Physica A 492 (2018) 1352–1363

Contents lists available at ScienceDirect

Physica A

journal homepage: www.elsevier.com/locate/physa

Universality in the dynamical properties of seismic vibrations

Soumya Chatterjee [a,b,*], P. Barat [a], Indranil Mukherjee [a]

[a] Maulana Abul Kalam Azad University of Technology, West Bengal, BF-142, Sector 1, Salt Lake, Kolkata–700064, India
[b] Academy of Technology, Adisaptagram, Hooghly, Pin-712121, West Bengal, India

HIGHLIGHTS

- Probability distribution functions of seismic vibration data taken from six different geographical locations obey scaling law.
- With increasing size of the data sets the PDFs exhibit a certain universality with respect to the different geographical locations.
- The different predictions of Random Matrix Theory (RMT) in respect of fluctuations and universality characteristics are supported by the data analysis.
- The results remain invariant when the data are randomized and the correlations in the data are thereby removed.

ARTICLE INFO

Article history:
Received 13 May 2017
Received in revised form 30 October 2017
Available online 22 November 2017

Keywords:
Seismic vibrations
Random Matrix Theory
Universality
Scaling

ABSTRACT

We have studied the statistical properties of the observed magnitudes of seismic vibration data in discrete time in an attempt to understand the underlying complex dynamical processes. The observed magnitude data are taken from six different geographical locations. All possible magnitudes are considered in the analysis including catastrophic vibrations, foreshocks, aftershocks and commonplace daily vibrations. The probability distribution functions of these data sets obey scaling law and display a certain universality characteristic. To investigate the universality features in the observed data generated by a complex process, we applied Random Matrix Theory (RMT) in the framework of Gaussian Orthogonal Ensemble (GOE). For all these six places the observed data show a close fit with the predictions of RMT. This reinforces the idea of universality in the dynamical processes generating seismic vibrations.

1. Introduction

The phenomenon of earthquake has evoked fear and curiosity among human beings since the beginning of civilization. Attempts have been made to unravel the nature and dynamics of earthquakes. The process responsible for the catastrophic vibration occurring at the surface of the earth is triggered at a focus point lying at a depth of tens to hundreds of kilometres below the earth's surface. A catastrophic vibration or mainshock is preceded by a cluster of foreshocks and followed by a cluster of aftershocks. There are also commonplace daily vibrations. All these vibrations are part of overall seismic activities of the earth's crust. Therefore, the observed magnitudes of all possible seismic vibrations are considered in our analysis of the universality in the dynamical properties of seismic vibrations. The seismic vibrations occurring in continuous time at the earth's crust are recorded in discrete time by seismometers placed at different parts on the surface of the earth. A seismometer records vibrations in the form of body waves and surface waves contained within a pulse at certain intervals of

* Corresponding author.
E-mail addresses: soumoch7@gmail.com, soumya.chatterjee@aot.edu.in (S. Chatterjee).

https://doi.org/10.1016/j.physa.2017.11.062
0378-4371/

time. The maximum value of a pulse is the magnitude of the vibration. The triggering processes causing seismic vibrations are activated due to a complex dynamics occurring between the tectonic plates at the fault which has a fractal geometry [1]. The physical properties of the materials of the earth's crust responsible for wave propagation like density, elastic moduli etc. and their spatial distribution are extremely heterogeneous. Thus, propagation of the seismic waves through the earth's crust is a complex process. The inhomogeneties of the earth's crust modify the amplitude, direction, phase and mode of the propagating waves in a random manner. The observed magnitudes of the earthquake measured on the surface of the earth should possess these intrinsic characteristics of randomness. As the spatio-temporal dynamics of the seismic activities appear to be random and unpredictable, it is difficult to construct a generalized and comprehensive model for this dynamics. However, several attempts have been made by different authors [2–4] to understand and formulate this fascinating dynamics. It is difficult to delineate whether the dynamics of the earthquake is stochastic in nature or arises from a low dimensional chaotic system, since the outcome of both is impossible to predict on longer time scales [5–8].

This dynamics is characterized by several power laws and spatial and temporal correlations [9–11]. The correlations are crucial to understand the short term and long term trends in the earthquake pattern. The power laws, which have been generally accepted to describe the seismic activities with a high degree of accuracy are the following,

1. The Gutenberg–Richter law [12] for the distribution $Q(m)$ of the earthquake magnitude m given as $Q(m) \sim 10^{-bm}$, where $b \approx 1$.

2. The Productivity law [13,14] for the number $N(m)$ of first generation aftershocks following a mainshock given as $N(m) \sim 10^{\alpha m}$.

3. The Omori law [15] for the rate of aftershock $R(t)$ since a main shock which states that $R(t) \sim t^{-p}$, where $p \approx 1$ for large earthquakes.

Taking these laws into account, over the years, studies have been carried out [16–24] primarily to determine whether for a particular region of the earth, the subsequent magnitudes of the seismic vibrations for short and long time scales, are temporarily correlated. The temporal correlation, with correlation time characteristic of the place, may show short or long term memory which leads to clustering of events like the phenomenon of aftershocks. Epidemic type aftershock model (ETAS) [16,17] assumes no temporal correlation and treats all earthquakes on the same footing. There are few studies [18–21] which analysed the distribution of inter occurrence times between the earthquakes to establish the existence of temporal correlation. Bak et al. [22] have shown that the inter occurrence times of the earthquakes recorded at California follow a unified scaling law ranging from tens of seconds to tens of years. A. Corral [23] has shown similar results for different regional geographical locations which may be treated as a signature of universality. The temporal distribution of recorded magnitudes in the Serbia earthquake catalogue has been studied in [24]. In another highly interesting study carried out by Gao et al. [25], fluctuations in the yearly usage frequencies of certain words describing natural and social phenomena have been analysed, these data being obtained from approximately five million digitized books published during the last two centuries. Using an adaptive fractal analysis computation of the Hurst exponent corresponding to the usage frequency of the term "earthquake" indicates that this phenomenon possesses persistent long range correlation. Moreover, the short temporal clustering like aftershocks may be treated as the short time limit of the general hierarchical properties of earthquakes. This means that foreshocks, aftershocks and mainshocks may all be considered as parts of one unique process. Hence, the earth's crust can be thought of as a self organized system showing fluctuations around a critical point manifesting both scale invariance and universality [26].

The motivation for the present work is two fold -

(i) To check whether scale invariance and universality are followed by the probability distributions of the magnitudes of seismic vibrations by carrying out a statistical analysis of the data containing the magnitudes of the seismic vibrations obtained from six different geographical locations.

(ii) Following a conjecture of Bohigas, Giannoni and Schmit [27], that certain universal properties of spectral features in classically chaotic systems are found to be well described by Random Matrix Theory (RMT), we have used the tools of RMT to understand the nature of the dynamical properties of seismic vibrations which is a complex process and for which the interactions between the components are not accurately known.

Since the geometrical and physical properties of the earth's crust do not necessarily change over a short period of time (such as the time period considered in this analysis), it is assumed that the dynamical properties of seismic wave propagation will remain invariant compared to the huge time span over which such seismic vibration have been occurring. As a result of this invariance, the magnitudes of the observed seismic vibration data at a place at different times are considered to be on the same footing by assuming them to be a part of the same unique process. We have also considered the earthquakes as point processes in space and time [28,29] by neglecting the spatial scale of earthquake rupture zones as well as the temporal scale of duration of each earthquake.

The paper is organized as follows. Section 2 describes the data set being investigated. Section 3 discusses the scaling behaviour and universality properties displayed by the data set. Section 4 applies the tools of RMT to analyse the data. Section 5 discuss the results obtained and attempts to draw some general inferences.

2. The data sets analysed

We have studied the time series data of seismic vibration magnitudes collected from earthquake catalogues of six regional geographical locations viz. North California, South California, Japan, New Zealand, Italy and Australia [30–35]. In