Predictive Skill: A Study of RSQSim and UCERF3 Using the Bayesian Inference

Cynthia Tong[1], Sebastien Rossouw[1], Jordan Cortez[2], Guillermo Beas[3], Katia Ascencio[4], Lewis Wang[5], Thomas H. Jordan[6], Kevin Milner[6], Jacqui Gilchrist[6], Jozi Pearson[6], Gabriela Noriega[6]

[1]Pasadena City College, [2]University of North Texas, [3]East Los Angeles College, [4]Los Angeles Harbor College, [5]University of Southern California, [6]Southern California Earthquake Center

Abstract

The undergraduate studies in earthquake information technology (UseIT) probabilistic forecasting team at the Southern California Earthquake Center (SCEC) worked closely with the High Performance Computing (HPC) team to calibrate parameters within the Rate State earthQuake Simulator (RSQSim), a physics-based multi-cycle earthquake simulator. The parameters varied included normal stress, earthquake slip rate, and rate- and state-friction coefficients. Java code was written to analyze a battery of catalogs generated from distinct variations of these parameters to calculate rates of earthquakes of specified magnitudes and regions. These rates were then compared to those of the statistics-based Uniform California Earthquake Rupture Forecast version 3 (UCERF3) in order to find the catalog (and set of parameters) most closely resembling the best understanding of seismic activity in California. The team then established a probabilistic framework for analyzing larger catalogs being generated with the chosen parameters. For a set of 9 fault sections on major faults in Southern California, we computed transition probabilities (defined here as the probability of any combination of the 9 fault sections rupturing within a fixed time window) directly from RSQSim catalogs by counting. While RSQSim catalogs often show strong coupling of neighboring faults, catalogs with finite lengths cannot fully sample this probability space. Even with long (1 million year) synthetic catalogs, event counts for many permutations of the 9 considered faults were low or zero. To address this and provide more robust probabilistic estimates, we also computed marginal probabilities assuming independence of each fault section. We then took a Bayesian approach using Laplace smoothing with marginal probabilities as our prior, and transition counts from RSQSim catalogs as data. The Laplace smoothing alpha parameter (α_0) controls the relative weight assigned to transition and marginal probabilities. We found optimal values for α_0 through log-likelihood testing using probabilities computed from one catalog to predict another. Finally, we compared the skill of UCERF3 with the forecasts from RSQSim data. From our statistical analysis, we provide a framework for analyzing the strengths of each forecasting system and evaluating physics-based earthquake models. This process improves our understanding of earthquake behavior, thus contributing to earthquake hazard and risk awareness.

Background

Fault model selection

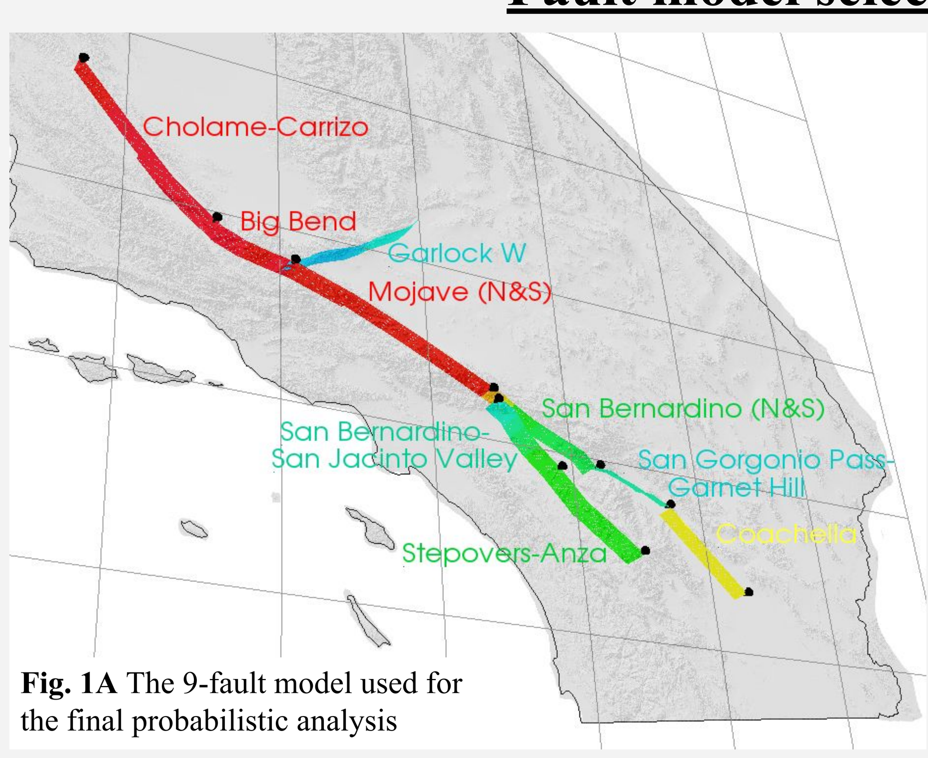

Fig. 1A The 9-fault model used for the final probabilistic analysis

For our region of interest, the San Andreas Fault Zone, a final 9-fault model was chosen after preliminary testing to comprehensively represent earthquake activity in Southern California with minimal rupture combinations and without significantly missing events. Events were counted using a 20% rupture minimum threshold in order to avoid double-counting events.

Carrizo	Big Bend	Mojave S	San Bern	San Gorg	Coach	Garlock	San Bern	Anza
0	0	0	0	0	0	0	0	1

Fig. 1B An example of how each of the 512 combinations is formatted, representing an event where only the Anza fault ruptures.

Methodology

Bayesian Inference

Two kinds of probabilities - Marginal and Transition - were considered. A third probability - the Posterior Probability - was then calculated using a modified Bayesian statistical method called Laplace smoothing, which modifies each Prior Probability using newer data to improve its hypothetical forecasting ability.

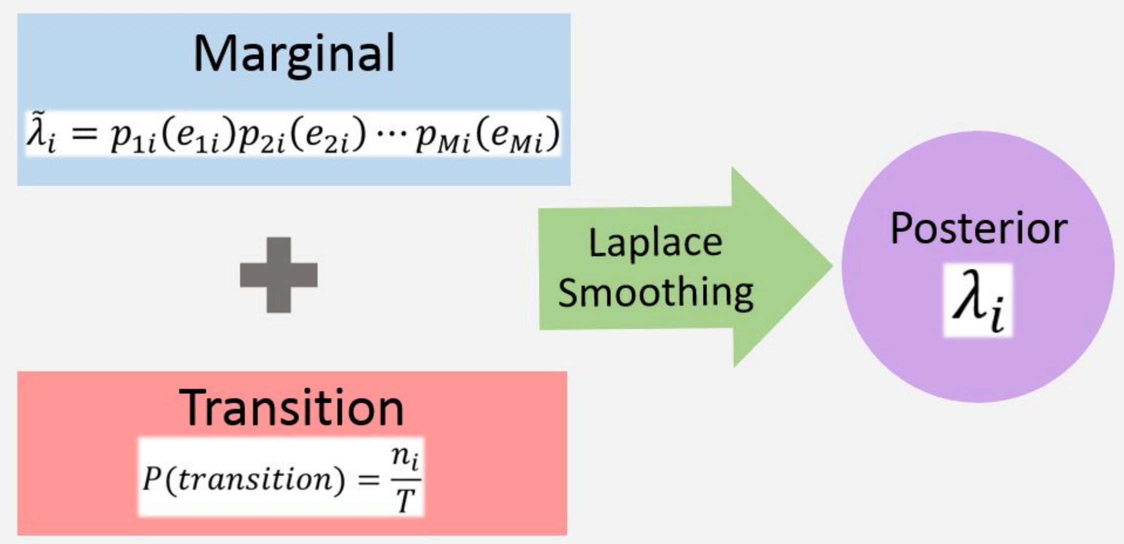

Fig. 2 Flowchart illustrating the process of additive smoothing for determining the Posterior Probabilities

Laplace Smoothing incorporates the smoothing parameter α_0 (a.k.a the pseudocount) to amend events with 0% prior probability:

$$\lambda_i = \frac{n_i + \alpha_0 \tilde{\lambda}_i}{T + \alpha_0}$$

α_0 establishes a relationship between catalog length with transitional and marginal probabilities: as ($T \rightarrow \infty$) the transition probability becomes the more reliable statistic; for smaller catalogs ($T \rightarrow 0$), the prior probability becomes more reliable.

Java coding

With Java, we implemented HashMap, a classification methodology, to link Keys and Indices. Each Key stands for an individual earthquake event which is defined by its rupture regions and magnitude. Each Index illustrates its corresponding Key with binary code. After combing through the catalog, the code produced counts of all combinations along with their marginal, transition, and posterior probabilities.

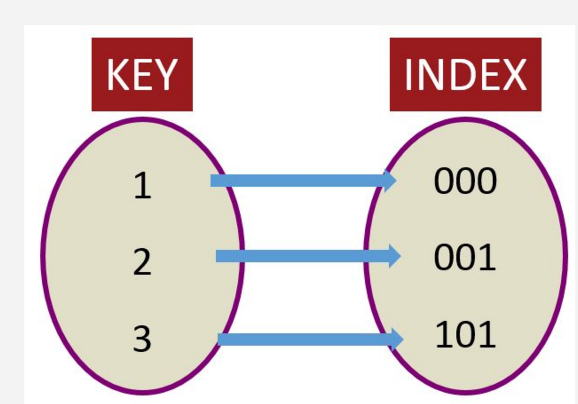

Fig. 3 Flowchart of HashMap logic used in our Java code

Logarithmic Scoring (LS)

The integrity of each forecast was investigated by calculating a corresponding Logarithmic Score (LS). This method integrates posterior probabilities from the previous forecast with observed counts from a new catalog:

$$LS(\boldsymbol{\lambda}\,;\mathbf{n}') = -\sum_{i=1}^{N} n_i' \log \lambda_i$$

To answer our Grand Challenge question, a final Skill statistic was calculated to compare the LS values for the UCERF3 and RSQSim models and reach a conclusion regarding their relative forecasting powers. The equation used was:

$$Skill = \frac{LS_{base} - LS_{UCERF3}}{LS_{base} - LS_{RSQSim}}$$

Results

Logarithmic Scores

The forecast derived from RSQSim was compared to UCERF3 by calculating the logarithmic score for 3 different interval lengths. Million year catalogs from RSQSim and UCERF3 were used to generate forecasts that were then tested against a million year RSQSim catalog.

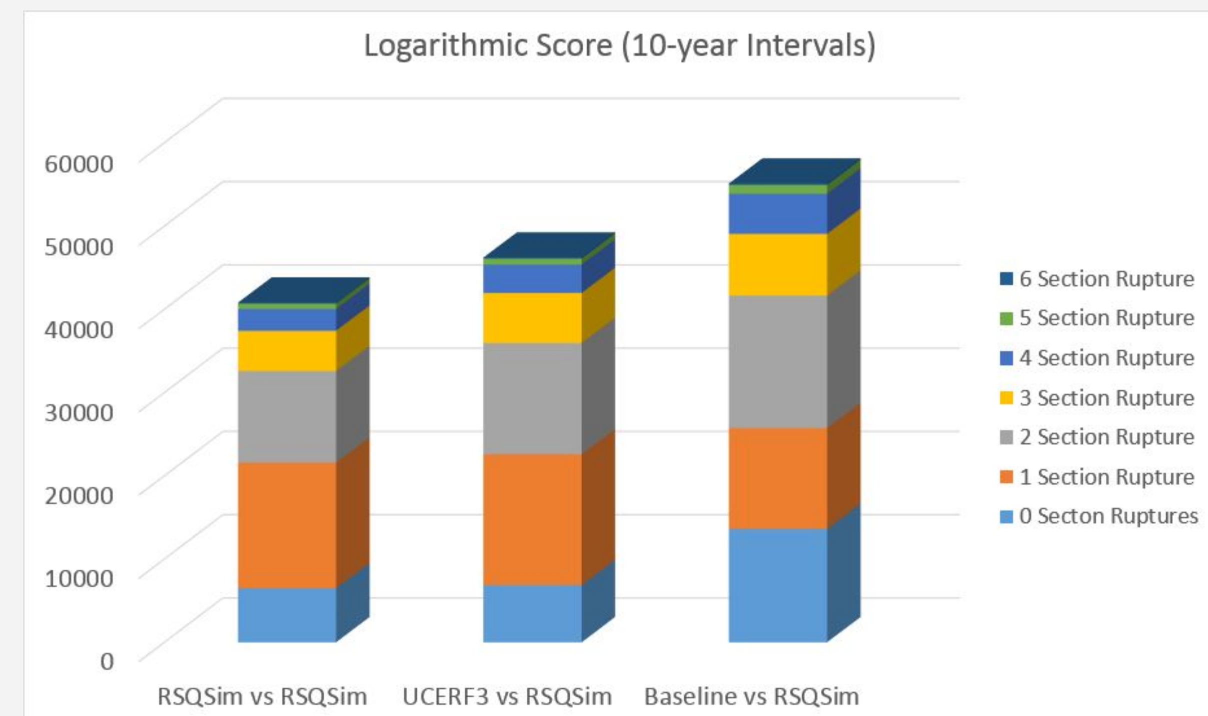

Fig. 4 Logarithmic Scores of each forecast test, categorized by number of fault ruptures

Summary

The Skill statistics for the 6 Logarithmic Scores were calculated to measure the relative forecasting powers of UCERF3 and RSQSim for the same catalog:

Interval Duration	Skill
1-Year	0.73
5-Year	0.66
10-Year	0.62

A Skill statistic of 1 would have indicated that RSQSim is able to forecast its own catalog as well as UCERF3. All results are much closer to 0, indicating that RSQSim forecasts its own catalog significantly better than UCERF3 does. The result of 0.6-0.7 indicates that while UCERF3 and RSQSim do not predict the behavior of RSQSim perfectly, there is some parity between their forecasts.

References

- Bloch, J., 2001, Effective Java: Programming Language Guide: Boston, Addison-Wesley.
- Jordan, T.H., 2018, Bayesian Updating of Time-independent Transition Probabilities (V3).
- Mathews, J., Walker, R., 1970, Probability and Statistics, in Mathematical Methods of Physics, W.A Benjamin, p. 372-379.

Acknowledgements

Anthony Guerra - Thank you for your coding assistance