SCEC Project 14051

Rupture Dynamics Code Validation 2014 Workshop (convened March 23, 2015)

Co-PIs: Ruth Harris and Ralph Archuleta

Report Delivered to SCEC March 31, 2015

The 2014 SCEC Dynamic Rupture Code Comparison Workshop was held March 23, 2015, at the Kellogg West Conference Center in Pomona, California. Approximately 34 people participated, including 22 in the meeting room and 12 remotely. Our workshop attendees, remote and in-person, this year included scientists from at least three countries (Germany, New Zealand, U.S.A.). Approximately one-half 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 (USGS) introduced the SCEC workshop to the participants, who learned for the first time (or remembered, if they were new to the code workshop series) what our 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 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 2015, including the benchmarks proposed for 2015, and 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, and discussions of the benchmark assignments that had been completed by the SCEC/USGS code-comparison group members in preparation for this workshop. Please note that there is also a report to SCEC that describes the recent year's progress of the SCEC/USGS dynamic rupture code comparison group (SCEC project 14111).

In the second talk of the day, Dynamic Rupture Code Comparison group member Jeremy Kozdon (NPS) introduced his newly 3D-capable code, BEARD, which he used to run all four of the benchmark problems assigned for early 2015, TPV29, 30, 31, 32. This code is a high-order discontinuous Galerkin finite-element code that uses absorbing boundary conditions and CUBIT meshes, and he is hoping to recruit additional users.

In the third talk of the day, Ralph Archuleta (UCSB) presented methods that he and his students and colleagues have developed and implemented to simulate large earthquakes on the Wasatch Front in Utah, and their potential strong ground shaking. These simulations used the spontaneous rupture code, MAFE, that was originally constructed by Ralphs's former student, and SCEC code-group member, Shuo Ma (SDSU). Ralph presented results of simulations that produced both lower and higher frequency strong ground shaking, that would also be consistent with geologically-inferred observations of previous fault slip in this seismically hazardous region of the U.S.A. He posed that the slip-rate function for the earthquake source is one of the most

important ingredients for understanding earthquake-generated ground shaking, and that this slip-rate function can only be reliably produced by using spontaneous (dynamic) earthquake rupture simulations.

In the fourth talk of the day, Nadia Lapusta (Caltech) presented studies of earthquake interactions of 'repeaters' in the Parkfield region of the San Andreas fault. She showed how the stress-change impact of one earthquake on another in this region doesn't extend for the usually expected one to two fault lengths, but instead extends up to six fault-lengths, due to the interactions of the repeating earthquake with the surrounding on-fault rocks. These simulations included both the dynamic inertial effects ('dynamic' triggering), and the longer term postseismic response, the latter of which plays an important role in the triggering process.

In the fifth talk of the day, which was both a science talk and a code talk, Alice Gabriel (LMU, Germany) showed results from using the spontaneous rupture code, SeisSol, for high-performance computing. This award-winning code (it was a 2014 Gordon Bell Prize finalist), which uses a high-order discontinuous Galerkin (ADER-DG) scheme, was demonstrated to be quite flexible and reliable for a range of scientific and numerical earthquake-science challenges. For rupture dynamics applications the code has been tested using numerous SCEC benchmark exercises (TPVXX), and is found to work for branching and dipping fault systems, heterogeneous background stresses, bimaterial faults, off-fault plastic deformation, and rate-state friction. It has also been used (on large-scale high-performance computers) to simulate geometrically complex earthquake ruptures, and the resulting strong ground motion, including the 1992 M7.3 Landers, California earthquake. Additional applications include the tsunamigenic 2011 Tohoku earthquake. An Open Source (BSD-3) beta version of SeisSol is currently available, and Alice looks forward to future adopters.

This concluded the morning session.

In the afternoon, Michael Barall (Invisible Software) introduced the four benchmarks that were tackled by the code group over this past year, The Problem Version (TPV) 29, 30, 31, 32. He briefly described an overview of their features, including that three were set in an elastic medium, and one was set in a viscoplastic medium, and that two incorporated a 1D layered velocity structure. He also discussed the nucleation strategies, initial stress conditions, and friction coefficients for these and other recent benchmark exercises. In the final benchmark-overview component of his presentation, Michael mentioned that these four benchmarks are the first where the codes were requested to produce synthetic seismograms at (relatively) more distant stations, with the furthest being 20 km from the faults.

Next Michael presented details of the group's benchmark simulations for the two 1D horizontally-layered velocity-structure benchmarks, TPV31 and 32. TPV31 has a discontinuous velocity structure, and a minimum shear-wave speed of 2250 m/s, and TPV32 has a continuous velocity structure, and a minimum shear-wave speed of 1050 m/s. Please also see our companion SCEC report for SCEC Project 14111 for information about these specific benchmark code comparisons. Note that descriptions of our benchmark exercises, presentation slides from many of our workshops, and assorted additional information related to our group exercise can be found on our SCEC website, scecdata.usc.edu/cvws.

The second speaker of the afternoon was Julian Lozos (Stanford/USGS). Julian spoke about dynamic rupture simulations that he has conducted to better understand the historical southern California earthquake of December 8, 1812. Evidence for this earthquake is found in some paleoseismic trenches on the San Andreas fault, but not in others. There are also historical

documents and precarious rock data available, both of which Julian considered for his hypothesis that this earthquake may have started on the northern San Jacinto fault, then subsequently propagated onto the San Andreas fault, rather than being a pure San Andreas event.

The third speaker of the afternoon was Kenny Ryan (UCR), who presented his work simulating dynamic earthquake ruptures and resulting tsunamis. Kenny concentrated his talk on two major simulation efforts, the first that was part of Lucy Jones' and Stephanie Ross's USGS SAFRR project, conducted in collaboration with the USGS's Eric Geist, among others, and consisted of simulations of an offshore Alaska subduction zone event. The second that has been part of the SCEC Ventura Special Fault Study area (SFSA), consists of a simulated event generated offshore of Ventura. For these simulations, Kenny used the FaultMod code by Michael Barall, and implemented rate-state friction for the earthquake source friction. These results were then combined with a tsunami simulation code.

Following a short break, Michael Barall (Invisible Software) returned to the presentation arena and gave a comprehensive talk explaining the details of the second set of the newest completed group benchmarks, the case of a rough vertical strike-slip fault set in an elastic halfspace (TPV29) or set in a viscoplastic halfspace (TPV30). The construction of the benchmarks and completion by the modelers of benchmark results achieved the second of the two goals set forth in the 2014 SCEC group proposal. Please also see our companion SCEC report for SCEC Project 14111 for information about these specific benchmark code comparisons. Note that descriptions of our benchmark exercises, presentation slides from many of our workshops, and assorted additional information related to our group exercise can be found on our SCEC website, scecdata.usc.edu/cvws.

Workshop attendees then heard from Norm Abrahamson (PG&E/UC Berkeley). Norm presented ideas about how our work might best be translated into engineering application. He highlighted that for this to occur, the dynamic rupture simulation results need to be compared with recorded strong ground motion data, perhaps in the form of median ground motions from GMPE's. He then gave a list of the 21 earthquakes used by the kinematic rupture modelers in the SCEC Broadband Platform's 2013 validation exercises, and asked questions about what frequency range the dynamic rupture group might be able to accomplish.

Discussions followed Norm's talk, including future science planning for our group. It was mentioned that the SCEC5 proposal is being written, and if people have ideas, that they should send them to the main proposal writers ASAP. Within the next year, the SCEC Dynamic Rupture code group plans to work on the next set of benchmarks, that were described in the 2015 group SCEC proposal, and include the vertically-layered fault zone, and a 3D velocity structure. The group also initiated planning for the next participatory publication, which might involve investigations into modeling resolution. This type of activity might help code users decide if the discretizations that they are assuming for their fault models are sufficient to produce reliable and repeatable earthquake and ground motion simulation results.

For more information about our group, to download our group's collaborative papers, for descriptions of our group's benchmarks that we use to compare our codes' results, and to view many of our workshop presentations, please see our SCEC website: **scecdata.usc.edu/cvws**.

SCEC Rupture Dynamics Code Comparison Workshop

Conveners: *Ruth Harris and Ralph Archuleta*

SUMMARY: The purpose of the SCEC Rupture Dynamics Code Comparison Workshop was to learn about new science, to discuss the results for our group's most recent benchmarks, and to plan our next science steps for 2015-2016. For more information about our code comparison group and the benchmarks, please see the SCEC/USGS Spontaneous Rupture Code Verification Project website: http://scecdata.usc.edu/cvws.

SCEC Rupture Dynamics Code Validation Workshop

Kellogg West Conference Center, Cal Poly Pomona
March 23, 2015

10:00-10:23 a.m.	Welcome and Introduction	Ruth Harris
10:23-10:30 a.m.	Meet a New Code	Jeremy Kozdon
10:30-11:00 a.m.	Wasatch Front Earthquake Simulations	Ralph Archuleta
11:00-11:30 a.m.	Lessons from Parkfield for Earthquake Interaction	Nadia Lapusta
11:30 a.m.-noon	High performance computing of dynamic rupture scenarios on natural fault zones with SeisSol	Alice Gabriel
noon-1:00 p.m.	Lunch	
1:00 -2:00 p.m.	Metrics and Benchmark Results, Part 1	Michael Barall
2:00-2:30 p.m.	A Case for Multi-Fault Rupture in the Southern California Earthquake of December 8, 1812	Julian Lozos
2:30-3:00 p.m.	Dynamic Models of Earthquakes and Tsunamis Offshore Ventura, California	Kenny Ryan
3:00-3:30 p.m.	Break	
3:30-4:15 p.m.	Benchmark Results, Part 2	Michael Barall
4:15-4:45 p.m.	Use of Dynamic Rupture Modeling in Earthquake Engineering Applications	Norm Abrahamson
4:45-5:15 p.m.	More Discussion and Future Plans	Ruth Harris/ All

Approximately 34 PARTICIPANTS (12 of them Remote):

Ruth Harris (USGS), Ralph Archuleta (UCSB), Tran Huynh (USC), Brad Aagaard (USGS), Norm Abrahamson (PG&E), Pablo Ampuero (Caltech), Kangchen Bai (Caltech), Michael Barall (Invisible Software), Jeff Bayless (URS), Sam Bydlon (Stanford), Eric Daub (Memphis), Eric Dunham (Stanford), Kenneth Duru (Stanford), Alice Gabriel (LMU, Germany), Yihe Huang (Stanford), Junle Jiang (Caltech), Yoshi Kaneko (GNS, New Zealand), Jeremy Kozdon (NPS), Christos Kyriakopoulos (UCR), Nadia Lapusta (Caltech), Dunyu Liu (Texas A&M), Julian Lozos (USGS/Stanford), Bin Luo (Texas A&M), Shuo Ma (SDSU), David Oglesby (UCR), Kim Olsen (SDSU), Arben Pitarka (LLNL), Daniel Roten (SDSU), Kenny Ryan (UCR), William Savran (UCSD), Zheqiang Shi (SDSU), Jennifer Tarnowski (UCR), Yongfei Wang (UCSD), Qian Yao (SDSU)