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Precursory signatures in the visibility graph analysis of seismicity: An application to the Kachchh (Western India) seismicity

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ABSTRACT

The Visibility Graph (VG) method maps time series into networks or graphs, converting dynamical properties of time series in topological properties of networks. The VG method was applied to the aftershock depleted catalogue of the Kachchh Gujarat (Western India) seismicity from 2003 to 2012, in order to identify possible precursory signatures in the pattern of the VG parameters. The k–M *slope* (the slope of the line fitting the relationship between the magnitude of the events and their connectivity degrees) seems to sharply increase significantly before the occurrence of the largest shocks ($M \geqslant 4.5$) of the sequence.

1. Introduction

The Visibility Graph (VG) method has been becoming a statistical approach used in different scientific fields for its capability to detect nonlinear dynamical transitions. Specifically, the VG method, developed by Lacasa et al. (2008), has been applied to study palaeoclimatological data (Donges et al., 2011a,b), hurricane frequencies (Elsner et al., 2009), turbulence (Liu et al., 2010), wind speed (Pierini et al., 2012), oceanic tidal measurements (Telesca et al., 2012), solar activity (Yu et al., 2012; Zou et al., 2014a,b). Recently, the VG method was successfully applied to investigate the dynamical properties of seismicity (Telesca and Lovallo, 2012; Aguilar-San Juan and Guzman-Vargas, 2013; Telesca et al., 2013; 2014a,b)

The VG method maps time series into networks and converts dynamical properties of time series into topological properties of networks and vice versa. In particular, if the time series is cyclic the corresponding network is regular, while if the time series is random the corresponding graph is also random; on the other side, fractal time series are mapped into scale-free networks (Lacasa et al., 2008; Donner and Donges, 2011; Campanharo et al., 2011).

In the VG approach a segment connects any two values of the series that are visible by each other, meaning that such 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 (Lacasa et al., 2008) is the following: 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:

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

Let's indicate with k_i the connectivity degree, which is the number of connections of each node i. The following properties always hold (Lacasa et al., 2008): 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. A simple visual sketch that explains how the VG method works is plotted in Fig. 1.

Telesca and Lovallo (2012) 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. (2013) performed the VG analysis of the sequences of earthquakes occurred in the subduction 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

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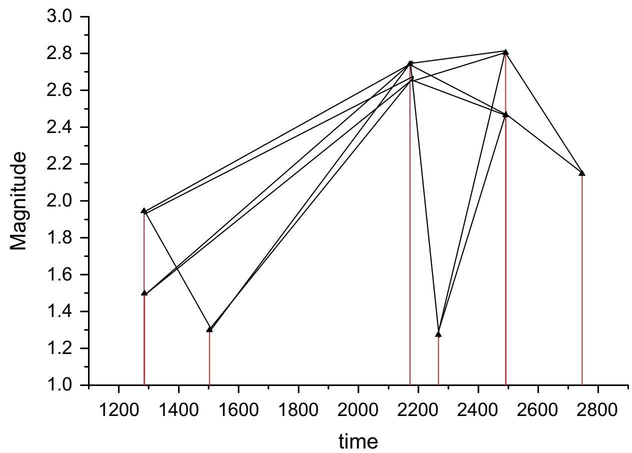

Fig. 1. Sketch of the VG applied to a synthetic seismic sequence.

increase of M, revealing, thus, the property of hub as typical of the higher magnitude events. Telesca et al. (2014a) found that the time variation of the k–M *slope* of the Pannonian region seismicity is closely related with that of the b-value for the shallow events as well as the deep ones. Telesca et al. (2014b), applied the VG method to the sequence of synthetic seismicity generated by using a simple stick–slip experiment with asperities and found that the relationship between the k–M *slope* of the synthetic events and their b-value still holds, suggesting a possible existence of universal laws.

In the present paper, we investigate the earthquake series occurred in Kachchh Gujarat (Western India) from 2003 to 2012, by analysing the time variation of the k–M *slope* through the application of the VG method. This area has been raising a great interest in the seismological community because it was struck by a strong earthquake on 26th January 2001 (Bhuj earthquake) with magnitude 7.7, causing more than 160,000 injured and more than 20,000 people killed, and, thus, making the search of earthquake precursory signatures challenging.

2. Seismotectonic settings

The Kachchh region in Gujarat State of Western India is one of the most seismically active intra-continental regions of the world, and suffering from a flurry of moderate to large magnitude earthquakes since historical times (Rajendran and Rajendran, 2001). The largest historical earthquake occurred in the region on June 16, 1819, and created an E–W-striking 100 km long highland known as Allah Bund (Johnston, 1996; Bilham, 1999; Rajendran and Rajendran, 2001). Another damaging earthquake of Mw 6.0 with maximum intensity of IX in MM scale occurred near Anjar, Gujarat in 1956. The recent one is the 26 January 2001 Mw 7.7 Bhuj strong earthquake that jolted the Gujarat district of Western India. This earthquake was the strongest ever happened in this part of India over last more than 175 years. The moderate shocks are still continuing from the region, although Kachchh lies ~400 km away from the boundary between the Indian and Eurasian Plates and their ongoing convergence is presumably bearing the current tectonics of this region (Stein et al., 2002; Copley et al., 2010). The major geological and tectonic proceedings of this region are: (i) break-up of Africa from the Indian block holding Madagascar and Seychelles; (ii) subsequent break-up of Madagascar from India due to Marion hotpot activity and (iii) break-up of the Seychelles plateau from India followed by eruption of Deccan volcanism related to interaction of Reunion hotspot activity occurred during the Mesozoic and Cenozoic periods (Naini and Talwani, 1983; Besse and Courtillot, 1988; White and Mckenzie, 1989; Storey et al., 1995). Thus, the passive continental margin of Western India has imprints of two hotspots, Marion and Reunion, evolved through several stages of rifting–crustal thinning, magmatic under plating and transient thermal effects (McKenzie, 1978; Cox, 1980; Devey and Lightfoot, 1986; Biswas, 1993). The Deccan flood basalts, which was erupted ~ 65 Ma ago during the northward movement of the Indian continent over the Reunion hotspot subsequent to separation from Madagascar (Morgan, 1981; Duncan and Pyle, 1988; Allegre et al., 1999), covered the large tracts of Saurashtra and Kutch. During the break-up of Gondwana in the Jurassic, the region was affected by rifting along Precambrian trend. The Kachchh rift, mainly described as failed rift of Late Cretaceous, was ceased during the pre-collision stage of Indian plate. The Kachchh rift initially subjected to extension, later transformed into zone of North–South compression giving rise to strike-slip and thrust tectonics under compression regime. The continued seismicity from Kachchh region is cause due to complex tectonic environment and statistical precursory study will definitely helpful for understanding the tectonic behaviour.

3. Results

We investigated the seismicity of Kachchh area occurred from 2003 to 2012. Before applying the VG method, we analysed the completeness magnitude. The time variation of the completeness magnitude (Fig. 2), calculated by using the method of the maximum curvature (Wiemer and Wyss, 2000), shows that it is not constant over the entire observation period. The maximum value of the completeness magnitude is 2.8; considering the correction term of 0.2 (Woessner and Wiemer, 2005), the maximum completeness magnitude is 3.0. Therefore, we considered the sequence of the events with magnitude equal or larger than 3.0. The space and time distribution of this seismicity is shown in Figs. 3 and 4, respectively.

We applied the VG analysis to the whole catalogue with minimum magnitude of 3.0 and calculated the time variation of the k–M slope. Fig. 5 shows the k–M relationship for the whole catalog. The k–M relationship is obtained calculating for each event the connectivity degree k, which is the number of links attached to that event, where each link satisfies the rule stated in Eq. (1). Therefore at each event of magnitude M is associated a value of connectivity degree. The k–M *slope* is calculated as the slope of the line fitting the k–M plot in a least square sense and for our catalogue it comes

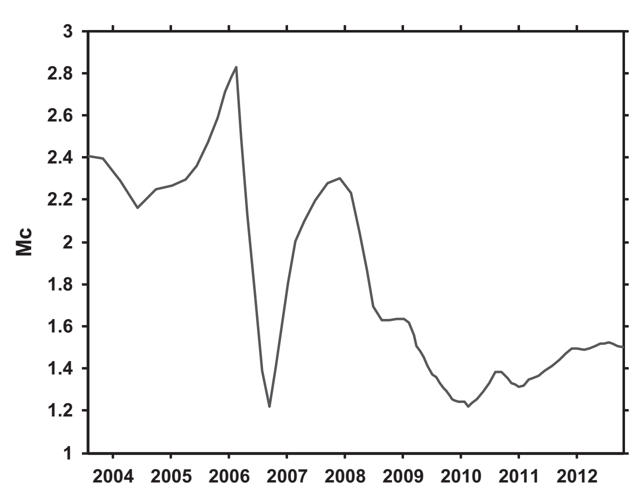

Fig. 2. Time variation of the completeness magnitude calculated by the maximum curvature method.