II. Technical Report

Updated Final Report

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

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Report for SCEC Award #18217

November 30, 2018 SCEC Workshop

Dynamic Rupture TAG – The 2018 Ingredients Workshop – Fault Geometry
(SCEC Project 18217)

Co-Principal Investigators:

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

The SCEC workshop "Dynamic Rupture TAG – The 2018 Ingredients Workshop – Fault Geometry" was held November 30, 2018, at Kellogg West Conference Center on the campus of California State University, Pomona, in Pomona, California. A total of 49 people participated, including 30 in the meeting room and 19 via remote-access. This year our workshop attendees included scientists from the U.S.A., Germany, China, Canada, New Zealand, Mexico, Japan, and Switzerland. More than one-quarter of our workshop participants were either graduate students or postdocs. The workshop agenda and participant list are on the last two pages of this report. Many thanks to Tran Huynh and her team for helping to make this workshop happen.

This workshop was the first of a series of proposed annual SCEC5 workshops designed to evaluate the importance of each of the four ingredients required for dynamic earthquake rupture simulations. The four ingredients are: initial stress conditions, fault geometry, rock properties, and fault friction (Figure 1). This workshop included views of what fault geometry looks like in the Earth, and discussed the significance of this fault geometry ingredient for everything from dynamic rupture simulations to hazard applications.

Ruth Harris (U.S. Geological Survey; USGS) welcomed the participants. She then introduced and quickly summarized the achievements of the SCEC/USGS Dynamic Rupture Code Verification group, which has tested computer codes that simulate earthquakes as dynamic ruptures, and shown that most of the codes produce matching results [Harris et al., 2018]. Harris described to workshop participants who might not be familiar with these types of simulations, how these simulations work (Figure 1), then she quickly described the range of fault geometry benchmark exercises that the code verification group has performed [Harris et al., 2018]. Harris mentioned that although the dynamic rupture community can now use their codes to computationally simulate many different earthquake rupture scenarios, there is a need to understand which of the four ingredients are most important, and at which scale they are needed, with the focus of this workshop on the fault geometry ingredient.

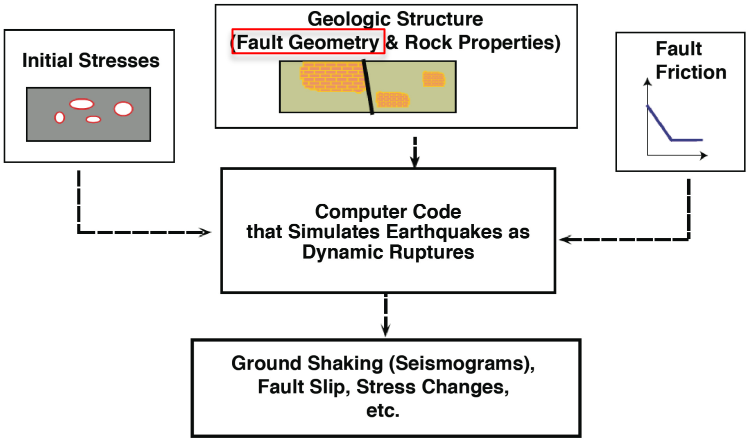

Figure 1. (Lightly modified Figure 1 from Harris et al., 2018). Components necessary for a spontaneous rupture simulation. Spontaneous earthquake rupture simulations need assumptions about the initial stresses on the fault (and off the fault also, if the medium is not elastic), the fault geometry, the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

The next three talks presented views of real fault geometry. Craig Nicholson (University of California, Santa Barbara) described the SCEC Community Fault Model (CFM) [e.g., Plesch et al., 2007; Nicholson et al., 2018], and explained how the CFM's 3D fault geometry in Southern California is inferred from surface traces, well data, hypocenter locations, and other data sources. He then focused on a few locations where, even after all available data is considered, there are still multiple ideas about what the fault geometry looks like. He noted that the effects of the choices for the fault geometry can make a big difference in modeling, for both earthquake generation itself, and, for faults near the California coastline, tsunami generation.

Glenn Biasi (USGS, Pasadena) presented the second fault geometry talk and he described his study compiling surface fault geometry information around the world and evaluating where specific geometrical features observed at Earth's surface appear to have stopped, or not stopped, earthquakes from rupturing farther along strike. He noted that it is important to do more than just measure the distances between faults. An interesting finding is that fault ruptures do not appear to deviate significantly from a straight line, even if the along-strike complexities include bends. He noted that earthquakes appear to ignore small steps in fault geometry, and it appears that earthquake ruptures in dip-slip faults can jump farther and traverse sharper bends than they can in strike-slip faults. Biasi also presented detailed analyses of a few specific fault geometries that were ruptured during large earthquakes, including 2016 M7.8 Kaikoura, New Zealand, 1911 M7.8 Chon-Kemin, Kyrgyzstan, and 1957 Gobi Altay, Mongolia.

Next, Jamie Kirkpatrick (McGill University, Canada) presented an overview of geometrical fault-roughness observational studies, from the micro scale where the roughness appears isotropic [Thom et al., 2017], to more visible scales where anisotropic fault roughness is revealed [e.g., Candela and Brodsky, 2016]. He showed the curious relation that the average roughness, when compiling evidence from multiple scales, appear to follow a Hurst exponent of 1, whereas the evidence at each individual scale appears to show a Hurst exponent looking more like 0.8. In either case, he noted that fault roughness is easily detectable in field studies, and that it appears to play an important role in earthquake behavior, with different scales being relevant to different parts of the earthquake rupture process [e.g., Shervais and Kirkpatrick, 2016].

Following the three talks about what fault geometry looks like, we had two talks focusing on hazard studies for the State of California, one from the state regulation perspective, and one from the earthquake probabilities perspective.

Tim Dawson (California Geological Survey) presented a talk about the State of California's Alquist Priolo Earthquake Fault Zoning (AP) Act, whose goal is to prohibit the siting of most structures for human occupancy across traces of active faults (https://www.conservation.ca.gov/cgs/rghm/ap). He mentioned that the Act was created following the destruction caused by the 1971 M6.6 San Fernando, California, earthquake. He noted that the AP Act deals with the hazard caused by fault rupture very near to and at Earth's surface, and that the geologic investigations mandated by the Act generate considerable information about fault geometry and fault activity that are important for hazard estimates. The next portion of Dawson's talk focused on how dynamic rupture modeling could help inform investigations into surface fault rupture distributions and displacements.

Next, Morgan Page (USGS, Pasadena) presented information about UCERF3 [e.g., Field et al., 2014], the most recent project by the Working Group on California Earthquake Probabilities. She discussed how UCERF3 was an improvement over its predecessor, UCERF2 [2007 Working Group on Earthquake Probabilities, 2008], in that UCERF3 allowed for the possibility of earthquakes rupturing many more combinations of faults. She showed how these changes permitted some very long simulated earthquake ruptures to occur, including the possibility of an earthquake that slips faults all of the way from the southernmost parts of California to near the Juan De Fuca plate in northern California. Page noted that the increased fault connectivity in UCERF3 permits more large earthquakes (M8) and fewer moderate earthquakes (M6-6.5) as compared to UCERF2, while preserving both moment-balance and earthquake-rate-balance. She presented an example of rupture of the Cucamonga Fault, and showed how the magnitude of the earthquakes that involve this fault have far-reaching consequences for the frequency and magnitudes of earthquakes on other faults in California. This affects the hazard calculations, because having more large earthquakes and fewer moderate earthquakes actually reduces the hazard due to the fact that moderate earthquakes are much more common than large ones. Page mentioned that future versions of California Earthquake Probabilities projects need a method to include the possibility of earthquakes starting near but not on a major fault, then transitioning onto the major fault, or vice versa, along with sophisticated approaches to replace the rule-based multi-fault rupture assumptions used in UCERF3.

Following this, we had a break for lunch, then we returned to hear a series of presentations about dynamic rupture simulations of earthquakes that have occurred, and scenarios of events that might occur. Stephanie Wollherr's presentation started this session.

Stephanie Wollherr (Ludwig Maximilian University of Munich, Germany) talked about sophisticated 3D models of the 1992 M7.3 Landers, California earthquake [Wollherr et al., 2018]. This earthquake was the first event where the earthquake community fully grasped the reality of multi-fault earthquake rupture. Wollherr's group investigated how the earthquake was able to rupture the faults that it did, and how the earthquake produced the amounts of fault slip that were observed. She found that to make the rupture traverse all the observed jumps, it is necessary to have a carefully-tuned variable initial stress field, off-fault plasticity, and, for the final jump, dynamic triggering. She also showed a good match between synthetic seismograms produced by their dynamic rupture model, and the seismic stations that recorded the earthquake.

The workshop had two talks about the 2016 M7.9 Kaikoura, New Zealand earthquake, one of the more complex, large, on-land earthquakes to have occurred in recent memory. This earthquake also challenged expectations that an earthquake rupture would not jump more than a few km to get to another fault (e.g., Wesnousky, 2006). Yoshi Kaneko (GNS Science, New Zealand) presented his work computationally simulating dynamic rupture of the earthquake, which included many of the faults that the earthquake actually ruptured [Ando and Kaneko, 2018]. He noted that there were still a few remaining issues to solve, but that overall, it was quite possible to successfully explain the rupture propagation pattern during the earthquake. The model suggests that at both the north and south ends of the rupture, arrest may have occurred due to unfavorable orientation of the fault relative to the regional stress field. Later in the day, Ralph Archuleta discussed specific ground motion recordings of the 2016 earthquake, and what they required of the rupture behavior, including that it appeared that there was backward rupture during the Kaikoura event.

Following Wollherr's and Kaneko's talks about simulations of multi-fault rupture earthquakes that have occurred in California and New Zealand, we had two talks about earthquake scenarios. The first of these two talks was by Roby Douilly (University of California, Riverside). Douilly described his dynamic rupture simulations for the Eastern San Gorgonio Pass, which explore two possible 3D geometries for the faults in that area, both based on the CFM. He showed the initial conditions used for each simulation, and the complex fault geometry, and mentioned how the fault connectivity (or lack thereof) was implemented for his simulations. Douilly concluded that the results depended on not the fault geometry alone, but also how the fault geometry interacts with the initial stress conditions, i.e., the regional stress field, and the proximity of the faults to failure.

The second talk about earthquake scenarios was by Julian Lozos (California State University, Northridge). Lozos discussed Cajon Pass. He noted that there were two previous studies of Cajon Pass earthquake rupture scenarios, including one by Anderson et al. (2003), and one by Lozos (2016), with the latter introducing an updated view of the complex fault geometry, the stress field, and the velocity structure. He next posed the question of whether or not an earthquake can jump between the San Andreas and San Jacinto faults, and answered 'yes'. Lozos followed this with a discussion of geometry details that might matter, including the non-vertical features of the San Andreas fault, and how fault dip may affect rupture propagation and amounts of slip because different dip angles may make the fault more or less favorably oriented relative to the stress field. In addition, he remarked that the Cucamonga Fault could be an important player in dynamic earthquake rupture. He noted that fault geometry alone is not the answer, instead what is important is how the fault geometry, which includes both big and small faults, interacts with the stress field.

Steve Day's (San Diego State University) talk about fault roughness in dynamic rupture simulations followed on Jamie Kirkpatrick's talk about observations of fault roughness, that was presented earlier in the day. Day demonstrated that the inclusion of fault roughness in dynamic earthquake rupture simulations creates seismograms with realistic high-frequency energy, and also plays a role in solving some conundrums presented by simple dynamic rupture modeling on planar faults. For example, by including fault roughness in dynamic rupture simulations, high-frequency signals can easily be simulated (e.g., Withers et al., 2018). Fault roughness also solves the ever-present issue of supershear rupture near the Earth's surface, which often occurs in flat-fault simulations that don't implement another mechanism for suppressing this fast rupture propagation (such as the introduction of high cohesion or low initial stress near the Earth's surface). In contrast, at depth the presence of roughness can generate transient bursts of supershear rupture. His talk showed that, although fault roughness is interesting and computationally easier to study with 2D simulations, 2D simulations are not adequate, because it is easy to stop a rupture with just one high-spot in the topography of the line-fault in 2D. In contrast, in 3D, ruptures can easily circumvent these topographic high spots, by circling around them on the fault surface. Day's presentation showed that using proxies for actual fault roughness might not work very well, and that instead, the real geometrical roughness needs to be included. He summarized that, among its features, geometrical roughness contributes to high-frequency ground motion, statistical variability in ground motions, and produces power-law coseismic surface slip fluctuations.

Ben Duan (Texas A & M University) talked about his work on multi-cycle earthquake simulations, which include not only the earthquake itself, but also the behavior of the fault zone during the intervening time between large earthquakes. He showed how these types of physics-based multi-cycle simulations are what is needed, and he presented examples of 2D simulations for the Aksay Bend along the Altyn Tagh fault in northwest China. Most multi-earthquake-cycle simulations are conducted in 2D, but Duan introduced his group's two new 3D finite-element based earthquake cycle simulators (e.g., Liu et al., 2018; Luo, et al., JGR in revision) that also include geometrical complexity. He noted that to fully understand what is happening, multi-cycle simulations are needed in general, because unlike single-event dynamic rupture simulations that are artificially nucleated, the stresses in multi-cycle simulations spontaneously evolve. He pointed out that this could lead to earthquake ruptures being stopped by a specific geometrical fault configuration sometimes, whereas other times this same fault geometry is unable to stop the earthquakes (an 'earthquake gate'). For example, a bend may stop a rupture several times, but each time the stresses surrounding the bend are increased, so that finally a rupture is able to traverse the bend and rupture the fault on the other side. He noted that the stress conditions play a key role.

Archuleta's talk about the behavior of the 2016 Kaikoura, New Zealand earthquake included mention that the idea of dynamically propagating multi-fault earthquakes is not new, instead, it was first simulated by Harris et al. [1991], even before the 1992 M7.3 Landers, California earthquake. He noted how these types of simulations have become more commonplace in the subsequent years, however, big questions remain. These questions include how to partition the seismic moment among multiple fault segments (in advance), and what to expect from the ground motions during a multi-fault rupture, including how to compare the ground motions from a simply-parametered Ground Motion Prediction Equation (GMPE).

Following Archuleta's talk on the 2016 Kaikoura, New Zealand earthquake, the workshop participants transitioned into the discussion session at the end of the day, with Harris mentioning that the next Dynamic Rupture Ingredients workshop, if it is funded, will focus on fault friction. There were many good points brought up during the discussion session. These included discussion of the key role of fault roughness (with Nadia Lapusta proposing that perhaps it could be related to fault friction), and mention of earthquake ruptures that appear to jump far ahead of where they're expected to be, along with those earthquake ruptures that seem to occasionally propagate backward (as presented in Kaneko's and Archuleta's talks about 2016 Kaikoura, and as mentioned during the discussion by Nicholson for the 2010 El Mayor Cucapah, Mexico earthquake, and Dalguer, Lozos, and Harris for the 1992 Landers earthquake). There were also frequent reminders about the role of the stress field (for example, as pointed out by Baoning Wu), a topic that was highlighted in every dynamic rupture talk, and that the stress field needs to be included as an important ingredient in addition to the fault geometry.

The workshop participants had a fast-paced day of talks and discussions about fault geometry, what it looks like, and what its roles are in earthquake rupture behavior.

For the workshop agenda and some of the presentation pdf's, please also see the workshop website: https://www.scec.org/workshops/2018/dynrup

Some References:

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SCEC Dynamic Rupture Group Ingredients Workshop on Fault Geometry

Conveners: Ruth Harris and Michael Barall
SCEC Award and Report: 18217
Location: Kellogg West Conference Center, Pomona, CA
Date: November 30, 2018

SUMMARY: The SCEC Dynamic Rupture Group will convene a workshop in 2018 to start an in-detail examination of the essential ingredients needed to understand earthquakes and produce viable large-earthquake source simulations. In 2018, we will focus on fault geometry. We have invited speakers from both outside and inside our group to present their ideas about the role(s) of fault geometry, both the small scale and the big scale, in determining rupture extent, ground shaking, and seismic hazard. We have knowledge that complex geometry at all scales exists in the field (e.g., Segall and Pollard, 1980 and references therein; Candela et al., 2012, etc.), and we can computationally simulate this roughness at some scales (e.g., Duru and Dunham, 2016; Shi et al., 2013, Ulrich and Gabriel, 2017), but we need to know if fault geometry at all scales makes a difference for earthquake source features such as rupture extent, and if it makes a difference for hazard.

FRIDAY, NOVEMBER 30, 2018

09:00	Workshop Check-In	
	Session 1: Overview, Motivation, and Desired Outcomes	
09:30	Welcome and Overview of Workshop Objectives, Introductions	Ruth Harris
	Session 2: What Does Fault Geometry Look Like?	
09:45	Observations from the Field - Big Scale – Community Fault Model (CFM)	Craig Nicholson
10:10	Inferences from the Field - Big Scale – Effects of Geometry on Earthquake Ruptures	Glenn Biasi
10:35	Observations from the Field - Big and Small Scale	Jamie Kirkpatrick
11:00	Discussion - Observations	*All*
11:15	*Break*	
	Session 3: Fault Geometry Applications - Hazards	
11:30	Fault Geometry Decisions and Alquist Priolo	Tim Dawson
11:55	Fault Geometry Decisions and UCERF3 (Rupture Extent)	Morgan Page
12:20	Discussion	*All*
12:30	*Lunch*	
	Session 4: Fault Geometry Applications - EQ's and Scenarios	
13:30	Fault Geometry Effects and the 1992 Landers earthquake	Stephanie Wollherr
13:55	The role of 3D fault geometry in the rupture propagation and arrest during the 2016 Kaikoura (New Zealand) earthquake	Yoshi Kaneko
14:20	Large EQ Scenarios for the Eastern San Gorgonio Pass	Roby Douilly
14:45	Large Earthquakes Near Cajon Pass	Julian Lozos
15:10	*Break*	

15:25	Earthquake Rupture on 3D Rough Faults	Steve Day
15:50	Fault Geometry and Multi-Cycle Models: From Single-Event Dynamics to Multicycle Dynamics of Geometrically Complex Faults	Ben Duan
16:15	Fault Geometry and Ground Motions	Ralph Archuleta
16:40-17:30	Discussion and Future Plans	All

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