Scenario Earthquake and Tsunami Simulations for a Pacific Rim GNSS Tsunami Early Warning System

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Abstract The first operational prototype for a Pacific Rim Tsunami Early Warning (TEW) system utilizing real-time data from the Global Navigational Satellite System (GNSS) is expected to be planned and developed over the next five years. Since the 2011 Tohoku-Oki earthquake and tsunami in Japan, advancements in the rapid determination of earthquake and tsunami parameters from land- and sea-based Global Positioning System (GPS) instruments have given rise to broad support from many international research and disaster organizations including NASA. The proposed Pacific Rim TEW prototype would use earthquake parameters rapidly determined from GPS data to select the most similar earthquake and tsunami scenario from a database of precomputed scenarios to guide alerts and disaster response. To facilitate the development of this Pacific Rim TEW system, I propose integrating tsunami modeling capabilities into the earthquake simulator Virtual Quake (formerly Virtual California). With this refinement, Virtual Quake would produce catalogs of tsunami scenarios for a wide range of simulated subduction zone earthquakes. Virtual Quake would also produce probabilities for these scenarios by extending previously developed techniques for computing conditional probabilities of large earthquakes.

1 Introduction

The recent catastrophic loss of life from great earthquakes and tsunamis in Indonesia and Japan serve as reminders of the hazard posed by subduction zones around the Pacific Rim to their adjacent coastlines. Great earthquakes occurring in the oceanic subduction zones represent substantial risk to lives and property from both ground shaking and tsunami inundation [6]. The Pacific Northwest of the United States is particularly vulnerable to potential tsunamigenic earthquakes from the Cascadia subduction zone [9].

Leveraging lessons learned from recent tsunamis, many international collaborations and research organizations like the Asia-Pacific Economic Cooperation (APEC), NASA, Association of Pacific Rim Universities (APRU), National Ocean and Atmospheric Administration (NOAA), and many more are now planning the deployment of an operational prototype Pacific Rim Tsunami Early Warning system. The development of this prototype has been accelerated given recent advancements in the rapid processing of GPS data that allows for accurate determination of earthquake magnitude, co-seismic displacements and faulting mechanism within 3-5 minutes [1, 2]. The operating algorithms used by the TEW system will rely on an accurate database of precomputed earthquake and tsunami scenarios [6]. I propose integrating tsunami modeling capability into the Virtual Quake earthquake simulator to produce catalogs of subduction zone earthquake and tsunami scenarios that represent a wide range of physically-realizable scenarios and to compute the probabilities for each scenario.

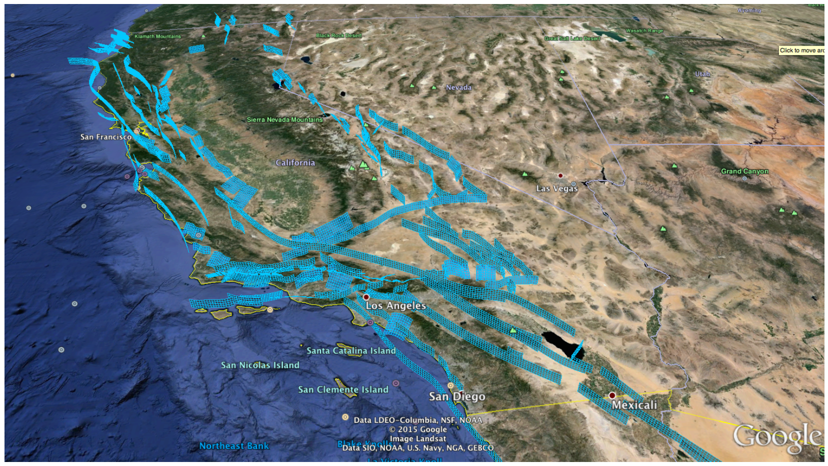

Figure 1: A California fault model used in Virtual Quake simulations, plotted with Google Earth.

2 Virtual Quake Simulator

Virtual Quake (VQ, formerly known as Virtual California) is a computer simulation that models earthquake fault systems [10, 11]. The most recent version of VQ is a modern scientific code that simulates earthquakes in a high performance computing environment [14, 17]. VQ takes an arbitrarily complex fault model along with geologically-observed slip rates as input. VQ meshes the fault model into square fault elements (Figure 1) and quasi-static elastic interactions are calculated between the elements [13]. Slip is applied to each element at the prescribed long-term rates, building stress on each element. This continues for all elements until the stress on a particular element reaches a critical stress value ("failure"). The specific value of failure stress is determined for each element by the fault model. A failed element slips and releases stress to the surrounding fault elements and, if other conditions are met, the neighboring elements are also allowed to slip, propagating the rupture throughout the fault: a simulated earthquake.

Virtual Quake makes many simplifications about the Earth to allow for the fast simulation of many thousands of years of seismic history. One important simplification is that the quasi-static interactions that govern the dynamics in the simulation are calculated assuming the faults are imbedded in a homogenous half-space [8]. A more accurate model would include the effects of a three-dimensional earth and the effects of a viscoelastic layer below the elastic crust. Though the current Virtual Quake does not yet incorporate these effects, Tullis et al. [18, 19] confirmed that VQ simulations are consistent with observed seismicity in California and consistent with independent simulations of the California fault system.

3 Proposed Work

The magnitude 9.0 Tohoku-Oki earthquake and tsunami of 2011 highlighted the limitations of existing TEW methods [6]. With recent advancements in the rapid analysis of real time Global Positioning System (GPS) data [5], the implementation of a prototype Tsunami Early Warning system around the Pacific Rim is currently being planned. To support the development of this prototype system, I propose the following work:

- Integrating tsunami modeling code into Virtual Quake
- Producing a database of simulated earthquake and tsunami scenarios with Virtual Quake
- Computing probabilities for earthquake and tsunami scenarios with Virtual Quake

3.1 Integrating tsunami modeling into Virtual Quake

I propose integrating into Virtual Quake a custom version of the Tsunami Squares method for tsunami propagation and inundation [20, 21, 22]. Tsunami Squares does not solve the non-linear continuity and momentum equations like typical tsunami calculations, but solves equivalent equations for a fixed grid of many uniform squares. At every time step, each square contains an amount of water with a specified height, velocity, and acceleration. Tsunami propagation and inundation are modeled by updating these conditions on each square at every time step by applying volume and momentum conservation and updating the frictional coefficients and the gravitational force as the bathymetry changes and when flows cross onto land.

Tsunami Squares has recently been employed to model the 2007 landslide-generated tsunami at Chehalis Lake in Canada [20], the 1982 El Picacho landslide in El Salvador [21], and the 2008 Gongjiafang landslide-generated tsunami in the Three Gorges Reservoir, China [22]. Tsunami Squares provides a fast, scalable method for systematically modeling many thousands of tsunami propagation and inundation scenarios.

3.2 Database of simulated earthquake and tsunami scenarios

Current methods for rapidly estimating tsunami intensity and inundation are divided into two types: (I) those that use rapid estimates of earthquake source parameters like magnitude and epicenter, and (II) those that use measurements of sea-surface disturbance from ocean-based sensors to assess tsunami hazard and model tsunami propagation without characterizing earthquake source parameters. The system employed by Japanese Meteorological Authority [15] is type (I) and uses seismological data to determine earthquake magnitude and epicenter. These quick estimates are used to query a database of precomputed earthquake and tsunami scenarios. These scenarios, determined well in advance of the event, are a range of earthquake magnitudes and locations that are used as input to tsunami propagation and inundation simulations. This method (I) requires an accurate database representing a wide range of earthquake and tsunami scenarios for the region, while both methods (I) and (II) rely on accurate tsunami propagation and inundation simulations to assess tsunami hazard.

I propose using a custom version of the Tsunami Squares method coupled with Virtual Quake to produce catalogs representing the a wide range of possible earthquake and tsunami scenarios for subduction zones around the Pacific Rim.

3.3 Forecasting subduction zone earthquakes and tsunamis

Virtual Quake was originally created to explore the seismicity of today's fault systems and to produce forecasts for future earthquake scenarios [10, 11]. Rundle et al. [12] introduced a method for computing conditional probabilities of large earthquakes from Virtual Quake simulation data. The method produces earthquake forecasts by computing the probability distributions for earthquake recurrence directly from long simulated seismic histories of a fault system. Example conditional probabilities, computed from a 50,000 year simulation of the faults shown in Figure 1, for magnitude 7.0 or larger earthquakes in northern California is shown in Figure 2.

Schultz et al. [17] showed that this method of computing probabilities with Virtual Quake is in rough agreement with a more sophisticated forecasting method that uses observed earthquake rates to forecast the occurrence of large earthquakes. Yoder et al. [23, 24] has

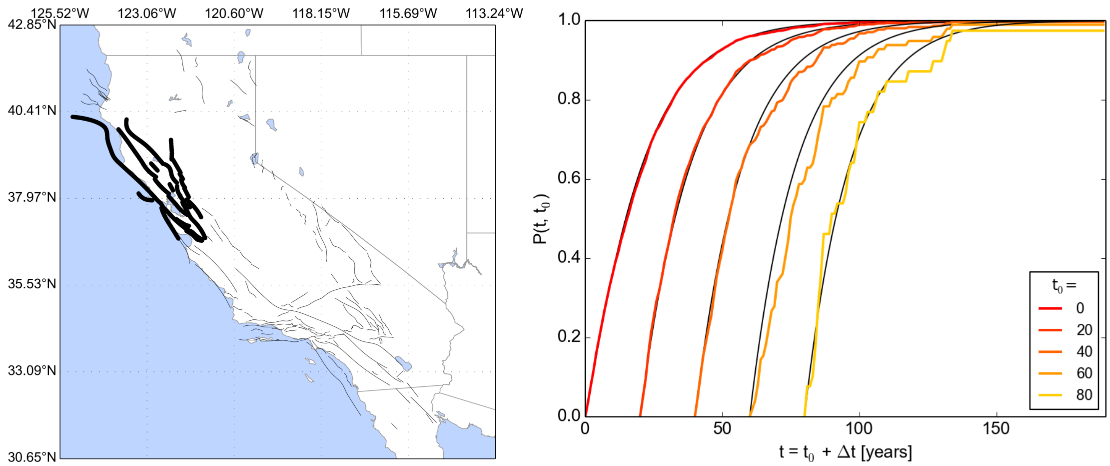

Figure 2: Virtual Quake probabilities for magnitude ≥ 7.0 earthquakes. Left: Faults included in the forecast. Right: Conditional probability of an earthquake at time t since the previous earthquake, given there has been no earthquake in t_0 years. Black lines are a fit to the Weibull distribution [17].

systematically analyzed Virtual Quake earthquake forecasts for California and will issue a follow up paper presenting improved forecasting techniques with Virtual Quake. I propose using Virtual Quake to compute subduction zone earthquake probabilities and to extend the method to compute tsunami probabilities. These probabilities would be integrated into the the database of earthquake and tsunami scenarios.

4 Computational Infrastructure for Geodynamics

Virtual Quake is now hosted by the Computational Infrastructure for Geodynamics. It is available for download (geodynamics.org/cig/software/vq/) and is regularly improved and updated. It comes with a user's manual that describes simulator physics in detail, how to create fault models, and how to run the simulator in a variety of computing environments. We intend to make available relevant simulation data products from this proposed work: e.g. fault models, technical reports and publications, and earthquake and tsunami plots and analyses. As an additional example of the extensibility of the Virtual Quake simulator, Figure 3 shows gravity changes and an Interferometric Synthetic Aperture Radar (InSAR) interferogram computed for a simulated earthquake on the San Andreas Fault.

Our goal in developing Virtual Quake is to provide a powerful fault modeling code that researchers can easily use for their own purposes. In its first six months on the CIG website, Virtual Quake has been downloaded more than 180 times by users from every continent except Antarctica. Over the past decade, Virtual Quake — whose development has been funded by NASA [14] — has been part of a multi-disciplinary effort to better understand earthquake hazards by integrating geophysical simulators with geodetic data and analysis tools known as QuakeSim [3]. As part of the QuakeSim team, Virtual Quake was selected as a co-winner of NASA's 2012 Software of the Year award [7].

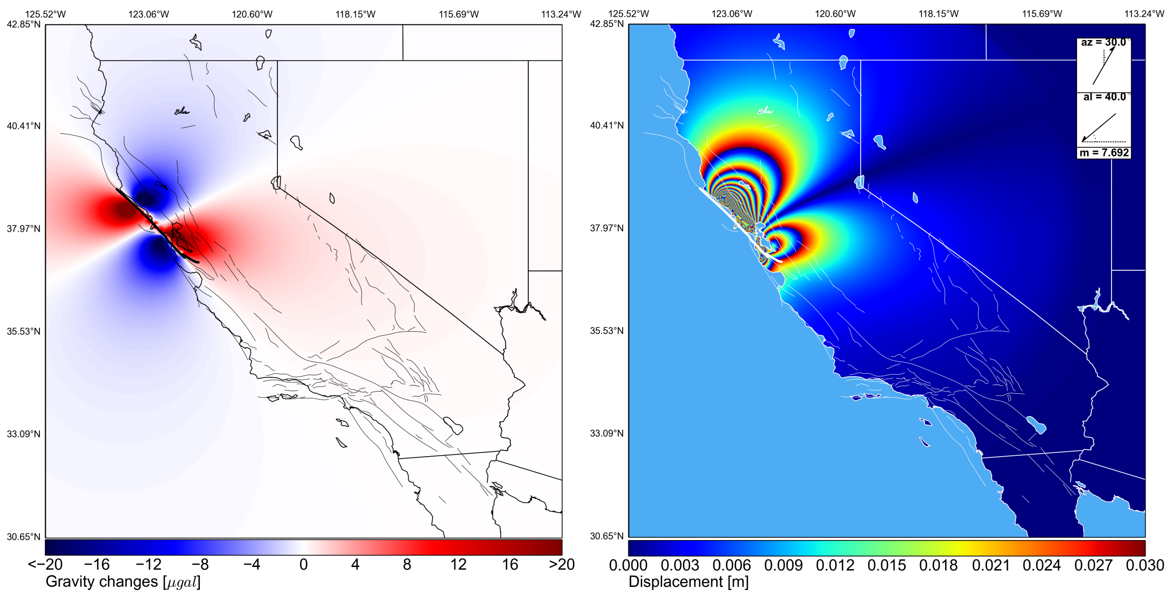

Figure 3: Virtual Quake surface patterns for a magnitude 7.69 simulated earthquake on the San Andreas Fault. Left: Surface gravity changes [16]. Right: Simulated InSAR interferogram [17].

5 High Resolution Simulations

Through close collaboration with the Computational Infrastructure for Geodynamics, I have gained access to computing resources at the Texas Advanced Computing Center (TACC). I propose installing Virtual Quake on the Stampede supercomputer at TACC to run multiple high resolution simulations of the recently released UCERF3 California fault model [4] and of models of subduction zone faults across the Pacific Rim. These large scale simulations will produce the most detailed Virtual Quake simulations to date.

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