地 震 研 究 所 彙 報
Bull. Earthq. Res. Inst.
Univ. Tokyo
Vol. 81 (2006) pp. 211-219

Earthquake System Science in Southern California

Thomas H. Jordan*

Southern California Earthquake Center, University of Southern California, Los Angeles, CA 90089-0742, USA

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).

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

---

* e-mail: tjordan@usc.edu

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_n and seismic moment magnitude m_n, 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 *ERF*s 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 quasi-periodic 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 *ERF*s 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 *AR*s 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 *AR*s which correctly model a number of key phenomena that are difficult to capture through this empirical approach. The phenomena include the amplification of ground motions 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)

Core Institutions (16)	Participating Institutions (40)
California Institute of Technology Columbia University Harvard University Massachusetts Institute of Technology San Diego State University Stanford University U.S. Geological Survey, Golden U.S. Geological Survey, Menlo Park U.S. Geological Survey, Pasadena University of California, Los Angeles University of California, Riverside University of California, San Diego University of California, Santa Barbara University of California, Santa Cruz University of Nevada, Reno University of Southern California (lead)	Arizona State University; Boston University; Brown University; Cal-State, Fullerton; Cal-State, Northridge; Cal-State, San Bernardino; California Geological Survey; Carnegie Mellon University; Case Western Reserve University; Central Washington University; CICESE (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 University; Rice University; SUNY Stony Brook; Texas A&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

The Center is open to any credible scientist from any research institution interested in collaborating on the problems of earthquake science. However, its program is structured to achieve prioritized science objectives, and its resources are allocated accordingly. Research projects are supported on a year-to-year basis by a competitive, collaboration-building process. In 2005, for example, SCEC sponsored 123 projects involving 156 principal investigators at 51 institutions. There are a number of additional investigators from the USGS, as well as many collaborators supported by SCEC's many partner organizations (Fig. 3).

SCEC sustains disciplinary science and related data-gathering activities through standing committees in *Seismology, Tectonic Geodesy,* and *Earthquake Geology* (Fig. 4). Interdisciplinary research is organized into seven science focus areas: *Lithospheric Architecture and Dynamics, Unified Structural Representation, Fault and Rupture Mechanics, Crustal Deformation Modeling, Earthquake Forecasting and Predictability, Ground Motion Prediction,* and *Seismic Hazard and Risk Analysis.* It maintains an active set of partnerships with earthquake engineering and emergency management organizations through its *Implementation Interface.* The Center's interdisciplinary focus groups and implementation interface are organized to translate knowledge of earthquake systems into seismic hazard products that can be used to reduce earthquake risk (Fig. 1).

SCEC is led by a Center Director (T. Jordan, USC), who chairs the Board of Directors, and a Deputy Director (R. Archuleta, UCSB), who chairs the Planning Committee. The Board members are representatives appointed by each core institution plus two at-large members elected from the participating institutions. The Planning Committee comprises the 15 working group leaders; it is responsible for reviewing the internal proposals and formulating an annual collaboration plan for distributing resources to projects within the working groups. The Center's external Advisory Council is charged with developing an overview of SCEC operations and advising the Director and the Board (Fig. 4).

5. Science Accomplishments

SCEC and its partners have accelerated the understanding of seismic hazards in Southern Califor-

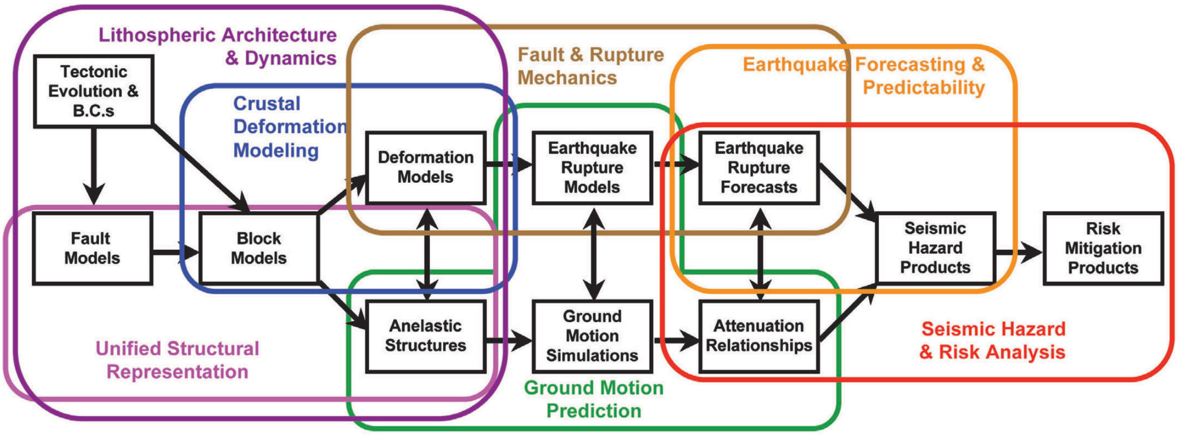

Fig. 1. The main components in SCEC's master model for earthquake system science (black boxes), showing the overlapping areas of interest of its interdisciplinary focus groups (colored boxes).

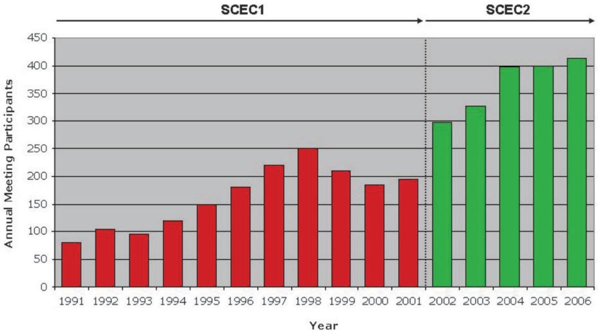

Fig. 2. Number of registrants at SCEC Annual Meetings from 1991 to 2006.

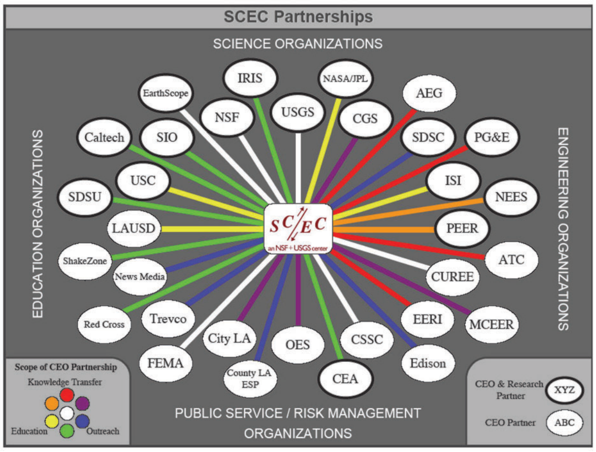

Fig. 3. SCEC's active partnerships with other organizations, positioned according to their mission. The connections are color coded by the type of partnership; e.g., a white connector indicates collaboration in all three areas—knowledge transfer, education, and outreach. Research partners are indicated by bold black borders.

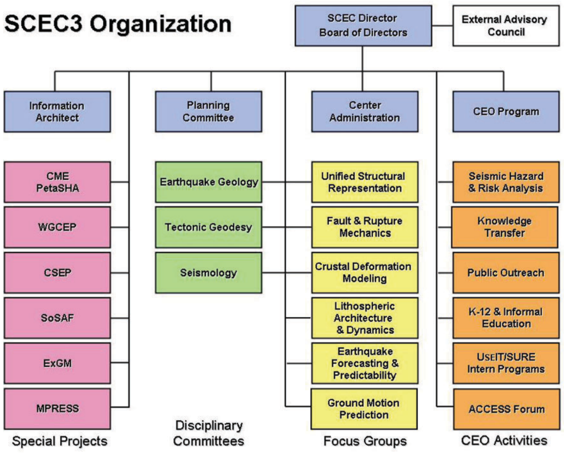

Fig. 4. The SCEC3 organization chart, showing the disciplinary committees (green), focus groups (yellow), special projects & operations (pink), CEO activities (orange), management offices (blue), and its external advisory council (white).

nia and elsewhere. The results have been incorporated into practical products, such as the National Seismic Hazard Map and its upcoming 2007 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 250-station 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 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:

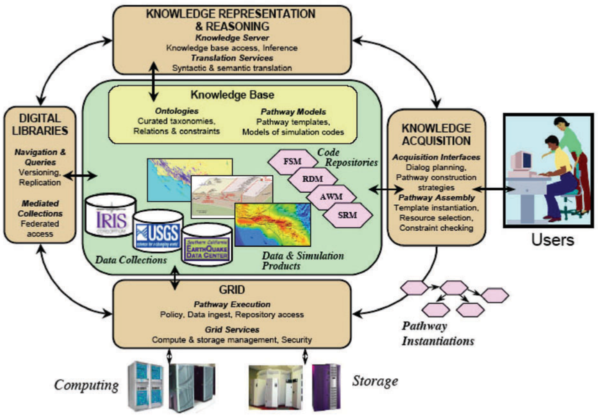

Fig. 5. The SCEC Community Modeling Environment is a collaboratory that applies advanced information technologies in knowledge acquisition, grid computing, digital libraries, and knowledge representation and reasoning (outside boxes) to earthquake system science.

Pathway 1: ERF→*AR*→*IM*

In physics-based PSHA, intensity measures are calculated directly from the ground motion: *GM*→*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⟷*AWP*→*NSR*→*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→*AWP*→*NSR*→*GM*,

and the dynamic rupture simulation,

Pathway 3: DFR⟷*AWP*→*KFR*.

The source descriptions S_n for the *ERF*s 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

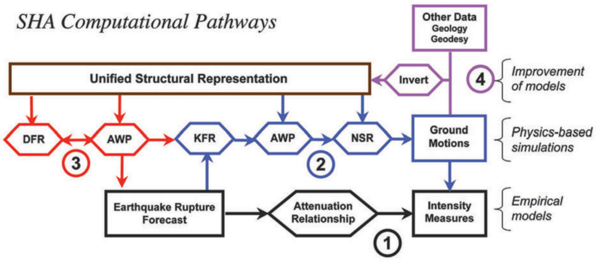

Fig. 6. Computational pathways for seismic hazard analysis, using notation described in the text.

Pathway 1: ERF**→*AR**→*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}→*INV*→*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, *INV* for seismic tomography can be constructed as *AWP*†, 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. *OpenSHA* is a open-source, object-oriented, web-enabled platform developed in partnership with the USGS for executing a variety of Pathway-1 calculations, including the comparisons of hazard curves and maps from different PSHA models calculations, and for delivering physics-based (Pathway-1*) seismic hazard products to end users [Field *et al.,* 2003, 2005].

TeraShake is a research platform for simulations of dynamic ruptures (Pathway 3) and ground motions (Pathway 2) on dense grids (outer/inner scale ratios $>10^3$) [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 *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.

CyberShake is a production platform that employs workflow management tools [Deelman *et al.,* 2006] to compute and store the large suites ($>10^3$) of ground motion simulations needed for physics-based PSHA (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 *KFR*s. Using receiver Green tensors and seismic reciprocity [Zhao *et al.,* 2006], we have synthesized the ground motions at individual sites for the full suite of *KFR*s and, from this database, we have used OpenSHA to compute hazard curves for spectral accelerations below 0.5 Hz [Graves *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 *PetaSHA* project has three main science thrusts: (1) Extend deterministic simulations of strong ground motions to 3 Hz 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. 3). 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. SCEC3 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 Collaboratory 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.

Table 2. Priority Science Objectives for SCEC3

1. Improve the unified structural representation and employ it to develop system-level models for earthquake forecasting and ground motion prediction
2. Develop an extended earthquake rupture forecast to drive physics-based SHA
3. Define slip rate and earthquake history of southern San Andreas fault system for last 2000 years
4. Investigate implications of geodetic/geologic rate discrepancies
5. Develop a system-level deformation and stress-evolution model
6. Map seismicity and source parameters in relation to known faults
7. Develop a geodetic network processing system that will detect anomalous strain transients
8. Test of scientific prediction hypotheses against reference models to understand the physical basis of earthquake predictability
9. Determine the origin and evolution of on- and off-fault damage as a function of depth
10. Test hypotheses for dynamic fault weakening
11. Assess predictability of rupture extent and direction on major faults
12. Describe heterogeneities in the stress, strain, geometry, and material properties of fault zones and understand their origin and interactions by modeling ruptures and rupture sequences
13. Predict broadband ground motions for a comprehensive set of large scenario earthquakes
14. Develop kinematic rupture representations consistent with dynamic rupture models
15. Investigate bounds on the upper limit of ground motion
16. Develop high-frequency simulation methods and investigate the upper frequency limit of deterministic ground motion predictions
17. Validate earthquake simulations and verify simulation methodologies
18. Collaborate with earthquake engineers to develop rupture-to-rafters simulation capability for physics-based risk analysis
19. Prepare post-earthquake response

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

Abrahamson, N.A., and K.M. Shedlock, 1997, Overview of ground motion prediction relations, *Seismol. Res. Lett.,* **68** (1), 9–23.

Aki, K., 2002, Synthesis of earthquake science information and its public transfer: A history of the Southern California Earthquake Center, *International Handbook of Earthquake and Engineering Seismology,* edited by W.H.

K. Lee, H. Kanamori, P.C. Jennings, and C. Kisslinger, Academic Press, San Diego, 39–49.

Chen, P., T.H. Jordan, and L. Zhao, 2007, Full 3D waveform tomography: A comparison between the scattering-integral and adjoint-wavefield methods, *Geophys. J. Int.,* in press.

Cui, Y., R. Moore, K. Olsen, A. Chorasia, P. Maechling, B. Minster, S. Day, Y. Hu, J. Zhu, A. Majumdar, and T. Jordan, 2007, Enabling very large scale earthquake simulations, *Lecture Notes in Computer Science,* Springer, in press.

Deelman, E., S. Callaghan, E. Field, H. Francoeur, R. Graves, N. Gupta, V. Gupta, T.H. Jordan, C. Kesselman, P. Maechling, J. Mehringer, G. Mehta, D. Okaya, K. Vahi, L. Zhao, 2006, Managing Large-Scale Workflow Execution from Resource Provisioning to Provenance tracking: The CyberShake Example, *e-Science 2006,* Amsterdam, December 4–6, 2006.

FEMA, 2000, *Estimated Annualized Earthquake Losses for the United States,* Federal Emergency Management Agency Report 366, Washington, D.C., September, 32 pp.

Field, E.H., 2007, Overview of the Working Group for the Development of Regional Earthquake Likelihood Models (RELM), Seismol. Res. Lett., 78 No. 1, pp. 1–16.

Field, E.H., T.H. Jordan and C.A. Cornell, 2003, OpenSHA: a developing community modeling environment for seismic hazard analysis, *Seismol. Res. Letters,* **74**, 406–419.

Field, E.H., N. Gupta, V. Gupta, M. Blanpied, P. Maechling and T.H Jordan, 2005, Hazard Calculations for the WGCEP-2002 Forecast Using OpenSHA and Distributed Object Technologies, *Seismol. Res. Lett.,* **76** No. 2, pp. 161–167.

Frankel, A.D., M.D. Petersen, C.S. Muller, K.M. Haller, R.L. Wheeler, E.V. Leyendecker, R. L. Wesson, S.C. Harmsen, C.H. Cramer, D.M. Perkins and K.S. Rukstales, 2002, Documentation for the 2002 Update of the National Seismic Hazard Maps: U.S. Geological Survey, Open-file Report 02–420, 33 pp.

Guatteri, M., P.M. Mai and G.C. Beroza, A pseudo-dynamic approximation to dynamic rupture models for strong ground motion prediction, 2004, *Bull. Seismol. Soc. Am.,* December 2004; v. 94; no. 6; p. 2051–2063; doi: 10.1785/0120040037.

Henyey, T.L., T.H. Jordan, J.K. McRaney and M.L. Benthien, 2002, *Accomplishments of the Southern California Earthquake Center,* Southern California Earthquake Center, 51 pp.

Jordan, T.H. and P. Maechling, 2003, The SCEC community modeling environment; An information infrastructure for system-level earthquake science, *Seismol. Res. Lett.,* **74**, 324–328.

McGuire, R.K., 1995, Probabilistic seismic hazard and design earthquakes: closing the loop, *Bull. Seismol. Soc. Am.,* **85**, 5, 1275–1284.

Olsen, K.B., S. Day, J.B. Minster, Y. Cui, A. Chourasia, M. Faerman, R. Moore, P. Maechling and T.H. Jordan, 2006, Strong Shaking in Los Angeles Expected From Southern San Andreas Earthquake, *Geophys. Res. Lett.,* **33**, L 07305, doi: 10.1029/2005GL025472.

Tromp, J., C. Tape and Q. Liu, 2005, Seismic tomography, adjoint methods, time reversal, and banana-donut kernels, *Geophys. J. Int.,* **160**, 195–216.

WGCEP (Working Group on California Earthquake Probabilities), 1995, Seismic hazards in southern California: Probable earthquakes, 1994 to 2024, *Bull. Seismol. Soc. Am.,* **85**, 379–439.

WGCEP (Working Group on California Earthquake Probabilities), 2003, Probabilities of large earthquakes in the San Francisco Bay region: 2002–2031, *USGS Open File Report, 03–214,* 235 pp.

WGCEP (Working Group on California Earthquake Probabilities), 2007, http://www.wgcep.org/.

Zhao, L., P. Chen and T.H. Jordan, 2006, Strain Green's tensors, reciprocity, and their applications to seismic source and structure studies, *Bull. Seismol. Soc. Am.,* **96**, 1753–1763.

(Received January 3, 2006)
(Accepted February 25, 2007)