2022 Crustal Deformation Modeling Workshop Report

Brad Aagaard (PI), U.S. Geological Survey
Sylvain Barbot (co-PI), University of Southern California
Brittany Erickson (co-PI), University of Oregon
Matthew Knepley (co-PI), University at Buffalo
Mark Simons (co-PI), Caltech
Charles Williams (co-PI), GNS Science, New Zealand

Overview

The 2022 Crustal Deformation Modeling Workshop was held June 20–24 at the Colorado School of Mines in Golden, Colorado. The workshop included two days of tutorials on the use of the open-source software PyLith for crustal deformation modeling followed by three days of science talks and discussions. The workshop focused on three primary themes:

- Earthquake cycle modeling;
- Inversions for fault slip; and
- Faulting, fluids, and surface loading.

The talks highlighted how computational models provide insight into intriguing observations of Earth and planetary behavior. These included (1) earthquake synchronization of rupture patches due to their proximity to each other, (2) the influence of fault geometry and damage zones on hypocenter depth and rupture propagation, (3) a lack of steady-state faulting behavior due to long time scales for grain size evolution in the mid-crust, (4) crustal deformation due to tidal, hydrological, and atmospheric loads, and (5) plumes of gas and icy particles due to tidal driven faulting on Enceladus (one of Saturn's moons). The talks also described new computational modeling capabilities for incorporating complex geologic structure into Bayesian inversions for fault slip and efficient implementation of earthquake cycle models using a symmetric interior discontinuous Galerkin method. The complete agenda is available on the Computational Infrastructure for Geodynamic (CIG) website.

Organization and logistics

This workshop continued a series of workshops that Mark Simons and Brad Hager began in 2002; the most recent prior workshop was held in June 2019. The 2022 workshop organizers included Brad Aagaard (U.S. Geological Survey), Sylvain Barbot (University of Southern California), Brittany Erickson (University of Oregon), Matthew Knepley (University at Buffalo), Mark Simons (Caltech), and Charles Williams (GNS Science, New Zealand). The Computational Infrastructure for Geodynamics at the University of California, Davis provided most of the funding for this workshop with additional funding from the Southern California Earthquake Center (SCEC) to cover travel costs for about one-third of the participants. Registration was first-come, first-served with a cap of 70 participants and open to anyone in the community with an interest in crustal deformation modeling. We sent email announcements to CIG, SCEC, UNAVCO, Incorporated Research Institutions for Seismology, and International Association for Geoscience Diversity email lists. With the size of the meeting room and lodging allotment, we were not able to accommodate everyone who wanted to attend, and 7 people remained on a waiting list.

Participants

With last minute cancelations due to COVID-19 related travel issues, we ended up with 63 participants from 8 countries. Approximately 75% (47) identified as early career researchers; 32% (20) identified as women; 41% (26) identified as White; 40% (25) identified as Asian or Asian Indian; 10% (6) identified as Hispanic, Latino, or Spanish; and 3% (2) identified as Middle Eastern or North African. Our combination of tutorials and science discussions drew very strong participation from graduate students and postdocs. Faculty who participated as graduate students or postdocs in earlier workshops in this series sent their own students and postdocs to this workshop, which demonstrates the long-term value and enthusiasm for our efforts.

Tutorials

The first two days of the workshop were dedicated to tutorials on the use of the open source, CIG-supported modeling code PyLith for two-dimensional (2D) and three-dimensional (3D) simulations of quasi-static and dynamic crustal deformation associated with earthquake faulting. About one week prior to the workshop, we posted videos and slides for the tutorials that would be presented in-person at the workshop to help participants prepare. Additionally, because the PyLith manual is continuously updated at pylith.readthedocs.io, users were able to become familiar with version 3.0 (v3.0) even before it was formally released.

The tutorials at the workshop focused on using PyLith v3.0 (a new major release) to model crustal deformation associated with earthquake faulting. The tutorials were divided into 9 sessions intermixed with dedicated time for running examples and receiving one-on-one help. The sessions discussed generating finite-element meshes in 2D using the Gmsh open-source software (https://gmsh.info/), constructing PyLith parameter files from the mathematical formulation of elasticity boundary value problems for a variety of cases, leveraging PyLith's ability to compute static Green's functions in fault slip inversions, strategies for troubleshooting simulations, and visualizing simulation output using ParaView (https://www.paraview.org/). The examples of 2D and 3D boundary value problems illustrated time-dependent Dirichlet and Neumann boundary conditions, prescribed fault slip, gravitational body forces, isotropic, linear elastic and viscoelastic bulk rheologies, and poroelasticity. Many of the participants applied the skills they learned in the tutorials to begin working on research problems in a variety of tectonic settings. For example, some students were able to construct 3D versions of 2D tutorials after other 3D tutorials were presented.

Science talks and discussions

The 12 invited presentations covered a wide range of topics within the three science themes. In addition to the research-focused talks on modeling the earthquake cycle given by Matt Wei, Sharadha Sathiakumar, Prithvi Thakur, and Kali Allison, Brittany Erickson provided an overview of the SCEC Sequences of Earthquakes and Aseismic Slip (SEAS) benchmarking effort (https://strike.scec.org/cvws/seas/). Dave May described a new open-source code, Tandem (https://github.com/TEAR-ERC/tandem), for modeling the earthquake cycle, which leverages advanced numerical modeling techniques for formulating the governing equations and enhancing the parallel scalability. Robert Walker summarized the poroelasticity implementation in PyLith and plans to extend the formulation to include interaction of pore fluids with faulting.

Key takeaways

Some of the key takeaways from the science talks (presenters listed in parentheses) included:

- Seismicity on closely spaced rupture patches can synchronize. It is unknown whether this behavior observed on oceanic transform faults could also occur on continental strike-slip faults like the San Andreas Fault, which have much longer recurrence times. (Matt Wei)
- The depth-distribution of seismicity on mature strike-slip faults, including hypocenters of large earthquakes, may be influenced by the geometry and rheological properties of the fault damage zone. (Prithvi Thakur)
- Fault structural complexities can influence rupture extent and recurrence patterns as demonstrated in the 2015 Gorkha, Nepal earthquake. (Sharadha Sathiakumar)
- Noise in geodetic signals, primarily global navigational satellite system (GNSS) observations, can likely be reduced by modeling atmospheric loading (associated with high and low pressure weather systems) and hydrological loading. (Hilary Martens)
- Grain size evolution may have a significant influence on earthquake cycle behavior and whether faults achieve long-term steady-state cyclic behavior. (Kali Allison)
- Bayesian inversions leveraging adjoint methods can provide much more computationally efficient methods for fault slip inversions compared to more conventional methods using Green's functions or Monte Carlo Markov Chain methods. Adjoint methods can include complex geological structure, such as 3D variations in elastic properties. (Thea Ragon, Simone Puel)
- Plumes of gas and icy particles ejected from Enceladus may be associated with shear heating along strike-slip faults in its ice shell driven by tidal loading. (Colin Meyer, Alex Berne)

Modeling tools

PyLith developers regularly seek input on the priorities for new features. The focus for the next year remains earthquake cycle modeling with coupling of quasi-static and dynamic problems that incorporate spontaneous rupture (fault friction). The science talks and PyLith tutorials inspired discussions about potential new development in four main areas:

- Development of a modular, computationally efficient Bayesian inversion framework targeting crustal deformation applications and leveraging existing forward simulation software (for example, PyLith);
- Support for arbitrarily complex spatial and temporal variations in fields for boundary conditions (especially surface loads) and fault slip;
- Implementation of Green's functions for surface loads in PyLith analogous to the existing user-friendly setup for static Green's functions; and
- User-friendly specification of boundary conditions and fault interfaces when modeling whole or large sections of planetary bodies.

The PyLith developers plan to incorporate these new ideas into updates of the PyLith Development Plan.

Lightning talks and posters

The workshop included a 1-hour session for lightning talks and two 1-hour sessions for poster viewing. We had 15 lightning talks and 10 posters. In future workshops we plan to do a better job of encouraging participants to prepare a poster. We also want to expand the lightning talks to include short incite or "big idea" talks with time for discussion.

Topics not covered

We had hoped to include a discussion about the current status of the SCEC Community Rheology Model and how it might be integrated into crustal deformation modeling workflows. However, Laurent Montesi (who is currently leading the development effort) was not able to attend the workshop and the SCEC Community Rheology Model lacks an Application Programming Interface for integration with other modeling tools, such as PyLith.

Future workshops

With such strong interest in the workshop, we plan to continue this series of workshops, preferably on a biannual basis. We plan to offer online tutorials and in-person, online, or hybrid hackathons in years without a workshop. The graduate students and postdocs showed strong interest in numerical modeling, with several wanting to contribute to the development of community software, such as PyLith.

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