2024 Crustal Deformation Modeling Workshop Report

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Overview

The 2024 Crustal Deformation Modeling Workshop was held June 10–14 at the Colorado School of Mines. The workshop included two days of tutorials on using PyLith for crustal deformation modeling, followed by three days of science talks and discussions. The workshop focused on four primary themes:

- Constraining long-term fault slip rates and their uncertainties using geodetic and geologic data;
- Earthquake cycle modeling with a focus on constraining models using seismic and geodetic data;
- Interaction of fluids and faulting; and
- Separating contributions of surface loading and tectonic loading in crustal deformation.

The complete agenda is available on the 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 2022. The workshop organizers included Brad Aagaard (U.S. Geological Survey), Matthew Knepley (University at Buffalo, New York), Eric Lindsey (University of New Mexico), Kathryn Materna (University of Colorado), Hilary Martens (University of Montana), and Charles Williams (GNS Science). The Computational Infrastructure for Geodynamics (CIG) at the University of California, Davis, provided most of the funding for this workshop, with additional funding from the Statewide 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 75 registered participants and open to anyone in the community with an interest in crustal deformation modeling. We sent email announcements to CIG, SCEC, EarthScope, and the International Association for Geoscience Diversity email lists. With the size of the meeting room and lodging allotment, we could not accommodate everyone who wanted to attend, and nine people were left on a waiting list.

Participants

We had 69 participants from 9 countries (United States, Germany, Canada, Great Britain, Mexico, New Zealand, Chile, Australia, and Tanzania). Approximately 65% (45) identified as early career researchers, 41% (28) identified as women, 52% (36) identified as White, 29% (20) as Asian or Asian Indian, 9% (6) as Hispanic, Latino, or Spanish, 4% (3) Black, African, African-American, or Afro-Caribbean, and 1% (1) as Middle Eastern or North African. Our combination of tutorials and science discussions continues to draw strong participation from graduate students and postdocs. As in several other SCEC sub-disciplines, we observe that faculty who participated as graduate students or postdocs in earlier workshops in this series are sending their students and postdocs to this workshop.

Future workshops

Given the strong interest, we plan to continue this series of workshops, preferably biannually. We will investigate a broader range of funding sources and allocations to ensure sufficient support for early career participants. In years without a workshop, we anticipate continuing to offer online tutorials and in-person, online, or hybrid hackathons.

Tutorials

The first two days of the workshop were dedicated to tutorials on using the open-source, CIG-supported modeling code PyLith (https://geodynamics.org/resources/pylith) for two-dimensional (2D) and three-dimensional (3D) simulations of quasi-static and dynamic crustal deformation associated with earthquake faulting. In the weeks leading up to the workshop, we recommended that participants review the extensive PyLith manual, continuously updated at pylith.readthedocs.io, as well as videos and slides from the tutorials presented in 2022. A few days before the workshop, we posted the slides and several videos for the tutorials that would be presented in person at the workshop.

The tutorials at the workshop concentrated on using PyLith version 4.1 to model crustal deformation associated with earthquake faulting. Version 4.1 added a few new examples focused on more advanced topics, such as modeling complex fault geometry, updated examples emphasizing the accuracy of numerical models using mesh refinement and higher-order spatial discretizations, and a new custom visualization application based on PyVista (https://docs.pyvista.org/). The tutorials were divided into seven sessions with dedicated time for running examples and getting one-on-one help. The sessions discussed generating finite-element meshes in 2D and 3D 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 PyVista. The 2D and 3D boundary value problem examples illustrated time-dependent Dirichlet and Neumann boundary conditions, prescribed fault slip, gravitational body forces, isotropic, linear elastic and viscoelastic bulk rheologies, and poroelasticity. Many participants applied the skills they learned in the tutorials to begin working on research problems in various tectonic settings.

We noticed a substantial increase in users using the Windows Subsystem for Linux as their computing environment. These users were able to use the PyLith Linux x86_64 binary package, but we encountered new issues related to missing libraries associated with Gmsh and PyVista. By the second day of the tutorials, we resolved nearly all of these issues and updated the PyLith installation instructions accordingly.

Science talks and discussions

In response to feedback at the end of the 2022 Crustal Deformation Modeling workshop, we reduced the number of invited presentations from 12 in 2022 to 7 in 2024 to allow more time for lightning talks and poster sessions. The seven invited presentations covered various topics within the four science themes. Kaj Johnson and Rich Briggs focused on the contribution of crustal deformation modeling in seismic hazard assessment. Daniel Douglas and So Ozawa discussed the interaction of fluid flow and faulting in the context of subduction zones. Louise Maubant and Richav Mallick highlighted spatial and temporal variations in interseismic and postseismic deformation. Grace Carlson demonstrated the importance of identifying and separating hydrological contributions from tectonic contributions in geodetic data.

Key takeaways

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

- Incorporating constraints of off-fault deformation will likely reduce the epistemic uncertainty in long-term slip rates inferred from crustal deformation models. (Kai Johnson)
- Seismic hazard models would benefit from expanding the depiction of fault networks to include uncertainty in fault geometry and slip rake angles. (Rich Briggs)
- Numerical models of poroelastic deformation indicate highly permeable outer rise fault zones embedded within the ocean crust with depth-dependent permeability in the Central American subduction zone. (Daniel Douglas)
- Numerical models of fluid injection with non-constant permeability can explain the migration of swarm-like seismicity for both under-stressed and critically stressed faults. Fault valve instability is a potential mechanism explaining the dynamics of slow slip events in subduction zones. (So Ozawa)
- Slow slip events equivalent to magnitude 7.3 earthquakes in the Hikurangi subduction zone, New Zealand, interact with plate coupling, releasing stress in the deep part of the subduction zone. These stress changes may have influenced the timing and location of a 2023 earthquake sequence. (Louise Maubant)
- Linear Burgers body and power-law bulk rheologies can explain geodetic observations from interseismic and postseismic deformation. Geodetic time series from earthquake sequences and constraints from petrological, laboratory experiments, and seismic observations can help distinguish between the bulk rheologies. (Rishav Mallick)
- Changes in water storage in the upper crust result in variability in the timing and magnitude of seasonal and multi-year signals in geodetic data. Removal of these signals using advanced signal decomposition or incorporating hydrologic loading in elastic models is essential to isolate contributions from tectonic processes. (Grace Carlson)

Modeling tools

PyLith developers regularly seek input on development priorities. The priorities for the next few years continue to target inversions of geodetic data for earthquake source parameters and long-term fault slip rates, earthquake cycle modeling with the coupling of quasi-static and dynamic problems with spontaneous rupture (fault friction), and complex temporal and spatial variations in boundary conditions. The science talks and PyLith tutorials reinforced these priorities. One of the major topics of the wrap-up discussion centered on how best to accommodate different levels of expertise in the tutorials. In a future workshop, we may develop two tracks for the tutorials, one for those relatively new to numerical modeling and one for those with experience in numerical modeling.

Lightning talks and posters

The workshop included two sessions for lightning talks and three poster viewing sessions. We had 17 lightning talks and about 18 posters. Encouraging participants to bring posters and prepare lightning talks in the weeks leading up to the workshop contributed to greater participation and lively discussions during the lightning talks and poster sessions.

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