II. Technical Report

Final Report

Submitted by Ruth Harris and Michael Barall
to the Southern California Earthquake Center

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October 27, 2020 SCEC Workshop

Dynamic Rupture TAG – The 2020 Ingredients Workshop – Rock Properties
(SCEC Project 20188)

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Proposal Category: Integration and Theory
Three SCEC Research Priorities (among others): P3.d, P4.a, P2.c

The Southern California Earthquake Center (SCEC) workshop "Dynamic Rupture TAG – The 2020 Ingredients Workshop – Rock Properties" was convened on October 27, 2020, in Zoom. A total of 55 people participated. Our workshop attendees included scientists from the U.S.A., Australia, China, England, Germany, Japan, Saudi Arabia, and Switzerland. Twenty of our workshop participants were early career scientists (14 students and 6 postdocs). The workshop agenda and participant list are on the last page of this report.
Many thanks to Tran Huynh and Edric Pauk for helping to make this fully online workshop a success.

This workshop was the third in our series of four SCEC5 workshops designed to evaluate the importance of each of the four ingredients required for dynamic earthquake rupture simulations. The four ingredients are: fault geometry, fault friction, rock properties, and initial stress conditions (**Figure 1**). The previous two workshops in the 'ingredients' series were the November 2018 SCEC workshop that focused on ingredient #1, fault geometry, and the January 2020 SCEC workshop that focused on ingredient #2, fault friction. This October 2020 workshop focused on ingredient #3, rock properties. This workshop included presentations about how our choices of velocity structures and off-fault yielding affect computationally simulated earthquake rupture behavior and ground motion. We also had one presentation that introduced everyone to a new 3D rupture dynamics benchmark that simulates thermal pressurization, and we were shown the results from the 5 codes that had simulated this benchmark by the time of the workshop.

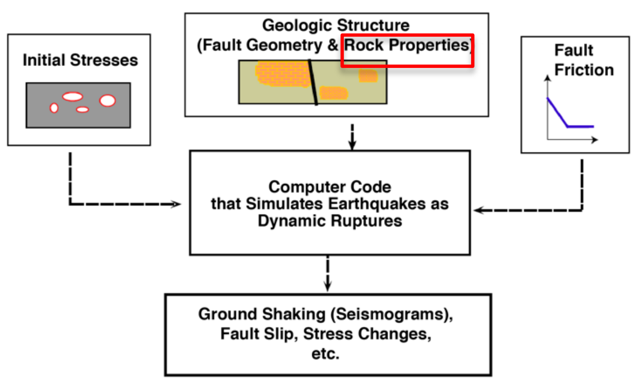

Figure 1. (Lightly modified Figure 1 from Harris et al., 2018). Components necessary for a dynamic (spontaneous) rupture simulation. Dynamic earthquake rupture simulations need assumptions about the initial stresses on the fault (and off the fault also, if the medium is not elastic), the fault geometry, the rock properties, and a failure criterion that 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. Please also see Harris [2004].

Ruth Harris (U.S. Geological Survey) welcomed the participants to the workshop. She then introduced and quickly summarized how dynamic rupture simulations work. She noted that at this time, the SCEC-USGS Dynamic Rupture Code Verification Group has done a good job checking that code results are reproducible for a variety of assumptions about the initial stresses, fault geometry, rock properties, and fault friction (e.g., as discussed in Harris et al., SRL, 2018). This means that what is mostly needed is a basis for choosing among the wide range of possibilities for these ingredients.

Harris presented the workshop participants with some topics to consider throughout the workshop. These included: Do we need to include rock property heterogeneity at all scales? Is it sufficient to assume elastic behavior, or is plastic behavior required? In terms of the ingredients, how do the rock property effects compare in relative importance to the effects of the fault geometry, the fault friction, and the pre-rupture stress state?

Following Harris's introduction, the participants then took turns introducing themselves.

In the next talk of the morning, Alice Gabriel (Ludwig Maximilians University, Munich) presented the new code verification exercise that implements 3D thermal pressurization. The objective of this code exercise is to test dynamic rupture codes' abilities to simulate the process of thermal pressurization (thermal heating of fluids that allows for a rapid drop in fault strength during dynamic earthquake rupture). Gabriel noted that the selection of parameters for designing the thermal pressurization exercise was not simple, because most thermal pressurization parameter values, as was discovered when the related 2D exercise was constructed by Eric Dunham and Michael Barall a number of years ago, lead to runaway rupture that does not stop (an infinite earthquake). The final version of the 3D benchmark exercise constructed by Gabriel and her team [Gabriel et al., 2020] results in a simulated earthquake with a finite rupture area, while also producing simulated temperatures that are not too high (e.g., that would not create substantial melting). Gabriel showed the results from the 5 groups of dynamic rupture modelers who used their codes to simulate the 3D thermal pressurization benchmark exercise. Their results matched well, as shown qualitatively, and also as shown quantitatively using metrics previously developed for the group [Barall and Harris, 2015]. For further information about the 3D thermal pressurization benchmark, including the detailed benchmark description, please see our group's webpage, https://strike.scec.org/cvws/tpv105_3D_docs.html.

During and after Gabriel's talk, questions included one by Kim Olsen and related ones by Yihe Huang and David Oglesby that asked what the main effect is of incorporating thermal pressurization versus not including it. Gabriel answered that thermal pressurization creates strong weakening and a more energetic rupture, making it hard to find a balance that allows for a well-behaved rupture that will eventually stop. Baoning Wu asked what the length scale is for the nucleation length in the simulation. Gabriel answered that it is not easy to determine, because a complex nucleation method (designed by Dunham) was used.

The workshop then returned to the theme of rock properties, with Andreas Plesch's (Harvard) talk about the Harvard version of the SCEC Community Velocity Model, CVM-H [Shaw et al., 2015]. CMV-H provides a 3D model of Vp, Vs, and density. Plesch noted that 3D velocity structures in the Earth, particularly in tectonically active regions, are complex and that there is heterogeneity at many scales. He also pointed out that an additional challenge is that our observations of these 3D structures come from a variety of field experiments and data interpretation techniques, with some regions more densely sampled than others, and therefore there is a range of model resolution depending on geographic location. For CVM-H, Plesch mentioned that the model incorporates information from many observations, including surface geologic mapping, 100,000 km of 2D industry seismic data, 3D seismic surveys, and 10,000 wells, much of which was available because in California companies are required to send data to the state. Plesch then described major components of CVM-H, with a particular focus on basin structures. He described how the shallowest layers are modeled, including the geotechnical layer, and how the deepest layers are modeled, including the basement.

There were a number of questions during and after Plesch's talk. Harris asked if it is better to use CVM-H than another SCEC community velocity model, CVM-S, where 'S' stands for SCEC (https://strike.scec.org/scecpedia/CVM-S4.26). Plesch answered that it depends on the application; CVM-S is an inversion to optimize travel times using many earthquakes. CVM-H also uses many other observations, so CVM-S may be better for waveform travel times, but CVM-H is a more detailed model. Phil Maechling asked what the next developments are for CVM-H. Plesch answered that they are starting to expand to central California, and also moving to a larger scale model.

The next three talks, by Kim Olsen (San Diego State University), Yongfei Wang (University of Southern California), and Yihe Huang (University of Michigan), discussed the effects of rock property structures on dynamic ruptures and on ground shaking.

Olsen presented a comprehensive overview of results and the latest thinking about the effects of 3D velocity structures on dynamic rupture simulations and on ground motions. He started with a focus on how velocity structures affect dynamic rupture propagation. He included studies of heterogeneous large-scale structures, small-scale perturbations, and damage zones. He showed an example of a large-scale velocity variation that was included in work by Susana Custodio, Shuo Ma, and Ralph Archuleta for their simulations of the 2004 M6 Parkfield earthquake. He noted that the velocity variation had a minor effect on the dynamic rupture process itself in that the velocity variation did not control rupture propagation during the Parkfield earthquake, but that a major effect was that the vertical velocity gradient amplified slip. He also noted only minor effects from having a different velocity structure on each side of the fault (a bimaterial case). Next, Olsen presented results from studies of small-scale velocity structures. He showed work by Sam Bydlon and Eric Dunham who examined 2D simulations of dynamic rupture on rough faults, using von Karman fields, and noted that while small-scale velocity perturbations can arrest rupture on a planar fault, inclusion of geometrical fault roughness overwhelms the effect of the velocity structure. Olsen then presented results with damage zones (also see the summary of Yihe Huang's talk), and mentioned that the presence of a low-velocity zone affects rupture speeds, slip pulse shape, and rise time, for example as shown by Ruth Harris and Steve Day, and Yihe Huang and coauthors.

Olsen next presented an overview of the effects of rock property structure on ground motions, including his published work on this topic. He noted that the choice between implementing a 3D or a 1D velocity structure can significantly change the modeled ground motion amplitude and duration. He mentioned that including stochastic small-scale heterogeneity in the velocity structure, for example as modeled by Bill Savran and Olsen, helps models better fit observed ground motions at distances farther from a rupture and at higher frequencies. He next discussed the effects of including anelastic attenuation Q(f), work by Kyle Withers, Olsen, and Steve Day. Olsen noted that it is most important for longer wave propagation paths, and that frequency-dependent attenuation has more of an effect at higher frequencies (e.g., 3 Hz or higher) than at lower frequencies. When examining inclusion of low-velocity zones and implementation of plasticity, work by Daniel Roten, Olsen, Day, and Yifeng Cui, Olsen concluded that there is a tradeoff between the two, whereby including a low-velocity zone might increase the simulated ground motions, but including plasticity would tamp them back down to a more reasonable, lower value.

Olsen received a number of comments and questions. Among them, Ralph Archuleta noted that plasticity would be less likely to come into effect if the shear modulus is also lower in the low-velocity zone; Olsen agreed. Christine Goulet asked about the relative impact on ground motion simulations at close and medium distances, of including roughness versus including small-scale rock property heterogeneity. Olsen answered that fault roughness is more important.

Wang presented his work about pulses in ground motion, their effects, potential causes, and what might prevent them from occurring. He noted that fault geometry is responsible for pulse-like ground motion in duration and amplitude, and that forward directivity can create a pulse, although plasticity can act to prevent a pulse from occurring. He then described what happens when off-fault plasticity is included. He showed that inclusion of plasticity in simulations can produce a flower structure damage pattern (e.g., the work of Shuo Ma) and can also produce lower slip near the Earth's surface than at depth. He showed how inelastic yielding weakens the fault-normal pulse relative to its appearance in an elastic medium, and that inelastic yielding can induce near-fault saturation of peak ground velocity (PGV) for large stress drops. Wang concluded that pulse-like ground motion poses a higher risk to structures, that fault geometry and directivity can lead to pulse-like motions, and that plasticity can modify this pulse-like behavior.

Following Wang's talk, questions and comments were mainly about damage mechanics and inferring source mechanics. Nadia Lapusta asked if it would be better to instead use damage models, which allow for reduction in shear modulus. Wang replied that it depends on the time scale. Bounded stress can reproduce the data, but damage might need to be directly included in more complex situations. Marlon Ramos asked if there is a way to infer source processes from observations. Wang answered that one can try to diagnose crack-like versus pulse-like rupture. On a simple planar fault it might be possible to tell the difference, but in the real world, roughness, heterogeneity, and other factors make it too complicated to directly determine the difference. In some cases (for example, the 2015 Nepal earthquake), the rupture is inferred from ground motion data to be pulse-like. In most cases, inferring earthquake rupture characteristics is more challenging.

In the final formal talk of the workshop, Huang talked about how near-fault low-velocity structures affect dynamic rupture and ground motion. She noted that in California, damage zones are inferred to be 100-400 meters wide, with a 25%-60% reduction in wave speed. She showed examples of how low-velocity zones change rupture dynamics, how attenuation and plasticity in fault zones change rupture dynamics, and how low-velocity sedimentary basins change ground motions. Huang concluded that low-velocity fault zones can generate slip pulses and supershear ruptures, and that the velocity structure (smooth or layered) affects the frequency dependence of ground motion. She also noted that inclusion of off-fault plastic deformation makes it feasible to compare simulation results with observations.

Following Huang's talk, questions and comments included Gabriel noting that if fault zones typically feature a 60% velocity reduction, this would imply that most ruptures are propagating at supershear speeds in the fault zone. Huang replied that there could be a wide range of velocity reductions, most damage zones in California have a 30%-50% velocity reduction, and ruptures propagate at 0.8-1.3 times the shear wave velocity of the host rock. Lapusta asked if the simulations were 2D. Huang replied yes, but that Pelties also saw some supershear rupture speeds in 3D simulations. Lapusta commented that pronounced reductions in (material) velocity might not occur at seismogenic depths due to healing, and that although some damage may be created during rupture, damage does not yet exist at the start of an earthquake. Huang responded that evidence of damage at depth may be inferred if we see evidence of reflected waves in seismograms from aftershocks at 7 to 8 km depth. Lapusta noted that the supershear transition requires a pre-existing low-velocity fault zone, but aftershocks look at the fault after the earthquake and may just show damage caused coseismically. Ben-Zion noted that geological and seismological studies show that damage zones are asymmetrical, and that ruptures occur on one side of damage zones. He also mentioned that damage lasts longer at shallower depths, whereas at deeper depths healing is faster. Dunyu Liu commented that in a discretized model, a smooth velocity variation becomes layered. Huang replied that a column of thin layers mimicking a smooth gradient has a similar effect, and that velocity changes smaller than a wavelength affect amplification. Archuleta noted that layers always have an effect, and Brad Aagaard pointed out that the vertical variation of structure is the most important factor. Aagaard also pointed out that it would be good to have more of a connection between rock property models and geologic models.

During the workshop's discussion session, Harris asked the participants to revisit the questions posed at the beginning of the workshop, namely, how important it is to include detailed velocity structure for dynamic rupture or ground motion simulations, if it is important to include plasticity, and what the relative significance is among the four ingredients. In terms of velocity structure, all respondents noted that the velocity structure details are very important for ground motions simulations. When just considering dynamic rupture simulations that are intended to examine the earthquake source, some noted that it may be sufficient to implement depth-dependent structure, and perhaps ignore some of the horizontally variable features. In terms of plasticity and fault damage zones, participants thought that they might be useful to include, and they also thought that it might be important to include near-fault damage zones in simulations. One suggestion was that the decision of whether or not to include plasticity might depend on the assumed fault geometry. At this rock properties workshop, rock properties were seen as important. However, the rock properties ingredient was ranked slightly lower than the two ingredients, geometry and friction, that were the foci of the previous two workshops. This conclusion about ingredient-ranking is for dynamic rupture simulations that aim to investigate the behavior of the earthquake source. As previously mentioned, when dynamic rupture simulations are used to simulate not just the earthquake source, but also the resulting ground motions, rock properties play a more significant role.

For the workshop agenda, a presentation pdf, and videos of most of the talks, please also see the SCEC workshop website: https://www.scec.org/workshops/2020/dynrup-oct

Some References:

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Munster (2015). Unified Structural Representation of the southern California crust and upper mantle. Earth and Planetary Science Letters, 415, 1-15, doi:10.1016/j.epsl.2015.01.016.

SCEC Dynamic Rupture Group Ingredients Workshop on Fault Friction
Conveners: Ruth Harris and Michael Barall
SCEC Award and Report: 20188
Location: Zoom (online)
Date: October 27, 2020

09:00 - 09:15 Introduction to the workshop (Ruth Harris)
09:15 - 09:35 Self-Introductions by all participants
09:35 - 10:00 Thermal pressurization 3D benchmark and results (Alice Gabriel)
10:00 - 10:30 SCEC Community Velocity Model (CVM-H) (Andreas Plesch)
10:30 - 11:00 Break
11:00 - 11:30 Effects of velocity and attenuation structure on dynamic rupture and ground motion (Kim Olsen)
11:30 - 11:50 Effects of off-fault inelasticity on near-fault directivity pulses (Yongfei Wang)
11:50 - 12:05 Break
12:05 - 12:30 How do near-fault low-velocity structures affect dynamic rupture and ground motion? (Yihe Huang)
12:30 - 13:15 Discussion and Wrap-up
13:15 Workshop Adjourns

Workshop Participants:

Brad Aagaard (USGS)	Rachel Abercrombie (Boston)	Pablo Ampuero (Caltech)
Ralph Archuleta (UCSB)	Khurram Aslam (U Oregon)	Annemarie Baltay (USGS)
Michael Barall (Inv. Software)	Yehuda Ben-Zion (USC)	Yuk Po Bowie Chan (CUHK)
Xiang Chen (CUHK)	Jordan Cortez (UCR)	Luis Dalguer (3Q-Lab)
Roby Douilly (UCR)	Ben Duan (TAMU)	Kenneth Duru (ANU)
Brittany Erickson (U Oregon)	Ahmed Elbanna (UIUC)	Alice Gabriel (LMU)
Percy Galvez (ETHZ)	Christine Goulet (USC)	Ruth Harris (USGS)
Zhifeng Hu (UCSD)	Yihe Huang (Michigan)	Tran Huynh (USC)
Junle Jiang (U Oklahoma)	Yuko Kase (AIST, GSJ)	Christos Kyriakopoulos (Memphis)
Valère Lambert (Caltech)	Nadia Lapusta (Caltech)	Duo Li (LMU)
Dunyu Liu (TAMU)	Julian Lozos (CSUN)	Shuo Ma (SDSU)
Phil Maechling (USC)	Laurent Montesi (Maryland)	David Oglesby (UCR)
Kim Olsen (SDSU)	Edric Pauk (USC)	Arben Pitarka (LLNL)
Andreas Plesch (Harvard)	Marlon Ramos (Michigan)	Thomas Rockwell (SDSU)
Daniel Roten (SDSU)	Kenny Ryan (AFRL)	Taufiq Taufiqurrahman (LMU)
Prithvi Thakur (Michigan)	Jagdish Vyas (KAUST)	Nan Wang (UCSD)
Yongfei Wang (USC)	Max Werner (Bristol)	Kyle Withers (USGS)
Baoning Wu (UCR)	Suli Yao (CUHK)	Te-Yang Yeh (SDSU)
Jiuxun Yin (Harvard)		