A SCEC SEAS Group Workshop

On Exploring Complexity and Resolution in Earthquake Sequences

Report for SCEC Award #18102
Submitted December 20, 2018

Investigators: Brittany Erickson (University of Oregon) and Junle Jiang (Cornell University)

I. Project Overview **i**

A. Abstract i
B. SCEC Annual Science Highlights i
C. Exemplary Figure ii
D. SCEC Science Priorities ii
E. Intellectual Merit ii
F. Broader Impacts ii
G. Project Publications ii

II. Technical Report **1**

I. Project Overview

A. Abstract

In the box below, describe the project objectives, methodology, and results obtained and their significance. If this work is a continuation of a multi-year SCEC-funded project, please include major research findings for all previous years in the abstract. (Maximum 250 words.)

The SCEC workshop "SCEC SEAS Group Workshop on Exploring Complexity and Resolution in Earthquake Sequences" was held on Nov. 29th, 2018, at Kellogg West Conference Center on the campus of California State Polytechnic University, Pomona, in Pomona, California. A total of 36 people participated, including 21 in the meeting room and 15 through remote access. This year our workshop attendees included scientists from the U.S.A., Canada, New Zealand, and Switzerland. Over half of our workshop participants were either graduate students or postdocs. This workshop discussed new science discoveries with SEAS models, as well as results from the second benchmark produced by the SEAS group. Many thanks to Tran Huynh and her team for all of their work that helped make this workshop successful.

B. SCEC Annual Science Highlights

Each year, the Science Planning Committee reviews and summarizes SCEC research accomplishments, and presents the results to the SCEC community and funding agencies. Rank (in order of preference) the sections in which you would like your project results to appear. Choose up to 3 working groups from below and re-order them according to your preference ranking.

Fault and Rupture Mechanics (FARM)
Stress and Deformation Over Time (SDOT)
Computational Science (CS)

C. Exemplary Figure

Select one figure from your project report that best exemplifies the significance of the results. The figure may be used in the SCEC Annual Science Highlights and chosen for the cover of the Annual Meeting Proceedings Volume. In the box below, enter the figure number from the project report, figure caption and figure credits.

Figure 4

D. SCEC Science Priorities

In the box below, please list (in rank order) the SCEC priorities this project has achieved. See *https://www.scec.org/research/priorities* for list of SCEC research priorities. *For example: 6a, 6b, 6c*

1d, 1e, 3f

E. Intellectual Merit

How does the project contribute to the overall intellectual merit of SCEC? *For example: How does the research contribute to advancing knowledge and understanding in the field and, more specifically, SCEC research objectives? To what extent has the activity developed creative and original concepts?*

The SCEC workshop was the primary meeting of our SCEC-SEAS group and other parties interested in computational earthquake cycle simulations.

F. Broader Impacts

How does the project contribute to the broader impacts of SCEC as a whole? *For example: How well has the activity promoted or supported teaching, training, and learning at your institution or across SCEC? If your project included a SCEC intern, what was his/her contribution? How has your project broadened the participation of underrepresented groups? To what extent has the project enhanced the infrastructure for research and education (e.g., facilities, instrumentation, networks, and partnerships)? What are some possible benefits of the activity to society?*

The SCEC workshop was the primary meeting of our SCEC-SEAS group and other parties interested in computational earthquake cycle simulations.

G. Project Publications

All publications and presentations of the work funded must be entered in the SCEC Publications database. Log in at *http://www.scec.org/user/login* and select the Publications button to enter the SCEC Publications System. Please either (a) update a publication record you previously submitted or (b) add new publication record(s) as needed. If you have any problems, please email *web@scec.org* for assistance.

Erickson, B. A., Jiang, J., Barall, M., Lapusta, N., Dunham, E., et al, The SCEC Community Code Verification Exercise for Simulating Sequences of Earthquakes and Aseismic Slip (SEAS), in preparation.

II. Technical Report

Final Report

Submitted by Brittany Erickson and Junle Jiang
to the Southern California Earthquake Center

December 20, 2018

Report for SCEC Award #18102

Nov 29, 2018 SCEC Workshop

SCEC SEAS Group Workshop on Exploring Complexity and Resolution in Earthquake Sequences

(SCEC Project 18102)

Co-Principal Investigators:

Brittany Erickson (University of Oregon) and Junle Jiang (Cornell University)

The SCEC workshop "SCEC SEAS Group Workshop on Exploring Complexity and Resolution in Earthquake Sequences" was held on Nov. 29th, 2018, at Kellogg West Conference Center on the campus of California State Polytechnic University, Pomona, in Pomona, California. A total of 36 people participated, including 21 in the meeting room and 15 through remote access. This year our workshop attendees included scientists from the U.S.A., Canada, New Zealand, and Switzerland. Over half of our workshop participants were either graduate students or postdocs. This workshop discussed new science discoveries with SEAS models, as well as results from the second benchmark produced by the SEAS group. Many thanks to Tran Huynh and her team for all of their work that helped make this workshop happen.

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

Brittany Erickson (University of Oregon) and Junle Jiang (Cornell University) introduced the SCEC-SEAS workshop to the participants. They began by discussing the scientific motivation for SEAS simulations, how they are now prevalent in earthquake research (addressing key SCEC objectives) but remain untested. They put the SEAS group efforts in context with those of the Dynamic Rupture Group and the Earthquake Simulators, while motivating the need for verified SEAS models that simulate longer periods of earthquake activity with increased computational and physical rigor. Erickson and Jiang then outlined the objectives of the SEAS working group - which are to lead the efforts of SEAS code verification in order to further advance computational capabilities and promote robust earthquake science. They gave an overview of past and current activities conducted with SCEC funding, including the group presentation at the 2018 SCEC annual meeting (*Erickson et al.* [2018]), discussed details of the SEAS online platform maintained by Michael Barall, provided a timeline for future activities, and then presented an overview of the day's workshop events. This portion of the workshop was then followed by introductions of the workshop attendees, both in person and remote.

The next portion of the workshop consisted of science talks discussing earthquake simulations across different scales and connecting models with lab or field observations. Yen-Yu Lin gave the first talk, discussing microseismicity simulated on asperity-like fault patches and how combining observations of microearthquakes and dynamic modeling can help us understand fault properties and their changes. This was followed by Yongfei Wang who discussed how intermediate-frequency deficit observed in source spectra can be accounted by physical mechanisms of path and source effects. Next, Ahmed Elbanna presented his recent work on physics constrained deep learning and how it can be applied to earthquake mechanics, followed by Yingdi Luo who presented work on a heterogeneous fault model of episodic tremor and slow-slip events. The morning of science talks was concluded with a presentation by Luc Lavier on simulations of earthquakes and slip transients in finite thickness shear zones with plasticity.

The afternoon of the workshop was dedicated to SEAS benchmark results and future activities of the group. Erickson kicked off this portion of the workshop by reviewing the first benchmark problem, BP1 (see Fig. 1). She gave an overview of the problem set-up, the various codes used in BP1, and the number of participants and model runs. She showed results of cumulative slip profiles as well as time series of model results at various stations along the fault during different events in the sequence. They discussed similarities between model results, and how

discrepancies were attributable to the choice of computational domain size and/or choice of far-field boundary conditions. Overall, excellent agreements were made between models with similar domain sizes/boundary conditions, and discrepancies present were removed by increasing computational domain size.

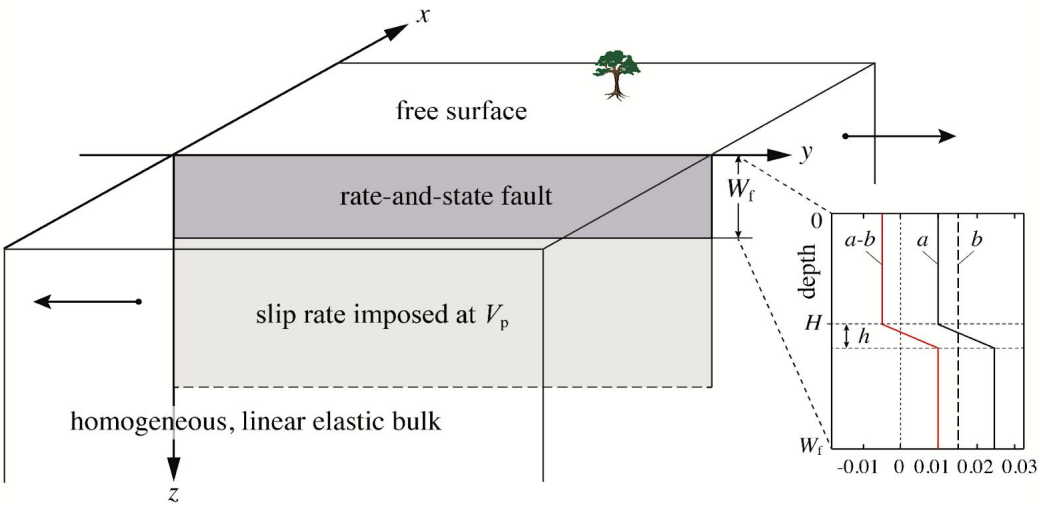

Figure 1. SEAS group benchmark problem 1 and 2 (BP1 and BP2). The exercises consist of a vertical strike-slip fault set in a homogeneous elastic half-space, and regularized rate-state friction with an aging law. The 2D problem involves antiplane shear motion. BP1 and BP2 differ in the size of the cohesive zone. For the detailed benchmark description, please see http://scecdata.usc.edu/cvws/seas/index.html.

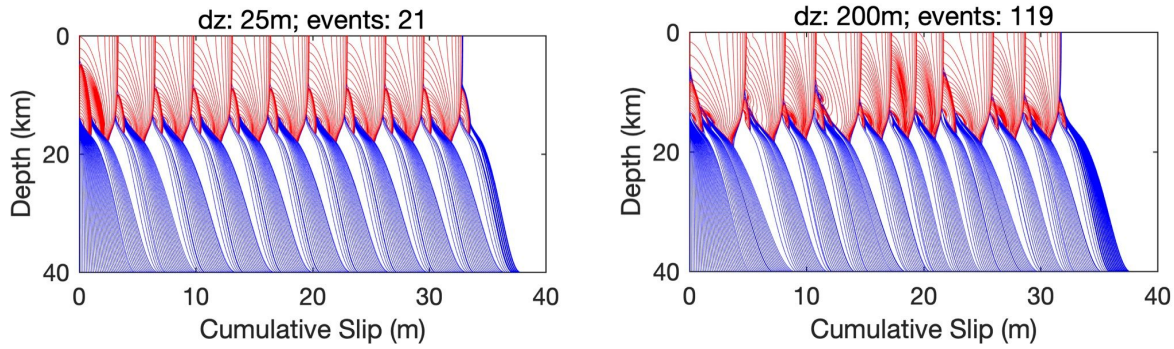

Figure 2. Cumulative slip profiles for BP2 from Jiang model results using a grid spacing of 25m (left) and 200m (right), plotted in blue every year during the interseismic periods, and in red every second during quasi-dynamic rupture. With decreasing cell size, model convergence is observed consisting of an alternating sequence of large (surface-rupturing) and small (buried) events. A loss of regularity is observed with increasing cell size.

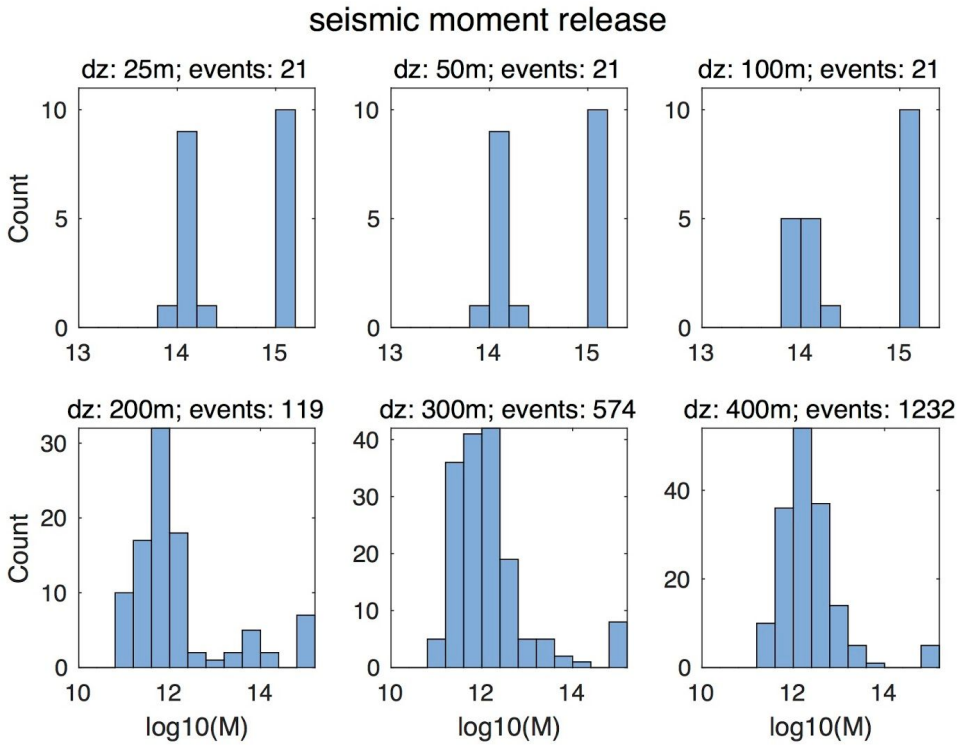

Figure 3. Event histograms for BP2 (from Jiang results) with seismic moment release per unit, using a grid spacing of 25m, 50m, 100m, 200m, 300m and 400m, suggesting model convergence with mesh refinement, and a wide range of event sizes with increasing cell size.

Next, Jiang led the discussion of results of the second benchmark problem, BP2 (see Fig. 1). He began by motivating the need to explore sequences of earthquakes with increasing rupture-style complexity. He outlined the problem set-up for BP2, how the two smaller physical length scales, the cohesive zone and nucleation zone sizes, give rise to event sequences of different sizes, and the objectives of this benchmark problem, namely, to understand complexity in simulated events and how to deal with numerical resolution issues. Next, he gave an overview of modeling groups and codes used for BP2, sharing plots of cumulative slip profiles with differing spatial resolution (see Fig. 2). He showed how large cell sizes that fail to resolve the cohesive zone give rise to event complexity, but that with decreasing cell size, the model results converge to an alternating sequence of large and small events. Jiang illustrated this result by computing a catalogue analysis of model results for the different modeling groups, with histograms showing the distribution of events of different moment release (see Fig. 3). In summary, the group found qualitatively similar behavior with small cell sizes, but drastic differences in small event patterns arose due to increasing cell sizes. We also found that model results with similar set-ups tend to produce results that are initially quite similar, but diverge over time (see Fig. 4). Overall, the qualitatively similar model behavior and divergence of models with increased cell size agree well with our expectations.

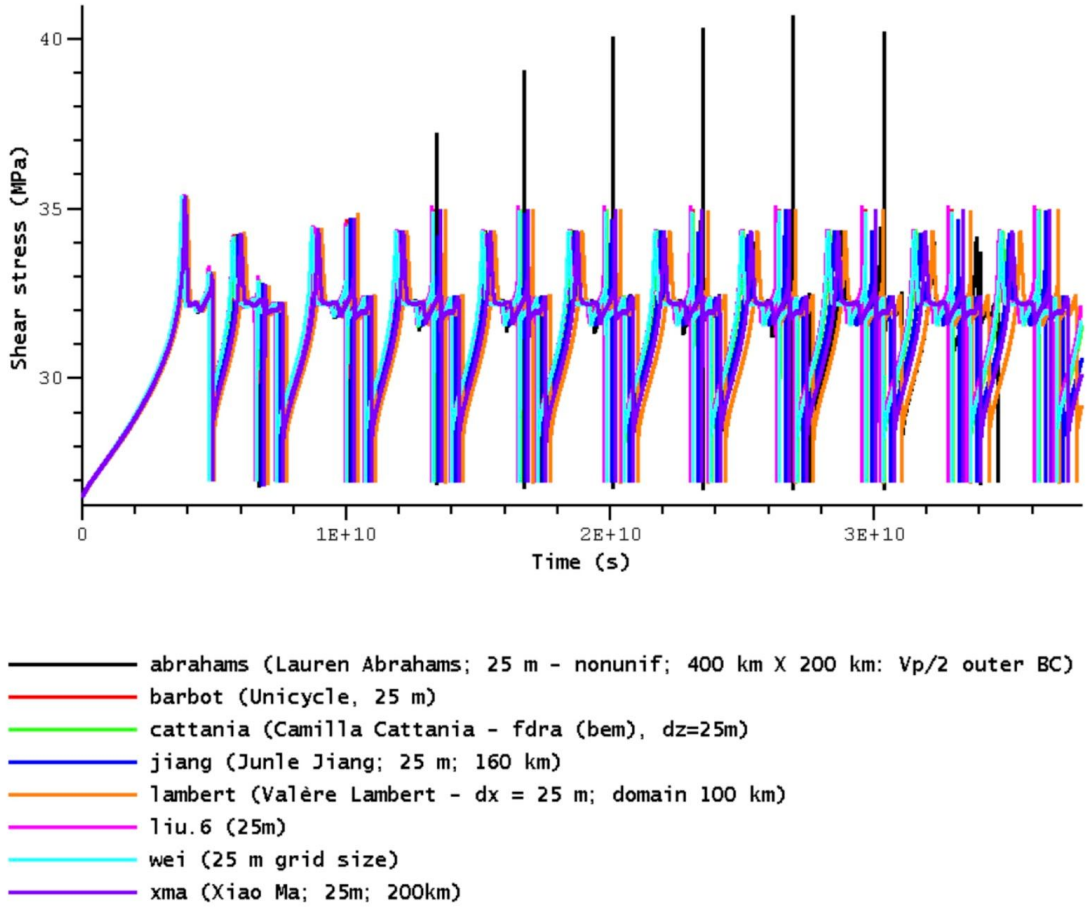

Figure 4. Shear stress time series for best resolved models with a cell size of 25m, at mid-seismogenic depth (14.4km) show excellent agreements, with divergence over time.

Erickson and Jiang then focused on future SEAS plans. They began by reviewing their general guidelines for benchmark designs: to start simple and incrementally increase model complexity, to learn from the experience of the dynamic rupture group, and to design problems that maximize participation. Towards this end, they discussed some future benchmark problems, BP3–BP6. BP3 consists of a 3D problem in a half-space, similar to BP1, while BP4 consists of a similar 3D problem in a whole space. BP5 is a 2D plane strain problem with two velocity-weakening regions separated and surrounded by VS patches, and BP6 is a 2D antiplane problem with the same set-up as BP1 except with inertia effects. Erickson and Jiang led the group discussion on the feasibility of benchmark problems BP3–BP6, and the group decided that over the next year they would address BP4 and BP6, with BP3 and BP5 addressed in later years. Next, plans for platform development were discussed. The group expressed the desire that the platform includes various tuning functions for plotting, namely, unit conversion, time window selection, and time translation. Also expressed was a desire to have a plotting function for slip contours and nonuniform time steps, as this is currently being done manually by Erickson and Jiang. Lastly, the group reviewed the timeline for future activities, including future workshops, presentations

(including a poster presentation at the 2018 AGU annual meeting, 2019 SCEC annual meeting), funding deadlines, and the first SEAS publication (to cover benchmark results from BP1 and BP2) that will be initiated in early 2019.

The workshop participants learned much about simulations of seismic cycles during the day-long event, and the group efforts and discussions will actively continue into the future.

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

References:

Erickson, B.A. et al. (2018), T*he Community Code Verification Exercise for Simulating Sequences of Earthquakes and Aseismic Slip (SEAS): Initial Benchmarks and Future Directions,* poster 192 presented at the 2018 SCEC annual meeting, Palm Springs, CA.

SCEC Workshop Agenda
Nov 29, 2018
SCEC SEAS Group Workshop on Exploring Complexity and Resolution in Earthquake Sequences
Kellogg West Conference Center, Cal Poly Pomona, Pomona, CA

Workshop Conveners: *Brittany Erickson and Junle Jiang*

SUMMARY: The goal of this workshop is to share recent advances in modeling sequences of earthquakes and aseismic slip (SEAS) and continue with the community code verification exercises for SEAS models. The science talks include topics on earthquake simulations across different scales and connecting models with lab or field observations. The second SEAS benchmark BP2 explores the complexity in the simulated earthquake sequence and its dependency on numerical resolutions, motivating our strategy to interpret and resolve seismicity characteristics in larger-scale models. Discussion will be held about increasing the reach and impact of SEAS modeling through upcoming verification benchmarks and future validation efforts.

Thursday Nov 29

9:30 Brittany and Junle: Welcome and Overview of Workshop Objectives, Introductions
9:45 Yen-Yu Lin: Microseismiticty simulated on aperity-like fault patches: on scaling of seismic moment with duration and seismological estimates of stress drops
10:10 Yongfei Wei: A physical interpretation for anomalous source spectra with a deficit at intermediate frequencies
10:35 Ahmed Elbanna (remote): Physics constrained deep learning - Towards applications in earthquake mechanics
11:00 Break
11:15 Yingdi Luo: A heterogeneous fault model of episodic tremor and slow-slip event with spatial-temporal variability
11:40 Luc Lavier: Simulation of slip transients and earthquakes in finite thickness shear zones with a plastic formulation
12:05 All: Group Discussion
12:30 Lunch
13:30 Brittany and Junle: Review of past benchmark results
14:00 Brittany and Junle: Benchmark BP2 Results
15:25 Break
15:40 Brittany and Junle: Future benchmarks and platform
16:40 Brittany and Junle: Progress in SCEC Community and Beyond
17:30 Workshop adjourns

36 Total Participants (15 Remote-Access):
Brittany Erickson (Univ. of Oregon), Junle Jiang (Cornell University), Ruth Harris (USGS), Tran Huynh (USC), Lauren Abrahams (Stanford), Lise Alalouf (McGill Univ.), Kali Allison (Stanford), Pablo Ampuero (Caltech, France), Khurram Aslam (U of Memphis), Michael Barall (Invisible Software), Maricela Best Mckay (Portland State Univ.), James Biemiller (UT Austin), Luis Dalguer (3Lab), Ahmed Elbanna (UIUC), Percy Galvez (KAUST, Saudi Arabia), Jacqui Gilchrist (USC), Bing He (URI), Benjamin Idini (Caltech), Yoshihiro Kaneko (GNS Science, New Zealand), Jeremy Kozdon (Naval Postgraduate School), Kayla Kroll (LLNL), Valere Lambert (Caltech), Nadia Lapusta (Caltech), Luc Lavier (U Texas), Yen-Yu Lin (Caltech), Yajing Liu (McGill), Yingdi Luo (JPL), Xiao Ma (UIUC), Phil Maechling (SCEC), Ollie Stevenson (Caltech), Yuval Tal (Caltech), Prithvi Thakur (Univ. of Michigan), Xinyue Tong (UT Austin), Yongfei Wang (UCSD), Meng Wei (URI), Bei Xu (URI)