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# Bayesian analysis of marked stress release models for time-dependent hazard assessment in the western Gulf of Corinth

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**Abstract**

We consider point processes defined on the space–time domain which model physical processes characterized qualitatively by the gradual increase over time in some energy until a threshold is reached, after which, an event causing the loss of energy occurs. The risk function will, therefore, increase piecewise with sudden drops in correspondence to each event. This kind of behaviour is described by Reid's theory of elastic rebound in the earthquake generating process where the quantity that is accumulated is the strain energy or stress due to the relative movement of tectonic plates. The complexity and the intrinsic randomness of the phenomenon call for probabilistic models; in particular the stochastic translation of Reid's theory is given by stress release models. In this article we use such models to assess the time-dependent seismic hazard of the seismogenic zone of the Corinthos Gulf. For each event we consider the occurrence time and the magnitude, which is modelled by a probability distribution depending on the stress level present in the region at any instant. Hence we are dealing here with a marked point process. We perform the Bayesian analysis of this model by applying the stochastic simulation methods based on the generation of Markov chains, the so called Markov chain Monte Carlo (MCMC) methods, which allow one to reconcile the model's complexity with the computational burden of the inferential procedure. Stress release and Poisson models are compared on the basis of the Bayes factor.


*Keywords:* Bayesian inference; Markov chain Monte Carlo methods; Magnitude distribution; Point processes; Self-correcting models

## 1. Introduction

The stress release (SR) model was introduced by Vere-Jones in 1978; it transposes Reid's elastic rebound theory in the framework of stochastic point processes and expresses the probability of instantaneous occurrence as an increasing function of the stress level accumulated in a region, that is, its hazard function is time dependent in contrast to the constant hazard of the most generally used Poisson process. Although the SR model has been successfully applied to model sequences of strong earthquakes in Japan, New Zealand, Iran and China (Vere-Jones and Yonglu, 1988; Zheng and Vere-Jones, 1991, 1994), its physical basis, like all the models in the literature, does not completely explain the process generating earthquakes which, as is known, is considerably more complicated. In fact, according to the elastic rebound theory we would expect a large earthquake to be

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followed by a period of quiescence whereas in reality a strong earthquake may be succeeded by a period of activation and sometimes by another shock of comparable magnitude. An extension of the original model, the *linked* SR model, describes this clustering behaviour of large earthquakes in terms of stress transfer among interacting subregions of the area investigated (Lu et al., 1999; Bebbington and Harte, 2003; Rotondi and Varini, 2003b). The conjecture that an earthquake can accelerate or delay the following one because of the stress transfer due to short or long-range interactions concurs with recent research on the self-organized criticality of earthquakes.

Every point process model is univocally defined by its conditional intensity function, that is, the probability that an event will occur in an infinitesimal interval. A characteristic of SR models is that their intensity function at any time $t$ depends on the entire history of the process up to that instant, that is, it is a function of the set $\{t_i, m_i\}_{i=1}^n$ of the occurrence times and magnitudes of the events recorded before $t$. Obviously, the longer and more complete the catalogue is used in its estimation, the better the results are. From the spatial viewpoint, the model requires the identification of regions that can be considered independent seismic units on the basis, for instance, of recognized geophysical subdivisions. Hence these models, on the basis of the occurrence of large earthquakes, aim at the long-term prediction of future shocks of comparable magnitude in the same area.

We have applied the original SR model to a single seismogenic zone, the western part of the Gulf of Corinth, in order to examine on a real test site the potential of the model and the issues involved in its application. An innovative element consists in the addition of the probability distribution of the magnitude dependent on the stress level and hence, in the assessment of a bivariate time-dependent hazard function. The zonation and the catalogue we have used are, as far as we know, the best data sets available for Greece. No previous studies applying SR models to forecast earthquakes in Greek seismic sources were found in the literature. Recent research related to earthquake prediction in Greece has mainly concerned precursory phenomena on an intermediate time-scale, magnitude, time and spatial distribution of foreshocks (Papadopoulos et al., 2000), seismic regularities (Papadimitriou and Sykes, 2001) and accelerated moment release (Papazachos and Papazachos, 2000).

The paper presents the model in Section 2 and the case concerned in Section 3. In Section 4 we illustrate the results obtained and indicate the weak points of this approach. The estimation problem is tackled in the Bayesian framework; the complexity of the model requires resort to recently developed procedures of stochastic simulation for inference, the Markov chain Monte Carlo methods. For a detailed explanation of these methods in this context we refer to Rotondi and Varini (2003a).

## 2. Stress release model

Let $\mathcal{H}_t = \{t_i, m_i\}_{i=1}^n$ denote the seismic history of an active region, that is, the set of events recorded in the time period $(T_0, T_1)$ of magnitude $m_i$, $i = 1, \ldots, n$, not less than a threshold $M_0$ and $t_i = T_i - T_0$, $T_i$ being the date of the $i$th event. We assume that the probability of occurrence depends on an unobserved quantity $X(t)$ which increases linearly between two events and decreases suddenly when the events occur. This quantity may be interpreted as the stress present in the region at any instant and hence it is given by

$$X(t) = X(0) + ct - S(t),$$

sum of the stress $X(0)$ in the region at the initial instant and of the stress accumulated through the constant loading rate $c > 0$, subtracting the stress $S(t)$ released through earthquakes occurred up to $t$, that is $S(t) = \sum_{i:t_i<t} x_i$ where $x_i = 10^{\beta\cdot(m_i - M_0)}$ is, according to Benioff's formula, an approximation of the stress released by a shock of magnitude $m_i$. The $\beta$ constant depends on the characteristics of the region, but is generally set at about 0.75.

To define a point process univocally one must assign what is called the conditional intensity function, that is the instantaneous probability of occurrence. In our case a mark, the magnitude, is also associated with each event. Consequently, to satisfy the assumption relating $X(t)$ and the occurrence probability, we must assign a bivariate conditional intensity function $\lambda(t, m)$ of the following type

$$\lambda(t, m) = \psi(X(t)) f(m|X(t)) \tag{1}$$

where $\psi(X(t))$ is a convex risk function increasing to infinity and $f(m|X(t))$ is the probability density function for the magnitude. In general the choice for this density falls on the exponential; considering the dependence on $X(t)$ we have chosen both right and left truncated exponential distribution on the domain $[M_0, M(t)]$:

$$f(m|X(t)) = \frac{\gamma e^{-\gamma m}}{e^{-\gamma M_0} - e^{-\gamma M(t)}} I_{[M_0, M(t)]}(m) \tag{2}$$

where $M(t)$ is the maximum magnitude that an event may have at time $t$ when the stress level present in the region is $X(t)$. From Benioff's formula one obtains the following expression for $M(t)$:

$$M(t) = M_0 + \frac{\log_{10} X(t)}{\beta}$$