Testimony of Prof. Thomas H. Jordan

Southern California Earthquake Center, University of Southern California

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Regarding the Earthquake Hazards Program of the United States Geological Survey

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Mr. Chairman and Members of the Subcommittee, I appreciate the opportunity to testify at this oversight hearing on the Earthquake Hazards Program of the U.S. Geological Survey (USGS/EHP). I am director of the Southern California Earthquake Center (SCEC) and W. M. Keck Foundation Professor of Earth Sciences at the University of Southern California. I am currently a member of the California Earthquake Prediction Evaluation Council (CEPEC) and the Council of the U. S. National Academy of Sciences (NAS). I chaired the NAS Committee on Seismology (1992-1998) and the NAS Committee on the Science of Earthquakes (1996-2002), and I was principal author of the latter's decadal report, *Living on an Active Earth: Perspectives on Earthquake Science* (2003). I also served from 2002 to 2006 on the Scientific Earthquake Studies Advisory Committee, which advises the USGS on its Earthquake Hazards Program.

The devastation caused by last week's magnitude-7.9 earthquake in Sichuan, China, reminds us that earthquake disasters pose the greatest natural threat to our built environment in many seismic regions. My home state of California has experienced two events of this size in the last 150 years—the Fort Tejon earthquake of 1857 and the San Francisco earthquake of 1906; chances are it will experience at least two more in the next 150 years. Science cannot predict when large earthquakes will occur, but we know they are inevitable, and science can provide key information and technologies for reducing earthquake risk.

Much of the science useful in earthquake risk reduction has come from research partnerships between the USGS and universities. These partnerships are primarily supported by external grants from the Earthquake Hazards Program (USGS/EHP). Under the President's proposed budget for FY2009, the funding for external grants would be cut by $3 million. In addition, the proposed budget would reduce the funding of the USGS's Multi-Hazards Demonstration Project by $2 million, the amount added by Congress to the President's request in FY2008. These actions would be a mistake for at least two reasons: (1) they would curtail targeted research activities that are critical to reducing our nation's earthquake risk, and (2) they would reduce the considerable leverage—as measured in both dollars and expertise—provided to the USGS/EHP by its partners in academia and the private sector.

USGS Partnership with the Southern California Earthquake Center

To illustrate these points, I will focus on the partnership between the USGS and the Southern California Earthquake Center (SCEC). SCEC was founded in 1991 as a consortium of eight universities under a cooperative agreement with the USGS and National Science Foundation (NSF). The Center now coordinates a comprehensive program in earthquake system science that involves over 600 researchers at 62 universities and research institutions worldwide. Its 16 core institutions—the University of Southern California (lead), Caltech, Stanford, Harvard, Columbia, MIT, the University of Nevada at Reno, San Diego State University, five campuses of the University of California, and the Golden, Menlo Park, and Pasadena offices of the USGS—each commit significant internal resources to the SCEC/USGS program.

Since the inception of the Center in 1991, the USGS/EHP has funded SCEC at a steady rate of about $1.1 million per year, while the total SCEC budget has grown from $2.6 million to over $12 million, including approximately $4.8 million in FY2008 from NSF. This funding leverage—more than a fourfold increase in 17 years—has allowed SCEC and its USGS partners to develop new tools for characterizing earthquake hazards and to provide the public with much-needed information about how to reduce earthquake risk. Such advances would have been difficult to achieve without the extra resources SCEC contributes to the USGS/EHP mission.

SCEC's program is carefully aligned with this mission. Its goals are threefold: (1) gather information on earthquakes in Southern California and elsewhere; (2) integrate available knowledge into a comprehensive, physics-based understanding of earthquake processes; and (3) communicate this understanding to society as useful knowledge for reducing seismic risk. Southern California is an outstanding natural laboratory for the study of earthquakes. It contains over 300 active faults, and the data on this fault system— seismographic, geologic, and geodetic—are among the best in the world. Moreover, the region is home to over 23 million people and the nation's largest industrial complex; it therefore comprises nearly half the national earthquake risk. I will briefly review some of the practical achievements of the SCEC/USGS program and outline the opportunities for future progress by this very successful partnership.

Time-Dependent Earthquake Forecasting

A major SCEC/USGS research goal is to develop "time-dependent" earthquake rupture forecasts that take into account what is known about a region's earthquake history. In a project funded in part by the California Earthquake Authority (the state's insurance rate-setting organization), SCEC has collaborated with the USGS and the California Geological Survey in a new Working Group on California Earthquake Probabilities (WGCEP 2007) that produced the first comprehensive Uniform California Earthquake Rupture Forecast (UCERF; see http://www.scec.org/ucerf/). In this forecast, event probabilities have been conditioned on the dates of previous earthquakes using models in which probabilities drop immediately after a large earthquake releases tectonic stress on a fault and then rise as the stress re-accumulates; such "stress-renewal" models are motivated by the elastic rebound theory of the earthquake cycle and calibrated for variations in the cycle using historical and paleoseismic observations. The long-term (time-independent) model that underlies UCERF was developed in partnership with the USGS's National Seismic Hazard Mapping Project, which has incorporated the WGCEP 2007 results into its 2008 revisions. The UCERF and the revised national maps were both released to the public last month. This state-of-the-art study is a prototype for constructing time-dependent forecasts in other seismic regions.

According to the UCERF model, one or more earthquakes with a magnitude greater than or equal to 6.7—the size of the destructive 1994 Northridge event—will almost certainly occur somewhere in California during the next 30 years; the mean probability is a whopping 99.7%.

Larger earthquakes are less frequent, but the mean 30-year probability of one or more with magnitudes greater than or equal to 7.5 is still high, about 46%. The odds of having such an event in Southern California (37%) are higher than in Northern California (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 of 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.

The comprehensive nature of the UCERF analysis has identified many opportunities for future model improvements. More paleoseismic investigations are needed to elucidate the history of California earthquakes prior to written records, especially in Southern California where the probability of a large event is especially high. This is the objective of the SCEC/USGS Southern San Andreas Fault Evaluation (SoSAFE) project, which is funded under the Multi-Hazards Demonstration Project. Other examples include the relaxation of fault segmentation and the inclusion of fault-to-fault ruptures, improved magnitude-area relationships, and the inclusion of earthquake triggering and clustering, as manifested in aftershock sequences.

Seismic-triggering models, calibrated to account for observed aftershock activity, are the basis for a second type of time-dependent earthquake rupture forecast. In California, the Short-Term Earthquake Probability (STEP) model developed by SCEC and USGS scientists is updated on a hourly basis (see http://pasadena.wr.usgs.gov/step). The STEP forecast is a useful, though experimental, tool for aftershock prediction as well as for conditioning the long-term probabilities of large earthquakes on small events that might be foreshocks. Currently, however, the probability gain in the latter application is relatively small.

As the UCERF and STEP examples illustrate, long-term (decades to centuries) and short-term (hours to days) predictability are being exploited by operational time-dependent forecasting models. A major research challenge is to unify the forecasting models across the temporal scales, which requires a better understanding of intermediate-term (weeks to years) predictability. The research toward such unification is now focused on gaining insights into the physical processes of stress evolution and seismic triggering. The SCEC/USGS Working Group on Regional Earthquake Likelihood Models (RELM) is currently testing a variety of intermediate-term models in California. 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 (CSEP; see http://www.scec.org/csep/).

The CSEP project has three primary goals: (a) support scientific earthquake prediction experiments in a variety of tectonic environments; (b) promote rigorous research on earthquake predictability through comparative testing of prediction hypotheses; and (c) help the responsible government agencies assess the feasibility of earthquake prediction and the performance of proposed prediction algorithms. The collaboratory is not being designed to implement operational prediction schemes, which involve economic and political issues well outside the project's scope; however, CSEP will provide facilities for testing the scientific hypotheses that underlie proposals for operational earthquake prediction. The development of CSEP has been funded by the W. M. Keck Foundation, but this grant will expire in 2009. The USGS is the appropriate agency to sustain CSEP activities on the decadal time scale needed to evaluate intermediate-term earthquake prediction experiments.

Ground Motion Prediction

Large earthquakes are rare events, and the data on strong shaking from them are sparse. For this reason, a number of key phenomena are difficult to capture through the empirical approach of traditional seismic hazard analysis, including the amplification of ground motions in sedimentary basins, source directivity effects, and the variability in strong ground motions caused by rupture-process complexity and three-dimensional geologic structure. To address these problems, the SCEC/USGS program is developing models that use the physics of seismic wave propagation to predict geographic variations in the ground motions excited by fault ruptures, including their weakening (attenuation) away from the source. 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 and USGS funding, SCEC has developed a cyberinfrastructure for earthquake simulation, the Community Modeling Environment (CME; see http://www.scec.org/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 the hardware, software, and expertise (wetware) needed to execute and manage the results from various types of seismic hazard calculations. Among the CME computational platforms, three deserve special mention.

OpenSHA is an open-source, object-oriented, web-enabled platform developed by the SCEC/USGS partnership for executing a variety of seismic hazard analysis calculations, including the comparisons of hazard curves and maps from different models calculations, and for delivering physics-based seismic hazard products to end-users. For instance, the Uniform California Earthquake Rupture Forecast was built on the OpenSHA platform, which allows end-users to easily compare the probabilities calculated from alternative models and will facilitate future updates of the forecast as new data and methods emerge.

TeraShake is a research platform for simulations of dynamic fault ruptures and ground motions on the dense numerical grids needed to resolve the effects of small-scale geologic structures, such as the sedimentary basins that amplify strong shaking. 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 Transverse Ranges. As a result, earthquakes scenarios with northwestward rupture produce unusually high long-period ground motions over parts of the greater Los Angeles region.

CyberShake is a production platform that employs workflow management software to compute and store hundreds of thousands ground motion simulations that are needed for physics-based seismic hazard analysis. Using up to 900,000 realizations of earthquake sources from the UCERF model, we have computed probabilistic hazard curves for low-frequency ground motions at various sites in Southern California.

SCEC is now increasing the performance of these computational platforms to take advantage of the petascale machines (computers capable of a thousand trillion calculations per second) that are currently being developed by NSF. This program has four main science thrusts:

- Extend deterministic simulations of strong ground motions to investigate the upper frequency limit of deterministic ground-motion prediction.
- Improve the resolution of dynamic rupture simulations to investigate the effects of realistic friction laws, three-dimensional variations in geology, and near-fault stress states on seismic radiation.
- Improve the Southern California structural models using full three-dimensional seismic waveform tomography.
- Compute physics-based seismic hazard maps and validate them using seismic and paleoseismic data.

Real-Time Seismic Information Systems

A major advance in seismic monitoring and ground-motion recording is the integration of regional seismic networks with strong-motion recording networks as components of the Advanced National Seismic System (ANSS). On regional scales, ANSS provides essential information for guiding the emergency response to earthquakes, especially in urban settings, and the continued funding of its development deserves a high priority.

Seismic data from a regional network can be processed immediately following an event and the results broadcast via the USGS ShakeCast system to end-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 have proven to be a powerful aid in rapid damage assessments. 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/).

Like the SCEC program, CISN leverages its USGS support against other sources, in particular State funding channeled through the California Office of Emergency Services, the California Geological Survey, and the University of California. However, this non-federal support is imperiled by the State’s current budget crisis; OES is facing a cut of $300,000 this fiscal year and more in the next. Therefore, maintaining USGS support for CISN is crucial.

Improvements in the real-time capabilities of ANSS have opened the door to “earthquake early warning.” Early warning 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 a number of early warning strategies, 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 at floors, conditioning electrical grids, etc.

Several countries have already invested heavily in earthquake early warning systems. Japan's is the most advanced, 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 early warning algorithms on the CISN system. However, the United States has been lagging in developing this promising technology, and the USGS needs the resources to implement a prototype earthquake early warning system as a component of ANSS. The USGS/EHP external grants are essential for mobilizing academic and commercial research on this important topic.

Quantifying and Reducing Seismic Risk

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 seismic *hazard*, a forecast of the faulting, ground shaking, and secondary earthquake effects such as landslides, liquefaction, and tsunami. 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" expresses these relationships in a compact (though simplistic) notation:

$$risk = hazard \times exposure \times fragility \div resiliency$$

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 guide the decision-making processes relevant to risk reduction. Risk quantification is an extremely difficult problem, however, because it requires detailed knowledge of the natural and the 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.

Risk estimates have been published for California earthquake scenarios adapted from historical events, such as the 1906 San Francisco earthquake, 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. The results of a SCEC/USGS study of the latter scenario, published in 2005, 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. The large range in the risk estimates comes from two types of uncertainty: the natural variability assigned to the earthquake scenario, as well as our lack of knowledge about the true risks involved.

The SCEC/USGS partnership is improving risk assessment by characterizing the natural variability and reducing the uncertainties due to knowledge gaps. For example, the CyberShake initiative 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 models now used in hazard analysis. It offers the possibility of end-to-end ("rupture to rafters") simulations that embed the built environment in an accurate three-dimensional geologic structure to calculate more realistically earthquake risk for urban systems, not just individual structures.

For megacities like Los Angeles, the key problem is holistic: how can we protect the societal infrastructure from extreme events that can "break the system," like Hurricane Katrina did in 2004 or the recent earthquake in Sichuan, China, did last week? Achieving this type of security depends on understanding how the accumulation of damage during event cascades leads to urban-system failure.

Earthquake simulations can provide cascade scenarios from which we can learn about, and possibly correct, the critical points of failure. As part of its Multi-Hazard Demonstration Project, the USGS has led the development of a comprehensive earthquake scenario based on a SCEC/CME simulation of a magnitude-7.8 rupture of the southern San Andreas fault. This scenario is representative of a potentially catastrophic earthquake in California and is comparable to the magnitude-7.9 Sichuan earthquake. The scenario is the basis for what will be the largest emergency response exercise in U.S. history, the "Great Southern California ShakeOut," planned for November, 2008. It will include the statewide "Golden Guardian" emergency-response exercise involving federal, state, and local emergency-response agencies, as well as millions of citizens at schools and work who will practice what to do during and after a major earthquake. SCEC and USGS are also working with the City of Los Angeles to host an International Earthquake Conference during the ShakeOut. The objective of these activities are to inspire Southern Californians to get ready for big earthquakes and to prevent disasters from becoming catastrophes.

Educating the Public

The SCEC/USGS partnership is providing the public with useful knowledge for reducing earthquake risk. The goals of its Communication, Education & Outreach (CEO; see http://www.scec.org/education/) program are to:

- coordinate productive interactions among a diverse community of SCEC scientists and with partners in science, engineering, risk management, government, business, and education;
- increase earthquake knowledge and science literacy at all educational levels, including students and the general public;
- improve earthquake hazard and risk assessments; and
- promote earthquake preparedness, mitigation, and planning for response and recovery.

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

The SCEC/CEO program offers a wide range of student research experiences, web-based education tools, classroom curricula, museum displays, public information brochures, online newsletters, and technical workshops and publications. For example, SCEC and the USGS have established the Earthquake Country Alliance with many preparedness partners to present consistent earthquake information to the public (see http://www.earthquakecountry.info/). New editions of the practical guide, *Putting Down Roots in Earthquake Country*, have been published in both English and Spanish. A companion guide for the San Francisco Bay Area, *Protecting Your Family From Earthquakes,* is also available in English, Spanish, Chinese, Vietnamese, and Korean (see http://www.earthquakecountry.info/roots/index.php). To date, over 7.5 million copies of the *Roots* brochures have been distributed to communities across the state, and versions are being prepared for other seismically active regions in the United States and abroad.

Conclusions

The partnership between SCEC and the USGS exemplifies the outstanding achievements of the USGS Earthquake Hazards Program and its external grants component. As further documented in Dr. Applegate's statement to this subcommittee, the partnerships with universities and other research organizations established under the USGS Earthquake Hazards Program have been very successful in providing the policy makers, first responders, state and local planners, and citizens with the tools needed to reduce earthquake risk.

Congress should reject the Administration's proposed reductions in the USGS Earthquake Hazards Program and restore the funding in the FY2009 Congressional budget process to continue these valuable partnerships.

Thank you for the opportunity to appear before this Subcommittee. I would be pleased to answer any questions or provide more information that would be helpful to the Subcommittee.