Earthquake System Science: Potential for Seismic Risk Reduction

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Abstract. *Earthquakes in megacities such as Tehran and Los Angeles pose huge risks that could jeopardize national prosperity and social welfare. Quantifying urban seismic risk is a difficult problem because it requires detailed knowledge of the natural and the built environments, as well as an understanding of both earthquake and human behaviors. Risk assessments can be improved through international collaborations that combine the expertise of earthquake scientists and engineers. The most effective strategies are seismic safety engineering, enforced through stringent building codes and disaster preparations informed by realistic scenarios of large earthquake cascades. These strategies rely on the ability to forecast earthquakes and their effects and to monitor earthquake cascades in near real time. The practical problems of risk reduction are, thus, coupled to the basic problems of earthquake system science: the interseismic dynamics of fault systems and the coseismic dynamics of fault rupture and ground-motion excitation. In the United States, the Southern California Earthquake Center (SCEC) coordinates an extensive research program in earthquake system science, which includes major efforts to improve time-dependent earthquake rupture forecasts through better understanding of earthquake predictability and to develop attenuation relationships that correctly model the physics of seismic wave propagation. Earthquake system science relies on the premise that detailed studies of fault systems in different regions 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, and it will require the deployment of a cyberinfrastructure that can facilitate the creation and flow of information required to predict earthquake behavior. In the not-too-distant future, we will be able to incorporate much more physics into seismic hazard and risk analysis through physics-based, system-level simulations.*

Keywords: *Seismic risk analysis; Risk assessment; Earthquake prediction; Seismic wave propagation.*

INTRODUCTION

Earthquakes and their effects pose the greatest natural threat to life and property in many urban regions. Prominent examples featured in this paper are Los Angeles, California, and Tehran, Iran–two megacities that are remarkably similar from an environmental perspective. Both are bounded by high mountains rising thousands of meters above fertile alluvial slopes and arid sedimentary plains. Their stunning but seismic geographies are being actively shaped by folding and faulting in the boundary zones between gigantic tectonic plates.

Tehran and LA each comprise more than 12 million people and account for much of their respective national earthquake risk. According to the Federal Emergency Management Agency [1], almost half of the total earthquake risk for the United States, measured as annualized economic losses, comes from Southern California; about 25% of it from the Los Angeles metropolitan area alone. I am not aware of any 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 proportionately higher [2-5]. Because megacity earthquakes can jeopardize prosperity and social welfare, we need to know more about them and learn to work together to reduce the societal risks.

Iran's long history of civilization has provided a

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remarkable record of earthquake activity pertinent to this goal [6-8]. During the past thirteen centuries, nine earthquakes with magnitudes greater than 7 have occurred less than 200 km 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 (Baladeh) earthquake struck a mountainous region 70 km north of Tehran on May 28, 2004 [9]; it killed 35 people, and preliminary assessments of its economic damage exceeded 125 billion Rials.

As citizens of "earthquake country", many of us share an interest in the earthquake problem. My focus will be on its scientific dimensions. 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 us 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 cross-cultural 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 tsunami, and set off destructive processes within the built environment such as fires and dam failures [10]. Seismic hazard can be defined as a forecast of how intense these effects will be at a specified site on the 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 earthquakes, 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, how quickly a community can recover from earthquake damage. The "risk equation", which is illustrated in Figure 1, expresses these relationships in a compact (though simplistic) notation:

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

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 behavior. Moreover, risk is a rapidly moving target, owing to the exponential rise in urban exposure to seismic hazards [11]; calculating risk involves predictions of how civilization will continue to develop, which is 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 depend on technological resources not yet available in many seismically active regions. The ability to assess and reduce seismic risk can be improved through international collaboration that shares the expertise of earthquake scientists and engineers from countries with well-developed risk reduction programs. For example, many countries have benefited from information about regional hazards produced by the Global Seismic Hazard Assessment Program (GSHAP) during the United Nations International Decade for Natural Disaster Reduction [12]. Iran added important data to the global seismic hazard map produced by GSHAP [5].

The first synoptic view of earthquake risk in the United States was published by the Federal Emergency Management Agency less than a decade ago [1]. This study employed the HAZUS methodology, a geographic information system developed by FEMA in cooperation with the National Institute of Building Sciences; it obtained an annualized earthquake loss for California of $3.3 billion per year. However, the study 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) obtained a statewide expected value that was twice as large [13]. A revision of FEMA [1] is currently underway, using a more advanced HAZUS methodology and better inventories of buildings and lifelines (see http://www.fema.gov/plan/prevent/hazus/hz_aelstudy.shtm).

Risk estimates have been published for California earthquake scenarios adapted from historical events such as the 1906 San Francisco earthquake [14], or 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 [15,16]. The results are sobering. The ground shaking from a major earthquake on the
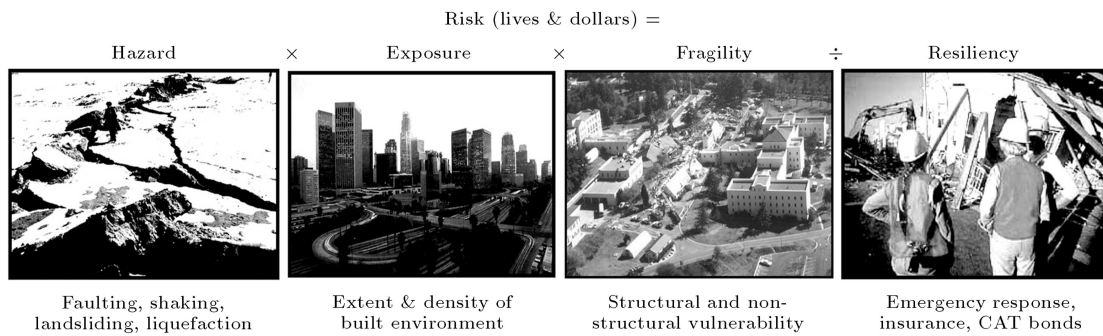
Risk (lives & dollars) =

Hazard			×		Exposure		×		Fragility		÷		Resiliency

Faulting, shaking,			Extent & density of			Structural and non-			Emergency response,
landsliding, liquefaction		built environment			structural vulnerability		insurance, CAT bonds

Figure 1. The risk "equation".

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 [16]. The large range in 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 [3]. Thus, the casualty figures for comparable earthquake scenarios in Los Angeles and Tehran 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

The basic strategies for reducing seismic risk can be categorized according to four terms in the risk equation. They will be illustrated here using examples drawn from California's efforts to mitigate seismic hazards.

Hazard

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 properly characterizing seismic hazard – forecasting earthquakes and their effects; charting earthquake cascades as they are happening – is, therefore, critical to risk reduction. For instance, current hazard forecasts contain large epistemic errors, which compromise the effectiveness of risk analysis in

guiding political policies and economic decisions. The next section will consider the role of earthquake system science in reducing these uncertainties by improving our statistical and physical models of earthquake processes.

Exposure

The exposure to hazard can be limited by land-use policies. An example is the Alquist-Priolo Special Studies Act, which was passed by the California state legislature after the damaging 1971 San Fernando earthquake. The law regulates the building and sale of houses and other occupied buildings near active faults according to fault-zone maps produced by the state geologist. In 1990, California enacted the Seismic Hazards Mapping Act, which significantly broadened the responsibilities of the state geologist beyond the Alquist-Priolo zones by requiring that the secondary hazards of landsliding and liquefaction be mapped throughout the state.

The Natural Hazards Disclosure Act, passed by the California state legislature in 1998, requires that sellers of real property and their agents provide prospective buyers with a "natural hazard disclosure statement" when the property being sold lies within state-mapped seismic hazard zones. This type of caveat emptor is typical of the rather weak compliance provisions in most land-use regulations. High land values and population pressure in Los Angeles, where "sprawl has hit the wall" [17], make the enactment of more stringent land-use policies very difficult. We can thus expect seismic exposure to continue rising in proportion to urban expansion and densification.

Fragility

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.

Efforts to promote seismic retrofitting have achieved mixed results. A 1981 Los Angeles City ordinance led to the demolition or retrofitting of almost the entire stock of unreinforced masonry buildings, the most fragile and dangerous class of inhabited structures. A contrasting example is a state law regulating the seismic safety of hospitals, which was passed after the 1994 Northridge earthquake (Senate Bill 1953). It had two major provisions:

(a) By 2008, all hospitals must be able to withstand earthquakes without collapse or significant loss of life.

(b) By 2030, all existing hospitals must be seismically evaluated and, if necessary, retrofitted to be reasonably capable of providing services to the public after disasters.

Achieving goal (a) proved to be economically infeasible, and the specter that many hospitals would be shut down rather than be retrofit has led to the postponement of the first compliance date and back-peddling on the second.

Performance-based design goes beyond building-code requirements for life-safety by improving the ability of structures to retain a specified degree of functionality after episodes of seismic shaking [18]. Goal (b) of SB1953 is an example of a performance-based design criterion. The impetus for performance-based design, which is largely economic, has raised new challenges for earthquake science and engineering [19]. In particular, engineers must be able to predict more accurately the damage state of structural systems – not just the system components – requiring more detailed description of ground motions. 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 (see http://peer.berkeley.edu/).

Resiliency

Community resiliency can be enhanced through the preparedness of public and private sectors and by better emergency response, insurance investments, catastrophe bonding and state-funded recovery assistance. All of these tools can reduce risks from a wide range of natural and human hazards, including wildfires, severe storms, floods, epidemics and terrorism. My comments will be confined to three basic points:

- Effective preparation and response to multiple hazards depend on a balanced view of relative risks. In the United States, there is concern that the recent emphasis on terrorist threats has distracted efforts to prepare for natural disasters. For example, the incorporation of FEMA into the Department of Homeland Security (DHS) in 2003 appears to have compromised the latter agency's capabilities, at least temporarily [20,21].

- Effective preparation and response to major urban disasters require cooperation across all levels of government. 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 and planning among local, state and federal agencies [22]. Emergency response exercises based on realistic disaster scenarios, if properly executed and evaluated, can be especially valuable mechanisms for improving coordination.

- 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 [23]. In the case of earthquakes, public awareness of the problem is greatly heightened after disruptive events, which motivate people to prepare for future disasters. The magnitude-7.9 Wenchuan earthquake of 13 May 2008, which caused so much loss of life and damage in Sichuan, China, was a grim reminder that citizens need to prepare. Even small earthquakes, if widely felt, can provide "teachable moments", as can the anniversaries of famous disasters. Two years ago, the centenary of the 1906 San Francisco earthquake motivated an extensive and successful public education campaign throughout California [24].

EARTHQUAKE SYSTEM SCIENCE

Earthquake system science concerns three basic geophysical problems [10]:

(a) The dynamics of fault systems – how forces evolve within fault networks, on time scales of hours to centuries, to generate sequences of earthquakes.

(b) The dynamics of fault rupture – how forces produce slip, on time scales of seconds to minutes when a fault breaks during an earthquake.

(c) The dynamics of ground motions – how seismic waves propagate from the rupture to shake sites on Earth's surface.

These coupled problems involve system-level behaviors that emerge through the complex and generally non-linear processes of brittle and ductile deformation.

A geosystem is a representation of nature defined by the terrestrial behavior it seeks to explain [25,26]. In the case of an active fault system, ground motion due to a fault rupture is one of the most interesting behaviors from a practical perspective, because experience tells us that fault displacement and attendant ground shaking are primary seismic hazards for cities such as Tehran and Los Angeles. System-level hazard analysis can be exemplified by the following set of problems:

1. Identify the active fault traces in a region and predict the maximum displacements that might occur across them.

2. From the shaking intensities recorded on a sparse network of seismometers during an earthquake, predict the intensities everywhere in the region occupied by the network.

3. Forecast the distribution of shaking intensities in a region from all future earthquakes.

A basic methodology for solving the seismic forecasting problem (3) is Probabilistic Seismic Hazard Analysis (PSHA). Originally developed by earthquake engineers [27], 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 [28,29]. A plot of the exceedance probability, P_k, as a function of IM is called the hazard curve for the kth 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% in 50 years for PGA $\geq$ 0.6 g and 2% in 50 years for PGA $\geq$ 1.0 g, where g is the acceleration of gravity at the Earth's surface (9.8 m/s^2). Other useful intensity measures are Peak Ground Velocity (PGV) and the maximum spectral acceleration, Sa(f), at a shaking frequency, f. 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 IM as a function of site position, $\mathbf{x}_k$, for fixed P_k. The official 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 [1] and CDMG [13] risk studies were based on the 1995 edition of the National Seismic Hazard Map [30]. Underway revisions to the FEMA assessment are incorporating the better knowledge of seismic hazards encoded in the NSHMP 2002 [31] edition. The latest edition, NSHMP 2008 [32], has just been released, and will be used for 2012 revisions to the Uniform Building Code.

PSHA involves the manipulation of two types of subsystem probability: the probability of occurrence of a distinct earthquake source, S_n, during the time interval of interest, and the probability that ground motions at $\mathbf{x}_k$ 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 as they attenuate with distance away from the source (Figure 2).

SCEC computational pathways

KFR = Kinematic Fault Rupture
DFR = Dynamic Fault Rupture
AWP = Anelastic Wave Propagation

NSR = Nonlinear Site Response
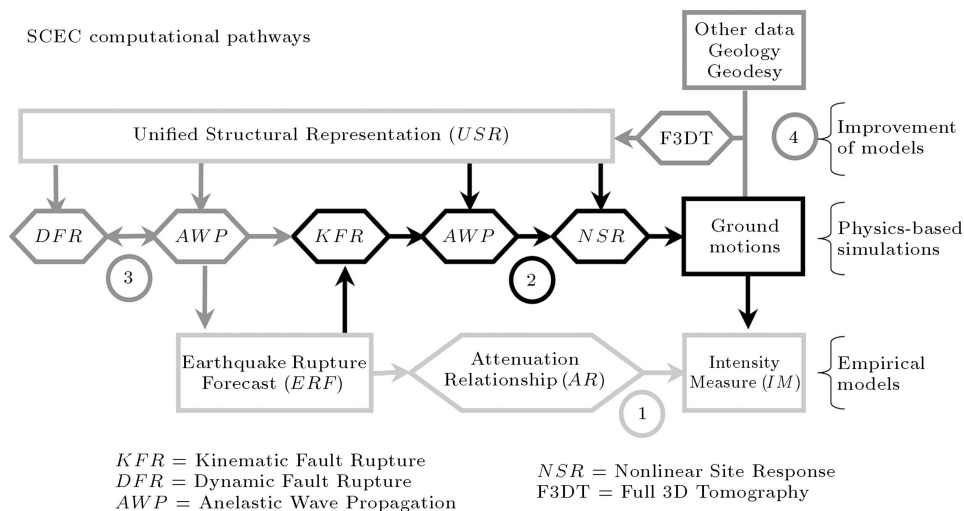F3DT = Full 3D Tomography

Figure 2. Four computational pathways used by SCEC in physics-based seismic hazard analysis: (1) Seismic hazard mapping; (2) Ground motion simulation; (3) Dynamic rupture simulation; and (4) Ground motion inverse problem.

In Southern California, the *ERF* in the NSHMP [32] model comprises approximately 13,000 distinct fault-based sources, each specified by a fault surface with rupture area A_n and seismic moment magnitude m_n, plus low-level background seismicity that follows a truncated power-law (Gutenberg-Richter) distribution. This *ERF* 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. Owing to stress-mediated fault interactions and seismicity triggering, earthquakes are not Poisson distributed so that information about a region's earthquake history can potentially be used to improve earthquake rupture forecasts.

The *AR*s commonly used by the NSHMP and earthquake engineers are empirical probability models that relate source and site parameters directly to *IM* values; i.e. the parameters of assumed functional relationships (often the coefficients of simple polynomials) are determined from the available data by regression [33]. Extant data do not span the full range of earthquake magnitudes and faulting types, nor do they adequately sample the near-source environment. Moreover, this strictly empirical approach does not correctly capture a number of key phenomena:

- Amplification of ground motions in sedimentary basins, a major problem for urban areas in California, Iran, and many other seismically active regions (e.g. [34]).

- Direction of rupture propagation (source directivity), which can have a huge effect on source radiation patterns (e.g. [35]).

- Small-scale phenomena caused by rupture-process complexity and 3D geologic structure, such as the rapid decorrelation of observed *IM* values with intersite distance [36].

In 2000, a major SCEC study recommended that empirical *AR*s should be supplemented with simulation-based models, concluding that "our best hope for reducing uncertainties is via waveform modeling based on the first principles of physics" [37]. The development of numerical simulations for this purpose provides the computational framework for physics-based SHA.

SOUTHERN CALIFORNIA EARTHQUAKE CENTER

The system-level study of earthquake hazards is "big science", requiring a top-down, interdisciplinary, multi-institutional approach. In the United States, the Southern California Earthquake Center (SCEC) is funded by the National Science Foundation and U.S. Geological Survey to coordinate an extensive research program in earthquake system science. The program now involves more than 600 experts at more than 62 research institutions ([38] see http://www.scec.org). 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. 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.

Since it was founded in 1991, the Center has worked toward these goals through interdisciplinary studies of fault system dynamics, earthquake forecasting and predictability, earthquake source physics, and ground-motion prediction. The science plan for the current 5-year phase of the program (2007-2012) comprises the 19 priority science objectives given in Table 1, a problem set that ranges across the entire spectrum of earthquake system science. Research on these objectives contributes to progress in each of the three product areas described in the previous section, and I will illustrate this point with two examples.

Time-Dependent Earthquake Rupture Forecasting

A major SCEC research objective is to develop time-dependent forecast models that account for what is known about the region's earthquake history (Table 1, #2). In the early 1990's, a SCEC-sponsored Working Group on California Earthquake Probabilities published a time-dependent *ERF* for Southern California [39]. SCEC has more recently collaborated with the U.S. Geological Survey, the California Geological Survey, and the California Earthquake Authority (the state's insurance rate-setting organization) to produce the first comprehensive Uniform California Earthquake Rupture Forecast [40]. 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 [32].

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 history-dependent models are motivated by the elastic rebound theory of an earthquake cycle and calibrated for variations in the cycle using historical and paleoseismic observations [41,42].

WGCEP [40] estimates that, in the Los Angeles region, the mean 30-year probability of an earthquake

Table 1. SCEC priority science objectives.

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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, time-dependent 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 an end-to-end ("rupture-to-rafters") simulation capability for physics-based risk analysis.

19. Prepare plans for the scientific response to a large regional earthquake.

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with a magnitude equal to, or greater than, 6.7 – the size of the destructive 1994 Northridge event – is about 67%. Because larger earthquakes occur less frequently, the chances of a magnitude $\geq$ 7.5 earthquake in the LA area during the next 30 years drop to about 18%. For the much larger Southern California region, the equivalent odds of a magnitude $\geq$ 7.5 event increase to 37%. The comparable value for Northern California is significantly less, about 15%, 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, i.e. sufficient stress has re-accumulated at the southern sections of the fault to make a large rupture more likely. The UCERF model will be used by decision-makers 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 [43]. In California, the Short-Term Earthquake Probability (STEP) model of Gerstenberger et al. [44] has been turned into an operational forecast that is updated hourly (see http://pasadena.wr.usgs.gov/step). The STEP forecast is a useful, though experimental,

tool for aftershock prediction, as well as conditioning the long-term probabilities of large earthquakes on small events that are potential foreshocks. It should be emphasized, however, that 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 is being exploited by operational time-dependent forecasting models. The challenge is to unify the forecasting models across temporal scales, which requires a better understanding of intermediate-term (weeks to years) predictability. This unification will not be straightforward, because long-term models based on stress renewal are less clustered than the Poisson model, whereas short-term models based on seismic triggering are more clustered. Current research is thus focused on gaining insights into the physical processes that control stress changes and evolution (e.g. [45]). The SCEC-USGS Working Group on Regional Earthquake Likelihood Models (RELM) is prospectively testing a variety of intermediate-term models [46,47]. 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 called the Collaboratory for the Study of Earthquake Predictability [48,49]. In the next section, I will elaborate on the exceptional opportunities presented by CSEP for international cooperation in earthquake system science.

Physics-Based Ground-Motion Prediction

Large earthquakes are rare events, and the strong-motion data from them are sparse [33]. 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 3D geologic structure. A second major objective of the SCEC program is to develop attenuation relationships that correctly model the physics of seismic wave propagation (Table 1, #13). 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.

The simulations needed for physics-based PSHA can be organized into a set of four major computational pathways [50] (Figure 2). For example, the pathway for conventional PSHA is to compute an IM from an AR, using sources from an ERF, schematically represented as:

Pathway-1: $ERF \rightarrow AR \rightarrow IM$.

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 ground-motion calculations. The complete computational pathway for ground motion prediction 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 usually 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 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 (e.g. [51]). 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 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 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 define a Unified Structural Representation (USR).

SCEC has developed a suite of 3D community models that provide a USR for Southern California [38,52-54]. Nevertheless, many of the current limitations on ground-motion simulations are related to the lack of details in the 4USR4, 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: $\quad GM_{\mathrm{obs}} \ \rightarrow \ INV \ \rightarrow \ USR.$

Computational solutions to the inverse problem require the ability to solve, often many times, the forward problems of Pathways 2 and 3. In particular, INV for seismic tomography can be constructed as $AWP\dagger$, the adjoint of anelastic wave propagation [55], similar to adjoint-based data-assimilation methods used in oceanography and other fields, or in terms of equivalent scattering integrals [56]. Recent advances in high-performance computing have allowed us to apply the scattering-integral method to improve seismic velocity models for the Los Angeles region by "full 3D waveform tomography" [57].

With NSF funding, SCEC has developed a cyberinfrastructure for earthquake simulation, the Community Modeling Environment (CME), which allows geoscientists and computer scientists to construct system-level models of earthquake processes using high-performance computing facilities and advanced information technologies. The CME infrastructure includes several computational platforms, each comprising the hardware, software and expertise (wetware) needed to execute and manage the results from one or more of the PSHA computational pathways described above.

OpenSHA is an 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 model calculations, and for delivering physics-based (Pathway-1*) seismic hazard products to end users [16,28]. WGCEP [40] implemented the UCERF framework on the OpenSHA platform, which allows end-users to easily compare the probabilities calculated from alternative models and will facilitate future updates of the framework as new data and methods emerge.

TeraShake is a research platform for simulations of dynamic fault ruptures (Pathway-3) and ground motions (Pathway-2) on dense grids (outer/inner scale ratios $> 10^3$) [58]. TeraShake simulations of ruptures on the southernmost San Andreas fault have

shown 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 [59]. Earthquakes scenarios with a northwestward rupture in which the guided surface wave is efficiently excited, produce unusually high long-period ground motions over parts of the greater Los Angeles region. These simulations have recently been extended to a DFR model using the Pathway-2/Pathway-3 decomposition. We have confirmed the waveguide effects, but have found that the amplitudes of the less coherent (and more realistic) DFR model are lower by factors of 2 to 3 in the LA Basin. The new DFR simulations show "sun burst" patterns outward from the fault, associated with rapid variations in rupture speed and direction [60].

CyberShake is a production platform that employs workflow management tools [61] to compute and store the large suites ($> 10^5$) of ground motion simulations needed for physics-based PSHA (Pathway-1*). For each large source, the hypocenter, rupture rise-time, velocity distributions and final slip distribution have been varied according to a pseudo-dynamic model, producing catalogs of more than 400,000 KFRs. Using receiver Green tensors and seismic reciprocity [62], we have synthesized the ground motions at individual sites for the full suite of KFRs and, from this database, we have used OpenSHA to compute hazard curves for spectral accelerations below 0.5 Hz [63].

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. This program has four main science thrusts:

- Extend deterministic simulations of strong ground motions to 3 Hz for investigating the upper frequency limit of deterministic ground-motion prediction.

- 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.

- Improve the Southern California structural models using full 3D waveform tomography.

- Compute physics-based PSHA maps and validate them using seismic and paleoseismic data.

OPPORTUNITIES FOR INTERNATIONAL COOPERATION

SCEC advances the science of earthquakes through a comprehensive program of system-specific studies

in Southern California. This approach 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 system was in 1857, before the pueblo of Los Angeles became a city and before the pendulum seismometer was invented. According to WGCEP [40], the 30-year probability of a large (magnitude ≥ 7.8) earthquake in Southern California is about 20%, 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 that 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, from large strike-slip earthquakes that have occurred in Turkey, Tibet and Alaska during the last decade [64-66]. 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 the San Andreas slip [67,68], and SCEC's current objective (Table 1, #3) is to "define the 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 upon 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 Network of Research Infrastructures for European Seismology (NERIES) is integrating over 100 seismic monitoring systems and observatories in 46 countries into a pan-European cyberinfrastructure [69].

On regional scales, 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 "ShakeMaps" of predicted ground motions conditioned on available strong-motion recordings, which can aid in damage assessments [70]. 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 (http://www.cisn.org/).

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 [71], but the most common relies on a dense network of seismometers to transmit records of the first-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, etc.

Several countries have already invested heavily in EEW systems. Japan's is the most advanced (in [72] see http://www.jma.go.jp/jma/en/Activities/eew.html), but systems are also operational in Mexico, Taiwan, and Turkey. SCEC is participating with Berkeley and Caltech scientists in a USGS-sponsored project to test the performance of three EEW algorithms – those of Allen & Kanamori [73], Wu & Kanamori [74], and Cua & Heaton [75] – 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 also 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 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. Similar capabilities are being developed in Japan and Europe. Making this cyberinfrastructure available for application in other regions is an excellent target for international scientific exchange. Such a program will entail the development of 3D geologic models of regional fault networks and seismic velocity structures. Here, the SCEC experience in synthesizing unified 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", like Hurricane Katrina broke the city of New Orleans in 2005? Achieving this type of security depends on understanding how the accumulation of damage during event cascades leads to urban-system failure. I will mention two ways in which earthquake system science is contributing to this goal.

Earthquake simulations can provide cascade scenarios from which we can learn, 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 [23]. 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 exercise is to improve public preparedness at all organizational levels; in the words of the ShakeOut leader Dr. Lucy Jones of the USGS "to keep earthquake disasters from becoming catastrophes".

SCEC's CyberShake program is generating large suites of simulations that sample the likelihoods of future earthquakes [63]. 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 environment in a geologic structure to calculate earthquake risk for urban systems more realistically, not just for 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 – 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. Promising developments include:

- Instrumental seismicity catalogs that incorporate smaller events, source mechanisms and other information now available from denser networks of high-performance seismic stations.

- Paleoseismicity catalogs that extended the earthquake record into the geologic past.

- Detection of new types of seismic and geodetic signal, such as slow precursors on mid-ocean ridge transform faults, silent earthquakes in subduction zones and along strike-slip faults, and periodic slow slip events and related episodes of seismic tremor in the lower reaches of subduction megathrusts.

- Improved models of static and dynamic stress interactions among faults and the effects of earthquake stress evolution on seismicity.

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 experiments 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 Sub-Commission 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.

As a remedy, SCEC and its international partners are building on the RELM project to establish a Collaboratory for the Study of Earthquake Predictability [48]. 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 prospective, comparative testing [49]. Testing centers have been established at SCEC, ERI Tokyo, ETH 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, 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.

CONCLUSIONS

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.

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 a cyberinfrastructure that can facilitate the creation and flow of information required to simulate and predict earthquake behavior.

Toward this end, SCEC has proposed 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. We can envisage a not-too-distant future when much more physics will be incorporated into seismic hazard and risk analysis through physics-based, system-level simulations.

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NOMENCLATURE

AR	Attenuation Relationship
AWP	Anelastic Wave Propagation (model)
CDMG	California Division of Mines and Geology (now CGS)
CEA	California Earthquake Authority
CEPEC	California Earthquake Prediction Evaluation Council
CEST	Center for Earthquake and Environmental Studies of Tehran
CFM	Community Fault Model
CGS	California Geological Survey
CISN	California Integrated Seismic Network
CME	Community Modeling Environment
CSEP	Collaboratory for the Study of Earthquake Predictability
DFR	Dynamic Fault Rupture (model)
DHS	Department of Homeland Security
INV	Inversion (model)
IM	Intensity Measure
EERI	Earthquake Engineering Research Center
EEW	Earthquake Early Warning
EMI	Earthquakes and Megacities Initiative
ERF	Earthquake Rupture Forecast (model)
ETAS	Epidemic Type Aftershock Sequence
GSHAP	Global Seismic Hazard Assessment Program
FEMA	Federal Emergency Management Agency
JICA	Japan International Cooperation Agency
KRF	Kinematic Fault Rupture (model)
MPRESS	Multinational Partnership for Research in Earthquake System Science
NERIES	Network of Research Infrastructures for European Seismology
NRC	National Research Council (United States)
NSR	Nonlinear Site Response (model)
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
SC2	Southern California Studies Center
SEAOC	Structural Engineers Association Of California
SHA	Seismic Hazard Analysis
STEP	Short Term Earthquake Probability
UCERF	Uniform California Earthquake Rupture Forecast
USR	Unified Structural Representation (model)
USGS	United States Geological Survey
WGCEP	Working Group on California Earthquake Probabilities

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