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Opportunities for International Collaboration in Earthquake System Science

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Earthquakes and their effects pose the greatest natural threat to life and property in many urban regions throughout the world. Two prominent examples are Los Angeles, California, where I live and work, and Tehran, Iran, the host city for the international workshop on Science as a Gateway to Understanding. From my perspective as a geoscientist, these megacities are remarkably similar. Each is bounded by high mountains rising thousands of meters above fertile alluvial slopes and arid sedimentary plains. Their stunning but seismic geographies are actively shaped by folding and faulting in the boundary zones between gigantic tectonic plates.

Tehran and Los Angeles each comprise more than 12 million people; consequently, they account for much of their respective national total earthquake risk. Measured as annualized economic losses, almost one-half of the total earthquake risk for the United States comes from Southern California; of that, about 25 percent comes from the Los Angeles metropolitan area alone (FEMA, 2000). I am not aware of a comparable synoptic risk quantification for Iran, but hazard assessments and studies of building fragility suggest that Tehran’s fraction of the national
earthquake risk may be even higher (Tavakoli and Ashtiany, 1999; CEST-JICA, 2000; EMI, 2006; Jafari, 2007).

Megacity earthquakes can jeopardize prosperity and social welfare, and so it is in our common interest to know more about them and learn how to work together to reduce societal risks. Iran’s long history provides a remarkable record of earthquake activity pertinent to this end (Ambraseys and Melville, 1982; Berberian, 1994). During the past 13 centuries, nine earthquakes with magnitudes greater than 7 have occurred less than 200 kilometers from Tehran. The last, in 1962, killed more than 12,000 people. Even much smaller, more frequent events can cause considerable damage. The magnitude-6.2 Firuzabad-Kojur earthquake, which struck a mountainous region 70 kilometers north of Tehran on May 28, 2004, killed 35 people, and preliminary assessments of its economic damage exceeded 125 billion rials.

As citizens of “earthquake country,” many of us at this workshop share an interest in the earthquake problem. My focus will be on its scientific dimensions. Of course, engineering conditions are no less important. In particular, I will outline some of the key areas where scientific collaboration among Iran, the United States, and other countries might lead to new understanding of earthquake behavior that can help reduce risk. My discussion is intended to support a broader thesis: the potential for scientific cooperation to address our common environmental problems—water and energy supply, pollution, climate change, ecological degradation, as well as earthquakes—can be a strong force for developing crosscultural understanding and improving international relations.

SEISMIC RISK ANALYSIS

Earthquakes proceed as cascades in which the primary effects of faulting and ground shaking induce secondary effects, such as landslides, liquefaction, and tsunamis. They set off destructive processes within the built environment, such as fires and dam failures (NRC, 2003). Seismic hazard can be defined as a forecast of
the intensity of these primary effects at a specified site on Earth’s surface during a future interval of time.

In contrast, seismic risk is a forecast of the damage to society that will be caused by an earthquake, usually measured in terms of casualties and economic losses in a specified area. Risk depends on the hazard, but it is compounded by a community’s exposure—its population and the extent and density of its built environment—as well as its fragility, the vulnerability of its built environment to seismic hazards. Risk is lowered by resiliency, or how quickly a community can recover from earthquake damage. The “risk equation” expresses these relationships in a compact (though simplistic) notation:

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\text{risk} = \text{hazard} \times \text{exposure} \times \text{fragility} \div \text{resiliency}
\]

Risk analysis seeks to quantify the risk equation in a framework that allows the impact of political policies and economic investments to be evaluated and thereby to inform the decision-making processes relevant to risk reduction.

Risk quantification is a difficult problem because it requires detailed knowledge of natural and built environments, as well as an understanding of both earthquake and human behaviors. Moreover, risk is a rapidly moving target, owing to the exponential rise in the urban exposure to seismic hazards. Calculating risk involves predictions of how civilization will continue to develop, which are highly uncertain. Not surprisingly, the best risk models are maintained by the insurance industry, where the losses and payoffs can be huge. However, the information from insurance risk models is usually proprietary and restricted to portfolios that represent (by design) a small fraction of the total exposure.

The synoptic risk studies needed for policy formulation are the responsibility of public agencies, and their accuracy and efficacy depends on technological resources not yet available in many seismically active regions. Risk assessments can be improved worldwide through international collaborations that share the expertise of earthquake scientists and engineers from countries with well-developed risk reduction programs. For example, many coun-
tries have benefited from the information about regional hazards produced by the Global Seismic Hazard Assessment Program during the United Nations International Decade for Natural Disaster Reduction (Giardini et al., 1999; Tavakoli and Ashtiany, 1999).

The first synoptic view of earthquake risk in the United States was published by the Federal Emergency Management Agency (FEMA) less than a decade ago (FEMA, 2000). This study obtained an annualized earthquake loss for California of $3.3 billion per year. However, it was based on a rather limited database of building stock and did not consider local site effects (e.g., soft soils) in computing the seismic hazard. A parallel but more detailed study by the California Division of Mines and Geology (now called the California Geological Survey) calculated a statewide expected value that was twice as large (CDMG, 2000). A revision of FEMA’s 2000 report is currently underway using advanced methodologies and better inventories of buildings and lifelines.

Risk estimates have been published for California’s historic earthquake events, such as the 1906 San Francisco earthquake (Kircher et al., 2006), and inferred from geologic data on the locations and magnitudes of prehistoric fault ruptures, such as the Puente Hills blind thrust system that runs beneath central Los Angeles (Field et al., 2005). The results are sobering. The ground shaking from a major earthquake on the Puente Hills Fault (magnitude 7.1-7.5), if it occurred during working hours, would probably kill 3,000 to 18,000 people and cause direct economic losses of $80 billion to $250 billion (Field et al., 2005). The large range in the loss estimates comes from two types of uncertainty: the natural variability assigned to the earthquake scenario (aleatory uncertainty) as well as our lack of knowledge about the true risks involved (epistemic uncertainty).

According to a similar scenario study, the loss of life caused by earthquakes of magnitude 6.7-7.1 on the North Tehran, Mosha, or Ray faults in greater Tehran ranges from 120,000 to 380,000 (CEST-JICA, 2000). The casualty figures for comparable earthquake scenarios in Los Angeles and Tehran thus show an order-of-magnitude difference, which derives primarily from the
greater fragility of the built environment in Tehran. This comparison underlines the fact that the implementation of seismic safety engineering is the key to seismic risk reduction in urban areas.

STRATEGIES FOR SEISMIC RISK REDUCTION

I will illustrate the basic strategies for reducing seismic risk using California examples. The strategies can be categorized according to the four factors in the risk equation. For example, the exposure to hazard can be limited by land-use policies, such as the Natural Hazards Disclosure Act, passed by the California state legislature in 1998. The law requires that sellers of real property and their agents provide prospective buyers with a “natural hazard disclosure statement” when the property being sold lies near an active fault or within other state-mapped seismic hazard zones. This type of caveat emptor is typical of the weak compliance provisions in most land-use regulations. The high land values and population pressures in Los Angeles, where “sprawl has hit the wall,” make the enactment of more stringent land-use policies quite difficult. We can thus expect seismic exposure to continue rising in proportion to urban expansion and densification.

A more effective strategy is to reduce the structural and non-structural fragility of buildings using building codes and other seismic safety regulations, performance-based design, and seismic retrofitting. The seismic safety provisions in the California building codes have been substantially improved by the tough lessons learned from historical earthquakes; in particular, revisions have corrected the design deficiencies identified in the aftermath of the destructive 1933 Long Beach, 1971 San Fernando, 1989 Loma Prieta, and 1994 Northridge earthquakes.

The efforts to promote seismic retrofitting have achieved mixed results. A 1981 Los Angeles city ordinance led to the demolition or retrofitting of almost its entire stock of unreinforced masonry buildings, the most fragile and dangerous class of inhabited structures. However, a state law regulating the seismic safety of
hospitals, passed after the 1994 Northridge earthquake, has proven to be economically infeasible. Faced with the specter that many hospitals would be shut down rather than be retrofit, the legislature has postponed the compliance date for basic life-safety provisions of the law and is back-peddling on its long-term goal that all hospitals be capable of serving the public after earthquake disasters.

The latter requirement typifies performance-based design. Performance-based design goes beyond the building code requirements for life-safety by improving the ability of structures to retain a specified degree of functionality after episodes of seismic shaking (SEAOC, 1995). The impetus for performance-based design, largely economic, has raised new challenges for earthquake science and engineering (FEMA, 2006). In particular, engineers must be able to predict more accurately the damage state of structural systems—not just the system components—requiring more detailed descriptions of the ground motion. A full structural analysis uses complete time histories of ground motion to account for the nonlinearities in the structural response and in its coupling with near-surface soil layers. In California, the Pacific Earthquake Engineering Research (PEER) Center at Berkeley has organized a multi-institutional research program for advancing performance-based design.1

Community resiliency can be enhanced through better emergency response, insurance investments, catastrophe bonding, and state-funded recovery assistance. All of these tools are applicable to a wide range of natural and human hazards, including wildfires, severe storms, floods, epidemics, and terrorism. However, effective preparation and response to multiple hazards depends on a balanced view of relative risks. In the United States, there is concern that the recent emphasis on terrorist threats has distracted officials from efforts to prepare for natural disasters. The poor performance of the emergency response to Hurricane Katrina and subsequent disaster-recovery programs, especially in the hard-hit city of New Orleans, illustrate the need for better coordination

1 See peer.berkeley.edu/.
and planning among local, state, and federal agencies (White House, 2006). One mechanism for improving coordination and planning is to conduct emergency response exercises based on realistic disaster scenarios.

Disaster mitigation can be enhanced by education. Public education is especially critical in preparing the response of megacities to catastrophic event cascades, during which government aid to the population might be insufficient and delayed (Perry et al., 2008). In the case of earthquakes, public awareness of the problem is greatly heightened after disruptive events, which motivate people to prepare for future disasters. Even small earthquakes, if widely felt, can provide “teachable moments,” as can the anniversaries of famous disasters. In 2006, the centenary of the 1906 San Francisco earthquake motivated an extensive and successful public education campaign throughout California (USGS, 2006).

The first factor in the risk equation—the seismic hazard—is qualitatively different from the other three. We have no direct means to reduce the primary hazards of faulting and ground shaking. Earthquakes involve great forces of nature that will remain beyond human control for the foreseeable future. Nevertheless, the hazard level sets the risk, and the properly characterizing seismic hazard—forecasting earthquakes and their effects and charting earthquake cascades as they are happening—is therefore critical to risk reduction. For instance, current hazard forecasts contain large epistemic errors that compromise the effectiveness of risk analysis when guiding political policies and economic decisions. One role of earthquake system science is to reduce these uncertainties by improving our statistical and physical models of earthquake processes.

**EARTHQUAKE SYSTEM SCIENCE**

A geosystem is a representation of nature defined by the terrestrial behavior it seeks to explain (NRC, 2000). In the case of an active fault system, the ground motion caused by a fault rupture
is one of the most interesting behaviors from a practical perspective, because experience tells us that fault displacement and concomitant ground shaking are the primary seismic hazards for cities such as Tehran and Los Angeles. System-level hazard analysis can be exemplified by the following set of problems:

- Identify the active fault traces in a region to predict the maximum displacements that might occur across them.
- Predict the intensities everywhere in the region occupied by the network from the shaking intensities recorded on a sparse network of seismometers during an earthquake.
- Forecast the distribution of the shaking intensities in a region from all future earthquakes.

A basic methodology for solving the seismic forecasting problem is probabilistic seismic hazard analysis (PSHA). Originally developed by earthquake engineers, PSHA estimates the probability that the ground motions generated at a geographic site from all regional earthquakes will exceed some intensity measure during a time interval of interest, usually a few decades. A plot of the exceedance probability as a function of the intensity measure is called the hazard curve for the site. In downtown Los Angeles, for instance, typical estimates of the exceedance probabilities for peak ground acceleration (PGA)—a commonly used intensity measure—are 10 percent in 50 years for PGA ≥ 0.6 g and 2 percent in 50 years for PGA ≥ 1.0 g, where g is the acceleration of gravity at Earth’s surface (9.8 m/s²). Other useful intensity measures are peak ground velocity (PGV) and the maximum spectral acceleration at a particular shaking frequency. From hazard curves, engineers can estimate the likelihood that buildings and other structures will be damaged by earthquakes during their expected lifetimes, and they can apply the performance-based design and seismic retrofitting to reduce structural fragility to levels appropriate for life-safety and operational requirements.

A seismic hazard map is a plot of the intensity measure as a function of site position for fixed exceedance probability. The offi-
cial seismic hazard maps for the United States are produced by the National Seismic Hazard Mapping Project, managed by the U.S. Geological Survey. Seismic hazard maps are critical ingredients in regional risk analysis. For example, the FEMA (2000) and CDMG (2000) risk studies were based on the 1995 edition of the National Seismic Hazard Map (NSHMP, 1996). The revisions to the FEMA assessment are incorporating the better knowledge of seismic hazards encoded in the 2002 NSHMP edition. The latest edition, NSHMP (2008), has just been released and it will be used for the 2012 revisions to the Uniform Building Code.

The system-level study of earthquake hazards is “big science,” requiring a top-down, interdisciplinary, multi-institutional approach. The Southern California Earthquake Center (SCEC) is funded by the U.S. National Science Foundation (NSF) and U.S. Geological Survey (USGS) with a mission to coordinate an extensive research program in earthquake system science. This program involves more than 600 experts at more than 62 research institutions (Jordan, 2006a). Southern California’s network of several hundred active faults forms a superb natural laboratory for the study of earthquake physics; its seismic, geodetic, and geologic data are among the best in the world. SCEC’s mission is to use this information to develop a comprehensive, physics-based understanding of the Southern California fault system, and to communicate this understanding to society as useful knowledge for reducing seismic risk.

One of the goals of the SCEC program is to improve the techniques of PSHA through physics-based, system-level modeling. PSHA involves the manipulation of two types of subsystem probabilities: the probability for the occurrence of a distinct earthquake source during the time interval of interest, and the probability that the ground motions at a site will exceed some intensity measure conditional on that event having occurred. The first is obtained from an earthquake rupture forecast (ERF), whereas the second is computed from an attenuation relationship (AR), which

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2 See www.scec.org.
quantifies the distribution of ground motions as they attenuate with distance from the source.

The ERF that underlies the current U.S. national seismic map (NSHMP, 2008) is “time-independent” in that it assumes that earthquakes are random in time (Poisson distributed); in other words, it calculates the probabilities of future earthquakes ignoring any information about the occurrence dates of past earthquakes. However, owing to stress-mediated fault interactions and seismicity triggering, earthquakes are known not to be Poisson distributed. A major SCEC research objective is to develop time-dependent forecast models that include more information about the region’s earthquake history. In the early 1990s, an SCEC-sponsored Working Group on California Earthquake Probabilities published a time-dependent ERF for Southern California (WGCEP, 1995). SCEC has more recently collaborated with the U.S. Geological Survey, and the California Geological Survey to produce the first comprehensive Uniform California Earthquake Rupture Forecast (WGCEP, 2007). The long-term (time-independent) model that underlies the UCERF was developed in partnership with the National Seismic Hazard Mapping Project, which has incorporated the results into its most recent release (NSHMP, 2008).

In the WGCEP forecasting models, the event probabilities are conditioned on the dates of previous earthquakes using stress-renewal models, in which probabilities drop immediately after a large earthquake releases tectonic stress on a fault and rise as the stress re-accumulates. Such models are motivated by the elastic rebound theory of the earthquake cycle and calibrated for variations in the cycle using historical and paleoseismic observations (WGCEP, 2003; Field, 2007b).

WGCEP (2007) estimates that, in the Los Angeles region, the mean 30-year probability of an earthquake with a magnitude equal to or greater than 6.7—the size of the destructive 1994 Northridge event—is about 67 percent. Because larger earthquakes occur less frequently, the chances of a magnitude \( \geq 7.5 \) earthquake in the Los Angeles area during the next 30 years drop to about 18 percent. For the much larger Southern California region, the
equivalent odds of a magnitude $\geq 7.5$ event increase to 37 percent. The comparable value for Northern California is significantly less — about 15 percent — primarily because the last ruptures on the southern San Andreas fault in 1857 and circa 1680 were less recent than the 1906 rupture of the northern San Andreas fault. Sufficient stress has reaccumulated of the southern sections of the fault to make a large rupture more likely. The UCERF model will be used by decisionmakers concerned with land-use planning, the seismic safety provisions of building codes, disaster preparation and recovery, emergency response, and earthquake insurance; engineers who need estimates of maximum seismic intensities for the design of buildings, critical facilities, and lifelines; and organizations that promote public education for mitigating earthquake risk.

A second type of time-dependent ERF conditions the probabilities using seismic-triggering models calibrated to account for observed aftershock activity, such as epidemic-type aftershock sequence (ETAS) models (Ogata, 1988). In California, the Short-Term Earthquake Probability (STEP) model of Gerstenberger et al. (2005) has been turned into an operational forecast that is updated hourly. The STEP forecast is a useful, though experimental, tool for aftershock prediction as well as the conditioning the long-term probabilities of large earthquakes on small events that are potential foreshocks. It should be emphasized, however, that the current probability gains in the latter application are relatively small.

The SCEC program seeks to improve time-dependent ERFs through better understanding of earthquake predictability. We have seen how long-term (decades to centuries) and short-term (hours to days) predictability are being exploited by operational time-dependent forecasting models. The challenge is to unify the forecasting models across the temporal scales, a task that requires a better understanding of intermediate-term (weeks to years) predictability. The research toward such unification is now focused on insights into the physical processes of stress evolution and seismic triggering (Toda et al., 2005). The SCEC-USGS Working Group

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3 See pasadena.wr.usgs.gov/step.
on Regional Earthquake Likelihood Models (RELM) is testing of a variety of intermediate-term models (Field, 2007a; Schorlemmer et al., 2007). Based on this experience, SCEC has formed an international partnership that is extending scientific earthquake prediction experiments to other fault systems through a global infrastructure for comparative testing. It is called the Collaboratory for the Study of Earthquake Predictability (Jordan, 2006b; CSEP, 2008). In the next section, I will elaborate on the exceptional opportunities presented by CSEP for international cooperation in earthquake system science.

Large earthquakes are rare events, and the strong-motion data from them are sparse. For this reason, a number of key phenomena are difficult to capture through a strictly empirical approach, including the amplification of ground motions in sedimentary basins, source directivity effects, and the variability caused by rupture-process complexity and three-dimensional geologic structure. Therefore, a major objective of the SCEC program is to develop attenuation relationships that correctly model the physics of seismic wave propagation. 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.

With NSF funding, SCEC has developed a cyber infrastructure for earthquake simulation, the Community Modeling Environment (CME), which allows scientists to construct system-level models of earthquake processes using high-performance computing facilities and advanced information technologies (Jordan and Maechling, 2003; Field et al., 2003). The CME infrastructure includes several computational platforms, each comprising the hardware, software, and scientific expertise (wetware) needed to execute and manage the results from different types of PSHA simulations. An example is the TeraShake platform for simulations of dynamic fault ruptures and ground motions on dense geographical grids. TeraShake simulations of ruptures on the southernmost San Andreas Fault have shown how the chain of sedimentary ba-
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sins 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, 2008). SCEC is now increasing the performance of these computational platforms to take advantage of the petascale computational facilities that will be developed during the next several years. In the not-to-distant future, we will be able to incorporate much more physics into seismic hazard and risk analysis through system-level simulations.

INTERNATIONAL SCIENTIFIC PARTNERSHIPS

Earthquake system science relies on the premise that detailed studies of fault systems in different regions, such as Southern California, Japan, and Iran, can be synthesized into a generic understanding of earthquake phenomena. Achieving such a synthesis will depend on international partnerships that facilitate the development and comparison of well-calibrated regional models. I will briefly outline some of the salient opportunities opened by recent developments in earthquake system science.

EXPLORING THE EARTHQUAKE RECORD

The science of seismic hazard and risk is severely data-limited. Even in the most seismically active areas, the recurrence rates of large earthquakes are long compared to rates of urbanization and technological change. The last large earthquake on the southern San Andreas was in 1857, before the pueblo of Los Angeles became a city and before the pendulum seismometer was invented. According to WGCEP (2007), the 30-year probability of a large (magnitude $\geq 7.8$) earthquake in Southern California is about 20 percent, too large for comfort, but small enough that it may be some time before we directly observe one or more of the “outer-
scale" ruptures which dominate the behavior of the southern San Andreas system.

The power-law statistics of extreme events illustrate why progress in earthquake system science depends so heavily on comparative studies of active faults around the world. International scientific exchange has allowed much to be learned about continental faulting of the San Andreas type; e.g., from large strike-slip earthquakes that have occurred in Turkey, Tibet, and Alaska just during the last decade (Barka, 1999; Heaussler et al., 2004; Klingner et al., 2005). A plausible goal is the creation of an international database—a global reference library—for archiving the field and instrumental information recovered from such rare events.

A second obvious goal is to extend the seismicity catalogs for active fault systems backward in time. Countries like Iran with long historical records have a head start, but our knowledge of past activity can be significantly augmented using the new tools of paleoseismology and neotectonics to decipher the geologic record. Systematic paleoseismic investigations have elucidated a thousand-year history of San Andreas slip (Grant and Lettis, 2002; Weldon et al., 2005), and SCEC’s current objective is to define slip rate and earthquake history of the southern San Andreas Fault system for the last 2000 years. Through international scientific exchange, these field-based techniques can be improved and applied to other fault systems.

The tectonics of Tehran and Los Angeles are both characterized by oblique convergence accommodated by complex systems of frontal thrust faults that are raising the Alborz Mountains and Transverse Ranges, respectively. A comparative study of these orogenic systems based on data from seismology, paleoseismology, remote sensing, and space geodesy would be a particularly good target for Iran-U.S. collaboration.
REAL-TIME SEISMIC INFORMATION SYSTEMS

A major advance in seismic monitoring and ground-motion recording is the integration of high-gain regional seismic networks with strong-motion recording networks to form comprehensive seismic information systems. A prime example of international collaboration is in the European-Mediterranean region, where the Network of Research Infrastructures for European Seismology (NERIES) is integrating more than 100 seismic monitoring systems and observatories in 46 countries into pan-European cyber infrastructure (Giardini, 2008).

On a regional scale, seismic information systems provide essential information for guiding the emergency response to earthquakes, especially in urban settings. Seismic data from a regional network can be processed immediately following an event and the results broadcast to users, such as emergency response agencies and responsible government officials, utility and transportation companies, and other commercial interests. The parameters include traditional estimates of origin time, hypocenter location, and magnitude, as well as Shake Maps of predicted ground motions conditioned on available strong-motion recordings, which can aid in damage assessments (Wald et al., 1999). In California, this type of information is provided by the California Integrated Seismic Network (CISN), which comprises more than a thousand seismic stations telemetered to central processing and data archiving facilities at the University of California, Berkeley, and the California Institute of Technology.4

Improvements in the real-time capabilities of these systems have opened the door to “earthquake early warning.” EEW is the prediction of imminent seismic shaking at a set of target sites, obtained after a fault rupture initiates but in advance of the arrival of potentially damaging seismic waves. There are several EEW strategies (Kanamori, 2005), but the most common relies on a dense network of seismometers to transmit records of the first-

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4 See www.cisn.org/.
arriving ($P$) waves to a central processor that can locate the event, estimate its magnitude, and broadcast predictions to the target sites in near real time. In Southern California, the warning times in Los Angeles for earthquakes on the San Andreas Fault could be a minute or more, enough for individuals to prepare for shaking (e.g., by getting under a desk) and for certain types of automated decisions that might reduce damage and increase resiliency: slowing trains, stopping elevators, shutting gas lines, conditioning electrical grids, and so forth.

Several countries have already invested heavily in EEW systems. Japan’s is the most advanced, but systems are also operational in Mexico, Taiwan, and Turkey (Horiuchi et al., 2005).\textsuperscript{5} SCEC is participating with Berkeley and Caltech scientists in a USGS-sponsored project to test the performance of three EEW algorithms on the CISN system. However, the United States has been lagging in the development of EEW and could profit from more international involvement in this area.

**DYNAMICAL MODELING**

Numerical simulations of large earthquakes in well-studied seismically active areas are important tools for basic earthquake science because they provide a quantitative basis for comparing hypotheses about earthquake behavior with observations. Simulations are playing an increasingly crucial role in our understanding of regional earthquake hazard and risk because they can extend our knowledge to phenomena not yet observed. Moreover, they can also be used for the interpolation of recorded data in producing ShakeMaps and in the extrapolation of recorded data for earthquake early warning.

SCEC is applying simulation technology to the prediction of salient aspects of earthquake behavior, such as the influence of rupture directivity and basin effects on strong ground motions.

\textsuperscript{5} See www.jma.go.jp/jma/en/Activities/eew.html.
Similar capabilities are being developed in Japan and Europe. Making this cyber infrastructure available for application in other regions is an excellent target for international scientific exchange. Such a program will entail the development of geologic models of regional fault networks and seismic velocity structures. Here, the SCEC experience in synthesizing three-dimensional structural representations may prove useful.

**SEISMIC RISK ANALYSIS**

From a practical point of view, the main role of earthquake system science is to promote risk reduction through better characterization of seismic hazards. For megacities like Tehran and Los Angeles, the key problem is holistic: how can we protect the societal infrastructure from extreme events that might “break the system,” the way that Hurricane Katrina broke the city of New Orleans in 2005? Achieving this type of security depends on understanding how the accumulation of damage during an event cascade leads to urban-system failure. I will mention two ways that earthquake system science is contributing to this goal.

Earthquake simulations can provide cascade scenarios from which we can learn about, and possibly correct, the critical points of failure. In November 2008, the USGS will coordinate the Great Southern California ShakeOut, a week-long emergency-response exercise based on a SCEC simulation of a magnitude-7.8 rupture of the southern San Andreas Fault (Perry et al., 2008). ShakeOut will involve federal, state, and local emergency-response agencies, as well as several million citizens at schools and places of business. The objective of this disaster exercise is to improve public preparedness at all organizational levels.

SCEC is generating large suites of simulations that sample the likelihoods of future earthquakes. This capability for physics-based prediction of seismic shaking will someday replace empirical attenuation relationships in PSHA. It offers the possibility of an end-to-end (“rupture to rafters”) analysis that embeds the built en-
environment in a geologic structure to calculate more realistically earthquake risk for urban systems, not just individual structures.

The interests of basic and applied science converge at the system level. Predictive modeling of earthquake dynamics comprises a very difficult set of computational problems. 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. Only through international collaboration can we extend such predictive models to all regions where the seismic risk is high.

EARTHQUAKE PREDICTION

Earthquake prediction *senso stricto*—the advance warning of the locations, times, and magnitudes of potentially destructive fault ruptures—is a great unsolved problem in physical science and, owing to its societal implications, one of the most controversial. Despite more than a century of research, no methodology can reliably predict potentially destructive earthquakes on time scales of a decade or less. Many scientists question whether such predictions will ever contribute significantly to risk reduction, even with substantial improvements in the ability to detect precursory signals; the chaotic nature of brittle deformation may simply preclude useful short-term predictions.

Nevertheless, global research on earthquake predictability is resurgent, motivated by better data from seismology, geodesy, and geology; new knowledge of the physics of earthquake ruptures; and a more comprehensive understanding of how active faults systems actually work. To understand earthquake predictability, scientists must be able to conduct prediction experiments under rigorous, controlled conditions and evaluate them using accepted criteria specified in advance. Retrospective prediction ex-
periments, in which hypotheses are tested against data already available, have their place in calibrating prediction algorithms, but only true (prospective) prediction experiments are really adequate for testing predictability hypotheses.

The scientific controversies surrounding earthquake predictability are often rooted in poor experimental infrastructure, inconsistent data, and the lack of testing standards. Attempts have been made over the years to structure earthquake prediction research on an international scale. For example, the International Association of Seismology and Physics of the Earth’s Interior convened a subcommission on Earthquake Prediction for almost two decades, which attempted to define standards for evaluating predictions. However, most observers would agree that our current capabilities for conducting scientific prediction experiments remain inadequate. Individual scientists and groups usually do not have the resources or expertise (or incentives) to conduct and evaluate long-term prediction experiments.

As a remedy, SCEC is working with its international partners to establish a Collaboratory for the Study of Earthquake Predictability. The goals of the CSEP project are to support scientific earthquake prediction experiments in a variety of tectonic environments; promote rigorous research on earthquake predictability through comparative testing of prediction hypotheses; and help the responsible government agencies assess the feasibility of earthquake prediction and the performance of proposed prediction algorithms. A shared, open-source cyberinfrastructure is being developed to implement and evaluate time-dependent seismic hazard models through comparative testing (CSEP, 2008). Testing centers have been established at SCEC, the Swiss Federal Institute of Technology in Zürich, and GNS Science in Wellington, New Zealand, and prediction experiments are now underway in several natural laboratories, including California, Italy, and New Zealand. Scientists from China, Japan, Greece, and Iceland have been participating in the development phase of CSEP, and we are encouraging other countries to initiate CSEP testing programs in the seismically active regions within their borders.
The research objectives of international partnerships in earthquake system science can be organized under four major goals: (1) discover the physics of fault failure and dynamic rupture; (2) improve earthquake forecasts by understanding fault-system evolution and the physical basis for earthquake predictability; (3) predict ground motions and their effects on the built environment by simulating earthquakes with realistic source characteristics and three-dimensional representations of geologic structures; and (4) improve the technologies that can reduce earthquake risk, provide earthquake early warning, and enhance emergency response. A common theme is the need to deploy cyberinfrastructure that can facilitate the creation and flow of information required to simulate and predict earthquake behaviors.

Toward this end, SCEC proposes the establishment of a Multinational Partnership for Research in Earthquake System Science (MPRESS) to sponsor comparative studies of active fault systems. The partnership would be organized to broaden the training of students and early-career scientists beyond a single discipline by exposing them to research problems that require an interdisciplinary, system-level approach and to enhance their understanding of how scientific research works in different countries, how different societies perceive the scientific enterprise, and how diverse cultures respond to scientific information about natural hazards.

This research was supported by the Southern California Earthquake Center. SCEC is funded by the NSF Cooperative Agreement EAR-0106924 and USGS Cooperative Agreement 02HQAG0008. The SCEC contribution number for this paper is 1210.

**DISCUSSION**

Thomas Jordan: You know, there are many stories about animal behavior before earthquakes. It is very easy to convince yourself that animals know what they are doing. After the big earthquake in Los Angeles in 1971, I went out into the field to map
the earthquake fault along the base of mountains. There were farms for raising horses. When I talked to the farmers, they said, “One hour before the earthquake the horses became very agitated.” However, what they don’t remember is one week before, when coyotes came down the mountains, the horses were also agitated. People tend to remember what happens before an earthquake, but not at other times. There is an historical record of earthquakes in Persia for more than two thousand years. Professor Ambrosias has looked at this. To properly interpret the data requires careful reading of the ancient texts and also geological investigations to try to match geologic features with ancient texts. It is a very important topic. It is a unique source of data. The historical record of earthquakes is extremely important to the study of earthquakes forecasting and prediction.

Yousef Sobouti: Do you have collaborations with institutions in neighboring countries, for instance Turkey?

Jordan: In Turkey we collaborate with four institutions.

Mostafa Damad: Is it possible to have that collaboration with Iranian institutions?

Jordan: Yes. Well I hope so. There are restrictions that have been imposed by the United States, but part of the reason we are here is to work with you to set up collaborations that make sense and then make sure that our governments understand what we are doing and approve. I see no reason why governments would not allow us to work on this common problem.

REFERENCES


LIST OF ABBREVIATIONS

AR—Attenuation Relationship
CDMG—California Division of Mines and Geology (now CGS)
CEST—Center for Earthquake and Environmental Studies of Tehran
CGS—California Geological Survey
CISN—California Integrated Seismic Network
CME—Community Modeling Environment
CSEP—Collaboratory for the Study of Earthquake Predictability
EEW—Earthquake Early Warning
ERF—Earthquake Rupture Forecast
ETAS—Epidemic Type Aftershock Sequence
FEMA—Federal Emergency Management Agency
JICA—Japan International Cooperation Agency
MPRESS—Multinational Partnership for Research in Earthquake System Science
NERIES—Network of Research Infrastructures for European Seismology
NSHMP—National Seismic Hazard Mapping Program
PEER—Pacific Earthquake Engineering Research Center
PGA—Peak Ground Acceleration
PGV—Peak Ground Velocity
PSHA—Probabilistic Seismic Hazard Analysis
RELM—Regional Earthquake Likelihood Models
SCEC—Southern California Earthquake Center
SEAOC—Structural Engineers Association of California
STEP—Short Term Earthquake Probability (model)
UCERF—Uniform California Earthquake Rupture Forecast
USGS—United States Geological Survey
WGCEP—Working Group on California Earthquake Probabilities