Earthquake System Science in Southern California

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Abstract
The Southern California Earthquake Center (SCEC) coordinates an extensive research program in earthquake system science involving more than 500 scientists at more than 50 research institutions. The Center works toward a physics-based, predictive understanding of earthquake phenomena in the Southern California natural laboratory through interdisciplinary studies of fault system dynamics, earthquake forecasting and predictability, earthquake source physics, and ground motions; it seeks to apply this understanding to improving seismic hazard analysis and reducing earthquake risk. This paper reviews the last 5-year research program (SCEC2, 2002–2007) and plans for the next (SCEC3, 2007–2012). It describes the Community Modeling Environment, a collaboratory for simulating earthquake processes using high-performance computing facilities and advanced information technologies. The SCEC3 plans include the establishment of a new infrastructure for conducting and evaluating scientific earthquake prediction experiments, the development of a uniform time-dependent earthquake rupture forecast for California, a major study of the Southern San Andreas Fault, and end-to-end (“rupture-to-rafters”) earthquake simulations that incorporate built structures into the geologic environment. SCEC also hopes to expand its international partnerships with Japan and other countries seeking to reduce seismic risk.

Key words: earthquakes, seismic hazard, rupture mechanics, collaboratory, fault systems

1. Introduction
The Southern California Earthquake Center (SCEC) was established in 1991 under a cooperative agreement between the U.S. National Science Foundation (NSF) and the U.S. Geological Survey (USGS). The SCEC program was renewed for a 5-year term in 2002 (SCEC2) and again in 2007 (SCEC3). The Center now involves over 500 scientists at more than 50 institutions.

SCEC’s main science goal is to understand the physics of the Southern California fault system using system-level models of earthquake behavior. Southern California’s network of several hundred active faults forms a superb natural laboratory for the study of earthquake physics, and its seismic, geodetic, and geologic data are among the best in the world. The region also contains 23 million people, comprising nearly one-half of the national earthquake risk (FEMA, 2000).

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Box 1. SCEC Mission
- Gather data on earthquakes in Southern California and elsewhere
- Integrate this information into a comprehensive, physics-based understanding of earthquake phenomena
- Communicate this understanding to society at large as useful knowledge for reducing risk

The Center’s mission (Box 1) emphasizes the connections between scientific information gathering, knowledge formation through physics-based modeling, and public communication of hazard and risk.

2. Earthquake System Science
Earthquakes are one of the great puzzles of geoscience. Their study concerns three basic geophysical problems: (a) the dynamics of fault systems—how forces evolve within a fault network on time scales of hours to centuries to generate a sequence of earthquakes; (b) the dynamics of fault rupture—how forces
act on time scales of seconds to minutes when a fault breaks to cause an earthquake; and (c) the dynamics of ground motions—how seismic waves propagate from the rupture to shake Earth’s surface. These problems are coupled through the nonlinear processes of brittle and ductile deformation. No theory adequately describes the basic features of dynamic rupture, nor is one available that explains the dynamical interactions among faults—we do not yet understand the physics of how matter and energy interact during the extreme conditions of rock failure.

The major research issues of earthquake science are true system-level problems: they require an interdisciplinary, multi-institutional approach to model the nonlinear interactions among many fault-system components, themselves often complex subsystems. SCEC attempts to advance earthquake science through a comprehensive program of system-specific studies in Southern California. It thus operates on the premise that detailed studies of fault systems in different regions, such as Southern California and Japan, can be synthesized into a generic understanding of earthquake phenomena. International partnerships are clearly necessary to achieve this synthesis.

3. Seismic Hazard Analysis

Probabilistic seismic hazard analysis (PSHA) provides the conceptual and computational framework for SCEC’s program earthquake system science. PSHA estimates the probability $P_k$ that the ground motions generated at a geographic site $k$ from all regional earthquakes will exceed some intensity measure $IM$ during a time interval of interest, usually a few decades [Cornell, 1968; McGuire, 1995; Field et al., 2002]. Common intensity measures are the peak ground acceleration, the peak ground velocity, and the spectral acceleration at a particular frequency. A plot of $P_k$ as a function of $IM$ is the hazard curve for the $k$th site, and a plot of $IM$ as a function of site position $x_k$ for fixed $P_k$ constitutes a seismic hazard map. Seismic hazard maps for Southern California are produced by the USGS National Seismic Hazard Mapping Project (NSHMP) in collaboration with the California Geological Survey (CGS) and SCEC.

PSHA involves the multiplication and summation of two types of subsystem probabilities: the probability for the occurrence of a distinct earthquake source $S_n$ during the time interval of interest, and the probability that the ground motions at $x_k$ will exceed intensity $IM$ conditional on $S_n$. The first is obtained from an earthquake rupture forecast (ERF), whereas the second is computed from an attenuation relationship (AR), which quantifies the distribution of ground motions with distance from the source.

In Southern California, the ERF in the NSHMP-2002 model comprises approximately 13,000 distinct sources, each specified by a fault surface with rupture area $A$, and seismic moment magnitude $m_o$, plus a background seismicity that follows a Gutenberg-Richter distribution [Frankel et al., 2002]. The NSHMP-2002 model is time-independent; i.e., it assumes that earthquakes are randomly (Poisson) distributed in time. Time-dependent ERFs have also been constructed to account for the known or estimated dates of previous large earthquakes along the San Andreas fault system, usually based on quasiperiodic renewal models of stress loading and release [WGCEP, 1995, 2003]. The California Earthquake Authority is currently sponsoring a SCEC-USGS-CGS Working Group on California Earthquake Probabilities [WGCEP, 2007] to develop a statewide time-dependent ERF, which will be completed in late 2007.

A major SCEC objective is to improve time-dependent ERFs through better understanding of earthquake predictability. The SCEC-USGS Working Group on Regional Earthquake Likelihood Models (RELM) is testing of a variety of intermediate-term models [Field, 2007]. Based on this experience, SCEC has formed an international partnership to extend scientific earthquake prediction experiments to other fault systems through a global Collaboratory for the Study of Earthquake Predictability (CSEP).

The ARs in common use are empirical probability models that relate source and site parameters directly to $IM$ values; i.e., the parameters of assumed functional relationships are fit to the available data [e.g., Abrahamson and Shedlock, 1997].

A second major objective of the SCEC program is to develop physics-based ARs which correctly model a number of key phenomena that are difficult to capture through this empirical approach. The phenomena include the amplification of ground mo-
tions in sedimentary basins, source directivity effects, and the variability caused by rupture-process complexity and three-dimensional (3D) geologic structure. Numerical simulations of ground motions play a vital role in this area of research, comparable to the situation in climate studies, where the largest, most complex general circulation models are being used to predict the hazards and risks of anthropogenic global change.

4. SCEC Organization

SCEC began as an NSF Science and Technology Center in 1991. The SCEC founders, led by its first director, the late Professor Keiiti Aki, articulated a powerful vision for the Center’s research program: disciplinary groups would work together to synthesize a “master model” for seismic hazards for Southern California [Aki, 2002; Henyey et al., 2002]. The main components in current master model are represented in Fig. 1.

SCEC is an institution-based center, composed of core and participating institutions (Table 1). The core institutions (currently 16) are committed to SCEC’s mission and offer sustained support for its programs; the participating institutions (currently 40) are self-nominated through their members’ participation and approved by the SCEC Board of Directors.

The size of the SCEC community can be measured by the active participants on SCEC projects (656 in 2006) and the registrants at the annual meeting of the SCEC collaboration (414 in September, 2006). Annual meeting registrations for SCEC’s entire 16 year history illustrate the growth of the Center (Fig. 2).

Table 1. SCEC Member Institutions (September, 2006)

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<th>Core Institutions (16)</th>
<th>Participating Institutions (40)</th>
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<td>California Institute of Technology</td>
<td>Arizona State University, Boston University, Brown University, Cal-State, Fullerton, Cal-State, Nordhoff, Cal-State, San Bernardino, California Geological Survey, Carnegie Mellon University, Case Western Reserve University, Central Washington University, CIGEOE (Mexico), ETH (Switzerland), Institute of Earth Sciences of Academia Sinica (Taiwan), Institute of Geological and Nuclear Sciences (New Zealand), Jet Propulsion Laboratory, Lawrence Livermore National Laboratory, National Chung Cheng University (Taiwan), National Taiwan University (Taiwan), National Central University (Taiwan), Ohio State University, Oregon State University, Pennsylvania State University, Rensselaer Polytechnic Institute, Rice University, SUNY Stony Brook, Texas A&amp;M University, UC Berkeley, UC Davis, UC Irvine, University of Colorado, University of Kentucky, University of Massachusetts, University of New Mexico, University of Oregon, University of Utah, University of Western Ontario, URS Corporation, Utah State University, Whittier College, Woods Hole Oceanographic Institute</td>
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nia and elsewhere. The results have been incorporated into practical products, such as the National Seismic Hazard Map and its upcoming revision, as well as the new seismic attenuation relations developed by the Next Generation Attenuation (NGA) Project, which is managed by the Lifelines Program of the Pacific Earthquake Engineering Research (PEER) Center. SCEC coordinated the development of the Southern California Integrated GPS Network (SCIGN), the Western InSAR Consortium (WInSAR), the Southern California Earthquake Data Center, and other infrastructure elements for regional earthquake science. SCEC’s achievements

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contributed to the launching of NSF's EarthScope initiative in 2003. For example, SCIGN served as a prototype for EarthScope's Plate Boundary Observatory.

Many of SCEC2 research accomplishments lie in six problem areas central to the earthquake system science. Some highlights are noted below in each area; more extensive descriptions and references can be found in the SCEC annual reports (http://www.scec.org/documents/).

**Fault mechanics.** New types of laboratory experiments have helped to elucidate the frictional resistance during high-speed coseismic slip, and these data have been combined with field studies on exhumed faults to develop better models of dynamic rupture.

**Earthquake Rupture Dynamics.** Codes for 3D dynamic rupture simulation have been verified by cross-comparison exercises; they are being validated by comparisons with laboratory experiments and data from real earthquakes, and they have been coupled with anelastic wave propagation models to investigate strong ground motions.

**Structural Representation.** The Community Velocity Model (CVM) has been improved by extending and refining its 3D elastic structure and incorporating attenuation parameters. A new Community Fault Model (CFM) representing more than 160 active faults has been developed and extended to a Community Block Model (CBM). A prototype Unified Structural Representation (USR) is merging the CVM into the CBM structural framework.

**Fault systems.** New deformation signals have been discovered by InSAR and GPS, and new data from SCIGN and GPS campaigns have been incorporated into the Crustal Motion Map (CMM). The geologic record of fault-system behavior has been significantly expanded; tectonic block models have been created for physics-based earthquake forecasting, and finite-element codes have been developed for a new CBM-based deformation model that will assimilate the CMM and geologic data.

**Earthquake forecasting.** Paleoseismic data and data-synthesis techniques have been used to constrain earthquake recurrence intervals, event clustering, and interactions among faults. Relocated seismicity has mapped new seismogenic structures and provided better tests of earthquake triggering models. Regional earthquake likelihood models have been formulated for use in PSHA and earthquake predictability experiments, and they are being tested for prediction skill using a rigorous methodology.

**Ground motion prediction.** Earthquake ground motions have been simulated using the CVM, realistic source models, and validated wave-physics codes. High-frequency stochastic methods have been combined with low-frequency deterministic methods to attain a broadband (0–10 Hz) simulation capability. Broadband predictions have been tested against precarious-rock data. Simulations have been used to improve attenuation relationships and create realistic earthquake scenarios.

6. The SCEC Collaboratory

Modeling of earthquake dynamics is one of the most difficult computational problems in science. Taken from end to end, the problem comprises the loading and eventual failure of tectonic faults, the generation and propagation of seismic waves, the response of surface sites, and—in its application to seismic risk—the damage caused by earthquakes to the built environment. This chain of physical processes involves a wide variety of interactions, some highly nonlinear and multiscale.

In 2001, SCEC was funded by the NSF Information Technology Research Program to develop a cyberinfrastructure for physics-based modeling of earthquake processes. This Community Modeling Environment (CME) now provides geoscientists and computer scientists with a collaboratory to simulate earthquake processes using high-performance computing facilities and advanced information technologies (Fig. 5). The terascale simulations have already delivered new (and worrisome) predictions about seismic hazards from California's San Andreas fault system [Olsen et al., 2006].

The CME collaboration, working within a much larger SCEC community, is providing the cyberinfrastructure to transform PSHA into a more physics-based science. The simulations needed for physics-based SHA can be organized into a set of computational pathways [Jordan and Maechling, 2003]. For example, the pathway for conventional PSHA is to compute an IM from an AR using sources from an ERF, schematically represented as:
In physics-based PSHA, intensity measures are calculated directly from the ground motion: $GM \rightarrow IM$. The ground motion is predicted from 4D simulations of dynamic fault rupture (DFR) and anelastic wave propagation (AWP). In some cases, especially for sites in soft soils, a nonlinear site response (NSR) may be included in the ground-motion calculations. The complete computational pathway can thus be written as:

$$DFR \leftrightarrow AWP \rightarrow NSR \rightarrow GM.$$  

The double-arrow indicates that rupture propagation on a fault surface is dynamically coupled to the seismic radiation in the crustal volume containing the fault. However, the DFR can always be represented by an equivalent kinematic fault rupture (KFR). Therefore, the earthquake calculation can be split into the simulation of ground motions from a kinematic source.

**Pathway 2:** $KFR \rightarrow AWP \rightarrow NSR \rightarrow GM,$

and the dynamic rupture simulation,

**Pathway 3:** $DFR \leftrightarrow AWP \rightarrow KFR.$

The source descriptions $S_n$ for the ERFs used in conventional PSHA do not contain sufficient information for physics-based PSHA. In addition to the rupture area $A_n$ and magnitude $m_n$, the KFR for Pathway-2 simulations must specify the hypocenter, the rupture rise-time and velocity distributions, and the final slip distribution. Stochastic rupture models that reproduce the variability observed in these parameters for real earthquakes are a major topic of seismological research [Guatteri et al., 2004]. Pathway-3 simulations are an important tool for investigating the stochastic aspects of dynamic ruptures, and they can be used to constrain an “extended” earthquake rupture forecast, $ERF^*$, which specifies a complete set of the KFR probabilities. The physics-based PSHA calculation can then be written as

**Pathway 1∗:** $ERF^* \rightarrow AR^* \rightarrow IM,$

where $AR^*$ is the attenuation relationship obtained from the Pathway-2 simulations.

Instantiation of the 4D simulation elements requires information about the 3D geologic environment. For example, $DFR$ depends on the fault geometry, the mechanical properties on both sides of the fault surface, and the stress acting on the fault, whereas $AWP$ depends on the density, seismic velocities, and attenuation factors throughout the lithospheric volume containing the source and site. The databases needed to represent the 3D geologic environment for the complete $GM$ simulation defines a unified structural representation (USR).

Some of the current limitations on ground-motion simulations are related to the lack of details in the USR, such as inadequate spatial resolution of seismic wavespeeds. Hence, improvement of the USR by the inversion (INV) of observed ground motions constitutes another important computational pathway:

**Pathway 4:** $GM_{obs} \rightarrow INV \rightarrow USR.$

Computational solutions to the inverse problem...
require the ability to solve, often many times, the forward problems of Pathways 2 and 3. In particular, \textit{INV} for seismic tomography can be constructed as \textit{AWPf}, the adjoint of anelastic wave propagation, analogous to inversion and data-assimilation methods in oceanography and other fields [Tromp et al., 2006; Chen et al., 2007]. The SHA computational pathways are summarized in Fig. 6.

The CME infrastructure currently includes three computational platforms. Each computational platform comprises the hardware, software, and expertise (wetware) needed to execute and manage the results from one or more of the SHA pathways of Fig. 6. \textit{OpenSHA} is a open-source, object-oriented, web-enabled platform developed in partnership with the USGS for executing a variety of \textit{Pathway-1} calculations, including the comparisons of hazard curves and maps from different PSHA models calculations, and for delivering physics-based (\textit{Pathway-1}*) seismic hazard products to end users [Field et al., 2003, 2005].

\textit{TeraShake} is a research platform for simulations of dynamic ruptures (\textit{Pathway 3}) and ground motions (\textit{Pathway 2}) on dense grids (outer/inner scale ratios > 10³) [Cui et al., 2007]. TeraShake simulations show how the chain of sedimentary basins between San Bernardino and downtown Los Angeles form an effective waveguide that channels surface waves along the southern edge of the San Bernardino and San Gabriel Mountains [Olsen \textit{et al.}, 2006]. Earthquakes scenarios with northwestward rupture, in which the guided surface wave is efficiently excited, produce unusually high long-period ground motions over much of the greater Los Angeles region.

\textit{CyberShake} is a production platform that employs workflow management tools [Deelman \textit{et al.}, 2006] to compute and store the large suites (> 10³) of ground motion simulations needed for physics-based PSHA (\textit{Pathway 1}†). For each large (m > 6.5) source, the hypocenter, rupture rise-time and velocity distributions, and final slip distribution have been varied according to a pseudo-dynamic model, producing catalogs of more than 100,000 \textit{KFR}s. Using receiver Green tensors and seismic reciprocity [Zhao \textit{et al.}, 2006], we have synthesized the ground motions at individual sites for the full suite of \textit{KFR}s and, from this database, we have used OpenSHA to compute hazard curves for spectral accelerations below 0.5 Hz [Graves \textit{et al.}, 2006].

SCEC is now increasing the performance of these platforms to take advantage of the petascale computational facilities that will be developed by NSF during the next several years. This \textit{PetaSHA} project has three main science thrusts: (1) Extend deterministic simulations of strong ground motions to 3Hz for investigating the upper frequency limit of deterministic ground-motion prediction. (2) Improve the resolution of dynamic rupture simulations by an order of magnitude for investigating the effects of realistic friction laws, geologic heterogeneity, and near-fault stress states on seismic radiation. (3) Compute physics-based PSHA maps and validate them using seismic and paleoseismic data.

7. Communication, Education & Outreach

SCEC provides the public with useful knowledge for reducing earthquake risk through partnerships in science, engineering, risk management, government advisement, and education (Fig. 5). The goals of its Communication, Education & Outreach (CEO) Program are to advance earthquake knowledge and science literacy at all educational levels; to improve earthquake hazard and risk assessments; and promote earthquake preparedness, mitigation, and planning.

The CEO Program offers a wide range of student research experiences, web-based education tools, classroom curricula, museum displays, public information brochures, online newsletters, and technical workshops and publications.

The Implementation Interface, a component of the CEO Program, integrates physics-based seismic hazard analysis into earthquake engineering research and practice through collaborations with Pacific Earthquake Engineering Research (PEER) Center, the Consortium of Universities for Research in Earthquake Engineering (CUREE), and the Next Generation Attenuation (NGA) Project. It is developing an interface between SCEC and NSF’s George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES).

CEO achievements include two successful intern programs, Undergraduate Studies in Earthquake Information Technology (UseIT) and Summer Undergraduate Research Experiences (SURE); the development of the Electronic Encyclopedia of Earthquakes.
as part of the NSF National Science Digital Library; the establishment of the Earthquake Country Alliance to present consistent earthquake information to the public; and new editions of the practical guide, *Putting Down Roots in Earthquake Country*, in both English and Spanish.

8. SCEC Science Plan

The science plan for next 5-year phase of the Center, SCEC3 (2007–2012), is articulated in terms of four basic science problems that organize the most pressing issues of earthquake system science.

- **Earthquake Source Physics**: to discover the physics of fault failure and dynamic rupture that will improve predictions of strong ground motions and the understanding of earthquake predictability.

- **Fault System Dynamics**: to develop representations of the postseismic and interseismic evolution of stress, strain, and rheology that can predict fault system behaviors.

- **Earthquake Forecasting and Predictability**: to improve earthquake forecasts by understanding the physical basis for earthquake predictability.

- **Ground Motion Prediction**: to predict the ground motions using realistic earthquake simulations at frequencies up to 10 Hz for sites in Southern California.

Table 2 displays the priority science objectives developed as part of this plan.

The science plan also involves a number of special projects that will augment the basic research program (the pink boxes in Fig. 4). Examples include the extension of the CME to a petascale cyberfacility (PetaSHA), the 2007 Working Group on California Earthquake Probabilities (WGCEP), and the new Laboratory for the Study of Earthquake Predictability (CSEP). A real-time demonstration project in earthquake early warning has been initiated in partnership with the California Integrated Seismic Network and USGS. SCEC and the USGS are also promoting a Southern San Andreas Fault Evaluation (SoSAFE) project that will enhance the collection and interpretation of geologic and paleoseismic data on 2000 years of this important fault’s slip history. In partnership with earthquake engineers, SCEC researchers are embedding built structures in geologic models to conduct end-to-end simulations (“rupture to rafters”) of earthquake risks.

SCEC is also establishing a Multinational Partnership for Research in Earthquake System Science (MPRESS) to foster the international collaborations needed for comparative studies of fault systems in a variety of tectonic environments.

Additional information about SCEC and its programs can be found at http://www.scec.org.

References


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