Virtual Japan: Earthquake Forecasting from Numerical Simulations

Project Summary

Kasey Schultz

Overview

In collaboration with Professor Shinji Toda at Tohoku University, I plan to build a model of the earthquake fault system in Japan and produce an earthquake forecast for the region. I will be using the Virtual Quake (formerly Virtual California) earthquake simulator, a physics-based earthquake simulation code originally developed by my advisor Professor John Rundle, but with more recent contributions from many others, notably Eric Heien and Michael Sachs.

I have been further developing Virtual Quake (VQ) and have used it to produce earthquake forecasts and statistics for the California fault system — I am currently preparing a paper for publication with these results. I am proposing to build a VQ compatible Japanese fault system from existing geological data. Using the Texas Advanced Computing Center's (TACC) Stampede supercomputer, I will run high resolution simulations of VQ using the developed Japan fault model. From the simulation data I will construct the earthquake statistics for Japan and produce an earthquake forecast. Given that much of the requisite data is in Japan and in Japanese, I must be in Japan collaborating with Japanese scientists and students to complete this project.

Intellectual Merit

Virtual Quake has become the standard fault system simulator code for California and it is the most widely used. It is now maintained by the NSF-supported Computational Infrastructure for Geodynamics (CIG)[†] . In the three months since being released on CIG, it has been downloaded more than 60 times by users on four continents. Virtual Quake will be one of the two earthquake simulators used to analyze the recently released UCERF3 fault model for California, the standard California fault system produced by the Working Group on California Earthquake Probabilities and the USGS. Furthermore, in 2012 Virtual Quake (then called Virtual California) — as a member of the QuakeSim team — was co-winner of NASA's Software of the Year award.

By design, Virtual Quake is the only physics-based fault system simulator that can produce earthquake statistics and forecasts on a global scale. To date VQ has only been applied to the fault system in California. This project serves to realize the full potential of the VQ simulator and also serves as a case study to guide researchers in adapting VQ for their own uses.

[†] http://geodynamics.org/cig/software/vq/

Broader Impacts

During the past decade earthquakes have killed nearly 800,000 people worldwide, more than the previous 30 years combined, and caused $44 billion per year in damages. In just the past four years we have seen two of the most devastating natural disasters ever recorded. The 2010 Haiti earthquake damages amounted to 120% of the country's gross domestic product. The Great East Japan Earthquake in March 2011 and subsequent tsunami caused more than $200 billion in damages, and crippled the country's energy production for years to come. Both Japan and California are particularly susceptible to these natural disasters, having two of the most active fault systems in the world in close proximity to some of the largest population densities. With such devastating impacts, the call for accurate earthquake forecasting has never been louder.

This project serves to produce tangible and useful science results from the growing interaction and collaboration between Association of Pacific Rim Universities (APRU) researchers studying natural hazards. Upon completion, results from this project will provide an independent, physics-based method for evaluating earthquake risk on the major faults in Japan. After EAPSI, I will submit these results to a major scientific journal for publication.

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Project Description

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1 Project Synopsis

In collaboration with Professor Shinji Toda at Tohoku University, I plan to produce an earthquake forecast for the Japanese fault system. To accomplish this, I will build a model of the earthquake fault system in Japan from existing geological data. I will use this fault model as input to an earthquake simulator and simulate tens of thousands of years of earthquakes. From the simulation data, I will compute the earthquake recurrence statistics for the Japanese faults and then produce an earthquake forecast for the region.

I will be using the Virtual Quake earthquake simulator (formerly called Virtual California), a physics-based earthquake simulation code originally developed by my advisor Professor John Rundle, with more recent contributions from many others. Virtual Quake is the only physics-based fault system simulator that can produce earthquake statistics and forecasts on a global scale. However, Virtual Quake simulations have only been used to study the fault system in California. I have analyzed the earthquake statistics and produced earthquake probabilities for the California fault system in the same manner I am proposing for Japan — I am currently preparing a paper for publication with these results.

This project serves to realize the full potential of the Virtual Quake simulator and also serves as a case study to guide researchers in adapting Virtual Quake for their own uses. I propose to build a Virtual Quake compatible Japanese fault system from existing geological data, and to use simulations of this fault system to provide an independent, physics-based method for evaluating earthquake risk on the major faults in Japan. Given that much of the requisite data for this project is in Japan and in Japanese, I must be in Japan collaborating with Japanese scientists and students to complete this project.

2 Timeline

Week 1: Collaborating with Prof. Toda to identify the best sources for the fault data

Weeks 2-3: Assimilating fault data from various sources

Weeks 4-6: Building a Virtual Quake compatible fault model from assimilated data

Week 7: Running simulations on Japan fault system

Weeks 8-9: Analyzing simulation results, preparing earthquake statistics and forecast

Post-EAPSI: Preparing a manuscript for publication

3 Background

My advisor Prof. John Rundle is currently the Executive Director of the Cooperation for Earthquake Simulations within the Asia-Pacific Economic Cooperation (APEC). He is also a Senior

Figure 1: The UCERF2 California fault model meshed into 3km x 3km elements. [1]

Advisor of the APRU Multi-Hazards Program and a Visiting Professor at the International Research Institute of Disaster Science (IRIDeS) within Tohoku University. This close collaboration with Japanese scientists resulted in my participation in the 2014 Multi-Hazards Summer School at Tohoku University, and eventually resulted in this proposed project.

This proposed project will use the Virtual Quake simulator to produce useful, tangible science results from the growing collaboration among APRU researchers studying natural hazards. Results from this project will provide an independent, physics-based method for evaluating earthquake risk on the major faults in Japan. After completing my proposed NSF-EAPSI project, I will submit these results to a major scientific journal for publication.

3.1 Virtual Quake earthquake simulator

Virtual Quake (VQ) is a computer program that simulates topologically realistic driven earthquake fault systems [6, 7, 8, 9]. It is designed to quickly simulate many thousands of events over tens or hundreds of thousands of years of simulation time (described in detail in [9, 4, 10]). Virtual Quake produces a rich dataset to study the statistical properties of earthquakes on the input fault system, and this can be used to compute the probabilities of earthquakes on a particular fault or groups of faults.

A Virtual Quake simulation consists of three main components: an input fault model, simulation physics, and a rupture (earthquake) model.

3.1.1 Fault Model

The fault model serves as the input for a Virtual Quake simulation. In general, fault models are comprised of fault geometry, long-term slip rates, and frictional parameters derived from field observations. The fault model is used to create the interacting members of a Virtual Quake simulation, the fault elements.

A portion of the California fault model used in the most recent Virtual Quake simulations is shown in Figure 1. This model is comprised of 181 fault sections corresponding to known faults in California [1]. Each fault section is partitioned into square elements that are approximately 3 km 3 km, for a total of 14,474 elements.

3.1.2 Simulation Physics

The behavior of the system is completely determined by interactions between elements via stress accumulation before events and stress release from elements during events. The stress on each element is computed by a custom implementation of Okada's Green's functions [5].

3.1.3 Rupture Model

A simulation begins with all elements in their equilibrium positions, and the elements are then driven at the long-term slip rates defined by the fault model. This builds stress on the elements until the stress on a particular element exceeds a critical value, at which point the element "breaks" and transfers stress to the surrounding segments by slipping back toward its equilibrium position. The transferred stress results in propagating ruptures through the system, a simulated earthquake.

4 Research Plan

In collaboration with Professor Shinji Toda at Tohoku University, I am proposing to build a Virtual Quake compatible Japanese fault system from existing geological data. This will require close collaboration with researchers at Tohoku University to first identify the best sources for the requisite geological data. After acquiring the fault data, I will then assimilate the information into a Virtual Quake input fault model.

Using the Texas Advanced Computing Center's (TACC) Stampede supercomputer, I will run high resolution simulations of VQ using the developed Japan fault model. From the simulation data I will construct the earthquake statistics for Japan and produce an earthquake forecast.

4.1 Computing Earthquake Probabilities with VQ

The Virtual Quake output data that are fundamental in generating earthquake probabilities are the recurrence times, defined as the time between successive earthquakes on a particular fault. From the simulation output it is simple to compute the statistical distribution of recurrence times. This distribution is fundamental to computing the probabilities of future earthquakes and assessing earthquake risk [8]. I will illustrate the method by providing an example forecast for magnitude 7.5 or larger earthquakes in Northern California.

For this forecast I am using data from a 50,000 year simulation of the California fault system using the ALLCAL2 model [13], a minimally-modified version of the UCERF2 model [1]. In this simulation there were 500 earthquakes with moment magnitudes $M \geq 7.5$ that caused slip on at least one fault section shown in Figure 2. These earthquakes have an average recurrence time of 99.3 years, with the maximum being 507.6 years. From this data I construct the distribution of recurrence times t, computed as the cumulative histogram of recurrence intervals, shown in Figure 3a as the $t_0 = 0$ curve. The smooth curves in Figure 3a are fits of the data to the Weibull distribution, the accepted distribution for recurrence statistics [8].

In addition to the distribution of recurrence times, for earthquakes with moment magnitudes $M \geq 7.5$ I compute the distribution of waiting times Δt until the next earthquake. The waiting times, shown in Figure 3b, are computed as a function of the time since the last large earthquake, t_0. Defining the last major earthquake in northern California to be the 1906 San Francisco earthquake determines $t_0 = 2014 - 1906 = 108$ years. The waiting time Δt is measured forward from the present, such that $t = t_0 + \Delta t$. I express the results in terms of the conditional cumulative probability $P(t, t_0)$ that an earthquake will occur in the waiting time $\Delta t = t - t_0$, given that the last major earthquake occurred t_0 years ago.

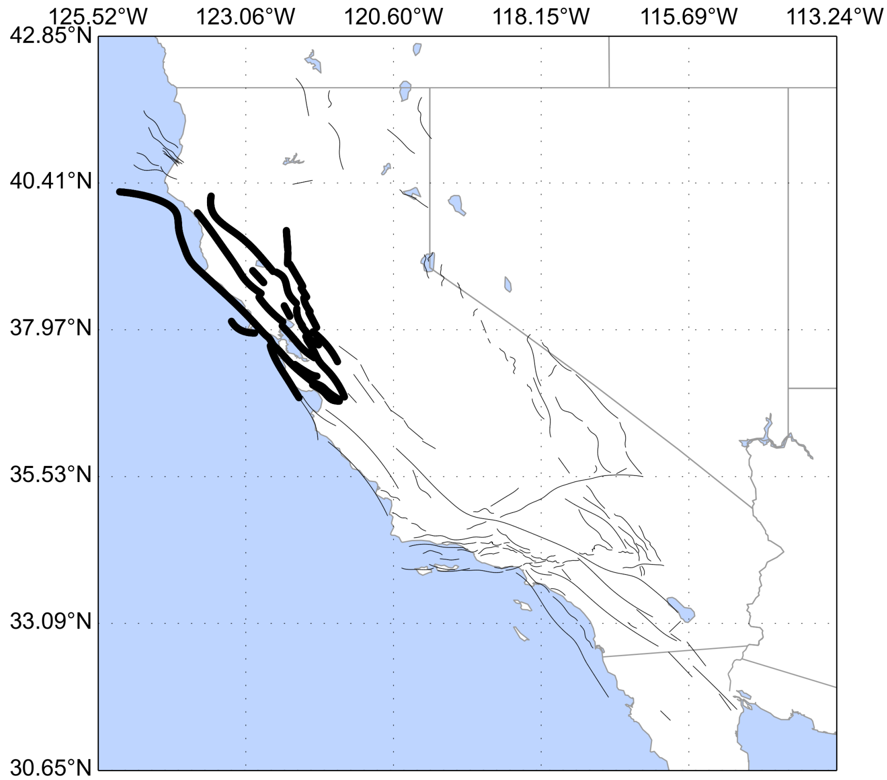
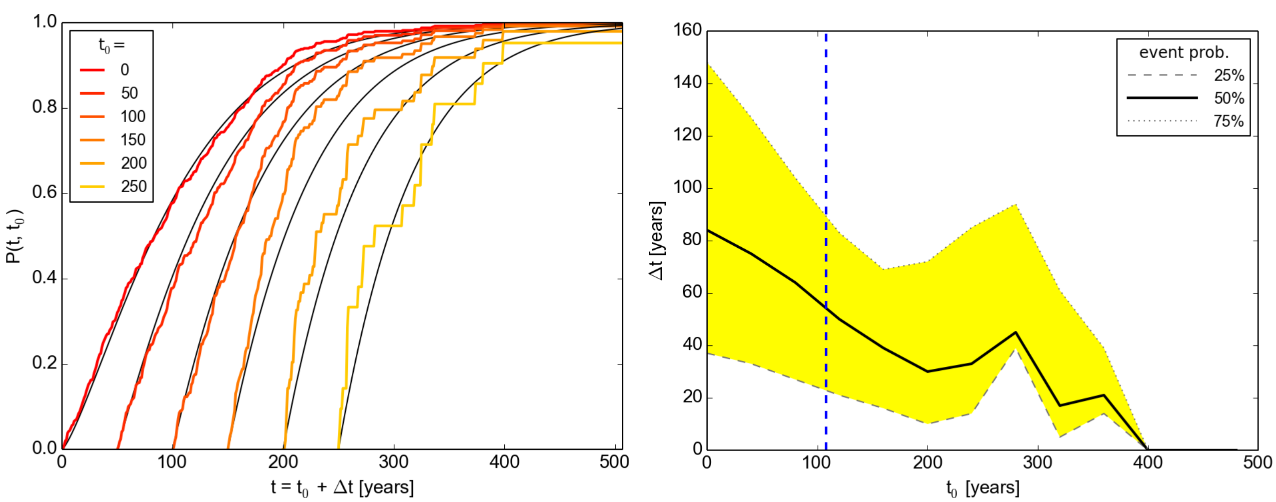


Figure 2: A subset of Northern California faults from the UCERF2 model used to construct statistics shown in Figure 3.



(a) Simulation-derived conditional cumulative probability $P(t, t_0)$ that an earthquake will occur at time $t = t_0 + \Delta t$, computed for various t_0 — the time since the last $M \geq 7.5$ earthquake — to show the evolution of the distribution. The smooth curves are a fit of the data to the Weibull distribution.

(b) The waiting times for the next earthquake as a function of t_0. The dark line indicates the median waiting time (50% probability), and the upper and lower edges of the yellow band represent the waiting times with 75% and 25% probability respectively. The blue vertical line denotes $t_0 = 108$ years.

Figure 3

Immediately after a large northern California earthquake, e.g. 1906, we have $t_0 = 0$ years. At that time, Figure 3 states that there was a 50% chance of having an earthquake with $M \geq 7.5$ in the next $t = 82$ years, i.e. by 1988. In 2014, it has been 108 years since the last great northern California earthquake. We see in Figure 3b that for $t_0 = 108$ years there is a 50% chance of having another great earthquake in the next $\Delta t = 57$ years, and a 75% chance in the next $\Delta t = 94$ years.

5 Proposed Host Researcher

For this project my proposed host researcher is Professor Shinji Toda of IRIDeS and the Department of Geophysics at Tohoku University. Prof. Toda's formal background is in geology and his research interest is to understand the mechanics of earthquakes using geophysical and geological techniques. He has recently published articles on stress transfer and earthquake probability associated with destructive earthquakes in Japan [12] and on earthquake probability studies using earthquake statistics, paleoseismic and historical data [11].

6 Scientific and Cultural Value

During the past decade earthquakes have claimed nearly 800,000 lives worldwide — more than the previous 30 years combined — and caused $44 billion per year in damages [14]. In just the past four years we have seen two of the most devastating natural disasters ever recorded. The 2010 Haiti earthquake damages amounted to 120% of the country's gross domestic product. The Great East Japan Earthquake in March 2011 and subsequent tsunami caused more than $200 billion in damages, and crippled the country's energy production for years to come [3].

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† http://geodynamics.org/cig/software/vq/

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Data Management Plan

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The data to be used, generated, managed, and shared in this project are of four types: **(1)** geological data from Japanese scientists or databases, and possibly from literature searches; **(2)** the assimilated Japanese fault model (Virtual Japan); **(3)** software related to the Virtual Quake simulator (formerly Virtual California); and **(4)** simulation data, science results, reports and publications.

We will use established best practices for data management and sharing, designed to ensure the integrity, preservation, and availability of all of these data:

(1) Japanese geological data. Much of the data to be used in this project will be retained for appropriate periods of time by each individual investigator who collects it. Regular backups will preserve the data locally, and sources will be cited in any publications.

(2) Assimilated fault model. The NSF-funded Computational Infrastructure for Geodynamics (CIG) currently maintains the release version of Virtual Quake. The resulting Japanese fault model, in addition to possibly being maintained by IRIDeS or Tohoku University, will be integrated into the fault models provided with the release version of Virtual Quake found on CIG http://geodynamics.org/cig/software/vq.

(3) Virtual Quake simulator is provided by CIG under the MIT license. Our group uses and is committed to modern practices for software development, including version control, use case testing, support for multiple platforms, and documentation within source code.

(4) Peer-reviewed publications and electronic supplements preserve data products (images, results of analysis of models, and so on), while metadata can be maintained locally through backup systems. Publications and presentations made at meetings (such as AOGS 2015), as well as manuals and technical reports, will be made available for download on the Virtual Quake page at CIG.

General data management practices: The Virtual Quake group uses a GitHub repository for source code and data storage, and we collaborate daily with Dr. Eric Heien (the head programmer/maintainer for CIG) who provides support and guidance for high performance computing, data management, software version control, and other related issues.