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 seven years. The number of participants has doubled over the last five years with approximately 60 participants (the majority of which were graduate students and postdocs) at the 2006, 2007, and 2008 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 annual workshop (August, 2004) was again 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. 30 scientists from 12 universities, the USGS, JPL, Los Alamos National Laboratory, and Sandia National Laboratory participated. This workshop had a "hands-on" emphasis. The goals of the workshop 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 fourth annual workshop (July, 2005) followed the pattern of the previous years quite closely. SCEC, LANL IGPP, NASA, and CIG jointly provided funding for the workshop. We had 42 participants, many of whom were new to the computational crustal deformation modeling community. The underlying goal of this workshop was to have all participants leave with a working finite-element code on their laptop or home machine to get them over the start-up hurdle. This goal was reasonably successful. In addition, this workshop 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 and 2007 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/`. Both 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 seventh workshop in June 2008 was also held in Golden, Colorado at the Colorado School of Mines. This workshop was attended by 57 researchers, including several from Japan and Taiwan. Refining the format to include science talks over four days with several hours of time each afternoon dedicated to tutorials and informal discussions was very successful. This permitted most researchers time to become familiar with the meshing and simulation software and begin applying these tools to problems of research interest. In past years very few participants were able to proceed beyond very simple toy example problems. For details of the workshop, please see `http://www.geodynamics.org/cig/workinggroups/short/workshops/`.

As in 2006 and 2007, we continued reaching out to the Fault And Rupture Mechanics (FARM) community with talks on laboratory friction models, dynamic slip modeling, and simulation of seismicity catalogs. This represents a concerted effort by the community to implement modeling codes that can handle time scales of seconds to thousands of years, truly a daunting task, but an important one if we want to make progress in understanding the evolution and impact of 3-D variations in crustal stress.

The community continued to develop a suite of benchmarks to verify the accuracy of the modeling codes. A new benchmark, based on the Savage and Prescott () problem of repeated rupture on a strike-slip fault, is under development. 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 post workshop survey was completed by half of the participants of the 2008 workshop, and the response was extremely positive, with strong enthusiasm for yet another incarnation to be held again at the Colorado School of Mines at about the same time of year. We expect that the greater maturity of the modeling tools, such as PyLith, will result in the next workshop having a greater emphasis on using the tools to solve complex research problems. However, we will retain a balance between pedagogical aspects targeting graduate students and cutting edge discussions targeting experienced modelers.