Final Report

For Submission by Ruth Harris to the Southern California Earthquake Center

March 22, 2016

March 11, 2016 Workshop
Rupture Dynamics Code Validation Workshop
(SCEC Project 15095)

Co-Principal Investigators:

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The SCEC Dynamic Rupture Code Comparison Workshop was held March 11, 2016, at the Kellogg West Conference Center in Pomona, California. 31 people participated, including 18 in the meeting room and 13 remote-access. This year our workshop attendees, both remote and in-person, included scientists from six countries (China, Germany, Japan, New Zealand, Switzerland, U.S.A.). One-third of our workshop participants were either students or postdocs. Many thanks to Tran Huynh for all of her work that helped make this workshop happen.

The workshop agenda and participant list are on the last page of this report.

Ruth Harris (U.S. Geological Survey) introduced the SCEC workshop to the participants, and explained what our SCEC/USGS Dynamic Rupture Code group does to test computer codes that simulate earthquakes as spontaneous ruptures, how we do this work, and why we do this work. Harris then quickly summarized the impressive range of spontaneous rupture code benchmarks performed by the group to date. These benchmarks enable the codes to be tested for their flexibility in modeling various earthquake-source scenarios, including variations in fault geometry, fault friction, initial stress conditions on and off the faults, and off-fault material structure (e.g., see Harris, PAGEOPH, 2004, and Harris et al., SRL, 2009 for the framework). She next showed where the group currently is in its research investigations, and mentioned the group's goals for the rest of 2016, including the code-validation work proposed for initiation in 2016, along with planning for SCEC5. Following this introduction to the code comparison project, the workshop attendees, both remote and in-person, introduced themselves.

The rest of the workshop consisted of an intellectually stimulating selection of science talks, discussions of the benchmark assignments that had been completed by the SCEC/USGS code-comparison group members in preparation for this March 2016 workshop, an introduction to the 1979 Imperial Valley earthquake and nearby seismic stations, and a review of how kinematic rupture modelers have conducted code validation, including using the SCEC Broadband Platform software system. Please note that there is also a separate report to SCEC that describes the recent year's progress of the SCEC/USGS dynamic rupture code comparison group (SCEC project 15091).

In the second talk of the morning, Dynamic Rupture Code Comparison group member Eric Daub (U Memphis) introduced his 3D finite-difference code, which he had used to run both of the benchmark problems assigned for early 2016, TPV33 and TPV34, along with some of the group's earlier benchmarks. His code is currently being used for classroom exercises at U Memphis. The code, written in C++ with MPI and Python, has flexible handling of friction models, uses the summation by parts/simultaneous approximation term (SBP/SAT) method developed by the Stanford group (Duru and Dunham, 2016), and incorporates complex fault geometries through coordinate transformations. Daub also showed work by his student, Sabber Ahamed, who has been using the code DynEarthSol3D for modeling long-term tectonic behavior, which sets up the initial conditions for dynamic rupture simulations.

The third talk of the morning was by Michael Barall (Invisible Software), who showed the setup of the code-group benchmark exercise The Problem Version (TPV)33. The TPV33 3D benchmark was the case of a low-velocity zone surrounding a vertical strike-slip fault, resulting in guided waves. Please see our group project report 15091, our SCEC website scecdata.usc.edu/cvws, and in particular, Michael's workshop presentation http://scecdata.usc.edu/cvws/download/mar11_2016/Barall_TPV33_Results_v10.pdf for more information about this along with all of our other dynamic-rupture code-comparison benchmark exercises.

In the fourth talk of the morning, Evan Hirawaka (SDSU/UCSD graduate student) presented his work on a new friction mechanism to explain dynamic rupture, while producing reasonable stress drops, and satisfying constraints on heat flow. His 2D models aim to improve upon the thermal pressurization models of others, so as to better match geophysical observations near earthquakes.

This concluded the morning session.

Ruth Harris introduced the afternoon session of the workshop with a quick mention of the goals for the afternoon: Learn about the 1979 Imperial Valley earthquake, learn about how the kinematic-rupture modelers conduct code validation, and discuss how the dynamic-rupture modelers should proceed.

In the first (regular length) talk of the afternoon, Ralph Archuleta (UCSB) presented his classic work (including Archuleta, JGR, 1984, in addition to other papers) conducted on the 1979 Imperial Valley earthquake. He introduced the workshop participants to both the earthquake and the strong ground motion data observed from the earthquake, and provided information about the novel science accomplished from the field observations and modeling of this notable seismic event. During his talk, Ralph pointed out that the Imperial Valley earthquake resulted in non-linear amplification effects, and in addition, the strong ground motion data could only be fit if a two-fault rupture were assumed, that is, the Brawley fault-zone also played an important role in the ground shaking, in addition to the Imperial fault.

In the second talk of the afternoon, Michael Barall (Invisible Software) described code-comparison benchmark exercise TPV34, implemented by 9 of the group's codes. He described an overview of TPV34's features, including that it is a vertical planar strike-slip fault set in a 3D velocity structure obtained from CVM-H, the Harvard Community Velocity Model. Barall also noted that the lowest velocities and densities of the CVM-H model needed to be truncated (e.g., Vs was truncated to 1400m/s) relative to their values in CVM-H, because the computational power available to the world's dynamic rupture modelers is not yet sufficient to implement the lowest velocities inferred for the upper crust in the Imperial Valley region. For more details about the benchmark description itself, along with code results, please see Michael Barall's workshop presentation,
http://scecdata.usc.edu/cvws/download/mar11_2016/Barall_TPV34_Results_v09.pdf

The third speaker of the afternoon was Rob Graves (USGS). Graves spoke about kinematic rupture simulations that he and Arben Pitarka conducted for the 1979 Imperial Valley earthquake, along with updated validation methods that they have constructed. Graves mentioned that the Graves and Pitarka (2010) paper that modeled the Imperial Valley earthquake used site-specific amplifications. The Graves and Pitarka method used both a deterministic component as well as a stochastic component so as to best match the observed data. He also mentioned that for the seismic stations near the Imperial Valley earthquake, directivity was an important factor. Following his discussion of the approach used in the 2010 paper, Graves showed the newer methodologies that he and Pitarka have been exploring, including using geometric fault roughness to add a stochastic component to the seismic source.

The fourth speaker of the afternoon was Christine Goulet (USC). Goulet presented results of code-validation work conducted over the past 5-10 years by a group of kinematic-rupture modelers using the SCEC Broadband Platform. She also mentioned that an overview of this work is published in a special issue of the journal Seismological Research Letters. Goulet showed the frequency ranges and test earthquakes for which the kinematic rupture codes were able to best agree and where the kinematic codes had difficulties. An important exercise for the

kinematic rupture methods was to demonstrate that they were producing results that more closely matched features of observed earthquake data than did the (mostly) empirical Ground Motion Prediction Equations (GMPE's).

Discussion occurred during all of the afternoon talks. It was agreed that to-date the dynamic rupture code comparison group has done an excellent job comparing (verifying) the dynamic rupture codes while implementing a wide range of assumptions about fault geometry, friction, initial stress, and material structure, presented in the code-comparison benchmark exercises, but that it was now time to venture out into the wide world of unknowns, and code validation. Many of the questions or comments during both the afternoon talks and the discussion periods aimed for an answer to the question of how exactly the dynamic rupture modelers might proceed with a new code validation endeavor and which forms of data from which earthquakes should be used for this upcoming validation effort.

During the workshop discussion some thought that the 1979 Imperial Valley earthquake might not be an easy one to use for code validation, particularly considering the computational limitations of the dynamic-rupture models to handle the lowest velocities in the Imperial Valley region, and also due to the inferred non-linear off-fault rock response during the Imperial Valley earthquake. Some workshop participants proposed that perhaps the group might start with a generic vertical strike-slip fault, vary some of the initial conditions (e.g., initial stress distributions and friction), and test if the resulting dynamic rupture simulations are able to come close to matching GMPE's.

It was also proposed by at least one workshop participant that perhaps the dynamic rupture code group could try modeling the Mw6.7 2000 Tottori, Japan earthquake, that occurred on a vertical fault, and for which there is a wealth of borehole data that reveals the velocity structure near the earthquake.

The workshop participants learned much during the day's events, and more discussions will ensue to decide how best to conduct dynamic rupture code validation.

Some References:

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March 11, 2016
SCEC Rupture Dynamics Code Validation Workshop
Kellogg West Conference Center, Cal Poly Pomona

Workshop Conveners: *Ruth Harris and Ralph Archuleta*

SUMMARY: The purpose of the workshop was to learn new science, discuss the results for our group's most recent benchmarks, and plan our next steps, especially for code-validation. For more information about our dynamic rupture code group, benchmark exercises, participants, codes, and workshop presentations, please see our project's website: http://scecdata.usc.edu/cvws.

10:00	Introduction to the Workshop	*Ruth Harris*
10:15	Meet a New Code	*Eric Daub*
10:45	TPV33 Results	*Michael Barall*
11:30	Dynamic Fault Weakening and Strengthening by Gouge Compaction and Dilatancy in a Fluid-Saturated Fault Zone	*Evan Hirakawa*
12:00	*Lunch*	
12:55	Imperial Valley Earthquake, Verification, Transitioning to Validation	*Ruth Harris*
13:00	Introduction to the 1979 Imperial Valley earthquake	*Ralph Archuleta*
13:30	TPV34 Results	*Michael Barall*
14:15	*Short Break*	
14:30	Some Insights on Imperial Valley from Kinematic Modeling and Validation	*Rob Graves*
15:00	Broadband Platform Validation Exercise	*Christine Goulet*
15:45	Group Discussion: How are we going to validate Imperial Valley, etc.	*All*

31 Total Participants (13 Remote-Access): Ruth Harris (USGS), Ralph Archuleta (UCSB), Tran Huynh (USC), Brad Aagaard (USGS), Sabber Ahamed (U Memphis), Pablo Ampuero (Caltech), Kangchen Bai (Caltech), Michael Barall (Invisible Software), Luis Dalguer (swissnuclear, Switzerland), Eric Daub (Memphis), Ben Duan (Texas A&M U), Kenneth Duru (LMU, Germany), Alice Gabriel (LMU, Germany), Christine Goulet (USC), Rob Graves (USGS), Evan Hirakawa (SDSU), Junle Jiang (UCSD), Yoshi Kaneko (GNS, New Zealand), Yuko Kase (GSJ, AIST, Japan), Jeremy Kozdon (NPS), Shuo Ma (SDSU), Phil Maechling (USC), Kim Olsen (SDSU), Arben Pitarka (LLNL), William Savran (UCSD), Zheqiang Shi (Tokio Marine Technologies), Cedric Twardzik (UCSB), Yongfei Wang (UCSD), Qian Yao (UCSD/SDSU), Stephanie Wollherr (LMU, Germany), Zhenguo Zhang (USTC, China)