Tectonophysics 682 (2016) 147–168

Contents lists available at ScienceDirect

Tectonophysics

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

Stress release model and proxy measures of earthquake size. Application to Italian seismogenic sources

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ARTICLE INFO

Article history:
Received 26 August 2015
Received in revised form 29 April 2016
Accepted 10 May 2016
Available online 19 May 2016

Keywords:
Point process
Probabilistic forecasting
Interevent time distribution
Seismogenic sources
Bayesian inference

ABSTRACT

This study presents a series of self-correcting models that are obtained by integrating information about seismicity and fault sources in Italy. Four versions of the stress release model are analyzed, in which the evolution of the system over time is represented by the level of strain, moment, seismic energy, or energy scaled by the moment. We carry out the analysis on a regional basis by subdividing the study area into eight tectonically coherent regions. In each region, we reconstruct the seismic history and statistically evaluate the completeness of the resulting seismic catalog. Following the Bayesian paradigm, we apply Markov chain Monte Carlo methods to obtain parameter estimates and a measure of their uncertainty expressed by the simulated posterior distribution. The comparison of the four models through the Bayes factor and an information criterion provides evidence (to different degrees depending on the region) in favor of the stress release model based on the energy and the scaled energy. Therefore, among the quantities considered, this turns out to be the measure of the size of an earthquake to use in stress release models. At any instant, the time to the next event turns out to follow a Gompertz distribution, with a shape parameter that depends on time through the value of the conditional intensity at that instant. In light of this result, the issue of forecasting is tackled through both retrospective and prospective approaches. Retrospectively, the forecasting procedure is carried out on the occurrence times of the events recorded in each region, to determine whether the stress release model reproduces the observations used in the estimation procedure. Prospectively, the estimates of the time to the next event are compared with the dates of the earthquakes that occurred after the end of the learning catalog, in the 2003–2012 decade.

1. Introduction

The formulation of stochastic models for seismic hazard assessment in probabilistic terms is essentially based on phenomenological analyses or physical hypotheses. Phenomenological analyses generate models that belong to the class of the self-exciting models (Hawkes and Oakes, 1974) that describe the temporal and spatial clustering of earthquakes (Kagan, 1991; Ogata, 1988, 1999; and references therein). These models were originally proposed to explain the decay of secondary shocks that follow a strong earthquake, and then they were applied for the detection of anomalies in seismic activity (Matsu'ura, 1986; Ogata, 1997). These empirical models aspire to provide a good descriptive fit to the data, but they do not necessarily strive for a context-specific physical explanation. Models based on physical hypotheses are more challenging, as these embody features that relate directly to the underlying scientific knowledge. Using these models, the aim is to explain how the evolution of the process depends on its history, in ways that can be interpreted in terms of the underlying mechanisms. Examples of such physical models are the block-slider, the branching for fractures, percolation, and cellular automata (Bhattacharyya et al., 2006); these operate typically on small space–time scales. The most popular models that attempt to incorporate physical conjecture into the probabilistic framework and are concerned with large space–time scales are those included in the class of self-correcting models. In the seismological context, the elastic rebound theory still has the leading role, even though it was proposed a century ago by Reid (1910). As a first approximation, modern measurements using global positioning systems (GPS) largely support the Reid theory as the basis of seismic movement along faults. Vere-Jones (1978) transposed this Reid theory into the framework of stochastic point processes, and in particular of the self-correcting models, through the first version of the stress release model. Enriched versions of this model have been extensively adopted for over 20 years now (Vere-Jones and Yonglu, 1988; Zheng and Vere-Jones, 1991, 1994; Bebbington and Harte, 2003; Kuehn et al., 2008). One of their peculiarities is that they allow for possible interactions among neighboring fault segments as an explanation for the presence of

Abbreviations: SR, stress release; MR, macroregion; McMC, Markov chain Monte Carlo; ISS, Individual Seismogenic Sources; CSS, Composite Seismogenic Sources.

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http://dx.doi.org/10.1016/j.tecto.2016.05.017
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clusters of even large earthquakes, in contrast to the quiescence that one would expect after a strong earthquake, according to the elastic rebound theory.

The stress release (hereinafter SR) model is based on a physical quantity that represents a proxy measure of the size of an earthquake, and that is generically indicated as stress. Translating the elastic rebound theory into stochastic terms, the occurrence probability in a SR model depends on the elastic stress stored on a fault, which is the result of its gradual accumulation due to tectonic forces, and of sudden releases during past earthquakes.

In this study, we focus on alternative choices for the proxy variable stress to identify which physical quantity among those considered produces the best performance of the model. We propose four versions of the SR model in which the evolution of the system over time is represented by the amount of strain, seismic moment, seismic energy, or scaled energy. The values of these quantities for the events considered are obtained by integrating the available information on the most common input to probabilistic seismic hazard assessment, that is, the historical (macroseismic) and instrumental catalogs of seismicity, which are characterized by epicentral/hypocentral location, origin time, and magnitude, and the map of seismogenic faults, as active faults deemed to be sources of large earthquakes and characterized by rupture parameters, such as area, mechanism, and magnitude.

In the literature the SR model was initially applied to strong earthquakes located in wide tectonic units, such as the northern China region (Vere-Jones and Yonglu, 1988). Then it turned out that the model fit can be improved by subdividing the region on the basis of seismicity, geophysical structure, and tectonic features, and by applying a different SR model to each subregion (Zheng and Vere-Jones, 1991, 1994). Analogously, in Section 2, the four versions of the SR model are analyzed on a regional basis, by subdividing the Italian territory into eight large tectonically coherent zones, hereinafter called the macroregions (MRs). Using publicly available databases (Section 3), we put together eight datasets, one for each MR, that are constituted by earthquakes of $M_w \geq 5.3$ that are most likely associated with the fault sources that are included in each MR. Statistical treatment of the possible incompleteness of the recorded seismicity is also taken into account (Appendix A).

In Section 4, the model parameters are estimated following the Bayesian paradigm and applying Markov chain Monte Carlo (McMC) methods for sampling from the posterior probability distributions of the parameters. In this way, we obtain not only the parameter estimates, typically as their posterior means, but also a measure of their uncertainty, as expressed through the simulated posterior distribution of each parameter. In Section 4.2, the four models are compared one to the other through the Bayes factor and the Ando & Tsay information criterion (Ando and Tsay, 2010), to determine which among the proposed measures of the size of an earthquake provides the best fit to the data, and which resulting model shows the best predictive accuracy. We have also examined the various models in the light of the probability distribution $F(\omega_t|\mathcal{H}_t)$ of the time to next event conditioned on the previous history $\mathcal{H}_t$ of the process. Results of the four SR models fitted to the data of each MR are shown in Section 5, and their performances are compared with each other and also with those of the Poisson model. Retrospective validation is performed by evaluation of the expected time to the next event immediately after each earthquake in the datasets (Section 5.2.2). The same analysis is then carried out in a prospective sense, which considers the earthquakes that occurred from the end of the learning catalog to the end of 2012 (Section 5.2.3). These test events were drawn from the available instrumental and parametric catalogs, while remaining as consistent as possible with the characteristics of the learning catalog.

All of the forecasts were carried out using data based on 2002 knowledge, as they were made available by the database compilers, so that our results are independent of subjective choices and only reflect the capability of the applied model in an actual context.

2. Self-correcting models

Let us take into account a region that can be considered as a seismic unit on the basis, for instance, of the kinematic context and the expected rupture mechanism, and with a sufficiently extensive historical record. Adopting the Reid elastic-rebound theory, we generically use the word stress to indicate the quantity X that governs the state of the system in that region. We assume that X increases linearly with time at a constant loading rate ρ imposed by external tectonic forces, until it exceeds the strength of the medium. X then abruptly decreases each time an earthquake occurs. This hypothesis can be formalized by:

$$X(t) = X_0 + \rho\, t - S(t), \tag{1}$$

which expresses the variation of $X(t)$ over $t \in [0,T]$, where X_0 is the initial level of stress and $S(t)$ is the accumulated stress released by the earthquakes in the region at times $0 < t_i < t$, which is $S(t) = \sum_{i:t_i<t} X_i$. Assuming that the probability $\lambda(t)$ of instantaneous occurrence in $(t, t+dt)$ is a monotonic increasing function ψ of the stress level, we have $\lambda(t|\mathcal{H}_t) = \psi[X(t)]$ where $\mathcal{H}_t$ is the accumulated history of the process. In the original version of this model, given by Vere-Jones (1978), the form of the intensity function was $\lambda(t) = [\nu + \beta(t - \tau S(t))]^+$, where $[x]^+$ is 0 if $x < 0$; otherwise $[x]^+ = x$. Then, to guarantee the positivity of λ, an exponential function for ψ was chosen such that:

$$\lambda(t|\mathcal{H}_t) = \exp\{\nu + \beta X(t)\} = \exp\{\nu + \beta[X_0 + \rho\, t - S(t)]\} \tag{2}$$

with $\beta > 0$.

This implies that when $X(t)$ assumes a positive and larger value (i.e., low seismic activity), the intensity $\psi[X(t)]$ is also larger, and the occurrence probability increases; conversely, smaller negative values of $X(t)$ reduce the probability (Fig. 1). This model belongs to the class of self-correcting point processes of Isham and Westcott (1979), with history-conditioned intensities. In other words, the model given by Eq. (2) can be thought of in terms of the balance between the expected and observed values of the physical quantity X. In Eq. (1), at each t_i, it can be seen that $X_0 + \rho t_i$ is the estimated stress in the region, whereas $S(t_i)$ is the stress released by all of the earthquakes before t_i, and thus represents the lowest boundary of the stress estimate in the region. This line of reasoning implies that when the observed accumulated stress is lower than the expected, a seismic event is more likely to occur.

In Eq. (2), X can be any physical parameter that constitutes a proxy measure of the strength of an earthquake, with the only constraint being that when dealing with long-term seismic hazard, this physical quantity can be evaluated from historical events. In the first applications of the stochastic model given by Eq. (2) (Vere-Jones and Yonglu, 1988; Zheng and Vere-Jones, 1991, 1994), $X(t)$ is a scalar quantity – the Benioff strain – that can be calculated from:

$$\log_{10} X = \frac{1}{2}\log_{10} E = 0.75\, M_s + 2.4 \tag{3}$$

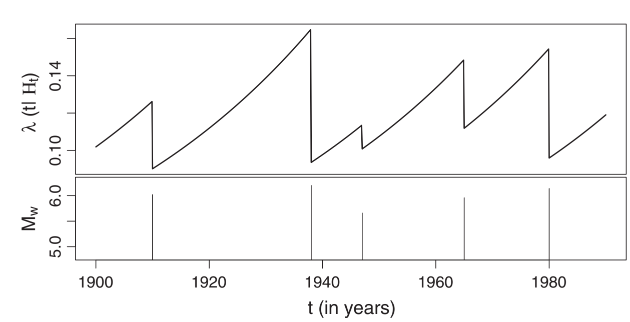

Fig. 1. Representation of the conditional intensity function $\lambda(t|\mathcal{H}_t)$ of the stress release model (top); moment magnitude versus occurrence times of the related seismic dataset (bottom).