Modeling earthquake source processes in California: building on SCEC success in integrating numerical, field, and laboratory studies

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Summary

Due to significant recent advances in modeling approaches, observational capabilities, and laboratory experimentation, earthquake science is positioned for rapid future progress towards physics-based, predictive modeling at scales of societal interest, including scenarios of large destructive earthquakes, prediction of strong ground motion, physics-based estimates of long-term seismic hazard, and potential for induced seismicity. Such modeling is indispensable for combining the full range of available knowledge – fundamental physical principles, field observations, and laboratory findings – into a comprehensive view of earthquake phenomena that can be updated as new knowledge comes online.

The Southern California Earthquake Center (SCEC) has made much progress on that front by building a close collaboration between modeling, observational, and laboratory scientists focused on a well-studied and societally important natural laboratory. Among many notable successes are community verified dynamic rupture codes simulating scenarios of large earthquakes in SoCal using increasingly more realistic fault geometries and bulk structure; modeling tools capable of reproducing long-term fault slip in terms of sequences of earthquakes and slow slip while accounting for fluid effects and/or bulk inelasticity; simulators that study the interaction of the entire fault network; and community fault, velocity, geodetic, thermal, and rheology models.

A SCEC-like Center for all of California could make the next conceptual leap by combining these modeling tools into the next-generation modeling platform applicable to continental transform tectonic environments world-wide while clarifying seismic hazard and risk for nearly 40 million people in California. Key scientific issues of interest that the Center would investigate include the potentially dominating role of fluids - both naturally occurring and added by anthropogenic activities - in the faulting processes in the crust; effects of inelastic processes and structural complexity of the lithosphere; and the role of shear heating, chemical reactions, and thermomechanical coupling. Of particular importance for future progress is the need to rigorously capture the effects of smaller-scale processes - which may be dominating in earthquake source problems due to extreme multi-scale localization of relevant structures - on the larger-scale phenomena of societal interest, such as destructive earthquakes and induced seismicity. The resulting next-generation modeling methodology can eventually be applied to other tectonic environments. This includes subduction zones, which could significantly benefit from the same focus on building community models and other knowledge base that SCEC has pursued in Southern California.

Need for integrative modeling of earthquake source processes

Earthquake occurrence is a multi-physics, multi-scale, multi-disciplinary problem with both profound societal implications and exciting fundamental science challenges. Integrative modeling of earthquake source processes is critically needed to deliver transformative science that capitalizes on recent progress in seismic, geodetic, geologic, laboratory, and numerical studies. What are the fundamental principles that control earthquake occurrence? How do we efficiently harness existing field, laboratory, and modeling approaches while creating game-changing capabilities for the future? How can all available data and physical understanding be used to forecast future scenarios of great earthquakes? How do we safely develop geo-resources without inducing damaging earthquakes? How can modeling improve our early warning algorithms and rapid post-event response? Answering these questions is key to making society resilient to seismic hazard, and also presents a challenging and fascinating scientific problem.

Field observations and laboratory studies provide only parts of the puzzle. The modern recorded period is too short compared to the complexity of the observed earthquake sequences and earthquake source behavior. Paleoseismic inferences are crucial for extending the earthquake record but provide sparse and limited information on surface rupturing events only. Interpreting data from remote observations such as geodesy and seismology in terms of the earthquake source behavior faces challenges due to resolution issues, inadequate coverage, and inherent non-uniqueness of the underlying inverse problems. Laboratory studies can only consider relatively small samples, short durations, and hence experience difficulty in considering realistic fault structures and time scales. Observational and laboratory data can often be qualitatively consistent with several plausible earthquake source scenarios.

This reality motivates a concerted effort to develop predictive earthquake source models that integrate all available knowledge about the earthquake source while highlighting crucial gaps. Such models can eventually move society beyond making decisions based on short-term incomplete earthquake data sets, by incorporating the ingredients that the field – seismic, geodetic, geologic – data do not directly provide, such as materials-science-based theories on how fault zone materials behave as well as measurable properties of geo-materials from the laboratory. The modeling provides a bridge between the relatively small laboratory scale and the relatively large scale of relevant observations, allowing us to uncover both the physical mechanisms and parameters relevant to natural faults. Such comprehensive modeling can be accomplished on a range of temporal and spatial scales and can be continuously improved as the new observations and laboratory findings unfold. In fact, such modeling is needed even to properly interpret most laboratory experiments and field observations.

Multi-scale, multi-physics, multi-disciplinary problem

The modeling faces significant challenges due to vast ranges of spatial and temporal scales; several highly relevant, coupled, non-linear physical and chemical processes; and the remote nature of most observations. The spatial scales span about twelve orders of magnitude, from the extent of the largest earthquakes of the order of 100-1000 km, to the 1-1000-m widths of damage zones around faults, to the widths of actively shearing layers in the fault core – the weakest and potentially controlling link in fault resistance to shear - of the order of 100-1000 microns with particle sizes of ~1 microns and less. The relevant temporal scales also span at least fourteen orders of magnitude, from thousands of years for short-term tectonic processes that provide fault loading to sub-second evolution of slip and fault properties at the tip of dynamic, wave-producing ruptures. Several physical and chemical ingredients have the potential to significantly affect and even dominate the earthquake source, some of them relevant to multiple spatial and temporal scales, including shear localization/delocalization, dilatancy/compaction, mechanical and chemical alterations, damage and healing, shear heating, visco-plastic processes, and a range of fluid effects. Furthermore, the different ingredients can be highly coupled and varying in both time and space.

Given the wide range of coupled scales and evolving ingredients in the earthquake source problem, the best strategy for identifying dominant features and property ranges, and hence formulating relevant physics-based models, is to reproduce a wide range of observations with the same physical model. Fortunately, seismological, geodetic, geological, and laboratory studies provide a broad and increasing range of observables about the behavior of the earthquake source. While a specific observation may be explained by a variety of physical processes, aiming to reproduce a range of independent observations should help discriminate between the more and less relevant model ingredients and/or constrain the relevant parameter ranges. At the same time, the observational inferences themselves may require improvement, as they are often based on non-unique inverse problems, use additional assumptions such as the knowledge of bulk structure, or interpret data based on oversimplified models that are no longer consistent with our current understanding. Hence the goal of modeling is not only to match observational inferences but also to verify and improve them based on our best understanding of earthquake source physics. Furthermore, modeling can suggest new types of observations that can help distinguish between different competing earthquake source hypotheses as well as motivate new laboratory experiments.

SCEC-like Center in California with emphasis on integrative modeling

Clearly, explicit inclusion of all scales and relevant processes in a single “master” model is not feasible at present or in the foreseeable future. Yet the most disparate scales and seemingly unrelated mechanisms can affect each other in profound ways. The modeling efforts so far have examined the interaction of a subset of relevant processes over several of the relevant spatial and temporal scales, with the goal of determining the potential links, couplings, and relation of outcomes to observations. The overall effort has been quite productive and informative, resulting in a number of discoveries and collectively establishing the potential importance of various scales and processes.

The important next step is to develop an integrative modeling framework that would enable synergistic coupling of intensifying modeling, field, and laboratory efforts. Transformative progress will come from systematic modeling studies that (i) combine all knowledge about relevant fault/bulk structure and mechanisms and (ii) use all available observations from the field and laboratory, with the goals to determine the coupled effects of the relevant mechanisms, constrain parameter spaces, and develop abstractions suitable for modeling at the largest scales of societal interest. A promising approach to rigorously bridge the many temporal and spatial scales involved is to couple numerical computations at different scales. Machine learning can potentially be integrated in these modeling paradigms.

However, such integrative modeling would require a number of inputs and should first be pursued for a well-studied region such as California. SCEC has been leading the community in connecting scientists from various disciplines and techniques relevant to earthquake science, developing the many needed modeling ingredients, and translating fundamental science into tools for seismic hazard assessment. One of the unique achievements of SCEC has been the development of community models that strive to capture our evolving understanding of fault geometry, seismic velocity structure, geodetic deformation, temperature, stress, rheology, and geology in the region, all needed inputs to large-scale integrative modeling. SCEC has established high-performance computing workflows for a number of modeling efforts, including simulations of large scenario earthquakes in SoCal using increasingly realistic fault geometry, bulk structure, and fault physics. SCEC has also invested into modeling tools capable of reproducing long-term fault slip in terms of sequences of earthquakes and slow slip while accounting for fluid effects and/or bulk inelasticity. Importantly, SCEC plays a key role in educating the next generation of research leaders in earthquake science steeped in the multi-disciplinary approach to the problem.

Due to the SCEC efforts, California is a perfect natural laboratory for making the leap to a next-generation multi-scale modeling framework for earthquake source processes, similar to paradigms in general circulation (climate) models. Using such a modeling framework, the California-based Center can investigate a number of fundamental research problems in geophysics such as the potentially essential role of fluids - both naturally occurring and related to anthropogenic activities - in the faulting processes in the crust; the effects of inelastic processes and structural complexity of the lithosphere; and the role of shear heating, chemical reactions, and thermomechanical coupling. Of particular importance for future progress is the development of constitutive relations that rigorously capture the effects of smaller-scale processes - which may be dominating in earthquake source problems due to extreme multi-scale localization of relevant structures - on the larger-scale phenomena of societal interest, such as destructive earthquakes and induced seismicity.

The developed modeling framework can then be applied to other seismogenic regions in the world. The subduction environment, in particular, differs in several important ways, e.g., in terms of bulk structure/rheology and fluid input as well as patterns of seismic/aseismic slip. At the same time, many aspects of the resulting earthquakes are universal, e.g., their average stress drop and rupture velocity, suggesting similarity in some generic aspects of the problem.

For more on earthquake source modeling challenges, current modeling approaches, and needed future developments, please refer to the NSF-sponsored white paper report on “Modeling earthquake source processes: from tectonics to dynamic rupture” by Lapusta, Dunham et al. that can be downloaded from http://www.seismolab.caltech.edu/modeling-earthquake-source-workshop.html