2019 SCEC Report

Advancing Simulations of Sequences of Earthquakes and Aseismic Slip (SEAS)

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Proposal Category: Collaborative Proposal

Focus Group: FARM, SDOT

SCEC Research Priorities (among others): P1.d, P1.e, P3.f.

Summary

Developing robust predictive models of earthquake source processes is one of the main SCEC goals. Research groups within the earthquake science community are contributing to this goal through the development of computational methods for simulating Sequences of Earthquakes and Aseismic Slip (SEAS). In SEAS models, the goal is to capture the interplay of interseismic periods and the associated aseismic fault slip—that ultimately lead to earthquake nucleation—and earthquakes (dynamic rupture events) themselves, in an effort to understand which physical factors control the full range of observables such as aseismic deformation, nucleation locations of earthquakes, ground shaking during dynamic rupture, recurrence times and magnitudes of major earthquakes. One of the significant challenges in the SEAS modeling effort arises from the varying temporal and spatial scales that characterize earthquake source behavior. Computations are further complicated when material heterogeneities, bulk inelastic responses, fault nonplanarity, and their evolution with time and slip, are included. However, accounting for such complexity is widely recognized as crucial for understanding the real Earth and predicting seismic hazards.

SCEC has supported community code exercises on verifying/validating spontaneous dynamic earthquake rupture simulations [*Harris et al.*, 2009, *Barall and Harris*, 2015*, Harris et al., 2018*] and comparing Earthquake Simulators [*Dieterich and Richards-Dinger, 2010; Tullis et al.*, 2012]. The dynamic rupture simulations have allowed us to investigate the underlying physics of what influences ground motion, but they are limited to single-event scenarios with imposed artificial prestress conditions and ad hoc nucleation procedures. In contrast, Earthquake Simulators can produce long-term earthquake sequences, but often adopt semi-kinematic assumptions and are missing key physical features that could potentially dominate earthquake and fault interaction, such as stress transfer generated by dynamic waves, aseismic slip within fault segments, and inelastic responses. A new generation of numerical SEAS models are thus needed to simulate longer periods of earthquake activity than single-event simulations but with the same level of computational rigor, while incorporating physical factors important over longer time scales. These verified SEAS models would better inform initial conditions and nucleation procedures for dynamic rupture simulations and provide physics-based approximations for larger-scale, longer-term earthquake simulators.

With SCEC support this past year, we have initiated and led the SEAS initiative, which consists of a series of community code verification exercises for SEAS models. Our main progress and achievements are to have:

- Gathered a group of researchers who are committed to recent benchmark exercises, or are interested in our current activity and/or future participation (~30 PIs, ~20 students/postdocs).
- Established our online platform for benchmark comparisons (http://scecdata.usc.edu/cvws/seas/)
- Designed our first two benchmarks, BP1 and BP2, for 2D antiplane problems.
- Organized our first workshop in Apr. 2018 jointly with the dynamic rupture group for meet-and-greets of modelers, introduction of numerical codes, and discussions on benchmark BP1 results.
- Organized a second SEAS-themed workshop in Nov. 2018 for sharing advancements in the field and discussing results of benchmark BP2.
- In BP1 exercises, we found excellent agreements between 11 modeling groups, when computational domain sizes, boundary conditions, and comparison schemes are appropriately chosen.
- In BP2 exercises, we found excellent agreements between most numerical codes, when important physical length scales are well resolved. The simulated complexity in earthquake sequence in insufficiently resolved models can be significantly different from the "true" fault behavior.
- Presented our group activities and benchmark results at 2018 SCEC/AGU Annual Meetings.

Platform Building and Development of Benchmark BP1

The SEAS initiative has grown significantly in its first year at SCEC, with strides in community building, development of code verification benchmarks, organizing workshops, and promoting visibility of SEAS modeling in the SCEC community and beyond. The overall strategy of our benchmark exercises is to produce robust results and maximize participation. To compare different computational methods, we seek agreements in resolving detailed fault slip history over a range of time scales. These efforts require us to better understand the dependence of fault slip history on initial conditions, model spin-up, fault properties, and friction laws. Given the complexity of this task, it is important to start from the most basic problem.

With SCEC funding over the past year, we developed our first benchmark, BP1, to test the capabilities of different computational methods in correctly solving a mathematically well-defined, basic problem in crustal faulting. This benchmark is a 2D antiplane problem, with a 1D planar vertical strike-slip fault obeying rate-and-state friction, embedded in a 2D homogeneous, linear elastic half-space with a free surface (Figure 1). The fault has a shallow seismogenic region with velocity-weakening (VW) friction and a deeper velocity-strengthening (VS) region, below which a relative plate motion rate is imposed. A periodic sequence of spontaneous, quasi-dynamic earthquakes and slow slip are simulated in the model.

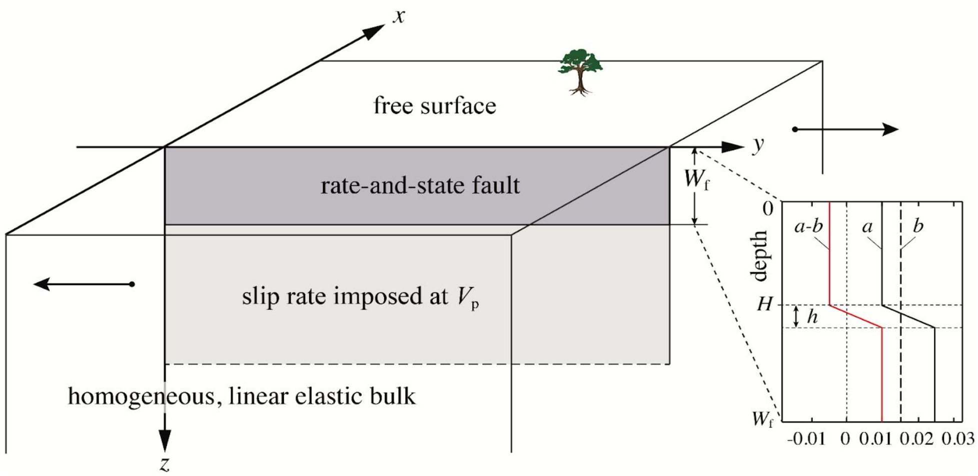

Figure 1. SEAS group benchmark problem 1 and 2 (BP1 and BP2). The exercises consist of a vertical strike-slip fault set in a homogeneous elastic half-space, and regularized rate-state friction with an aging law. The 2D problem involves antiplane shear motion. BP1 and BP2 differ in the size of the cohesive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

We gathered over 10 modeling groups to participate in this benchmark. Many modeling groups chose to participate in this study with their own funding, some from independent SCEC awards and others from other funding sources. To facilitate the submission and comparison of simulation results, we have established an online platform that provides access to community resources and supports the submission, storage, visualization, and comparison of benchmark results. For our first benchmark, we have adopted the platform developed for the SCEC dynamic rupture group by software engineer Michael Barall (http://scecdata.usc.edu/cvws/seas/). Barall has configured the existing platform for our benchmark problems. To minimize our startup costs in the past year, we have relied on the platform's existing ability to receive and plot time-series data with minimal changes.

We held our first workshop in April 2018, during which we introduced different modeling groups and their methodologies, recent advances in SEAS modeling and BP1 benchmark results. In this initial code verification exercise, we found that domain truncation and boundary conditions strongly influence interseismic fault stressing, earthquake recurrence, and coseismic rupture speed, and that agreement between models is only achieved with sufficiently large domain sizes. We also found that some models initially agreed with the others, but diverged over time, without settling into a periodic sequence. In the weeks following the workshop we found that this departure from periodic behavior was due to the lower-order-accuracy post-processing techniques used to evaluate slip on the fault. After increasing the accuracy of the post-processing and/or increasing computational domain size, the comparison of ~20 models from 11 groups using different numerical methods (FDM/FEM/BEM) show excellent general agreements, in terms of cumulative slip over multiple earthquakes and time histories of fault slip rates and surface velocities at selected locations (Figure 2). These problematic numerical issues in SEAS codes would not be revealed and resolved as systematically without this code-verification effort. This benchmark exercise thus benefits individual PIs by motivating systematic code testing and providing confidence in the application of SEAS modeling in scientific studies. Results from this exercise were summarized and shared in our 2018 SCEC presentations [*Jiang and Erickson, 2018; Erickson et. al 2018*].

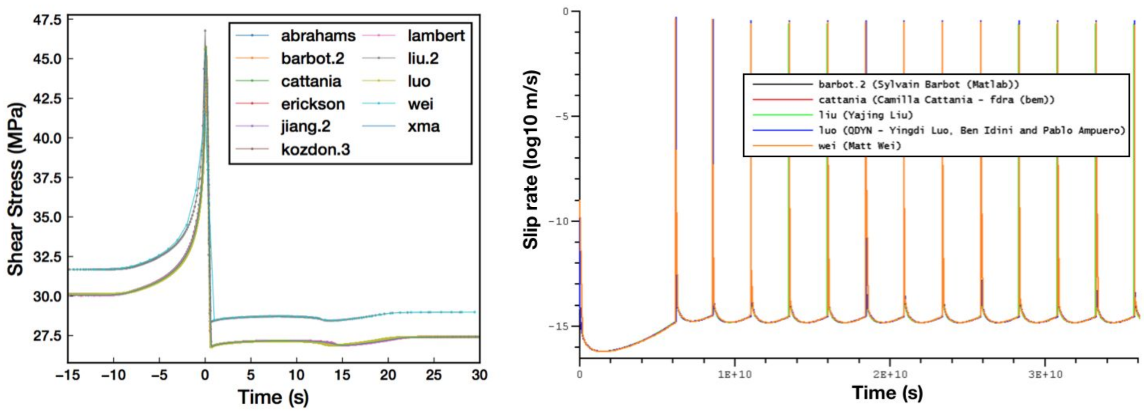

Figure 2. Results from BP1. Left: plots of max shear stress during first event for all model results show qualitative similarities but discrepancies due, in part, to different domain sizes and boundary conditions. Right: time series of maximum slip rates over the first ~10 events with similar domain sizes show good agreement across multiple codes.

Exploring Increased Model Complexity in Benchmark BP2 and in Future

Building on the first benchmark, we decided during the April 1018 workshop to explore increased model complexity without significant changes to the problem and online platform. With a consensus among modelers, we developed the second benchmark BP2 that is similar to BP1 but includes bimodal earthquake sizes (every large event is accompanied by a smaller event in the sequence) as a result of reduced characteristic slip evolution distance L. Besides aiming for agreements between different models, one main objective is to understand complexity in simulated events and how to deal with numerical resolution issues.

In November 2019, we hosted a SEAS-themed SCEC workshop, during which we discussed the results of the benchmark BP2. For this benchmark, we suggested submissions of multiple models with different spatial resolutions from each group. Before the workshop, we received results from ~10 modeling groups. By design, models with a cell size/node spacing that does not resolve critical length scales—nucleation zone size and cohesive zone size—would produce increased complexity in earthquake sequences, as can be seen in the cumulative slip profiles (Figure 3) and histograms of moment release during seismic events (Figure 4). While model behaviors are qualitatively similar for small cell sizes, drastic differences in small event patterns arise due to increasing cell sizes. We found that with decreasing cell sizes, the model results converge to an alternating sequence of large and small events among most models. We also found that model results with similar set-ups tend to produce results that are initially quite similar, but diverge over time (Figure 5). Overall, the qualitatively similar model behavior and divergence of models with increased cell size agree well with our expectations.

Although our initial benchmarks have a simple setup, comparison of results for tens of models have yielded some unexpected and important insights, affirming the importance of starting simple in a community code verification exercise. The workshops have also proven to be particularly valuable in providing an ideal platform for all modelers to share and follow recent scientific progress in the field, discuss details in benchmark design/results, and collectively decide the directions of our future efforts, with considerable inputs from students and early career scientists. The results and lessons from our initial benchmarks prepare us for future benchmark problems that incrementally incorporate additional, potentially dominating physical factors, including fully dynamic ruptures, coupling with fluids, multiple fault segments, nonplanar fault geometries, and inelastic bulk constitutive behavior, and should advance the state-of-the-art computational capabilities in our field.

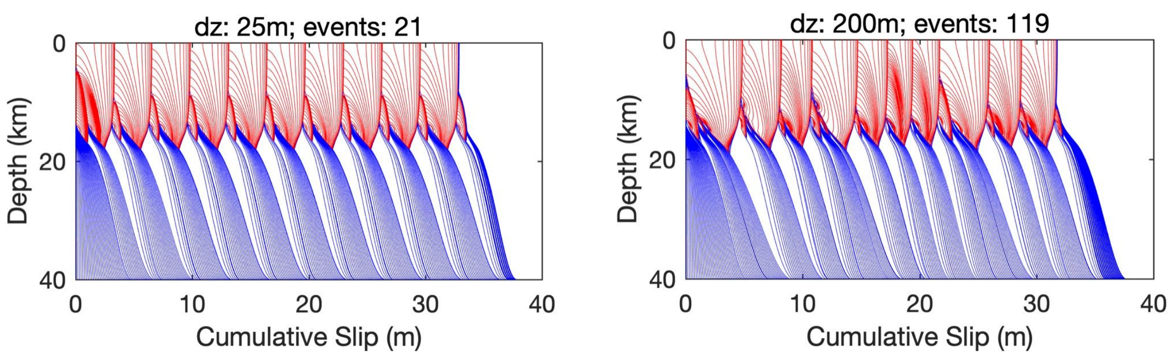

Figure 3. Cumulative slip profiles for BP2 from Jiang model results using a grid spacing of 25m (left) and 200m (right), plotted in blue every year during the interseismic periods, and in red every second during quasi-dynamic rupture. With decreasing cell size, model convergence is observed consisting of an alternating sequence of large (surface-rupturing) and small (buried) events. A loss of regularity is observed with increasing cell size.

Related presentations/publications

Jiang, J., & Erickson, B. A. (2018, 08). Advancing Simulations of Sequences of Earthquakes and Aseismic Slip [SEAS]. Oral Presentation at 2018 SCEC Annual Meeting. SCEC Contribution 8325

Erickson, B. A., Jiang, J., Barall, M., Lapusta, N., Dunham, E. M., Harris, R. A., Abrahams, L., Allison, K. L., Ampuero, J., Barbot, S. D., Cattania, C., Elbanna, A. E., Fialko, Y., Idini Zabala, B., Kozdon, J. E., Lambert, V. R., Liu, Y., Luo, Y., Ma, X., Segall, P., Shi, P., & Wei, M. (2018, 07). The Community Code Verification Exercise for Simulating Sequences of Earthquakes and Aseismic Slip (SEAS): Initial Benchmarks and Future Directions. Poster Presentations at 2018 SCEC Annual Meeting (SCEC Contribution 8214) and 2019 AGU Annual Meeting, Washington, D.C.

Erickson, B. A., Jiang, J., Barall, M., Lapusta, N., Dunham, E. M., Harris, R. A., Abrahams, L. S., Allison, K. L., Ampuero, J., Barbot, S. D., Cattania, C., Elbanna, A. E., Fialko, Y., Idini, B., Kozdon, J. E., Lambert, V. R., Liu, Y., Luo, Y., Ma, X., Segall, P., Shi, P., & Wei, M. (2019). The SCEC Community Code Verification Exercise for Simulating Sequences of Earthquakes and Aseismic Slip (SEAS). *Seismological Research Letters*, (in preparation). SCEC Contribution 9066

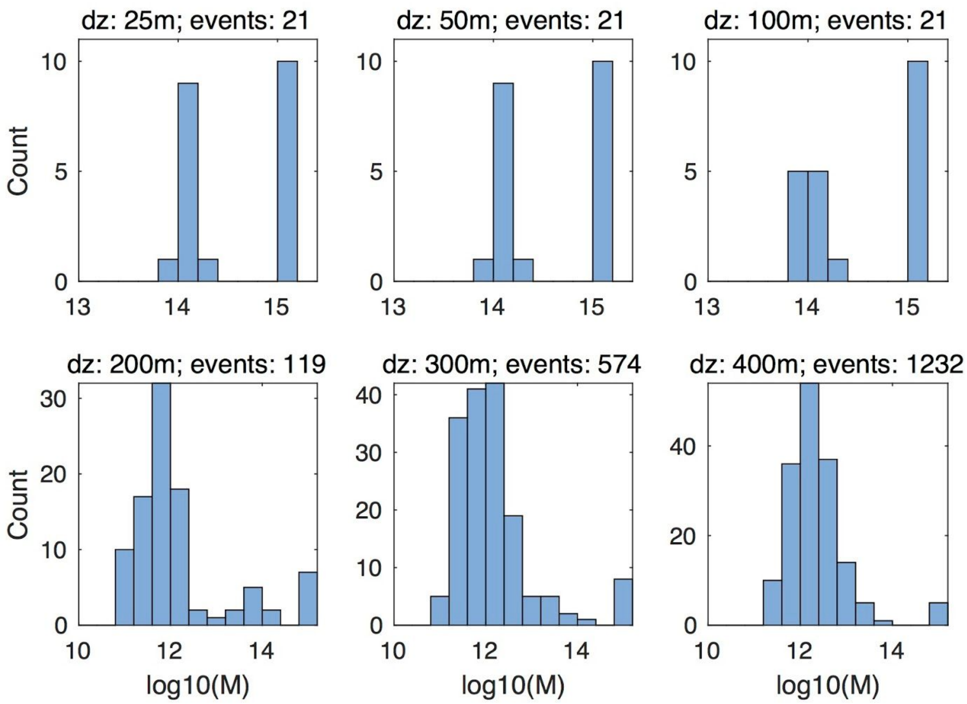

Figure 4. Event histograms for BP2 (from Jiang results) with seismic moment release per unit, using a grid spacing of 25m, 50m, 100m, 200m, 300m and 400m, suggesting model convergence with mesh refinement, and a wide range of event sizes with increasing cell size.

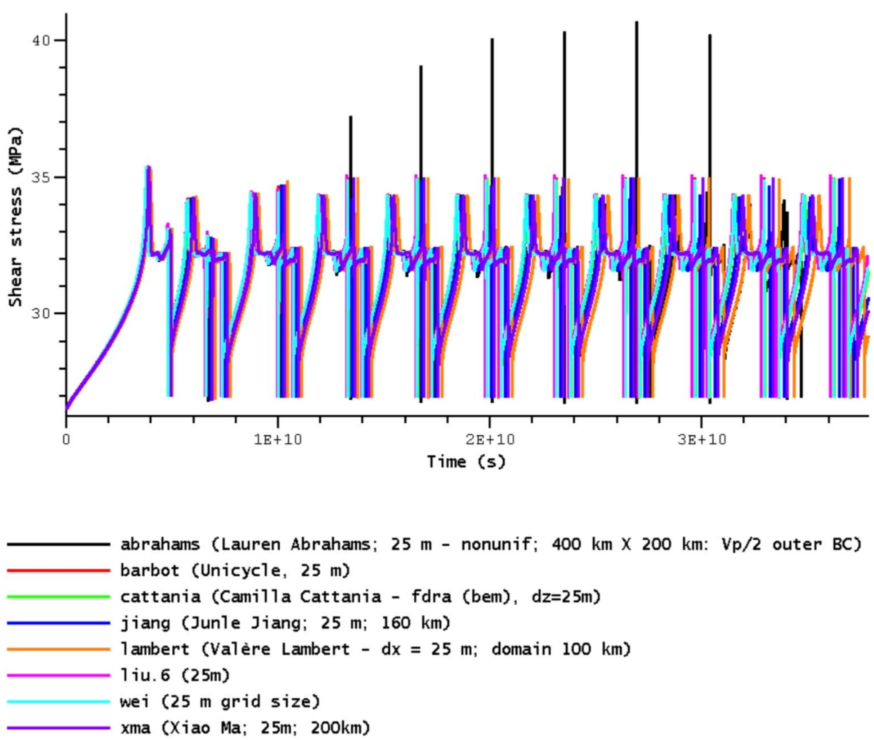

Figure 5. Shear stress time series for best resolved models with a cell size of 25m, at mid-seismogenic depth (14.4km) show excellent agreements, with divergence over time.

References

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Dieterich, J. H., & Richards-Dinger, K. B. (2010). Earthquake recurrence in simulated fault systems. *Pure and Applied Geophysics*, 167(8-9), 1087-1104.

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.

Harris, R.A., M. Barall, R. Archuleta, E. Dunham, B. Aagaard, J.P. Ampuero, H. Bhat, V. Cruz-Atienza, L. Dalguer, P. Dawson, S. Day, B. Duan, G. Ely, Y. Kaneko, Y. Kase, N. Lapusta, Y. Liu, S. Ma, D. Oglesby, K. Olsen, A. Pitarka, S. Song, E. Templeton (2009), The SCEC/USGS dynamic earthquake rupture code verification exercise, *Seism. Res. Lett.*, 80, 119-126, doi:10.1785/gssrl.80.1.119.

Harris, R.A., M. Barall, B. Aagaard, S. Ma, D. Roten, K. Olsen, B. Duan, D. Liu, B. Luo, K. Bai, J.P. Ampuero, Y. Kaneko, A.A. Gabriel, K. Duru, T. Ulrich, S. Wollherr, Z. Shi, E. Dunham, S. Bydlon, Z. Zhang, X. Chen, S.N. Somala, C. Pelties, J. Tago, V.M. Cruz-Atienza, J. Kozdon, E. Daub, K. Aslam, Y. Kase, K. Withers, L. Dalguer (2018), A Suite of Exercises for Verifying Dynamic Earthquake Rupture Codes, *Seism. Res. Lett.*, 89(3), 1146-1162, doi: https://doi.org/10.1785/0220170222.

Jiang, J., and B.A. Erickson (2018), *Advancing Simulations of Sequences of Earthquakes and Aseismic Slip [SEAS]*, invited talk presented at the 2018 SCEC annual meeting, Palm Springs, CA.

Tullis, T.E., Richards-Dinger, K., Barall, M., Dieterich, J.H., Field, E.H., Heien, E.M., Kellogg, L.H., Pollitz, F.F., Rundle, J.B., Sachs, M.K. and Turcotte, D.L., (2012), Generic earthquake simulator, *Seism. Res. Lett.*, *83*, 959-963, doi:10.1785/0220120093.