always hold [1]. 1. Connection: each node is visible at least by its nearest neighbors (left and right). 2. Absence of directionality: no direction is defined in the links. 3. Invariance under affine transformations (rescaling of both axes and 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]. Furthermore, concerning more specifically the fractional Brownian motions (fBm), whose degree k distribution follows the power-law $P(k) \sim k^{-\gamma}$, the exponent γ is related to the Hurst exponent H of the fBm by means of the linear relationship, $\gamma = 3 - 2H$; such a relationship leads to $\gamma = 4 - \beta$, where β is the spectral exponent of $1/f^{\beta}$ noise [4].

Very recently an application of the VG method to the analysis of earthquake magnitude time series was performed in Telesca and Lovallo [5] in relationship with the Italian seismic catalog. Their findings pointed to the presence of power-law behavior in the degree distribution of the magnitude point process. They also found that the form of the degree distribution is independent of the time-clustering structure, and of the increase of the magnitude threshold.

In the present study, we apply the VG method to analyze the time dynamics of five earthquake magnitude time series extracted from the seismic catalog of the Mexican subduction zone. Each magnitude time series corresponds to one seismic area of the Mexican subduction zone; in particular they are Guerrero, Oaxaca, Chiapas, Jalisco and Michoacan. These five seismic areas are characterized by different seismo-tectonic settings (see the following section); therefore, the aim of our study is to evidence dynamical differences among these five seismic areas using the VG methodological approach.

2. The seismicity data

The analyzed data correspond to the seismicity catalog of the Mexican subduction zone. This zone is characterized by an oblique motion, as in transform faults, between the Rivera, Cocos and North America plates boundary. We assume the segmentation proposed by Mendoza-Ponce [6], Singh et al. [7] and Zuñiga and Wyss [8], who took into account the geometry of the subducted Rivera and Cocos plates beneath the North American lithosphere (Fig. 1). The main hypotheses in their regionalization are the differences in the estimation of local a- and b-values in the Gutenberg–Richter law [9] from which the local recurrence time is estimated. Then, the southern Mexico may be segmented into the following five regions: the Jalisco–Colima (J) region to the west, where the Rivera plate subducts at a steep angle that resembles the geometry of the Cocos plate beneath the Caribbean plate in Central America; the Michoacán (M) region, where the dip angle of the Cocos plate decreases gradually towards the southeast; the Guerrero (G) region bounded approximately by the onshore projection of the Orozco and O'Gorman fracture zones, where the subducted slab is almost subhorizontal and under the upper continental plate for about 250 km; and the Oaxaca (O) and the Chiapas (CH) regions in southeastern Mexico, where the dip of the subduction gradually increases to a steeper subduction in Central America.

3. Data analysis and discussion

We analyzed the seismicity of each area which occurred from 2005 to 2012. In order to deal with complete catalogs, we estimated the completeness magnitude M_c, defined as the lowest magnitude of the catalog above which all the events are reliably detected [10], using the Entire-magnitude-range (EMR) method, firstly developed by Ogata and Katsura [11] and then modified by Woessner and Wiemer [12]. A maximum-likelihood estimation is used for a model, which comprises the complete (modeled as a power-law distribution) as well as the incomplete (modeled as a normal distribution) part of the frequency–magnitude distribution. The complete part is characterized by the Gutenberg–Richter law [9] parameters, a and b, while the incomplete part by the parameters μ that is the magnitude at which 50% of the earthquakes are detected, and σ, that is the standard deviation describing the width of the range where earthquakes are partially detected. By using the maximum likelihood estimation method all the parameters are calculated. The Gutenberg–Richter (G–R) law states that the (cumulative) number of earthquakes with magnitude greater than (or equal to) M, $N(>M)$, occurring in a specified area and time is given by $N(>M) = 10^{a-bM}$, where b varies only slightly from region to region and a gives the logarithm of the number of earthquakes with magnitude greater than zero.

The EMR method is implemented in the Matlab software ZMAP [13]. Table 1 shows for each catalog the Gutenberg–Richter law parameters (M_c, b and a).

In Table 1 we can see that the b-values range from about 1 and 2 for the five regions; this range is in agreement with the values already obtained by Mendoza-Ponce [6] and Zuñiga and Wyss [8] for the same regions. The size of the seismic sequence of events with magnitude larger than or equal to the corresponding completeness magnitude is: 762 for Chiapas, 1272 for Guerrero, 93 for Jalisco, 182 for Michoacan and 525 for Oaxaca.