II.   Technical Report

Final Report

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A Collaborative Project:
Rupture Dynamics, Validation of the Numerical Simulation Method
(SCEC Project 17075)

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* these co-PIs did not request or receive SCEC funds for this project

INTRODUCTION

This is the final report for the 2017-funded collaborative multi-investigator Southern California Earthquake Center (SCEC) project 17075. The project was completed on April 23, 2018.

This year's multi-co-PI collaborative project (17075) included SCEC investigators (senior PIs, postdocs, and students) from at least six countries. A long-term goal of the project has been to ensure that the computational tools that are used to simulate dynamic earthquake rupture propagation (**Figure 1**) are working correctly. During the past decade, the SCEC-USGS dynamic rupture code verification group constructed and performed more than 37 benchmark exercises, then demonstrated that more than 12 spontaneous rupture codes (**Table 1**) could reproduce each other's results. These earthquake rupture simulations incorporated a range of assumptions for the fault geometry, from simple planar to multi-fault rupture and rough faults, the velocity structure, from homogeneous to 1D to 3D along with elastic versus plastic or viscoplastic rock response, a range of initial stress conditions that ranged from homogeneous to stochastic heterogeneous, and multiple formulations for fault friction. The group also implemented a benchmark exercise using a model of the M6.0 Parkfield 2004 earthquake and compared the simulated synthetic seismograms with recorded seismograms in the 1 Hz range. Please see **Figure 1**, and Harris [2004] for more explanation about what spontaneous rupture codes do, and Harris et al. [2009, 2011, 2018], and our group's website *http://www.scecdata.edu/cvws* for more information about our collaborative scientific project.
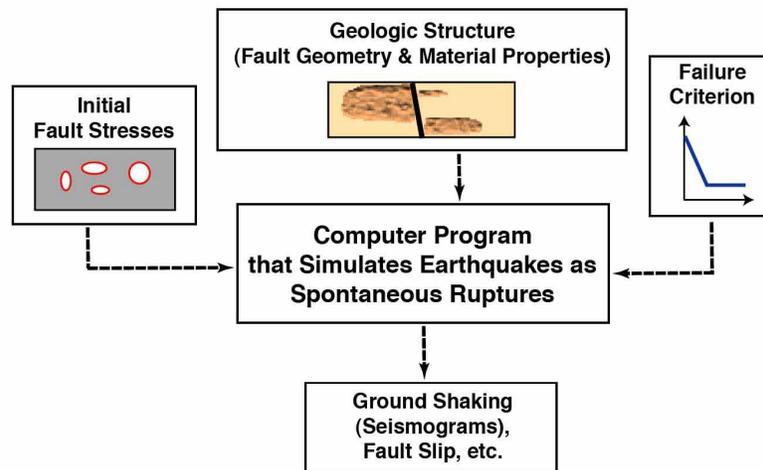

Figure 1. Components necessary for a spontaneous rupture simulation. Spontaneous earthquake rupture simulations need assumptions about the initial stresses on the fault (and off the fault also, if the medium is not elastic), the fault geometry, the off-fault materials, and a failure criterion, which describes how fault friction works. These physics-based computer simulations can be used to produce many different types of results, including patterns of fault slip, ground and sub-surface shaking, heat generation, etc. See Harris [2004] for more details.

**Table 1. List of many of our group's dynamic earthquake rupture codes
(from Harris et al., 2018)**

Code Name	Code Type	References	Notes	Code Availability
AWP-ODC	finite difference	Roten et al., 2016; Dalguer and Day, 2007		contact author Roten
beard	discontinuous Galerkin finite element	Kozdon et al., 2015		contact author Kozdon
CG-FDM	finite difference	Zhang et al., 2014		contact author Zhang
EqSim	finite element	Aagaard et al., 2001	superseded by PyLith	
DFM	finite difference	Day and Ely, 2002		contact author Dalguer
DGCrack	discontinuous Galerkin finite element	Tago et al., 2012		contact authors Tago or Cruz-Atienza
EQdyna	finite element	Duan and Oglesby, 2006		contact author Duan
FaultMod	finite element	Barall, 2009		contact author Barall
fdfault	finite difference	Daub, 2016		https://github.com/egdaub/fdfault
Kase code	finite difference	Kase and Kuge, 2001		contact author Kase
MAFE	finite element	Ma et al., 2008; Ma and Andrews, 2010		contact author Ma
PyLith	finite element	Aagaard et al., 2013		https://geodynamics.org/cig/software/pylith/
SeisSol	discontinuous Galerkin finite element	Pelties et al., 2012; Pelties et al., 2014		https://github.com/SeisSol/SeisSol/wiki
SESAME	spectral element	Galvez et al., 2014	same as SPECFEM3D	
SORD	finite difference	Ely et al., 2009; Shi and Day, 2013		contact author Shi
SPECFEM3D	spectral element	Galvez et al., 2014		https://geodynamics.org/cig/software/specfem3d/
SPECFEM3D-old	spectral element	Kaneko et al., 2008	superseded by SPECFEM3D	
WaveQLab3D	finite difference	Duru and Dunham, 2016		https://bitbucket.org/ericmdunham/waveqlab3d

In 2017-early 2018, the focus of the group was to investigate potential methods for dynamic rupture code validation. Whereas code verification was achieved by our group (see Harris et al., SRL, 2018), code validation is different and difficult. Code validation questions include which information is to be validated, and which activities are sufficient to be declared successful. Possible approaches to code validation include using a test set of observations from multiple earthquakes and examining how well codes can match overall features of these observations. A successful validation would imply that the code(s) can be used as predictive tools for future earthquake behavior, a goal of many earthquake physics and ground motions studies.

CODE-VALIDATION

Our group held discussion sessions about how to proceed with code validation. These included a group conversation at the SCEC 2017 annual meeting, and formal discussions at the April 2018 (2017-funded) Harris, Erickson, and Jiang co-convened SCEC joint workshop on dynamic rupture code validation and simulations of earthquake sequences and aseismic slip. Before the 2018 SCEC workshop, although there had been a number of ideas presented about how to proceed with dynamic rupture code validation, there was no decision about which path forward is best. The group has observed the challenges encountered by the participants of other groups, including the broadband exercise (Goulet et al., 2015), and noted that it took many years, along with considerable funding, for other groups to achieve success. There is also the question about the relative roles of spontaneous (dynamic) earthquake rupture modeling and kinematic earthquake rupture modeling (**Figure 2**), and whether or not it makes sense for spontaneous rupture codes to be used directly for ground motion validation tests. Perhaps it makes more sense if spontaneous rupture models are used to inform the construction of physically realistic kinematic rupture simulations, which are then in turn, used to simulate strong ground shaking? Kinematic rupture codes have the advantages of being computationally more efficient than spontaneous rupture simulations and thereby kinematic rupture simulations are better able to simulate seismic waves arriving at more-distant seismic stations, as well as the low material velocities near Earth's surface.
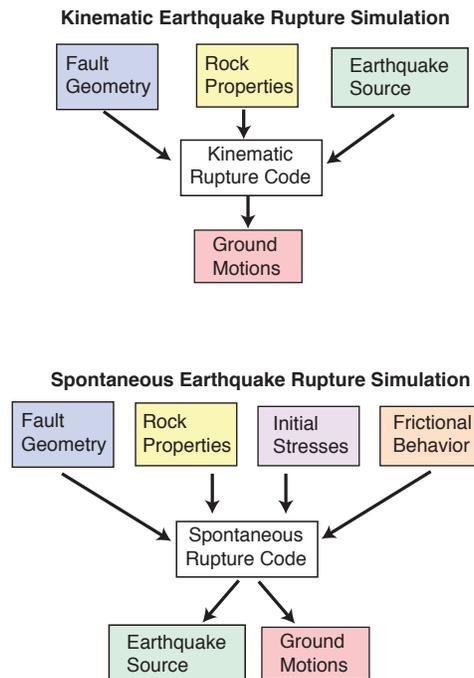

Figure 2. From Harris [2017] Figure 9. The assumptions and results for kinematic (top) and spontaneous (bottom) earthquake rupture simulations have similarities and differences. Kinematic rupture simulations are not necessarily physically self-consistent. They are however computationally efficient. Spontaneous rupture simulations are physically self-consistent, but they require significant computational resources.

Four dynamic rupture group members presented their code-validation ideas during SCEC workshop presentations on April 23. Michael Barall's talk 'What does validation look like?' [Barall, 2018] asked the question of what we are trying to accomplish. He defined validation as 'Is the software a sufficiently accurate model of reality so that we can rely on it in a given application?' and he also mentioned that the software should provide additional value in that it is a sufficient affordable improvement to alternative approaches. He mentioned that what gets validated is a platform (that in turn consists of multiple codes along with the ingredients to do the simulations), along with directions showing how to use the platform. Barall's talk next said that the users decide if the product (platform plus workflow) is validated, and that different users will have different types of standards, for example, peer-reviewed journal articles, or other requirements. Barall finished his talk with a suite of ideas for dynamic rupture code validation. He said that the modelers need to connect more with engineers to learn what the engineers want, e.g., waveforms, spectra, etc. He mentioned that we need to define what constitutes 'good enough', and we need to demonstrate a goodness of fit in a way that is appealing to the users of the information (seismograms, etc.). Barall proposed a dynamic rupture platform that would combine one or more dynamic rupture codes with other codes and the relevant datasets needed to perform the computations.

Next, Brad Aagaard presented his talk 'Validating spontaneous rupture ground-motion simulations, capturing epistemic uncertainty (why getting the same answer may be bad)' [Aagaard, 2018]. Aagaard started the talk with slides showing that our motivation is to limit our ground motion models to physically realistic options, i.e., via spontaneous rupture models. He defined validation as verifying that a model fits observations to within a specific tolerance, where observations might include ground motion records, geodetic time series records, InSAR or LiDAR measurements, or surface rupture slip measurements. One of his primary points was that it is the methodology that needs to be validated, and that one would need the method to be able to forecast the ground motions only using the information that would be available before an earthquake (e.g., the fault geometry, velocity structure, etc.). He gave an example where the group could hypothetically revisit the 2004 M6.0 Parkfield simulations, but with a focus on capturing what he called "technically defensible" spontaneous rupture models. The modelers would devise a method for setting up models without advance knowledge of the slip-distribution on the fault (which was a known for the dynamic code verification benchmark, TPV35). The modelers would then generate a suite of ground motions, by varying the parameters that are not held fixed in their methodologies. He also noted that this would involve a significant amount of work.

The third speaker was Shuo Ma, who presented his talk 'Further validation of the Andrews and Ma (2016) heterogeneous stress model and some preliminary results' [Ma, 2018]. Ma showed how it is not necessary to include all of the complexities on a fault, such as small scale geometrical fault roughness, and that instead it can be represented as self-similar stresses on a planar fault. He showed two models, one a high-sliding-stress model without an asperity that produces Gaussian ground motions, the second a high-stress asperity model that consists of low sliding stress and produces non-Gaussian ground motions. He included a 1D hard-rock velocity structure and assumed that normal stress increases linearly with depth, where a random field defines the shear/normal stress ratio. Ma implemented time-weakening friction which allows the stress to drop as quickly as possible, and a finite element mesh with variable sizing that resolves up to 3 Hz. He found that the mean spectrum and standard deviation for simulated magnitude-7 events

matched GMPEs. However, when he worked with simulations of magnitude-6.5 events, he had a worse match with the GMPEs, and he is continuing to work on this issue. Two questions from the audience asked if the problem with the mismatch between the simulated magnitude-6.5 events and the GMPEs was more an issue with the GMPEs, in that they're based on the ergodic assumption, rather than being regionally focused.

The fourth speaker was Luis Dalguer. Dalguer's talk, 'GMPEs and dynamic rupture models: Which direction to go for validation' [Dalguer, 2018], focused on the challenges with using GMPEs for probabilistic seismic hazard assessment (PSHA), and for code validation. He mentioned that modern GMPEs contain many ingredients, whereas the older GMPEs were much simpler formulations. Dalguer noted that in order to apply GMPEs to PSHA, many adjustments need to be made. These include post processing to account for local soil effects (site conditions), and that GMPEs are not able to capture the complexity of earthquake sources, wave propagation paths, and local site conditions. In contrast, physics-based models, such as spontaneous rupture simulations can include all of these features. Dalguer continued his discussion of the challenges with using GMPEs. These include that the ergodic assumption is used, whereas nature is non-ergodic, and that GMPEs generally focus on only one component of the ground motion. He also noted that the zone of interest for PSHA is close-in distances to large earthquakes, whereas in contrast most of the data that is used to construct GMPEs comes from outside these distance and magnitude ranges. Dalguer then focused his talk on the benefits of using spontaneous rupture simulations. He noted that they are physics based, they include wave propagation, stress, and friction, and they need the best information available about the faults and the 3D velocity structure. He posed that spontaneous rupture simulations are ideal for site-specific or region-specific seismic hazard assessment. Dalguer also mentioned that we should not rely on GMPEs by thinking of them as data, instead GMPEs too, are models. Dalguer's suggestions for code validation are to use source characterization (e.g., from kinematic inversions) and 3D velocity structure, then to perform (forward) spontaneous rupture simulations using a range of inputs to produce synthetic ground motions. He suggested performing 10-20 models, for statistical comparisons with observed data. Then once the validation is successful, the spontaneous rupture method can be used to predict future earthquake behavior that is not necessarily similar to past earthquakes.

Discussion following this talk touched on a number of topics. There was mention of the need for validation for a range of possible earthquakes, and another comment that the simulations need to be better than the GMPEs. In this vein, it was noted that the SCEC broadband platform simulations [summarized in Goulet et al., 2015], that included kinematic rupture simulation codes, among others, did not always produce results that were better than the GMPEs. Another discussion point was that it is difficult (or impossible) to know how fault friction, one of the essential ingredients for spontaneous rupture simulations, works at each location on a fault, and that knowledge of the friction mechanism(s) is essential for predicting viable near-field ground motions. It was also mentioned that variability in ground motions comes from not only the earthquake source but also the wave propagation path, and that the variability needs to be simulated stochastically, using a suite of models.

As the reader can see, the workshop presentations and discussions covered a range of thoughtful points and recommendations for paths forward. Everyone agreed that code validation is a process whereby the (spontaneous rupture) method itself would be validated, that a suite of simula-

tions would be required, and that these would involve sets of assumptions based on stochastic models.

FUTURE PLANS:

We have started on our path of code validation, whereby we develop methods for using spontaneous rupture code results to predict observations from well-recorded earthquakes. Our first steps were to make sure that we could first succeed at producing similar results among the codes, for a real earthquake, which we accomplished during the previous year. Next, we need to figure out how to take the bigger steps, to start with random initial conditions then attempt to match some observed aspects of recorded data, perhaps via comparison with GMPEs. The overall question is what we should be validating and what our best strategies are for accomplishing this multi-year goal. The talks and discussions about code validation at the April 2018 workshop focused on these issues, and presented ideas for future work.

In the meantime, later this year our dynamic rupture group plans to start a series of annual workshops that investigate the ingredients of spontaneous rupture simulations, and at which scale(s) the requisite information about fault geometry, rock properties, stress conditions, and friction are needed. Year 1 (2018) is the year of investigating fault geometry.

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SCEC workshop presentations discussing code validation:
(Please also see https://www.scec.org/workshops/2018/cvws-seas)

Aagaard, B. (2018), Validation: Why getting the same answer may be bad, April 23, 2018 SCEC workshop presentation

Barall, M. (2018), What does validation look like?, April 23, 2018 SCEC workshop presentation

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Publication about the SCEC Broadband Platform:

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