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

Report for SCEC Award #22123
Workshop held November 18, 2022
Report Submitted December 18, 2022

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

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. 18th, 2022, remotely on Zoom. A total of 35 people participated. This year our workshop attendees included scientists from the U.S.A., Sweden, France, New Zealand, the Netherlands, Canada, Japan, and Switzerland. Almost half of our workshop participants were either graduate students or postdocs. This workshop discussed results from the seventh and eighth benchmarks produced by the SEAS group, as well as scientific talks given about synergistic community activities going on in SZ4D/MCS, CIG and SCEC. Many thanks to Edric Pauk and Tran Huynh for 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 1

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 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., Lambert, V., Abdelmeguid, M., Almquist, M., Ampuero, J.-P., Ando, R., Barbot, S., Cattania, C., Chen, A., Dal Zilio, L., Dunham, E. M., Elbanna, A., Gabriel, A.-A., Harvey, T. W., Huang, Y., Kaneko, Y., Kozdon, J., 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. (2022), Incorporating full elastodynamics effects and dipping fault geometries in community code verification exercises for simulations of earthquake sequences and aseismic slip (SEAS), accepted*, Bull. Seismol. Soc. Am.*

Jiang, J., Erickson, B., 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., and Y. van Dinther (2022a), Community-Driven Code Comparisons for Three-Dimensional Dynamic Modeling of Sequences of Earthquakes and Aseismic Slip (SEAS). *J. Geophys. Res*. 127, doi:10.1029/2021JB023519

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 (SEAS) (2020), *Seismological Research Letters*, 91 (2A): 874-890, doi: 10.1785/0220190248.

II. Technical Report

Final Report

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

December 18, 2022

Report for SCEC Award #22123

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

Nov 18, 2022

(SCEC Project 22123)

Co-Principal Investigators:

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

The SCEC Workshop on Advancing Simulations of Sequences of Earthquakes and Aseismic Slip (SEAS) was held on Nov. 18th, 2022, remotely on Zoom. A total of 35 people participated. This year our workshop attendees included scientists from the U.S.A., Sweden, France, New Zealand, the Netherlands, Canada, Japan, and Switzerland. Almost half of our workshop participants were either graduate students or postdocs. This workshop discussed results from the seventh and eighth benchmarks produced by the SEAS group, as well as scientific talks given about synergistic community activities going on in SZ4D/MCS, CIG and SCEC . Many thanks to Edric Pauk and Tran Huynh for their work that helped make this workshop successful.

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

Valère Lambert (UC Santa Cruz) kicked off the workshop by welcoming everyone to the workshop, providing an overview of the workshop agenda, discussing past and current SCEC-funded SEAS activities. They reviewed the long-term science targets of the SCEC-SEAS initiative — to promote advanced earthquake models with robust physical features.

Brittany Erickson (University of Oregon) and Junle Jiang (University of Oklahoma) moderated the next part of the workshop, which involved talks on synergistic activities going on in the earthquake modeling community. Eric Dunham and Leif Karlstrom shared insight into the SZ4D/MCS (Subduction Zone 4D/Modeling Collaboratory for Subduction) efforts, including volcano verification and validation exercises. Then Kevin Milner shared details of the SCEC Seismic Hazard Analysis platforms. Finally, Sylvain Barbot provided an overview of the seismic cycling modeling efforts of CIG (Computational Infrastructure for Geodynamics).

The second half of the workshop was devoted to reviewing results from the latest two benchmark problems BP6 and BP7, see Figure 1. Lambert reviewed major findings from these exercises, as well as next steps to improve comparisons. First discussed was BP7, a 3D problem with a circular velocity-weakening asperity with repeating seismic and aseismic events. A total of 6 modeling groups participated in the quasi-dynamic version BP7-QD-A and 2 groups in the fully-dynamic version BP7-FD-A. The BEM-based codes show good overall agreement in BP7-QD-A, including SBEM codes with sufficiently large domain sizes (see Figure 2, left), but still needed to be checked are the results from volume-based codes. A point was brought up during the discussion that it will be important to get more volume-based codes involved in 3D problems. Results from SBEM codes agree with each other for

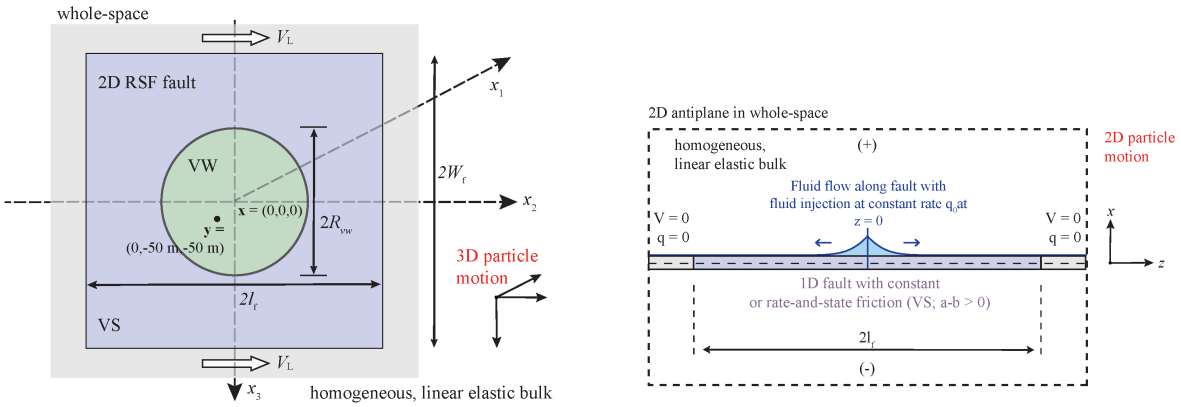

Figure 1. Left) BP7 is a 3D problem with a planar fault governed by rate-and-state friction with a circular velocity-weakening asperity (green) surrounded by velocity-strengthening regions (blue). B) We have chosen sets of model parameters that produce different sequences of either characteristic repeating earthquakes or sequences of alternating aseismic and seismic slip events. Right) BP6 considers a planar fault embedded in a homogeneous, linear elastic whole-space where fault slip is induced by the injection of fluid in the middle of the fault.

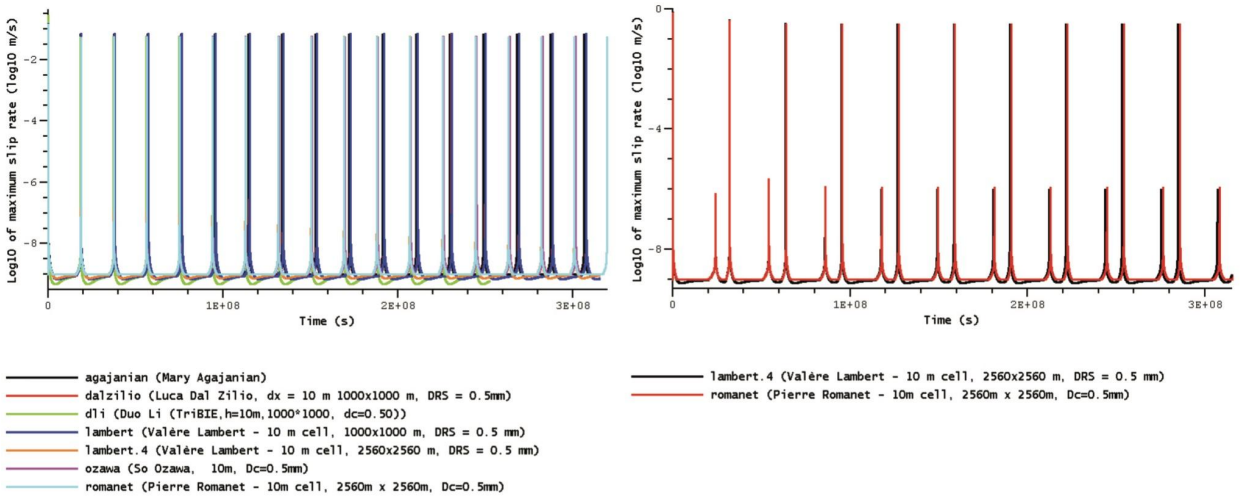

Figure 2. We found that the recommended domain size of 1000-m for BP7-QD-A contributes to discrepancy for SBEM discrepancy mitigated with larger domain (left), e.g. 2560 x 2560 m. The inclusion of full-dynamics shows a transition from periodic seismic events (quasi-dynamics, left), to repeating seismic and aseismic sequences (right) in BEM/SBEM for BP7-FD-A.

similar domain sizes in BP7-QD-A, and simulations of BP7-FD-A (i.e. with full treatment of inertial effects) result in different sequences of repeating seismic and aseismic event, compared to the quasi-dynamic simulations, see Figure 2 (right). Different stress evolution results in larger slip in seismic events and different aseismic transients; correspondingly longer recurrence time between seismic events. In wrapping up the discussion on BP7, we agreed that further analysis still needs to be done, for example quantifying seismic vs aseismic partitioning.

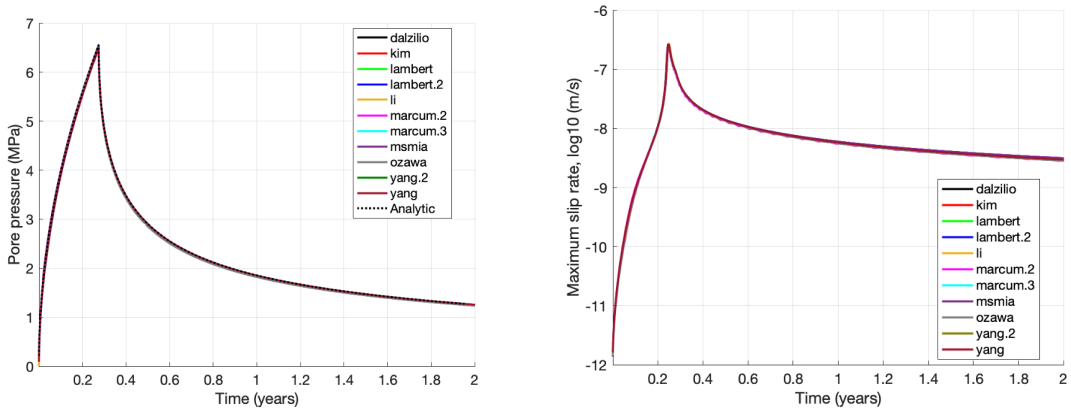

Figure 3. Comparable agreements made across modeling groups for BP6-QD-A including time series of pore pressure (left) and maximum slip rate (right).

The second benchmark discussed was BP6-QD-A/S/C, a 2D problem of a fault with either velocity-strengthening or constant friction with fluid injection and along-fault pore fluid diffusion. The results show excellent agreements across 8 modeling groups for BP6-QD-A, see Figure 3. Good agreements also were found among 6 groups for BP6-QD-S, with slightly greater variation in accumulated slip and timing of rupture arrival compared to BP6-QD-A. While simulated results for both BP6-QD-A and BP6-QD-S showed good overall agreement, results for both problems exhibited small but increasing differences in resolved slip with time potentially due to differences in adaptive time-stepping schemes.. The discussion on this benchmark was wrapped up with a discussion of plans to compare choices in time-stepping and preparation of a paper for BP6.

Lambert and Erickson concluded the workshop with group planning for 2023, which included determining the next benchmarks, continuing an analysis of BP6 and BP7, inspection and development of the SEAS online platform with SCEC developers, and workshop planning for Winter/Spring 2023. The group leaned towards building on current benchmarks when planning future exercises. They discussed taking prior benchmark problems and adding increased physical and/or geometrical features, such as 2D fully-dynamic dipping faults, quasi-dynamics on multiple faults, rough fault geometries and bulk elastic heterogeneity. Also of interest to the group were alternative rate-and-state formulations, flash heating, and bimaterial interfaces.

The workshop participants gained insight into other seismic cycles community activities, and learned much about the latest two benchmark problems; the group efforts and discussions will actively continue into the future.

References:

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. (2020). The SCEC Community Code Verification Exercise for Simulating Sequences of Earthquakes and Aseismic Slip (SEAS). *Seism. Res. Lett.*, 91 (2A): 874-890, doi: 10.1785/0220190248.

Erickson, B. A., Jiang, J., Lambert, V., Abdelmeguid, M., Almquist, M., Ampuero, J.-P., Ando, R., Barbot, S., Cattania, C., Chen, A., Dal Zilio, L., Dunham, E. M., Elbanna, A., Gabriel, A.-A., Harvey, T. W., Huang, Y., Kaneko, Y., Kozdon, J., 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. (2022), Incorporating full elastodynamics effects and dipping fault geometries in community code verification exercises for simulations of earthquake sequences and aseismic slip (SEAS), accepted*, Bull. Seismol. Soc. Am.*

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Jiang, J., Lambert, V. R., Erickson, B. A., Abdelmeguid, M., Almquist, M., Ampuero, J.P., et al. (2022b). Community Code Verification Exercises for Simulations of Sequences of Earthquakes and Aseismic Slip (SEAS): From 3D, Full Elastodynamics and Dipping Faults to Fluids and Fault Friction Evolution. SCEC Annual Meeting.

Lambert, V. (2022). Advancing models of earthquake source processes towards physics-informed seismic hazard assessment. Invited talk at the 2022 SCEC Annual Meeting.

Lambert, V., Jiang, J., Erickson, B., Abdelmeguid, M., Almquist, M., Ampuero, J.P., et al. (2022). Community Code Verification Exercises for Simulations of Sequences of Earthquakes and Aseismic Slip (SEAS): From 3D, Full Elastodynamics and Dipping Faults to Fluids and Fault Friction Evolution. In AGU Fall Meeting.

SCEC Workshop Agenda
November 18, 2022
SCEC SEAS Group Workshop on Advancing Simulations of Earthquake Sequences and Aseismic Slip
Hosted on Zoom

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

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 discuss developing community activities revolving around and of interest to SEAS modeling efforts and to compare results from our most recent benchmark problems BP6 and BP7, which focus on fluid and 3D effects, respectively, as well as different treatments of fault friction. We will also discuss research targets and plans for SEAS in the near and longer term for the group.

Workshop Agenda

	Session 1: Workshop Goals and Introductions	
	Moderator: Valere Lambert	
08:30 - 08:45	Introductions, Workshop Goals, and Science Targets	Valere Lambert
	Session 2: Community Modeling Activities	
	Moderators: Brittany Erickson and Junle Jiang	
08:45 - 09:00	Modeling Collaboratory for Subduction	Eric Dunham
09:00 - 09:15	Modeling and Verification of Volcanic Systems	Leif Karlstrom
09:15 - 09:30	SCEC Seismic Hazard Analysis Platforms	Kevin Milner
09:30 - 09:45	Computational Infrastructure for Geodynamics Seismic Cycles Group	Sylvain Barbot
09:45 - 10:00	Discussion	*All*
10:00 - 10:30	Break	
	Session 3: Comparison of New Benchmark Results	
	Moderator: Valere Lambert	
10:30 - 12:00	Discussion of Benchmark Results from BP6 and BP7	*All*
	Session 4: Future Directions for SEAS	
	Moderators: Brittany Erickson, Junle Jiang, and Valere Lambert	
12:00 - 12:30	Group Planning for 2023	*All*
12:30	Adjourn	

35 Total Participants:

Mohamed Abdelmeguid (UIUC)
Martin Almquist (Uppsala U)
Jean-Paul (Pablo) Ampuero (Université Côte d'Azur)
Laura Bagur (ENS)
Michael Barall (USGS)
Sylvain Barbot (USC)
Segun Bodunde (U Oklahoma)
Camilla Cattania (MIT)
Jinhui Cheng (ENS)
Judi Chester (TAMU)
Ben Duan (TAMU)
Eric Dunham (Stanford)
Brittany Erickson (U Oregon)
Ruth Harris (USGS)
Yihe Huang (Michigan)
Junle Jiang (U Oklahoma)
Leif Karlstrom (U Oregon)
Taeho Kim (Caltech)
Christos Kyriakopoulos (U Memphis)
Valère Lambert (UCSC)
Nadia Lapusta (Caltech)
Meng Li (Utrecht)
Dunyu Liu (UT Austin)
Yajing Liu (McGill)
Amy Lu (McGill)
Shuo Ma (SDSU)
Phil Maechling (SCEC/USC)
Kevin Milner (USC)
So Ozawa (U Tokyo)
Edric Pauk (USC)
Andrea Perez (Victoria)
Paul Segall (Stanford)
Victor Vescu (Caltech)
Jiayi Ye (ETH Zurich)
Jeena Yun
Peng Zhai (U. Michigan)
Wenqiang Zhang (McGill)