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The Weibull–log Weibull transition of interoccurrence time for synthetic and natural earthquakes

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ABSTRACT

We study the interoccurrence time distributions of events by analyzing synthetic catalogues and three natural catalogues of the Japan Meteorological Agency (JMA), the Southern California Earthquake Data Center (SCEDC) and the Taiwan Central Weather Bureau (TCWB). We find a universal feature, i.e. the Weibull–log Weibull transition, in the interoccurrence time statistics. This transition demonstrates that the interoccurrence time statistics of earthquakes possess the hybrid Weibull and log Weibull statistics. We further find that the crossover magnitude m_c^{**} from the superposition regime to the pure Weibull regime is averagely proportional to the plate velocity. In the end of this paper we summarize a region-independent relation, i.e. $m_c^{**}/m_{\max}=0.54\pm0.06$, which represents a novel empirical relation related to the Weibull–log Weibull transition for earthquake processes.

1. Introduction

Statistical properties of time intervals between successive earthquakes (hereinafter the interoccurrence times and the recurrence times) have been frequently studied in order to predict when the next big earthquake will happen. Interoccurrence times and recurrence times mean the time intervals between the events on all faults in a region and on a single fault/segment, respectively. Previous studies (Utsu, 1984; Madhava Rao and Kaila, 1986; Papadopoulos, 1987; Papazachos et al., 1987; Dionysiou and Papadopoulos, 1992; Wang and Kuo, 1998; Bak et al., 2002; Matthews et al., 2002; Corral, 2004; Shcherbakov et al., 2005; Abaimov et al., 2008; Enescu et al., 2008) have been mainly focused on the determination of the underlying probability distribution and the presentation of the scaling law. For instance, the Weibull distribution (Abaimov et al., 2008), the exponential distribution (Enescu et al., 2008), the Brownian passage time distribution (Matthews et al., 2002), the gamma distribution (Wang and Kuo, 1998), the generalized gamma distribution (Bak et al., 2002; Corral, 2004; Shcherbakov et al., 2005), the log normal distribution (Matthews et al., 2002), the Poissonian distribution (Dionysiou and Papadopoulos, 1992), the negative binomial distribution (Madhava Rao and Kaila, 1986), the Gaussian distribution (Papazachos et al., 1987) and the Bayesian distribution (Papadopoulos, 1987) were used for candidates of the distribution functions of interoccurrence and recurrence times. However, the most appropriate distribution function of the interoccurrence and recurrence time remains under debate and open. Utsu (1984), for instance, applied four probability models to analyze interoccurrence times for Japanese earthquakes and discussed their significances. Recently, in the stationary regime, a unified scaling law of the interoccurrence time statistics was proposed by Corral (2004). Abe and Suzuki (2005) on the other hand showed that the cumulative distribution of interoccurrence times is very well fitted by the q-exponential distribution ($q>1$) corresponding to the power law. Two underlying assumptions should be noticed in those papers: (a) Earthquakes can be considered as a point process in space and time; (b) There is no distinction between foreshocks, mainshocks, and aftershocks.

Except for real earthquake data used in abovementioned papers, due to the limitation of real earthquake data, the time-interval statistics have also been studied by means of numerical simulations of earthquake models (e.g. Rundle et al., 2000; Abaimov et al., 2007; Hasumi, 2007; Hasumi et al., 2009a). Both the conceptual spring-block models (Abaimov et al., 2007; Hasumi et al., 2009a) and the sophisticated Virtual California model (Yakovlev et al., 2006) show the Weibull distribution of the recurrence times. Hasumi (2007) reported that the cumulative distribution of interoccurrence times in the two-dimensional (2D) spring-block model can be described as the Zipf–Mandelbrot type power law which has been early observed by Abe and Suzuki (2005).

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Yet another new statistical feature on the interoccurrence times, the Weibull–log Weibull transition, was very recently proposed by analyzing the Japan Meteorological Agency (JMA) catalogue (Hasumi et al., 2009b). Hasumi et al. (2009b) found that the probability distribution of interoccurrence times can be very well fitted by the superposition of the log Weibull distribution and the Weibull distribution. The results in Hasumi et al. (2009b) demonstrate that the interoccurrence time statistics probably contain both the Weibull and log Weibull statistics and, as the threshold of magnitude m_c increases, the predominant distribution could change from the log Weibull distribution to the pure Weibull distribution. The distribution of large earthquakes obeys the Weibull distribution with an exponent less than unity indicating that the process of large earthquakes is not a Poissonian process. Importantly, those hybrid distributions and the Weibull–log Weibull transition can be also found in synthetic catalogues produced by the 2D spring-block model (Hasumi et al., 2009a). The applicability to other tectonic regions of the Weibull–log Weibull transition however remains unsolved. Whether or not is the Weibull–log Weibull transition universal?

In this study we investigate the interoccurrence time statistics by analyzing the Southern California and Taiwan earthquake catalogues. Together with the previous results from the JMA and synthetic catalogues shown in Hasumi et al. (2009a,b), a universal Weibull–log Weibull transition can be obtained in all of these catalogues. We also suggest that a crossover magnitude m_c^{**} between the superposition regime and the pure Weibull regime is proportional to the plate velocity and, at the end of this paper, we elucidate its implication in the geophysical sense.

2. Data and methodology

For studying the interoccurrence time statistics we analyzed three natural earthquake catalogues of the Japan Metrological Agency (JMA), the Southern California Earthquake Data Center (SCEDC) and the Taiwan Central Weather Bureau (TCWB), as well as one synthetic catalogue generated from the 2D spring-block model. Information on each catalogue are listed in Table 1, where $m_{\min}$ corresponds to the minimum magnitude in the catalogue and m_c^0 is the magnitude of completeness, that is the lowest magnitude at which the Gutenberg–Richter law holds. We basically consider events with magnitude greater than and equal to m_c^0 because events smaller than m_c^0 are supposedly incomplete for recording.

The synthetic catalogue is produced by the 2D spring-block model with the velocity-weakening friction law (Carlson et al., 1991). The 2D spring-block model is characterized by five parameters: the stiffness l_x^2 and l_y^2, the decrement of the friction force α, the plate velocity ν, and the difference between the maximum friction force and dynamical friction force σ. We have set those parameters as $l_x^2=1$, $l_y^2=3$, $\alpha=3.5$, $\nu=0.01$ and $\sigma=0.01$, which make the model reproduce several realistic aspects of events in the Gutenberg–Richter relation with a b-value of 1 (Kumagai et al., 1999; Hasumi, 2007), the constant stress drop (Kumagai et al., 1999), the interoccurrence time statistics (Hasumi, 2007) and the hypocenter interval statistics (Hasumi, 2009). For many details on simulation of the 2D spring-block model, we refer the readers to the papers of Hasumi (2007, 2009). Event magnitude m in the model is defined as $m = m_0 + \log_{10}\left(\sum_{i,j}^{n} \delta u_{i,j}\right)/1.5$, where $\delta u_{i,j}$ and n are the total slip at the cell (i, j) and the total number of slipping blocks, respectively. m_0 is set at 0.7 for shifting m to a positive value. The occurrence time of an event is the simulating time step when the beginning block slips during an event. The nth interoccurrence time τ_n is defined as $t_{n+1}-t_n$, where t_n and t_{n+1} are occurrence times of the nth and $n+1$th events, respectively.

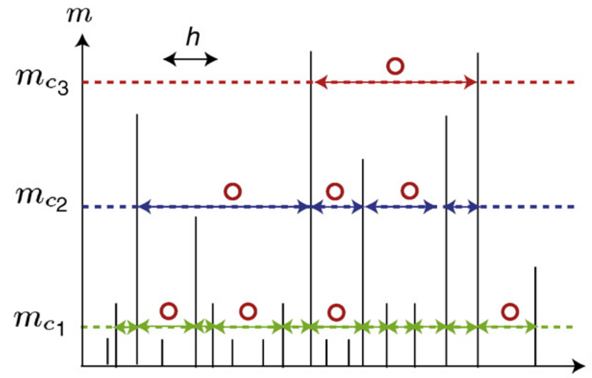

Fig. 1. The schematic diagram for our analysis. m_{c1}, m_{c2}, and m_{c3} are different thresholds of magnitude. We consider the interoccurrence time distribution in the time domain $\tau>h$, corresponding to °.

We show the schematic illustration of our analyzing procedure in Fig. 1. The procedure is the same as that used in the previous studies by Hasumi et al. (2009a,b) and is briefly explained as following: (a) We divided the studied region into the spatial windows with the size of $L\times L$; (b) For each spatial domain, events larger than a certain threshold of magnitude m_c were considered; (c) We calculated interoccurrence times and then performed the distribution fitting over the interoccurrence data τ_i larger than h days. Note that the procedure (a) is used for the JMA catalogue only, because its coverage is much bigger than those of the SCEDC and TCWB catalogues. Also, we focus on the interoccurrence time statistics for long time domain for eliminating the aftershock effect. Although there exist several de-clustering algorithms (e.g. Davis and Frohlich, 1991), the best way for removing aftershocks from the catalogue remains under debate still. We have therefore introduced the temporal parameter h in the procedure (c) for eliminating the immediately time-correlated events. Same strategy has been utilized in Corral (2004) and in Enescu et al. (2008), except we set a larger h value of 0.5 for real catalogues. As for the synthetic catalogue, the 2D spring-block model without the viscous factor does not produce aftershocks. The procedure (c) is therefore skipped, corresponding to $h=0$.

An important goal in this study is to detect the change in the probability distribution of interoccurrence time $P(\tau)$ by varying the magnitude threshold m_c. Here, same as the previous works by Hasumi et al. (2009a,b), we consider five candidate functions for $P(\tau)$, namely, the Weibull distribution P_w, the log Weibull distribution P_{lw}, the power law distribution P_{pow}, the gamma distribution P_{gam} and the log normal distribution P_{ln}. The probability density functions of these distributions are

$$P_w(\tau) = \left(\frac{\tau}{\beta_1}\right)^{\alpha_1-1}\frac{\alpha_1}{\beta_1}\exp\left[-\left(\frac{\tau}{\beta_1}\right)^{\alpha_1}\right], \quad (1)$$

Table 1
Information on the used earthquake catalogues.

Catalogue name	Coverage	Term	Number of earthquakes	$m_{\min}$	m_c^0	$m_{\max}$
JMA	25°–50°N and 125°–150°E	01/01/2001–31/10/2007	130,244	2.0	2.0	8.0
SCEDC	32°–37°N and 114°–122°W	01/01/2001–31/12/2007	10,838	0.0	1.4	5.7
TCWB	21°–26°N and 119°–123°E	01/01/2001–31/12/2007	148,155	0.0	1.9	7.1
Synthetic	50×50 (System size)	–	297,040	0.0	0.3	2.8