2007 SCEC Project Report

Statistical modeling of seismic moment release in SAF system

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Proposal category: Integration and Theory

1 Summary

Problem. Recent studies have reported dramatic discrepancies between the observed seismic moment and its long-term predictions based on space-born data (GPS, VLBI) and tectonic models (*e.g.,* Kreemer *et al.*, 2003; Holt *et al.*, 2000, 2005; Shen-Tu *et al.*, 1998; Meade and Hager, 2005; Bird and Kagan, 2004; McCaffrey, 1997). Notably, several studies have reported the seismic moment deficiency for California — one of the best studied seismic regions in the World. The seismic moment release in California during the 20-th century should have been twice as large as the observed in order to match the long-term strain rates. (Meade and Hager, 2005; Bird and Kagan, 2004; Shen-Tu *et al.*, 1998). This poses a question: *Whether the observed discrepancy can be used to advocate an increased probability of a large impending earthquake in southern California?* The magnitude of such an earthquake should be approximately $M8$ in order to match the long-term tectonic predictions (Meade and Hager, 2005).

Given the dramatic economical and social consequences of such an earthquake, this project has developed and analyzed a SAF-specific model of seismic moment release. The project also considered several auxiliary problems, connected to statistical analysis of clustered seismicity and modeling the dynamics of the slope of the magnitude distribution.

Specifically, the project was focused on the following questions:

Research questions.

(Q1) Which of the three regimes of seismic moment release is realized in the SAF system for different time scales and magnitude ranges?

(Q2) How to make inference about the long-term moment release rates in SAF system based on observations of limited duration? And vice versa, How to predict the observed moment release given the long-term rates in SAF system?

(Q3) Does the moment deficiency consistently observed in southern California imply an increased risk of a large earthquake?

Results. The project has taken advantage of a general statistical methodology for modeling seismic moment release developed by the proposers within a 2006 SCEC project. The main conclusion is that the observed discrepancies between the observed and predicted seismic moment release in CA do fit a moment release model based on the power-law seismic moment distributions and not necessarily justify an increased probability of an impending earthquake.

In short, the project has obtained the following answers to the research questions:

(A1) In most settings, we see a borderline case between the Regime 2 (see below) – irregular moment release, and Regime 3 — regular release.

(A2) By and large, the values of the long-term average and the observed moment will be within a factor 2-5 from each other (precise distributions can be computed). The results show a clear need in using geodetic and geological information to better constraint the furute regional moment release. Estimations based solely on observed earthquakes are intrinsically unstable and this drawback

cannot be resolved by purely statistical methods. The combined use of geological, geodetic, and statistical methods for SHA in CA is proposed for a 2008 SCEC project.

(Q3) The reported two-fold discrepancy between the observed moment and the long-term average can not be considered as a significant deviation from the model. Accordingly, the proposed methodology does not support a claim about an increased probability of an impending earthquake.

Broader impact. The project results can be independently used by the community as an element of regional seismic hazard assessment in SAF system. The project involved training of a graduate student Suresh Kumar from the Department of Mathematics and Statistics at UNR.

2 Approach and previous findings

2.1 Seismic coupling

Our main object of analysis is seismic coupling χ, defined as the ratio between the observed and the predicted (reference) seismic moment:

$$\chi = \frac{\text{Observed moment}}{\text{Predicted moment}} = \frac{\sum_i M_i}{\Sigma_{\text{ref}}}. \tag{2.1}$$

Here M_i denotes the seismic moment from an individual earthquake and the summation in the numerator is taken over all earthquakes within the region and time of interest. Our goal is to find a model for χ such that it will closely reproduce the observed seismic coupling. To specify this model we have to choose a) the process that will assign values to M_i and b) reference model for Σ_{ref}.

2.2 Previous findings relevant to the project

During our SCEC 2006 projects, it was established that:

a) There exist three regimes in a non-linear seismic moment release; the regimes are consistently observed for a wide collection of time-dependent models.

- Regime 1. Moment deficit, $\chi \ll 1$. This regime is seen within the regions with small numbers of events. It corresponds to a heavy-tailed highly skewed total moment distribution. The total seismic moment is best described by a Pareto (or tapered Pareto) random variable.

- Regime 2. Irregular moment release, $\chi \ll 1$ and $\chi \gg 1$ are possible. This regime is seen within the regions with intermediate numbers of events; it is a transition between Regimes 1 and 3.

- Regime 3. Regular moment release, $\chi \approx 1$. This regime is only seen in large regions with many events; here the Central Limit Theorem applies, and the total seismic moment can be approximated by Gaussian distribution.

b) Realization of one or another regime is controlled by two parameters: the number N of the observed earthquakes and the range $m_c - m_t$ of magnitudes considered.

c) Moment deficit usually does not imply the risk of a large regional earthquake.

2.3 Models of seismic coupling

The earthquake size distribution can be nicely approximated by the Gutenberg-Richter relation, which gives the number $N(M)$ of earthquakes with seismic moment above M (Ben-Zion, 2003):

$$N(M) \propto M^{-\alpha}, \ \alpha \approx 2/3. \tag{2.2}$$

This law is known in statistics as *Pareto distribution*. To take into account the finiteness of seismic energy, we consider the *tapered Pareto distribution*

$$N(M) \propto F(M) = 1 - \left(\frac{M_t}{M}\right)^{\alpha} \exp\left(\frac{M_t - M}{M_c}\right), \ M_t \leq M < \infty, \tag{2.3}$$

where M_c is the corner moment — a parameter that primarily controls the distribution in the upper ranges of M (Vere-Jones *et al.*, 2001; Kagan and Schoenberg, 2001; Kagan, 2002a, 2002b).

Accordingly, the appropriate model for χ is defined as

$$\chi_N = \frac{\sum_{i=1}^{N} M_i}{E\left(\sum_{i=1}^{N} M_i\right)}, \tag{2.4}$$

where M_i are independent identically distributed random variables with distribution (2.3). (Similar results are obtained using the truncated Pareto distribution.) In general, the number N of earthquakes is also a random variable. Our analysis refers to constant N, and N being the number of events in a renewal process up to time t.

3 Analysis

Our results are divided into two categories: a) modeling of seismic moment release in SAF, and b) developing general framework and methods for statistical analysis of seismic data. We decsribe below in some detail the analysis in part a).

We use California earthquake catalog produced by the Advance National Seismic System (ANSS), and consider earthquakes with magnitude $m \geq 3.0$ that fall within the square region bounded by $126°W$, $114°W$, $30°N$, $42°N$ during January 1, 1932 - August 1, 2007.

The analysis was done for the entire region, in every of the nine subregions shown in the Fig. 1, as well as in particular subregion combinations. The analysis was done for different magnitude thresholds ($m > 3.0$, $m > 4.0$, and $m > 5.0$) and within different time intervals (1932–2007 and 1987–2007), to ensure stability of conclusions. The analysis was also performed for the alternative subregions used by K. Feltzer in estimating the moment release in California; this analysis leads to essentially the same results.

For every considered region, we estimated the long-term moment release assuming the truncated Pareto moment distribution (2.3) and using a procedure based on the corner magnitude estimator $\hat{m}_c$ proposed by Kagan and Schoenberg (2001). Then, we computed the corresponding distribution of the (average) seismic moment released by a fixed number n of earthquakes, with n varying from 1 to 10^4. In order to reflect possible underestimation of the corner moment, an effect described in detail by Kagan and Schoenberg (2001), we repeated the analysis with $\tilde{m}_c = \hat{m}_c + 1$. The obtained (average) moment distributions have been compared to the long-term moment release, computed using the value of $\hat{m}_c$ or $\tilde{m}_c$, in order to establish a particular moment release regime in the region.

This analysis was performed for over a hundred of individual regions, magnitude thresholds, and time periods. Two examples of the resulting distributions, which correspond to the entire California, are shown in Fig. 2.

4 Dissemination of results

The project results were presented at the Annual SCEC 2007 meeting and at the Nevada Bureau of Mines and Geology seminar in the Fall 2007. Two publications have resulted from a project (SCEC numbers 1137 and 1156).

5 SCEC workshop participation

Geodetic measurements provide the best data to determine the tectonic moment rate in the western U.S. However, in some areas no geodetic data is available, or they yield significant different moment rates than can be inferred from the geologic and paleoseismic records, possibly indicating that the geodetic data may record processes other than the sought-after interseismic strain accumulation. The most sensible approach to obtain the best representative map of tectonic moment rate distribution in the western U.S. may therefore be to combine geologic and geodetic data. In order to do so, it is crucial to properly account for the uncertainties that are are associated with the geologic estimates of fault slip rates. To better understand the sources of these uncertainties, Corné Kreemer has participated in the SCEC Fault Systems/SoSAFE Workshop held from 01/31-2/02, 2007, in Pomona, CA, where these issues were discussed in depth.

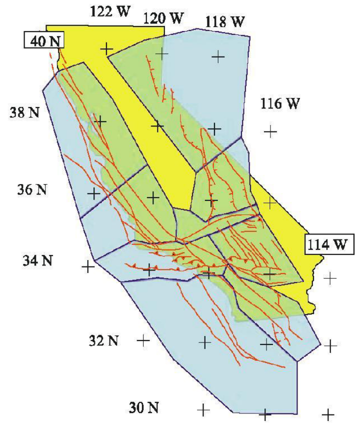

Figure 1: California subregions used for analysis.

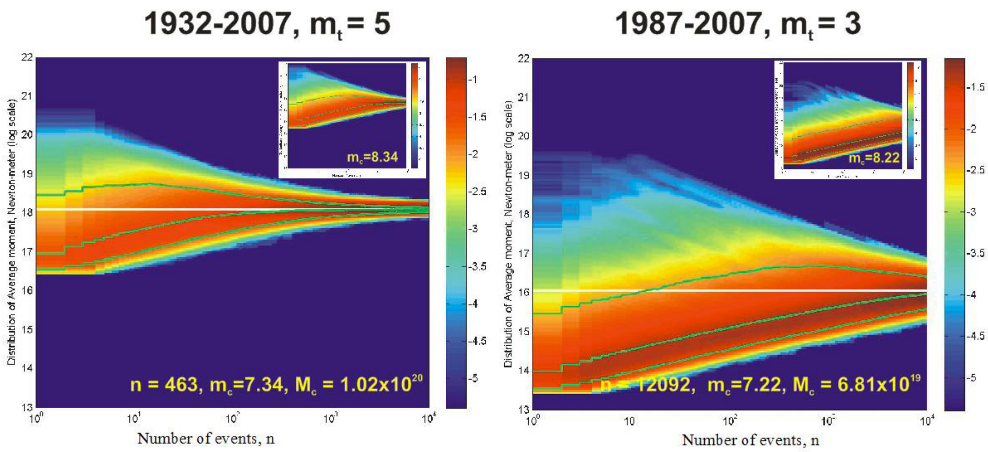

Figure 2: Two examples of the resulting moment distributions. White horizontal line corresponds to the estimated long-term moment release. Green curves are 5%, 50%, and 95% quantiles. The actual number n of earthquakes in the region isshown in each panel. The inserts correspond to the analysis with $\tilde{m}_c$ (see text).

Project publications

Gabrielov, A., Keilis-Borok, V., and Zaliapin, I., 2008. Predictability of extreme events in a branching diffusion model, submitted, SCEC publication number 1156.

Zaliapin, I., Gabrielov, A., Keilis-Borok, V., and Wong, H., 2007. Aftershock identification, in review, SCEC publication number 1137.

Zaliapin, I., S. Kumar, Y. Kagan, and F. Schoenberg, 2007. Statistical Modeling of Seismic Moment Release in SAF system. Abstract of Southern California Earthquake Center (SCEC) 2006 Annual Meeting, September 9-12, Palm Springs, California.