Introduction for the special issue: the role of fractals in seismology

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Fractal analysis is fast developing and has drawn a great deal of attention in varied disciplines of science and engineering. Over the past couple of decades, fractals and multifractal analyses have been formalized into a thorough mathematical framework and have found a variety of applications with significant impact in several branches of earth system sciences. It is well established that geophysical properties exhibit fractal behavior; hence, the existing formulation for the geophysical and geological problems needs to be readdressed incorporating the fractal behavior of the geophysical/geological parameters, to model the Earth's processes. Hence, *Fractals in Earth System Sciences* highlights the role of advanced data processing techniques in present-day research in various fields of earth system science. In this special issue, different articles on the use of fractals in seismology are compiled which include seismicity analysis in the NE/NW Himalaya, stable continental region (SCR) of western peninsular India, Andaman–Sumatra subduction zone, reservoir-induced seismicity for Koyna–Warna region and for the Enguri dam in west Georgia and one article on the multifractal study on the slope configuration for the western continental margin of India.

Himalaya is said to be one of the world's most complex geological setup with different kinds of seismotectonic systems. The North Eastern region has experienced two of the world's strongest earthquakes, like Shillong earthquake of 1897 known as Assam earthquake and subsequent 1950 earthquake in Arunachal Pradesh, both of 8.7 magnitude and also several other strong earthquakes. Roy and Chowdhury used fractal correlation dimension (Dc) to study the seismicity for the period 1961 to recent for understanding the pattern of seismic hazard. The entire area has been divided into four major tectonic blocks, and each block events were divided into consecutive fifty events window for seeing spatiotemporal patterns. After comparing the patterns, they have identified that Block of

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Eastern Himalaya near Main Central Thrust (MCT), Main Boundary Thrust (MBT), north of Kopili Lineament and Block of Shillong plateau near Daukii Fault are having relatively intense clustering of events in recent times which may be identified as potential zones to have a strong event.

Ashutosh Chamoli and Yadav studied the multifractal behavior of inter-event time sequences for the earthquake events in the NW Himalaya. Multifractal detrended fluctuation analysis (MF-DFA) is used to understand the multifractal behavior of the earthquake data. For this purpose, a complete and homogeneous earthquake catalog of the period 1965–2013 with a magnitude of completeness M_w 4.3 is used. The analysis revealed the presence of multifractal behavior and sharp changes near the occurrence of three earthquakes of magnitude (M_w) >6.6 including the October 2005, Muzaffarabad–Kashmir earthquake.

In the SCR of western peninsular India, Singh et al. analyzed the seismic source characteristics in the Kachchh rift basin and Saurashtra horst tectonic blocks using the earthquake catalog data for the three mainshock, the 2001 Bhuj earthquake (M_w 7.7) in the Kachchh rift basin and the 2007 and 2011 Talala earthquakes ($M_w > 5.0$) in the Saurashtra horst for the period 2006–2011 recorded by a 52-station broadband seismic network. The b -value (frequency–magnitude relation) and D_c (fractal correlation dimension) cross sections image the seismogenic structures that shed new light on seismotectonics of these two tectonic regions. The mainshock sources at depth are identified as lower b -value or stressed zones at the fault end. Crustal heterogeneities are well reflected in the maps as well as in the cross sections. A positive correlation between b - and D_c -values in both the tectonic regions is found.

The Andaman–Sumatra subduction zone is one of the most seismically active corridors in the world. Recently, the region faced three major earthquakes of magnitude more than 8.5 ($M \sim 9.1$ on December 26, 2004; $M \sim 8.6$ on March 28, 2005; and $M \sim 8.6$ on April 11, 2012). Tiwari and Krishnaveni have analyzed inter-event time series of seismic activities of Sumatra regions with magnitude ($m_b \geq 4.8$) and period spanning over 1973–2012 using modern techniques of nonlinear dynamics. The rank order statistics of inter-event time series reveal mixed response with distinct breaks in slope suggesting that earthquake dynamics in this region is unstable but “self-organized”. Comparison of return maps of the data with random, stochastic and chaotic time records is dealt with. Dimensionality of earthquake-generating mechanism using a nonlinear predictor technique on two-dimensional phase portrait constructed by recurrence time series is also analyzed. The nonlinear forecasting analysis suggests that the earthquake processes in the Sumatra region evolve on a non-random low-dimensional chaotic plane.

In a study, Tiwari and Ashutosh Chamoli have analyzed the complexity in the earthquake mechanism as manifested in different forms such as fractal distribution and clustering of seismicity and characterized as critical phenomenon. Researchers have suggested multiple causes of earthquake generation in this region including the one with possible correlation of tidal stresses with earthquake occurrences. The latter issue, however, has been hotly debated in view of the fact that a small stress generated due to tidal forcing cannot cause such a bigger magnitude earthquake. The impact of tidal forcing on critically generated earthquake phenomena is studied and examined the statistical behavior of recurrence time interval of earthquakes using the available data for period of about 40 years from 1973 to 2009. A simple empirical toy model using the concept of catastrophe theory to evaluate the impact of small tidal forcing on the critical state of earthquakes occurrences is used.

The scaling properties of the spatial distribution of the December 26, 2004, Sumatra aftershocks are analyzed by Padhy et al. The epicentral distribution of aftershocks recorded by a local network operated by Geological Survey of India (GSI) is used to compute the spatial correlation dimension, D_2 . The correlation dimension was computed both for real as well as synthetic data sets that include randomly generated point sets obtained using uniform distributions and mimicking the number of events and outlines of the effective areas filled with epicenters. The results are discussed in order to add constraints on the use of synthetic data and of different approaches for uncertainty analysis on spatial variation of D_2 . The relative change in D_2 values can be interpreted in terms of clustering and diffuse seismic activity associated with the low and high D_2 values, respectively. Overall, a relatively high D_2 and low b -value is consistent with high magnitude, diffuse activity in space in the source region of the 2004 Sumatra earthquake.

A review of b -value imaging and fractal dimension studies in the Andaman–Sumatra subduction is carried out by Kirti Srivastava et al. The seismicity analysis of the large earthquakes source region is carried out by several researchers and quantified the spatial and temporal variation of b -value as indicators of differential stress conditions and fractal dimension which is an indicator of material heterogeneity and strength. The results of all these studies clearly bring out the low b -value corresponding to locales where sizable magnitude earthquakes have occurred.

In yet another study, Ramana et al. used the fractal analysis to study the Reservoir Triggered Seismicity (RTS) for the Koyna–Warna region in Western India. The porous crustal rocks of Koyna–Warna region respond to changes in the prevailing stress/strain regime. This crustal section is highly fractured and is being fed by rivers and reservoirs. The ongoing seismicity thus requires understanding of coupled hydrological and tectonic processes in the region. Water table fluctuations are reflection on the ongoing hydro-tectonics of the region. The fractal dimension of water levels in the bore wells of the region is used as measure of the nonlinear characteristics of porous rock, revealing the underlying complexity. The spatiotemporal changes in the fractal dimensions show that hydro-seismically the region behaves as a low-dimensional nonlinear dynamical system.

Telesca et al. analyzed the fractal and multifractal properties of the earthquake time series occurred around the Enguri dam in west Georgia by applying the methods of detrended fluctuation analysis (DFA) and MF-DFA. Their findings show that the water level variation may influence the fractal properties of earthquake temporal distribution in the local area around the Enguri dam. In particular, it is observed that time distribution features of seismicity occurred in the second period is more persistent than the natural seismicity occurred in the first period. Furthermore, the seismic process of the second period shows a lower multifractal degree than that of the first period, indicating that the influence of quasi-periodic fluctuation of water level features the seismicity as more regular compared to the natural seismicity.

Chakraborty et al. presented the slope configuration of the submarine gullies, ridges and the adjacent slump zone off Goa, along the western continental margin of India (WCMI) utilizing multibeam bathymetric and single channel seismic data. The fluid flow migration signature in the form of pockmark seepages, traces of mud volcanoes and enhanced reflectors is observed in the area. A stochastic multifractal technique has been employed to understand the nature of the fine-scale seafloor processes active in the slope region. The three estimated parameters of the depth profiles, i.e., the degree of multifractality (α), sparseness ($C1$) and the degree of smoothness (H), substantiate a very high degree of multifractality for all the thirty-three bathymetric profiles. Except for the five adjacent profiles (four from the slump zone and one of the ridge), the remaining twenty-eight depth

profiles of the gully, ridges and slump zones show negligible difference. Based on the multifractal study, they conclude that the observed discrimination might be due to the significant interaction between the bottom currents off Goa and the varied seafloor morphological aspects with seepages and faults.

We are glad to have been invited as Guest Editors for fractals in seismology in Natural Hazard Journal. We hope that the special issue compiled after detailed pre-review process will help the readers and academicians in a better understanding of the use of Fractals in Seismology. We wish to thank Prof Tad- Murthy, Editor, Natural Hazards, for his invitation and support in bringing out this volume. We also wish to thank the several reviewers who have contributed their time and efforts in the past 1 year in the review of the manuscript. We also sincerely thank Mrs Harini and Mr. Nagarjuna for their assistance in bringing out this issue.