2021 SCEC Report

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

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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, and understand which physical factors control the full range of observables such as aseismic deformation, earthquake nucleation, ground shaking during dynamic rupture, recurrence times and magnitudes of major earthquakes. One of the significant challenges in SEAS modeling efforts 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 continued our efforts to lead the community code verification exercises for SEAS models. Our main progress and achievements in 2020 have been:

- Engaged a growing number of researchers who are committed to recent benchmark exercises, or are interested in our current activity and potential future participation (~36 PIs, ~34 students/postdocs).
- Designed two new benchmarks, BP3 (dipping fault 2D case) and BP5 (a second 3D case).
- Organized our fourth SEAS-themed workshop in October 2020 for sharing advancements in the field and discussing results of benchmarks BP3-QD and BP5-QD (the quasi-dynamic versions of BP3 and BP5). A total of 54 people participated.
- In the BP3-QD exercises, we found excellent agreements between 3 modeling groups (with 3 additional groups performing the exercise after the workshop), when similar domain sizes and boundary conditions were adopted.
- In the BP5-QD exercises, we explored long-term time series at various fault locations, showing good agreements across modeling groups. Comparisons of the rupture contours showed minor discrepancies attributable to different treatments of the surface nodes and/or domain sizes.
- Presented our results at the 2020 SCEC Annual Meeting.
- Have two new papers (one on our recent 2D benchmark problems, and one on 3D) in preparation, with aimed submission in late Spring 2021.
- **Welcomed new co-leader Valère Lambert, who will be taking over Junle Jiang's position**.

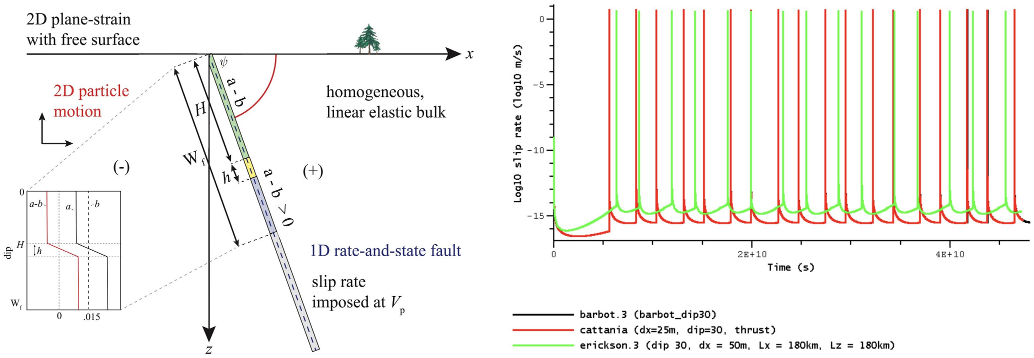

Figure 1. Left: BP3-QD considers a planar, dipping fault embedded in a homogeneous, linear elastic half-space with a free surface where motion is plane-strain. The fault is governed by rate-and-state friction down dip to a distance Wf and creeps at an imposed constant rate Vp down to the infinite dip distance. The left and right sides of the fault are labeled with “(-)” and “(+)”, respectively. For the detailed benchmark description, please see https://strike.scec.org/cvws/seas/index.html. Right: time series from two different codes (boundary element and finite difference) showing discrepancies attributable to thrust versus normal faulting assumption.

Exploring Dipping Fault Geometries and 3D benchmark problems

The SEAS initiative has grown in its third year at SCEC, with strides in community building, development of new 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 simple problem setups. With SCEC funding over the past year, we developed two new benchmarks, BP3 and BP5 (both quasi-dynamic and fully dynamic descriptions have been developed, although the exercises this past year only considered the quasi-dynamic versions). These benchmarks are designed to test the capabilities of different computational methods in correctly solving mathematically well-defined, basic problems in crustal faulting. Benchmark BP3 is our first 2D plane strain problem, with a 1D dipping fault obeying rate-and-state friction, embedded in a 2D homogeneous, linear elastic half-space with a free surface (Fig. 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. The simulations include the nucleation, propagation, and arrest of quasi-dynamic earthquakes, and aseismic slip in the post- and inter-seismic periods. We asked modelers for results from three dipping angles, at 30, 60 and 90 degrees. BP5-QD (see Fig. 2) consists of a 2D planar fault embedded in a 3D, homogeneous half space, with quasi-dynamic events, with the main objective to understand resolution issues and verify models in 3D.

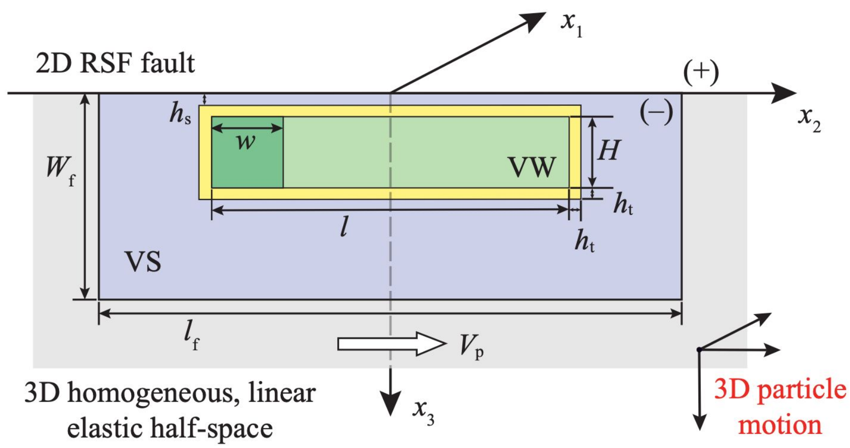

Figure 2. BP5 is a 3D problem with a planar fault embedded vertically in a homogeneous, linear elastic half-space. The fault is governed by rate-and-state friction in the colored region, surrounded by regions in gray with an imposed rate Vp. A favorable nucleation zone (dark green square) is located at one end of the VW patch.

In October 2020, we hosted our fourth SEAS-themed SCEC workshop, during which we first discussed the results of the benchmarks BP3-QD and BP5-QD. For BP3-QD we analyzed results from three different modeling groups, including those from boundary-element based codes, and a finite difference code. We realized that the problem did not state whether to assume normal or thrust motion, an oversight that took some time to find the underlying cause of major discrepancies, see Figure 1, right. Once we sorted this out, we were able to make better informed comparisons and found good agreements across codes, with discrepancies attributable to computational domain size and cell size. We were also able to make sense of results from thrust versus normal faulting assumptions by plotting normal stress changes, as well as profiles of slip contours, see Figure 3. A thrust assumption (top) is associated with increased normal stress change, which decreases the critical nucleation length, allowing events to nucleate sooner and deeper than the normal faulting case (below). In a thrust scenario, therefore, earthquake cycles occur with a decreased recurrence interval and less slip with each rupture. The vertical fault case (not shown) is characterized by repeated (uni-modal) events, whereas faults that dip at 30 degrees (Figure 3) show bi-modal event sequences. Following the workshop we updated the benchmark description to include a specification of thrust versus normal faulting. We also made plans to do additional comparisons of time-series of off-fault surface stations, and (for codes with a volume discretization) to further explore dependency on computational domain size and cell size.

For BP5-QD we analyzed results from six modeling groups. This included time series comparisons from a set of on-fault and off-fault stations, comparisons of coseismic rupture contours of the first event, as well as cumulative slip and stress evolution along several depths and strike locations.

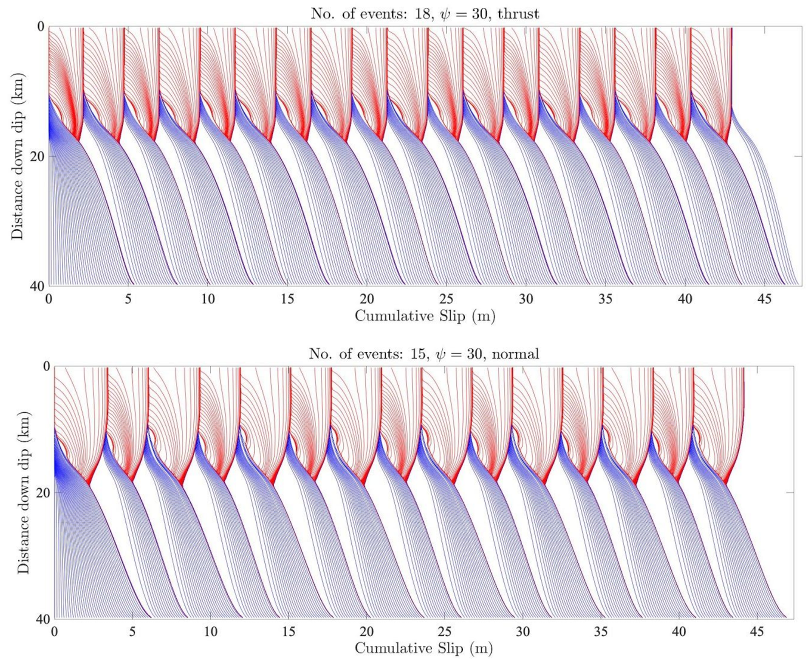

Figure 3. Cumulative slip profiles from a BP3-QD simulation with a 30-degree dipping fault and (top) thrust and (bottom) normal faulting assumption from a boundary-element based code.

For two different cell sizes (1 km and 500 m), long-term time series at various fault locations showed good agreements across modeling groups, while plots of the rupture contours showed minor spatial offsets due to different treatments of the surface node locations (see Fig.3). Comparisons of along-depth and along-strike cumulative slip demonstrated the high similarity of earthquake rupture patterns in different models. Some differences in the coseismic behavior were persistent from the first or later events in the simulations, suggesting some other factors are at play. The group agreed that more simulations are needed for more informed comparisons, in particular to improve agreements in coseismic behavior. We were encouraged to see evidence of convergence of many models with decreasing cell size and increased domain size, as well as the fact that many of the earthquake characteristics agreed well despite variability in rupture direction and nucleation processes. We conclude that we have achieved good benchmark verification results for BP5-QD, having addressed some issues that we encountered for BP4. We are currently preparing improved benchmark results for publication, with a few new participants and additional 3D simulations.

Platform Development and Comparisons

Benchmark BP5-QD was our second effort to compare 3D SEAS models. Although the 3D problems have had a simple setup: a 2D planar fault embedded in a 3D, homogeneous whole space, with quasi-dynamic events, the 3D benchmark are still challenging due to considerably different model setup, output, computational cost, and comparison strategies compared to BP1–BP3. We also had to take into account the more complex model behavior, including variability of earthquake hypocenters and coseismic slip distributions, and needed to develop benchmark strategies and key metrics for code verification tailored to these increasingly complex simulations.

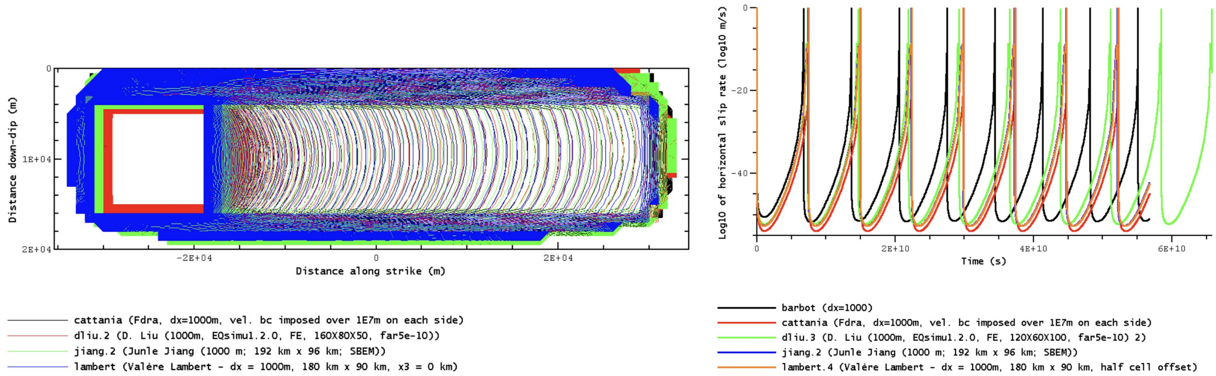

Figure 4. Results from BP5-QD. Left: Comparison of the first coseismic event rupture front across several modeling groups. Right: Time series of horizontal surface slip rate showing good initial agreement.

For all our code verification efforts, the workshops have 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 the recent benchmarks prepare us for the next benchmark problems in which we plan to incrementally incorporate additional physical factors, including increased complexity of 3D problems and fluid effects, which should advance the state-of-the-art computational capabilities in our field.

Related presentations/publications.

Erickson, B. A., Jiang, J., Barall, M., Abdelmeguid, M., Abrahams, L. S., Allison, K. L., Ampuero, J.-P., Barbot, S. D., Cattania, C., Duan, B., Dunham, E. M., Elbanna, A. E., Fialko, Y., Harris, R. A., Idini, B., Kozdon, J. E., Lambert, V. R., Lapusta, N., Li, M., Liu, D., Liu, Y., Luo, Y., Ma, X., Pranger, C., Segall, P., Shi, P., Thakur, P., van den Ende, M., van Dinther, Y., and Wei, M. (2020). The Community Code Verification Exercise for Simulating Sequences of Earthquakes and Aseismic Slip (SEAS): Exploring Full Dynamics and 3D effects. Poster Presentations at 2020 SCEC Annual Meeting (Poster #166).

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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.