# SCEC Workshop for Advancing Simulations of Sequences of Earthquakes and Aseismic Slip (SEAS)

Report for SCEC Award #21139
Workshop held November 2, 2021
Report Submitted December 17, 2021

Investigators: Brittany Erickson (University of Oregon), Junle Jiang (University of Oklahoma) and Valère Lambert (University of California, Santa Cruz)

## I. Project Overview



## II. Technical Report

## 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 on Advancing Simulations of Sequences of Earthquakes and Aseismic Slip (SEAS) was held on Nov. 2nd, 2021, remotely on Zoom. A total of 60 people participated. This year our workshop attendees included scientists from the U.S.A., Sweden, France, Switzerland, China, Germany, England, Japan, Canada, Brazil, and New Zealand. Almost half of our workshop participants were either graduate students or postdocs. This workshop discussed results from our recent 2D and 3D benchmark problems produced by the SEAS group, which include important new features of full dynamics, dipping fault geometries and 3D effects, and outlined details of our upcoming benchmark problems. The workshop also included scientific talks given by SEAS modelers. Many thanks to Tran Huynh and Edric Pauk 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 2. Rupture contours for BP4-QD (whole space problem) show excellent quantitative agreement at suggested resolution (0.5 km) across participating codes. The high computational demand limits participating models at the suggested resolution (BEM/SBEM models), however good agreement is achieved for more models (BEM/SBEM/FEM/FDM) at 1 km resolution (not shown).

## 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.

Jiang, J., Erickson, B. A., Lambert, V., Ampuero, J. P., Ando, R., Barbot, S., Cattania, C., Dal Zilio, L., Duan, B., Dunham, E. M., Gabriel, A.-A., Lapusta, N., Li, D., Li, M., Liu, D., Liu, Y., Ozawa, S., Pranger, C., van Dinther, Y. Community-Driven Code Comparisons for Three-Dimensional Dynamic Modeling of Sequences of Earthquakes and Aseismic Slip (SEAS), in review, 2021.

Erickson, B. A., Jiang, J., Barall, M., Lapusta, N., Dunham, E., Harris, R., Abrahams, L. S., Allison, K. L., Ampuero, J.-P., Barbot, S., Cattania, C., Elbanna, A., Fialko, Y., Idini, B., Kozdon, J. E., Lambert, V., Liu, Y., Luo, Y., Ma, X., Mckay, M. B., Segall, P., Shi, P., van den Ende, M., Wei, M. The Community Code Verification Exercise for Simulating Sequences of Earthquakes and Aseismic Slip, *Seismological Research Letters*, 2020. doi:10.1785/0220190248

## II. Technical Report

*Final Report*

*Submitted by Brittany Erickson, Junle Jiang and Valère Lambert*
*to the Southern California Earthquake Center*

*December 17, 2021*

Report for SCEC Award #21139

**Nov. 2, 2021 SCEC Workshop**

# SCEC SEAS Group Workshop on Advancing Simulations of Earthquake Sequences and Aseismic Slip (SEAS)

(SCEC Project 21139)

Co-Principal Investigators:

**Brittany Erickson (University of Oregon), Junle Jiang (University of Oklahoma), Valère Lambert (UC Santa Cruz)**

The SCEC Workshop on Advancing Simulations of Sequences of Earthquakes and Aseismic Slip (SEAS) was held on Nov. 2nd, 2021, remotely on Zoom. A total of 60 people participated. This year our workshop attendees included scientists from the U.S.A., Sweden, France, Switzerland, China, Germany, England, Japan, Canada, Brazil, and New Zealand. Almost half of our workshop participants were either graduate students or postdocs. This workshop discussed results from our recent 2D and 3D benchmark problems produced by the SEAS group, which include important new features of full dynamics, dipping fault geometries and 3D effects, and outlined details of our upcoming benchmark problems. The workshop also included scientific talks given by SEAS modelers. Many thanks to Tran Huynh and Edric Pauk for all of their work that helped make this workshop successful.

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

Brittany kicked off the workshop with a brief history of SEAS activities since its initiation in 2018 and an overview of the workshop schedule and goals. Everyone in the meeting room introduced themselves and gave brief statements about why they were attending the meeting. Brittany then provided an update on the current status of model results and the corresponding paper for the two recent 2D benchmarks BP1-FD (the first fully dynamic problem) and BP3-QD (the first plane strain problem with a dipping fault). She described how quantitative agreements have been made for BP1-FD (see Figure 1) for several modeling groups, while other participating modeling groups are still working to update/upload new results.. For BP3-QD, she showed how on-fault time series match well across codes, and discrepancies in off-fault surface stations have been addressed by resolving an ambiguity in the benchmark description. A draft of the paper will soon be circulated among modelers, and sent to the involved coauthors by the end of the year.

Next, Junle summarized highlights and lessons from the code comparison exercises for 3D SEAS benchmarks. A total of 10 modeling groups together explored how various computational and physical factors affect simulation outputs for all phases of multiple seismic cycles. The excellent agreement among best-resolved simulations lend confidence to participating numerical codes, offering best-practice examples to improve numerical simulations (see Figure 2). These comparisons also reveal different sensitivities of model observables, which are important for

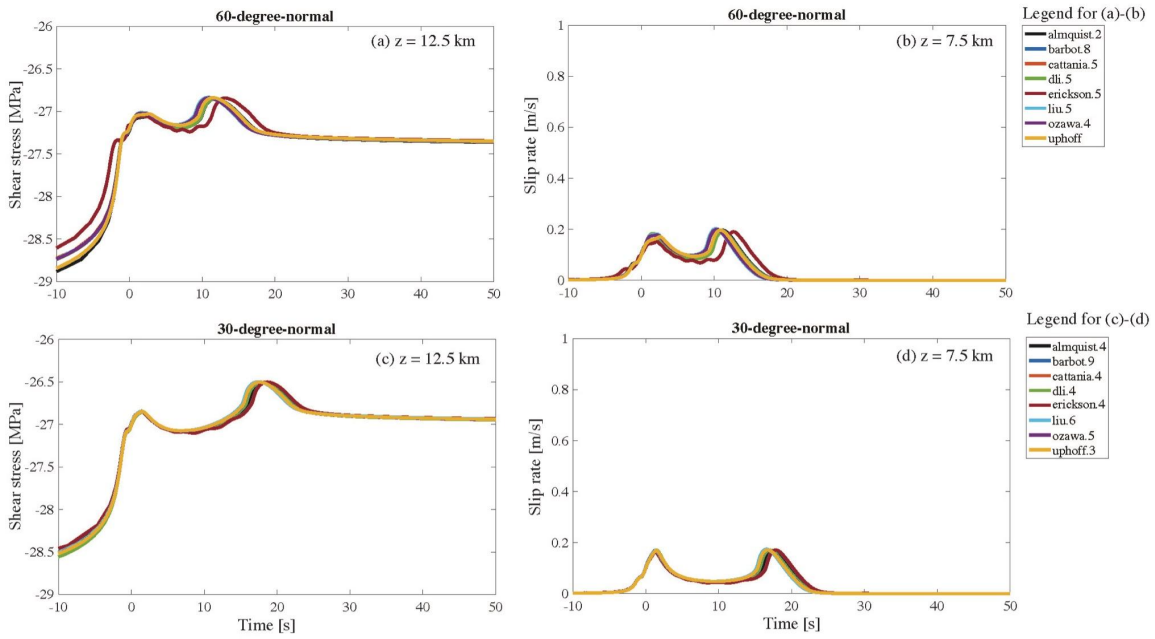


**Figure 1**. Coseismic time series for BP3-QD across all modeling groups show qualitative (and in some cases quantitative) agreements with sufficiently large computational domain size. For volume-based codes, we found that results are sensitive to choices in boundary conditions truncating the semi-infinite domain, as well as computational choices in grid stretching.

integrating models with geophysical observations. The manuscript for 3D benchmarks is currently in review, with the preprint available here: https://doi.org/10.1002/essoar.10508582.1.

Next, a total of 5 SEAS-modeling science talks were given by Stacy Larochelle, Yuyun Yang, Sylvain Barbot, Pierre Romanet, and Duo Li (4 of which are early career scientists). These talks focused on using SEAS modeling to understand the effects of fluids, friction, complex fault geometries and full dynamics on fault slip.

During the afternoon session, Valère gave an overview of two new sets of benchmark problems for 2022. The first, BP6-QD-A/S/C, is a 2D quasi-dynamic problem of a 1-D fault with either constant or velocity-strengthening friction exhibiting an aseismic slip transient arising due to changes in effective normal stress from fluid injection and along-fault pore fluid diffusion. The second, BP7-QD/FD-A/S, is a 3D problem focusing on the interplay between aseismic slip and earthquake nucleation on a circular velocity-weakening asperity. See Figure 3. He explained how BP6 and 7 have been modified based on feedback during previous group discussions, such as using a smooth nucleation procedure for the initial rupture in BP7 and suggesting a finite domain size for volume-based methods.

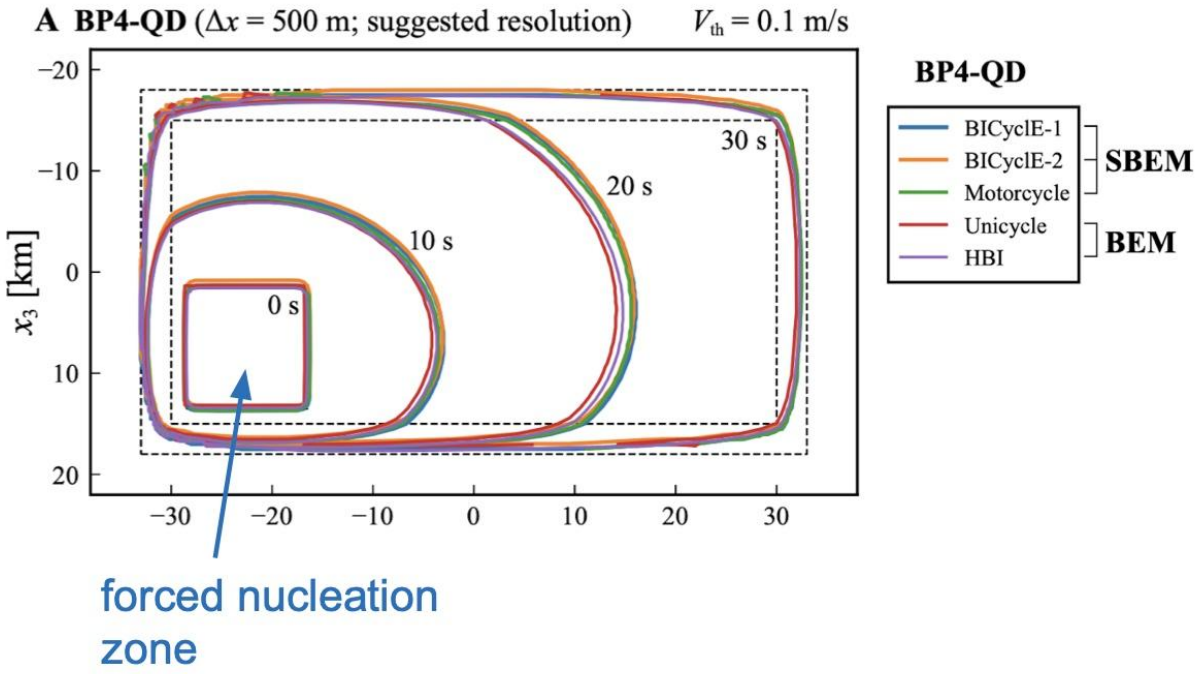


**Figure 2.** Rupture contours for BP4-QD (whole space problem) show excellent quantitative agreement at suggested resolution (0.5 km) across participating codes. The high computational demand limits participating models at the suggested resolution (BEM/SBEM models), however good agreement is achieved for more models (BEM/SBEM/FEM/FDM) at 1 km resolution (not shown).

To conclude the meeting, Brittany, Junle and Valère discussed SEAS activities for the coming year, including possible future benchmark problems, how to best maximize participation in SEAS benchmarks, and the importance of high-performance computing in the advancement of code. The group also discussed possible collaborations between SEAS and other groups (e.g. RSQSim) in future activities.

The final discussion highlighted how three general problems stood out as potential future benchmarks based on a poll sent out prior to the workshop: 1) a 2D antiplane problem like BP1 but including bulk viscoelastic deformation, 2) a 2D dipping fault problem like BP3 with depth-variable normal stress, and 3) a 2D problem including a low-velocity damage zone. Looking forward, the group discussed how we are exploring options to revamp the online platform and welcome any input from the group on what the new platform should look like and include, such as any specific tools and functionality.

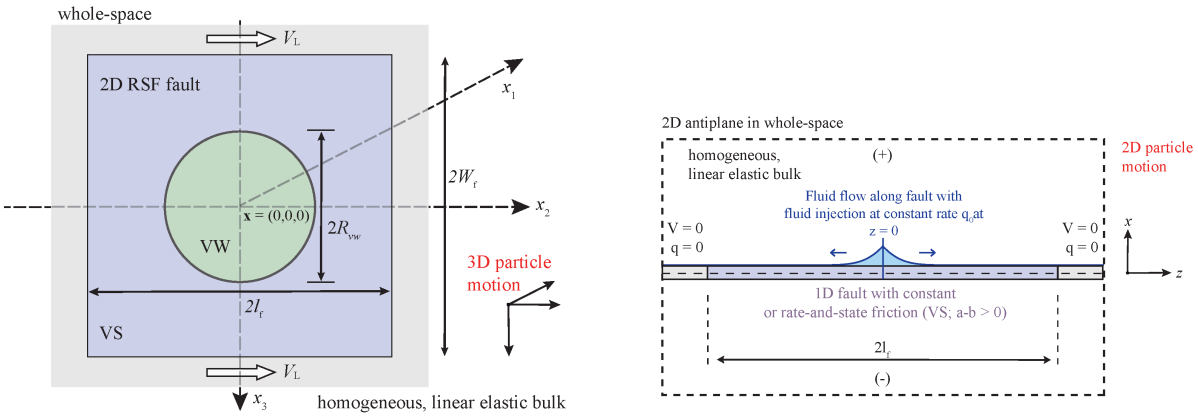


**Figure 3.** Problem set-ups for new benchmarks. Left: BP6-QD-A/S/C is a 2D problem of fault with velocity-strengthening or constant friction with fluid injection and along-fault pore fluid diffusion. Right: 3D problem with a circular velocity-weakening asperity.

**References:**


Jiang, J., Erickson, B. A., Lambert, V. R., Ampuero, J., Ando, R., Barbot, S. D., Cattania, C., Dal Zilio, L., Duan, B., Dunham, E. M., Gabriel, A., Lapusta, N., Li, D., Li, M., Liu, D., Liu, Y., Ozawa, S., Pranger, C., & van Dinther, Y. (2021). Community Code Verification Exercises for Simulations of Earthquake Sequences and Aseismic Slip (SEAS): Three-Dimensional Problems. Poster Presentation at 2021 SCEC Annual Meeting.

Erickson, B. A., Jiang, J., Abdelmeguid, M., Almquist, M., Ampuero, J., Ando, R., Barbot, S. D., Cattania, C., Chen, A., Dal Zilio, L., Dunham, E. M., Elbanna, A. E., Gabriel, A., Harvey, T., Huang, Y., Kaneko, Y., Kozdon, J. E., Lambert, V. R., Lapusta, N., Li, D., Li, M., Liang, C., Liu, Y., Ozawa, S., Pranger, C., Segall, P., Sun, Y., Thakur, P., Uphoff, C., van Dinther, Y., & Yang, Y. (2021). Community Code Verification Exercises for Simulations of Earthquake Sequences and Aseismic Slip (SEAS): Dynamic Effects and Dipping Fault Geometries. Poster Presentation at 2021 SCEC Annual Meeting.

Jiang, J., Erickson, B. A., Lambert, V., Abdelmeguid, M., Almquist, M., Ampuero, J.-P., Ando, R., Barbot, S., Catania, C., Chen, A., Dal Zilio, L., Duan, B., Dunham, E. M., Elbanna, A. E., Gabriel, A.-A., Harvey, T., Huang, Y., Kaneko, Y., Kozdon, J. E., Lapusta, N., Li, D., Li, M., Liang, C., Liu, D., Liu, Y., Ozawa, S., Pranger, C., Segall, P., Sun, Y., Thakur, P., Uphoff, C., van Dinther, Y., Yang, Y. (2021). Community Code Verification Exercises for Simulations of Earthquake Sequences and Aseismic Slip (SEAS): 3D Effects, Fully Dynamic Ruptures, and Dipping Fault Geometries. Poster Presentation (S55D-0168) at 2021 AGU Annual Meeting.

Jiang, J., Erickson, B. A., Lambert, V., Ampuero, J. P., Ando, R., Barbot, S., Cattania, C., Dal Zilio, L., Duan, B., Dunham, E. M., Gabriel, A.-A., Lapusta, N., Li, D., Li, M., Liu, D., Liu, Y., Ozawa, S., Pranger, C., van Dinther, Y. Community-Driven Code Comparisons for Three-Dimensional Dynamic Modeling of Sequences of Earthquakes and Aseismic Slip (SEAS), submitted, 2021.

Erickson, B. A., Jiang, J., Barall, M., Lapusta, N., Dunham, E., Harris, R., Abrahams, L. S., Allison, K. L., Ampuero, J.-P., Barbot, S., Cattania, C., Elbanna, A., Fialko, Y., Idini, B., Kozdon, J. E., Lambert, V., Liu, Y., Luo, Y., Ma, X., Mckay, M. B., Segall, P., Shi, P., van den Ende, M., Wei, M. The Community Code Verification Exercise for Simulating Sequences of Earthquakes and Aseismic Slip , *Seismological Research Letters*, doi:10.1785/0220190248, 2020.

**SCEC Workshop Agenda**
**Nov. 2, 2021**
**SCEC SEAS Group Workshop on Advancing Simulations of Earthquake Sequences and Aseismic Slip**
*Remotely on Zoom*

Workshop Conveners: *Brittany Erickson, Junle Jiang and Valère Lambert*

SUMMARY: Our group is working to advance computational methods for simulating Sequences of Earthquakes and Aseismic Slip (SEAS) by conducting a suite of code verification exercises. In SEAS models, the goal is to capture the interplay of aseismic fault slip—that ultimately lead to earthquake nucleation—and dynamic earthquake ruptures themselves, in an effort to understand which physical factors control the full range of observables such as aseismic deformation, earthquake initiation locations, ground shaking during dynamic rupture, recurrence times and magnitudes of earthquakes.

The goal of this workshop is to share some recent progress in SEAS modeling that considers fluid effects and increased frictional and geometric complexity and to introduce our next benchmark problems BP6 and BP7, which focus on fluid and 3D effects, respectively. We will summarize results from the most recent benchmarks BP3-QD, BP1-FD, and BP5 which focused on dipping fault geometries, full dynamic and 3D effects, respectively. We will also discuss research targets and plans for SEAS in the near and longer term for the group.

**Tuesday Nov 2**

8:00 Brittany: Workshop Goals and Science Targets
8:10 Group Introductions
8:30 Brittany and Junle: Review of SEAS Group Benchmark Results
8:50 Break
9:00 Stacy Larochelle: Fluid-induced slip and earthquake nucleation on a rate-and-state fault
9:20 Yuyun Yang: Fault slip coupled to fluid migration with porosity and permeability evolution
9:40 Sylvain Barbot: Fault dynamics in non-isothermal conditions
10:00 Break
10:10 Pierre Romanet: Fully-dynamic earthquake cycle on a non planar fault using the spectral boundary element method
10:30 Duo Li: Spatiotemporal complexity of slow slip events on 3D non-planar subduction faults
10:50 Group Discussion
11:00 Break
12:00 Valère: New Benchmarks BP6 and BP7
12:20 Group Discussion
13:00 Group Planning for 2022
13:30 Group Discussion: Recommendations for Future Research Beyond 2022
14:00 Adjourn

**60 Total Participants (all remote):**

Mohamed Abdelmeguid (UIUC), Kali Allison (UC Davis), Martin Almquist (Uppsala Univ), Pablo Ampuero (Uni Côte d'Azur), Michael Barall (USGS), Sylvain Barbot (USC) Yehuda Ben-Zion (USC), Segun Bodunde (U Oklahoma), Alexandre Chen (U Oregon), Luca Dal Zilio (ETHZ), Luis Dalguer (3Q-Lab), Shuai Deng (Sichuan Univ), Ben Duan (TAMU), Eric Dunham (Stanford), Brittany Erickson (U Oregon), Alice Gabriel (Munich), Christine Goulet (USC), Ruth Harris (USGS), Tobias Harvey (U Oregon), Jessica Hawthorne (Oxford), Yihe Huang (Michigan), Tran Huynh (USC), Junle Jiang (U Oklahoma), Yoshi Kaneko (GNS), Taeho Kim (Caltech), Jeremy Kozdon (NPS), Christos Kyriakopoulos (U Memphis), Valère Lambert (UCSC), Stacy Larochelle (Caltech), Duo Li (LMU Munich), Dunyu Liu (UT Austin), Yajing Liu (McGill), Amy Lu (McGill), Betsy Madden (Brasilia), Phil Maechling (USC), Rishav Mallick (EOS/Caltech), Brendan Meade (Harvard), Enrico Milanese (MIT), Shiying Nie (USC), So Ozawa (U Tokyo), Edric Pauk (USC), Andrea Perez (Victoria), Fred Pollitz (USGS), Casper Pranger (LMU Munich), Sohom Ray (Dalhousie), Pierre Romanet (NIED), Nico Schliwa (LMU Munich), Paul Segall (Stanford), Md Shumon Mia (UIUC), Yudong Sun (MIT), Yuval Tal (Caltech), Prithvi Thakur (Michigan), Ben Thompson, Yuan Tian (Stanford), Carsten Uphoff (LMU Munich), Yongfei Wang (USC), Meng Wei (URI), Joseph Wick (UCSC), Yuyun Yang (Stanford), Wenqiang Zhang (McGill)