Workshop Final Report: Numerical Modeling of Crustal Deformation Associated with Earthquake Faulting

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Introduction and Motivation

Over the past several years, the SCEC Crustal Deformation Modeling (CDM) group has implemented a coordinated community effort to (1) build and validate 3-D quasi-static, finite-element codes for modeling crustal deformation; (2) construct deformation models of Southern California consistent with observed topography, fault geometries, rheological properties, geologic slip rates, geodetic motions, and earthquake histories; and (3) use these models to infer fault slip, rheologic structure, and fault interactions through stress transfer. We have helped catalyze the development of a suite of tools for studying crustal deformation in Southern California, including PyLith, an open-source, portable, parallel finite-element code for modeling quasi-static and dynamic crustal deformation; and a suite of benchmarks for comparison and verification of numerical codes for modeling pre- and post-seismic deformation. An ultimate goal of our modeling community is to derive physically based models of the distribution of lithospheric stress in space and time via simulation of the strain accumulation, dynamic rupture propagation, and postseismic relaxation over multiple earthquake cycles. Recent earthquake cycles provide rich observational constraints, whereas hundreds of earthquake cycles provide stable statistics for clustering and seismicity.

The SCEC CDM community has developed into a cohesive group with the following Mission Statement: (1) build tools to aid in the understanding of slip characteristics and rupture propagation using seismological and geodetic constraints; (2) build tools to aid in the understanding of rheological structure based on geodetically constrained postseismic deformation; and (3) simulate interactions among fault systems through the earthquake cycle in order to understand the evolution of regional strain rates, stresses, topography, and earthquake hazards.

History of the Workshops

An essential part of our strategy for community building and interacting with the NASA-sponsored SERVO QuakeSim group and the NSF Computational Infrastructure for Geodynamics (CIG) project has been a series of workshops held once a year for the last eight years. The number of participants has doubled over the last six years with approximately 60 participants (the majority of which were graduate students and postdocs) at the 2006, 2007, 2008, and 2009 workshops. Of the attendees at the last three workshops approximately 35% were graduate students, 15% were postdocs, 30% were researchers, and 20% were faculty. For the last several years, the workshops have involved scientific talks and discussions as well as hands-on tutorials in using modeling tools. These activities promote discussion of current research topics and empower researchers, especially graduate students and postdocs, with the tools they need to move forward in their work.

The first CDM workshop at Caltech (June, 2002) focused on assessing the accuracy, speed, and ability to modify software in use by members of the community. The community concluded that much of the software in use at that time was not capable of handling realistic geologic models. The second workshop (August, 2003) was expanded in both length and participation. The workshop was hosted by Los Alamos National Laboratory, enabling SCEC scientists to benefit from attendance by Lab experts, particularly those with expertise in meshing. By leveraging SCEC, NASA, and LANL support, we were able to increase the number of students and senior researchers attending, as well as meet for five days instead of two. A highlight of the workshop was intense discussion of computational frameworks and how they might be used to construct a state-of-the-art modular numerical code for crustal deformation modeling. Because members of the NASA-sponsored SERVO QuakeSim group participated in the workshop, there was significant exchange of ideas and software.

The third and fourth annual workshops (August, 2004 and July, 2005) were also at LANL. Based on the success of previous workshops, the funding base was expanded to include NSF EarthScope, as well as

SCEC, LANL IGPP, and NASA. The participation grew from 30 scientists from 12 universities, the USGS, JPL, Los Alamos National Laboratory, and Sandia National Laboratory in 2004 to 42 scientists in 2005. This workshop had a "hands-on" emphasis. The goals of the workshops were (1) to leave the workshop knowing how to do more with basic tools than before the workshop; (2) to use Southern California and the benchmark suite as convenient and important examples for developing the next generation of crustal deformation modeling tools; (3) to focus on the constructing meshes with realistic geologic structures, e.g., learning how to use LaGriT; and (4) to learn to use GeoFEST and Lithomop (aka TECTON) - what it takes to get these up and running, what they can do, and how they can be modified. The 20005 workshop also focused on defining the tools necessary for end-to-end modeling from conceptualizing and constructing a geologic model, discretizing the model using a mesh generator, running a simulation, to finally, visualizing the results. Because modest support from SCEC has enabled our community to organize and articulate its priorities and plans, we have been able to take advantage of the NSF-IT CIG initiative from its conception. At this workshop, we spent significant time defining our community's priorities and needs with respect to CIG activities.

The June of 2006, 2007, and 2008 workshops were held on the campus of the Colorado School of Mines in Golden, Colorado. For details of the workshops, please see `http://www.geodynamics.org/cig/workinggroups/short/workshops/`. All three of these workshops were attended by over 60 participants, the majority of which were students and postdocs. The format of the workshop changed with a much stronger emphasis on science application presentations and discussions. Starting in 2006, we began reaching out to the Fault And Rupture Mechanics (FARM) community with talks on laboratory friction models and dynamic slip modeling.

Our Most Recent Workshop

Our eighth workshop in June 2009 was also held in Golden, Colorado at the Colorado School of Mines. This workshop was attended by 57 participants (26 graduate students, 3 postdocs, and 28 faculty and research scientists), including eight from Mexico and Europe. Several of the faculty attended previous CDM workshops as graduate students. We used the same format as in 2008 with science talks spread over four days with several hours each afternoon dedicated to tutorials and informal discussions. This format did not seem as successful as it in 2008. In 2010 we plan to revise the format as discussed later. For details of the workshop, please see `http://www.geodynamics.org/cig/workinggroups/short/workshops/nmcdef-09/`; the agenda includes links to the slides for all of the presentations.

This year's workshop included several presentations on fault rheology with a focus on postseismic and interseismic deformation and/or the role of fluids in fault behavior. Other presentations discussed the role of plasticity and fluids in rupture dynamics and transient bulk rheologies in the lower crust and upper mantle. The workshop also include a couple of presentations on crustal deformation associated with rifting and volcanoes, and one presentation on a toolkit for adaptive mesh refinement with application to multiscale geodynamics problems. We continue to promote interaction with the Fault And Rupture Mechanics (FARM) community with talks on laboratory friction models and dynamic slip modeling.

The community continues to develop a suite of benchmarks to verify the accuracy of the modeling codes. A new benchmark, based on the Savage and Prescott (1978) problem of repeated rupture on a strike-slip fault, was presented for inclusion in the benchmark suite. This problem expands the focus of the benchmarks into multiple-earthquake cycles with more complex boundary conditions while continuing to test the viscoelastic rheologies. A discussion of benchmarks and codes for computing analytic solutions identified some other potential benchmark problems.

A discussion at the end of the workshop indicated overwhelming support for continuing the series of annual workshops. The discussion also identified two important recomendations for improving the workshops. Spreading the science talks over four days made it difficult for several senior faculty to attend all of the scientific talks (nearly all were able to attend the workshop for at least three days) and participants did not have sufficient time following the tutorials in the first two days for hands-on experimentation. In 2010, we plan to begin the workshop with two days of tutorials followed by three days of science talks, discussion, and informal tutorials. This revised format will also permit senior researchers to attend all of the science talks, which will be condensed to three days. The emphasis will remain on balancing pedagogical aspects targeting graduate students and cutting edge discussions targeting experienced modelers.