Numerical Seismicity Prediction with STAN

award number 01HQGR0008
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program element II
Fault Stress Interactions, Seismotectonics, Strain Measurements, Regional Modeling

Non-technical summary (<100 words)

This year I developed some flexible and objective new models of seismic activity. These models use probability theory to test alternative theories of earthquake generation, mostly based upon the triggering of earthquakes by other earthquakes through the transfer of stresses. Some tests are predictive tests, which segregate data being fit from data being used to evaluate the test. Other tests focus on aftershock sequences, which are still not fully understood, and have abundant observations useful for constraining models of earthquake generation. This year I discovered that when aftershock sequences overlap their effects do not add linearly.

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Investigations Undertaken

Construction of STAN

STAN is a new kind of seismicity model which incorporates both spatial and temporal variations in activity, and quantifies how well we understand the earthquake nucleation process. STAN can be used to make formal seismicity rate forecasts, fit models of stress transfer triggering, and invert for tectonic loading patterns given observed seismicity. Although STAN is by no means fully developed, it has already been productive. In implementing STAN, I had to decide what seismicity response was expected when a volume is repeatedly stressed, and developed a new approach to that problem. STAN is constructed with a minimum of free parameters, and it allocates these parameters in proportion to the data, with a clustering algorithm which breaks apart three dimensional space in proportion to the seismic activity. Although STAN can be constructed with any underlying set of assumptions, the current version does not assume that seismicity is concentrated on mapped faults. It instead assumes that the long term spatial seismicity distribution will persist, and be modified by stress transfer from observed mainshocks. The stress transfer generates aftershocks in each volume in proportion to the stress step multiplied by the activity level of that volume. It is assumed that each volume produces background seismicity in proportion to that same intrinsic activity level multiplied by a loading rate. The loading rate can be assumed constant or varied with location. Similarly, STAN can be constructed with a great variety of assumed temporal aftershock decay models.

A key element of every STAN model is the battery of statistical tests used to evaluate the fit. Since STAN defines an expected seismicity rate as a function of time and space, it is well suited to evaluation with maximum likelihood techniques. Non-parametric Komolgorov-Smirnov (K-S) statistics are also used, because they provide better information about the quality of the fit than likelihood fits do. STAN models can also be evaluated by the quality of their forecasts. Ideally, we would wish that the models have predictive skill, and expect that the best models would make the most successful predictions. After some goodness of fit measure such as the K-S statistic has been optimized, so that the misfit is minimized, the fit can be re-evaluated for true skill by comparing it with predictions based upon a much simpler algorithm, such as persistence. Tests such as these provide an objective basis for evaluating a huge variety of seismicity models, from exceedingly simple to absurdly complex.

Failure time re-mapping

When a seismic sequence with more than one mainshock or an unusually large aftershock occurs, there is a compound aftershock sequence. The secondary aftershocks need not have exactly the same decay as the primary sequence, with the difference having implications for the failure process. When the stress step from the secondary mainshock is positive but not large enough to cause immediate failure of all the remaining primary aftershocks, failure processes which involve accelerating slip will produce secondary aftershocks that decay more rapidly than primary aftershocks. This is because the primary aftershocks are an accelerated version of the background seismicity, and secondary aftershocks are an accelerated version of the primary aftershocks.

Numerical friction model

Of course the stress perturbations that generate aftershocks can also move faults farther from failure, and heterogeneities in mainshock stress fields mean that the real world situation is quite complicated. I will first describe and verify my picture of secondary aftershock decay with reference to a simple numerical model of slipping faults which obeys rate and state dependent friction and lacks stress heterogeneity. With such a model, it is possible to generate secondary aftershock sequences with perturbed decay patterns, quantify those patterns, and develop an analysis technique capable of correcting for the effect in real data. The secondary aftershocks are defined in terms of frequency linearized time $s(T)$, which is equal to the number of primary aftershocks expected by a time T,

$$s \equiv \int_{t=0}^{T} n(t)dt,$$

where the start time $t = 0$ is the time of the primary aftershock, and the primary aftershock decay function $n(t)$ is extrapolated forward to the times of the secondary aftershocks. In the absence of secondary sequences the function $s(T)$ re-scales the time so that approximately one event occurs per new time unit; the aftershock sequence is gone. If this rescaling is applied in the presence of a secondary sequence, the secondary sequence is shaped like a primary aftershock sequence, and can be fit by the same modeling techniques applied to simple sequences.

Aftershock Prediction

I also studied real data, specifically the decay of Hector Mine aftershocks as perturbed by the stress step from the Landers mainshock. Although attempts to predict the abundance of Hector aftershocks based on stress overlap analysis are not very successful, the analysis does do a good job of interpreting variations in aftershock rate as a function of time.

Table 1 shows STAN prediction tests, as evaluated with rank correlations between the predicted number of aftershocks for the various spatial subsets and the observed count of Hector aftershocks. The higher the rank correlation, the better the prediction. The table includes three different classes of variation in the predictions. The first character in the first column (-, 0 or +) represents the treatment of negative Hector stress steps. The - cases leave the sign of the stress step unchanged, the 0 cases assign zero to all negative stresses, and the + cases make negative stresses positive. The latter half of the first column shows whether the times of the events in the secondary sequence were re-mapped in accordance with the observed decay of Landers aftershocks. Sequential models assume that the failure process of secondary aftershocks are independent of the primary sequence, and re-mapped models assume that the primary sequence would have continued through the time of the secondary sequence, and consequently the decay of the secondary aftershocks will be more rapid (for the case of positive Landers stress steps). The third class of model is the aftershock decay curve used. MOM is an abbreviation for the standard Modified Omori Model, with b signifying background

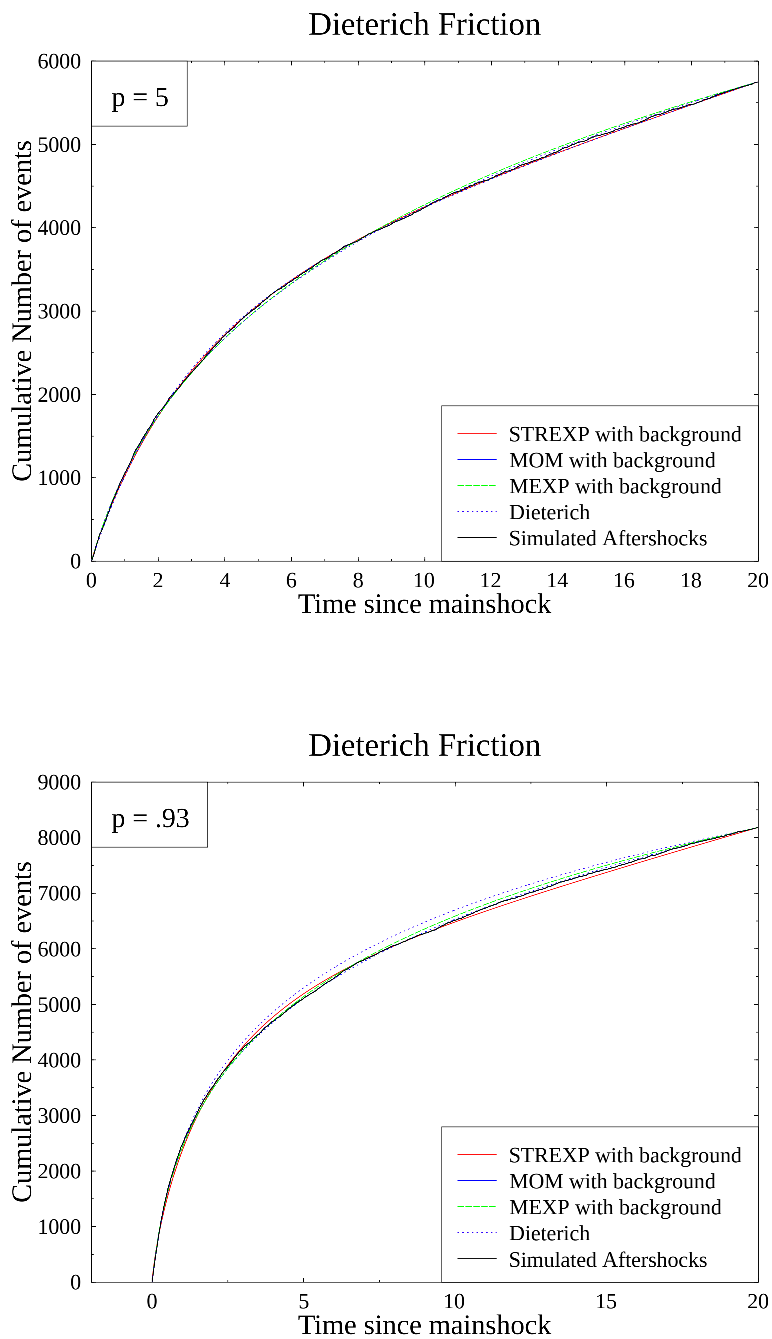

Figure 1: These curves of cumulative number of aftershocks illustrate the more rapid decay of secondary aftershocks (lower plot) as contrasted with primary aftershocks (upper plot). The decay curves in the secondary sequence are modeled more accurately when the failure time re-mapping is applied.

Table 1: Rank Correlations of Hector Aftershock Predictions

	MOMb	MOMB	Strexpb	MOMF
- Sequential	.406	.390	.410	.391
- Re-mapped	.350	.329	.344	.359
0 Sequential	.417	.398	.416	.401
0 Re-mapped	.346	.329	.334	.349
+ Sequential	.582	.611	.584	.641
+ Re-mapped	.526	.491	.509	.621

The most successful predictions are made by MOMF, the modified Omori model with fixed background and no variation in p or c-values. The best model computes aftershock abundance assuming stress steps are all positive, and also does not apply the theory of failure time re-mapping discussed above.

fit to the Landers aftershocks, and B representing background computed from the background period. MOMF is a modified Omori model fit to the Landers sequence as a whole, without allowing for any variations of decay parameter with location. Strexpb is a stretched exponential model originally developed by Carl Kisslinger (1993, JGR p1913-1922).

The most successful predictions in Table 1 are for the unremapped Modified Omori model with all positive Landers stress steps and background rates derived from the background period. This is one of the simplest models in the table. The improvement that comes from changing the sign of negative stress steps appears to be due to events quite near the nodes, where the sign of stress step may be in doubt and fairly minor errors in model assumptions are magnified. These aftershock count prediction results contradict decay curve results, omitted here because of limited space. For those tests, adjustable model parameters only improve the fits, and the best model is stretched exponential with re-mapped failure times. Since re-mapping has its most dramatic effects on the distribution of events in time, which the aftershock counts do not detect, and re-mapping does not introduce any additional free parameters, the preliminary evidence is slightly in favor of failure time re-mapping applying to the processes that generate secondary aftershocks.

Northridge paper

Under this grant I revised the paper about the Northridge sequence referenced below, and it was published.

Results

- Simple models produce the most statistically significant predictions.
- Triggering occurs on nodes of the stress step field.
- Failure time re-mapping slightly improves fits to the decay of Hector aftershocks.
- Failure time re-mapping dramatically improves fits to secondary aftershocks generated with a numerical model.

Reports published

Gross, S. J., A model of tectonic stress state and rate using Northridge aftershocks, *Bull. Seism. Soc. Am.*, **91**, 263-275, 2001.

Availability of data

The research did not involve the collection of any new data, only the construction of models, so this topic does not apply.