



Northridge 20 Symposium Summary Report

The 1994 Northridge Earthquake: Impacts, Outcomes, and Next Steps

January 16–17, 2014

Los Angeles, California



SPONSORS



PARTICIPATING ORGANIZATIONS



Executive Summary

On the 20th anniversary of the Northridge earthquake, more than 600 people gathered in Los Angeles to share the impacts of the 1994 earthquake, highlight accomplishments of the past two decades, and identify necessary steps forward to make our communities more resilient to future earthquakes. This event, called the Northridge 20 Symposium, drew participants from a broad range of disciplines, including earth scientists, structural engineers, risk modelers, emergency managers, and public officials.

This summary report presents the findings and recommendations for each of the 11 key areas studied during the symposium. For each topic area, several of the conference participants collaborated to summarize symposium discussions and to determine the next steps needed in these fields to achieve earthquake resilience.

The following themes can be drawn from the recommendations presented in each chapter of this report.

- ▲ While the lessons learned from Northridge led to two decades of dedicated research, seismic public policy development, building code development, seismic retrofit, insurance reform, risk modeling, mitigation, and education, more work is needed to make our communities resilient to future earthquakes.
- ▲ Working groups with statewide representation should be established in nearly all of the topic areas to further refine the Northridge 20 recommendations and further collaboration between diverse stakeholders.
- ▲ Education is needed to help California residents, business owners, and government decision makers understand, evaluate, and mitigate their risk of loss from earthquakes. This educational messaging must be presented in ways that are relevant, understandable, and personal so that our communities can make informed decisions about their risk.
- ▲ There needs to be funding and support for engineers, scientists, researchers, lifeline operators, and others to continue learning and implementing lessons from other disasters (e.g., Christchurch, New Zealand, and Tohoku, Japan). These investigations and follow-up research studies help the earthquake community understand the correlation between the seismic performance of components, structures, networks of infrastructure and lifelines, and regional resilience.
- ▲ Sustained support is needed for both proven and innovative programs that either do provide or have the potential to provide substantially reduce earthquake risk. Examples include earthquake early warning research, lifelines councils, ground motion prediction model development programs, hazard and fault mapping programs, Shake Cast, and others.
- ▲ Communities should adopt public policy measures to identify inventories of known vulnerable buildings and develop short- and long-term solutions to mitigate those vulnerabilities. There are many examples from across the state that can be modified for use by other jurisdictions with vulnerable building stock.
- ▲ Continued research efforts are needed to benchmark and improve performance-based earthquake engineering procedures and incorporate them into design and analysis standards. The development of these guidelines and tools should be extended to include non-building structures, communities, and lifelines.
- ▲ Actions are needed that will speed post-earthquake economic recovery.

While the report chapters outline many actions that need to be taken, the report does not prioritize these recommendations or identify interdependencies between disciplines. The next step is to create a prioritized integrated list that addresses the concerns of the key areas under study. Follow-up activities are needed to transform the current “wish list” of recommendations in this report into a useful White Paper with clear, succinct recommendations for private and public sector actions (from local to national levels), and, in particular, a specific action plan for the State of California.

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Preface

HEIDI TREMAYNE, STEPHEN MAHIN, JANIELE MAFFEI, DICK MCCARTHY, AND JOHN BWARIE

PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER (PEER), PEER, CALIFORNIA EARTHQUAKE AUTHORITY, CALIFORNIA SEISMIC SAFETY COMMISSION, AND U.S. GEOLOGICAL SURVEY

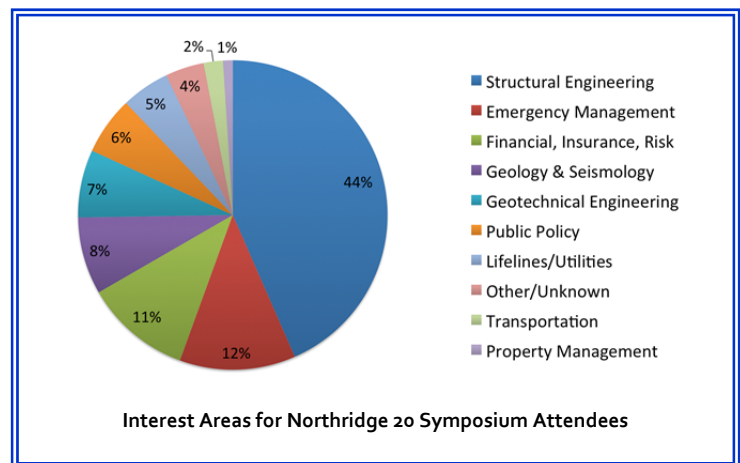
On the 20th anniversary of the Northridge earthquake, more than 600 people gathered in Los Angeles to share the impacts of the 1994 earthquake, highlight accomplishments of the past two decades, and identify necessary steps forward to make our communities more resilient to future earthquakes.

While the lessons learned from Northridge led to two decades of dedicated research, seismic public policy development, building code development, seismic rehabilitation, insurance reform, mitigation, and education, more work is needed. "We have made great progress over the last 20 years, but we still have much work to do to ensure our homes and communities are more resilient when the big one strikes," said Janiele Maffei, co-chair of the Northridge 20 Symposium and Chief Mitigation Officer of the California Earthquake Authority. "This Symposium is an important step to renew our effort to collaborate on seismic safety issues."

A steering committee consisting of representatives from all participating organizations led the planning of the event, with subcommittees on Finance, Outreach, Logistics, and Program.

PARTICIPANTS & ATTENDEES

From January 16-17, 2014, over 600 attendees participated in the symposium from a broad range of disciplines, including earth scientists, structural engineers, risk modelers, emergency managers, and public officials. From the registration data shown in the figure, 44% of the audience was interested in structural engineering, followed by 12% emergency management, 11% financial and risk services, and 8% seismology. This attendance number exceeded the expectations of the steering committee and achieved an impressive level of diversity among participants.



PROGRAM

The two-day program of the symposium combined keynote speakers, technical presentations, policy panel discussions, and audience participation. The first day consisted of a plenary session that began with an introduction and welcome by Program Committee Co-Chair, Janiele Maffei. This was followed by keynote presentations by:

- ▲ Former Governor Pete Wilson
- ▲ Former FEMA Director James Lee Witt
- ▲ Dave Jones, California Insurance Commissioner

These keynote speakers described their personal experiences



Northridge 20 Keynote Speakers

during the Northridge earthquake, shared perspectives on what has been accomplished since 1994, and called the audience to action to help achieve community earthquake resilience.

Panel discussions with policymakers were used to obtain feedback from the technical recommendations of the speakers and to discuss the feasibility of funding earthquake mitigation programs from a political perspective. These policy panels were planned and led by moderators Leslie Chapman-Henderson, John Bwarie, and Richard McCarthy. Insights shared by these policymakers allowed the audience to expand their thinking beyond *what* actions are needed to *how* actions get effectively implemented. The participating policymakers included:

- ▲ Ken Cooley (California Assembly)
- ▲ Bob Blumenfeld (Los Angeles City Council)
- ▲ Mitch Englander (Los Angeles City Council)
- ▲ Tom LaBonge (Los Angeles City Council)
- ▲ Raymond Chan (Los Angeles Department of Building and Safety)
- ▲ Anna M. Caballero (California Business, Consumer Services, and Housing Agency)
- ▲ Tina Curry on behalf of Mark Ghilarducci (California Office of Emergency Services)
- ▲ Michael Gardner (Riverside City Council and California Seismic Safety Commission)



Northridge 20 policymaker panelists discuss the issues

Technical presenters shared their perspectives on what has been accomplished in their field of expertise in the last 20 years and presented some recommendations on the next steps needed in their field to ensure resilience to future earthquakes. These presenters included:

- ▲ Earth Science & Seismology – Lucy Jones (USGS)
- ▲ Ground Motion and Ground Failure – Jonathan P. Stewart (UCLA)
- ▲ Lifelines and Utilities – Craig A. Davis (LADWP)
- ▲ Transportation Systems – Thomas A. Ostrom (Caltrans)
- ▲ Residential Wood-Frame and Soft Story Buildings – John W. van de Lindt (Colorado State)
- ▲ Concrete Buildings – Michael Mehrain (URS Corp.)
- ▲ Steel Buildings – Thomas A. Sabol (Englekirk Institutional)
- ▲ Business, Insurance, and Financial Implications – Glenn Pomeroy (California Earthquake Authority)

Audience participation was also encouraged through small group discussions and facilitated conversations on symposium topics when time permitted. Additionally, John Bwarie moderated small group discussions and feedback sessions at several times throughout the day to acquire written feedback and attendee engagement from the audience.

During a networking reception on Friday evening, student researchers from campuses affiliated with PEER presented research posters to symposium attendees. This opportunity allowed the PEER students to engage with a wider cross section of earthquake mitigation experts from across the state of California than is typically found at PEER Annual Meetings, and also introduced this future generation of earthquake professionals to the broad multi-disciplinary aspects of earthquake resiliency.

On Friday, January 17th, the program hosted a series of concurrent sessions on a variety of related topics. These sessions provided a more detailed examination within their topic area of impacts from the Northridge earthquake and next steps needed to move forward. These sessions utilized speakers, panels, and discussion sessions to study their topic area in more depth. Each session had two or three co-chairs who organized and moderated the session.

The list of concurrent sessions was:

- ▲ Earth Science and Seismology
- ▲ Ground Motion Hazard, Site Response & Ground Failure
- ▲ Transportation Systems
- ▲ Lifelines & Utilities
- ▲ Steel Structures
- ▲ Concrete Buildings
- ▲ Wood-Frame & Soft-Story Buildings
- ▲ Performance-Based Earthquake Engineering
- ▲ Business, Insurance, & Financial Implications
- ▲ Resilience Case Studies & Tools
- ▲ Risk Communication: Tools & Resources for Policymakers

More information about the speakers in each session along with their presentation slides can be found at the event website: www.northridge20.org. In total, over 115 people presented content as a speaker or panelist during the symposium, along with nearly 30 student poster presenters.

STATEMENT OF SUPPORT

The participating organizations and many of the attendees signed a Statement of Support committing to make California communities more earthquake resilient. This symbolic gesture of cooperation and collaboration is a critical step towards achieving communities with greater earthquake resilience, and has established a momentum that is continuing beyond the symposium during the development of this report and subsequent follow-up activities.

Specifically, speakers and session chairs in 11 key areas pledged to develop a list of recommended next steps in their topic area to achieve regional (e.g., Los Angeles) and California state-wide earthquake resilience. The topic areas included earth science and seismology, ground motions and ground failure, lifelines and utilities, transportation, building types (residential, concrete, steel), risk communication, and business and insurance. These recommendations are summarized in this report.

INTENT OF THIS REPORT AND FOLLOW-UP ACTIONS

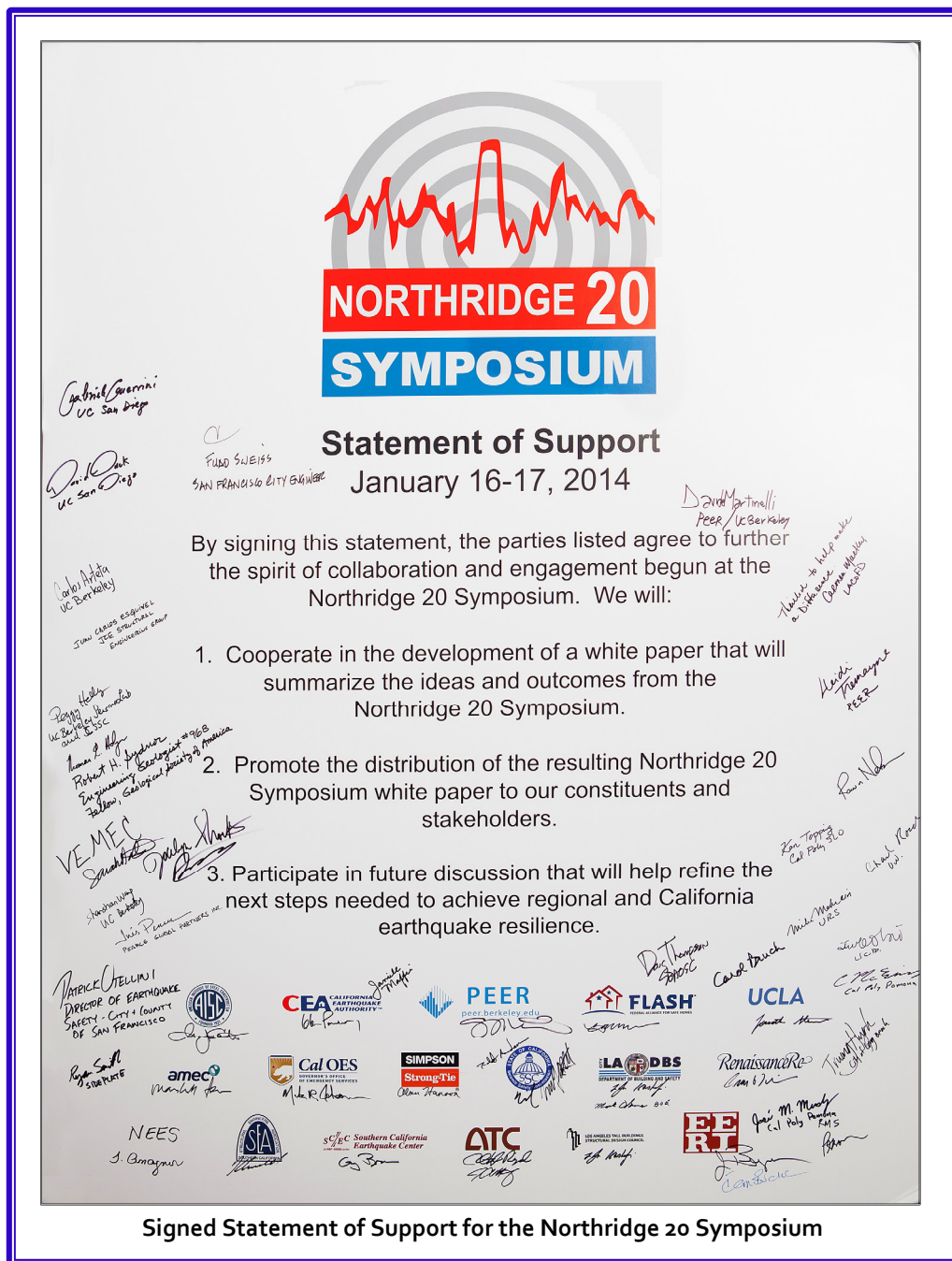
Each chapter in this report presents the findings and recommendations for each of the 11 key areas studied, which were based up the plenary presentations, concurrent session presentations, and discussion during the symposium. Each chapter



Leaders from participating organizations sign the statement of support



Chris Rojahn signs the statement of support on behalf of the Applied Technology Council



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Earth Sciences and Seismology

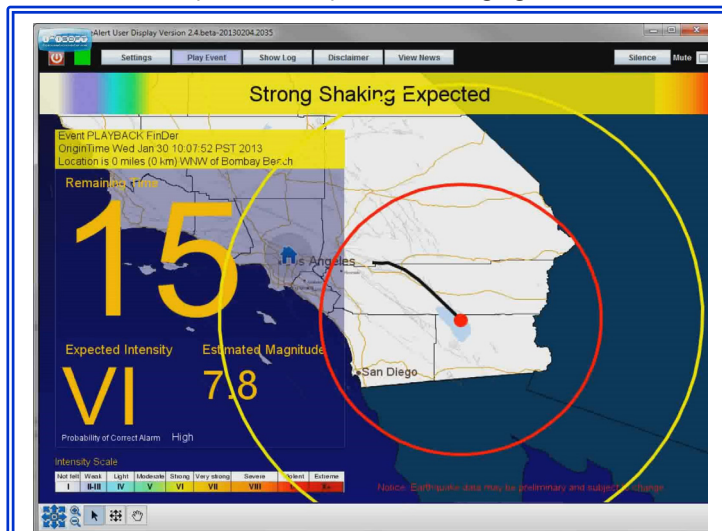
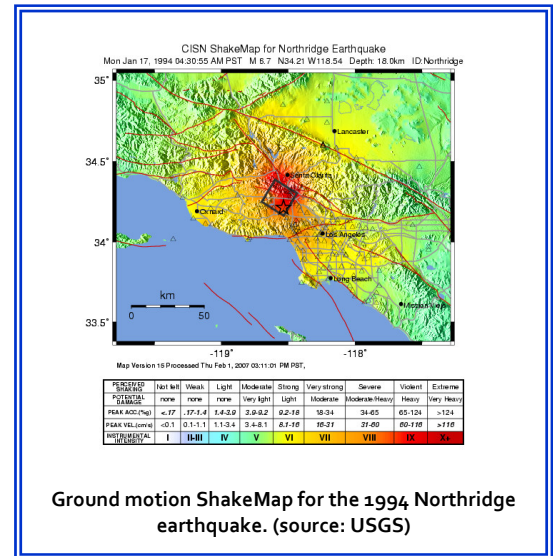
LUCY JONES, KEN HUDNUT, GREG BEROZA, AND ROBERT GRAVES

U.S. GEOLOGICAL SURVEY (USGS), USGS, STANFORD UNIVERSITY/SOUTHERN CALIFORNIA EARTHQUAKE CENTER, AND USGS

FINDINGS

The magnitude 6.7 1994 Northridge earthquake was a moderate earthquake by seismological standards. It did not rupture to the Earth's surface. It occurred in the northern suburbs of Los Angeles, but the strongest energy was directed towards the north—into relatively lightly populated regions. Yet its impacts were profound. The Northridge earthquake resulted in 60 deaths, 10's of billions of dollars in damage, and it registered some of the most intense shaking ever recorded—over 1.5 meters/second of ground velocity. While the Northridge earthquake was a disaster, there are earthquakes that lurk in our future that are certain to put urban areas of Southern California to a test that will be much more severe.

In the 20 years since Northridge, it has become clear that there are faults closer to, and even directly underneath, Los Angeles that could lead to stronger shaking, have longer duration, and impact a greater geographical area than the Northridge earthquake did. Moreover, geoscientists know that seismic waves will be guided into, and amplified by, the sedimentary basin that underlies much of metropolitan Los Angeles. The continuing threat of earthquakes cannot be ignored. Unfortunately, many buildings were not designed to handle the larger shaking levels that have long been postulated by seismological models, and which have been confirmed by numerous post-Northridge ground motion observations.



Earthquake Early Warning is already up and running as a statewide prototype, operated by Caltech, U.C. Berkeley, and the USGS as part of the California Integrated Seismic Network. (source: CISN)

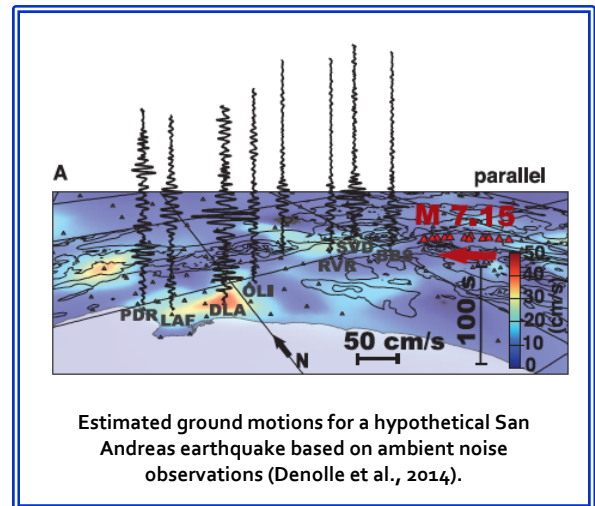
Furthermore, there have been great improvements in our understanding of the hazard posed by earthquakes. During that same time period, entirely new technologies have emerged that allow reporting of earthquake information in real time while an earthquake is underway. Moreover, new approaches in the geosciences, enabled by new technology, will allow us to deepen our understanding of earthquakes, and in doing so will provide the necessary foundation to mitigate the risks they pose.

In addition to the plenary session keynote talk given by Dr. Lucy Jones (USGS), we convened an in-depth session, including concerned engineers and scientists with a common interest in working together to help characterize earthquake hazard, reduce earthquake risk, to highlight and discuss achievements since the time of the Northridge earthquake, and to consider

potential future systems and solutions. To develop these findings and recommendations, this special session was held during the Northridge 20 Symposium, a gathering of nearly 600 professionals with a broad range of expertise. We explored the ways in which science, engineering, and technology can mesh for positive outcomes in seismic hazard characterization and risk reduction. Our recommendations take into account the scientific and technological progress of the past two decades, and synthesize that knowledge to specify future actions are required, making us more resilient to and safer from future earthquakes.

RECOMMENDATIONS

- ▲ A primary recommendation from Earth Science and Seismology is to fully implement Earthquake Early Warning Systems for the western United States. Public alerts prior to damaging shaking will help prevent future loss of life and property, and the technology has already been developed and demonstrated successfully. The Governor of California has signed SB 135, thereby requesting CalOES to identify \$80M to support this initiative. Greater engagement from local governments and private partners will help facilitate this process.
- ▲ Continue to support ongoing maintenance and modernization of earthquake monitoring networks. Evolve and upgrade these networks to take advantage of opportunities presented by new technologies to further improve earthquake monitoring capabilities.
- ▲ Continue to investigate, characterize, and map active fault traces, both on the surface and at depth (including blind faults).
- ▲ Zoning is needed for areas of potential deformation above blind thrusts and near active surface faults, especially within urban areas (and areas that might be developed rapidly in the foreseeable future).
- ▲ A working group of engineering and scientific experts should be convened to review specific ways in which science can provide inputs that will then be used by engineers.
- ▲ Earthquake professionals all need to communicate more effectively. We need to find ways to describe our work and analyses that non-earthquake professionals can understand. Public officials should have tools beyond probabilistic seismic hazard analysis (PSHA) to understand the hazard they face. Our communities can make informed decisions about their risk when we make sure they are well informed.
- ▲ We need to take advantage of the latest developments in earthquake science to simulate, measure, and, in collaboration with earthquake engineers, validate models of earthquake rupture processes and 3D amplification effects so that they can be used to the benefit of public safety.
- ▲ We need to incorporate our understanding of the time dependence of earthquake probabilities, the hazard from ground shaking, and propagate that hazard into risk models so that the public and governments can make decisions based on the best possible information that earthquake science can provide. Improving the predictive value of earthquake forecasting will require fundamental research across the full spectrum of geosciences that contributes to understanding earthquake occurrence.



Ground Motions and Ground Failure

MARSHALL LEW AND JONATHAN P. STEWART

AMEC AND UNIVERSITY OF CALIFORNIA LOS ANGELES

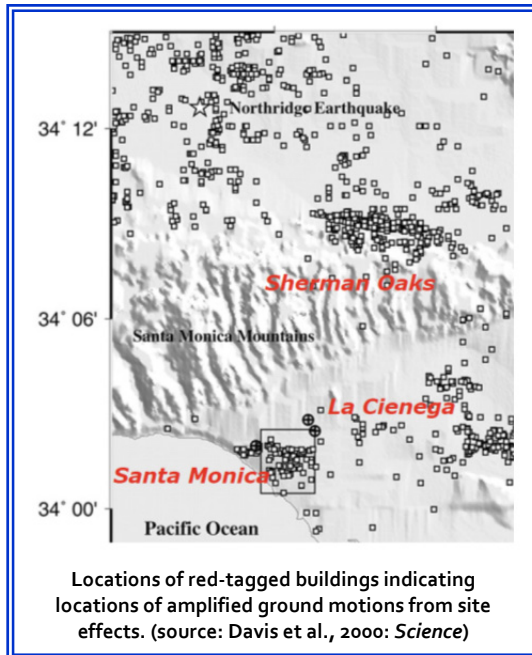
FINDINGS AND OUTCOMES

The 1994 Northridge earthquake produced a substantial ground motion inventory, the largest in the world at the time, the analysis of which provided insights into near-fault ground motions and site effects on ground shaking intensity. The most intense shaking occurred not in the epicentral region (Reseda, Northridge), but above the shallow (north) end of the blind thrust fault near Granada Hills and Santa Clarita. As such, the most severe shaking from Northridge occurred in areas of relatively low-density infrastructure and commercial development. Angelinos may be less fortunate during the next large earthquake, given the many faults lurking beneath urbanized regions.

We have learned a great deal about near-fault ground motions since Northridge, including hanging-wall effects and rupture directivity effects, which are now included in many of the predictive models used to forecast seismic hazards in future earthquakes. A great deal has also been learned about site effects that caused concentrated patterns of structural damage in areas relatively distant from the fault such as Sherman Oaks, Santa Monica, and the La Cienega region of west Los Angeles. These site effects resulted from a complex combination of factors involving the deep geologic structure of

sedimentary basins and amplification within relatively shallow soft soil layers. Our ability to model these effects has improved substantially since Northridge, which is reflected (for example) in vastly improved site factors in building code provisions.

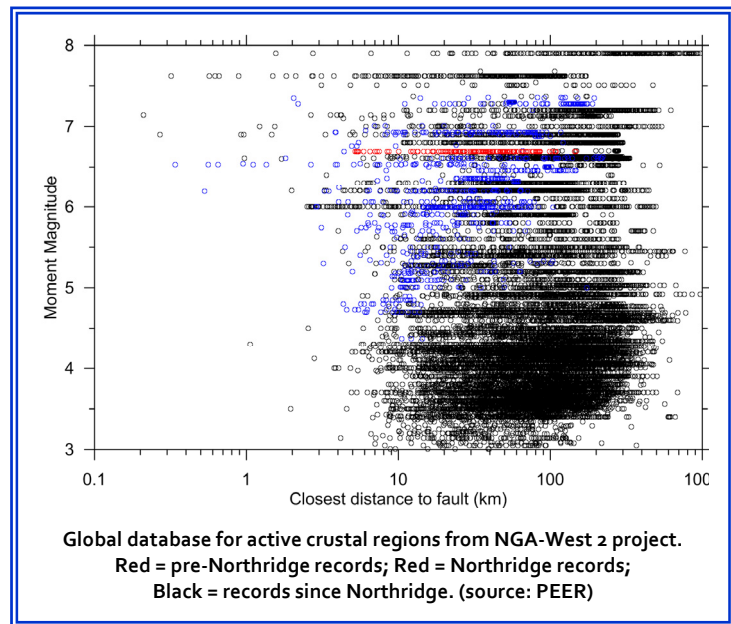
Ground failure during the Northridge earthquake included the dramatic flow slide of a tailings dam north of Simi Valley, liquefaction features that ruptured pipelines and seawalls, and thousands of landslides in the Santa Monica and Santa Susana Mountains. One of the most interesting ground failure outcomes of the earthquake involved damaging ground displacements for soil conditions that prior to Northridge had not been recognized as threatening. These include the softening of fine-grained clayey soils that can give rise to ground lurching and other instabilities as well as settlements of poorly compacted structural fill materials. Great strides have been made in the intervening years in understanding these hazards and developing procedures with which they can be predicted. Unfortunately, some of the analytical techniques to evaluate ground deformations for slopes have yet to be adopted by regulatory agencies.



RECOMMENDATIONS

Much has changed since the Northridge earthquake, both in the advancement of our technical knowledge and the manner by which large research programs are organized and their results disseminated. These are positive outcomes that have substantially improved seismic risk assessment in engineering practice. Many of our recommendations are to urge sustained support for proven programs providing vitally valuable outcomes for earthquake risk reduction.

In the ground motion area, the years since Northridge have seen establishment of the PEER Next Generation Attenuation (NGA) research programs that bring together top researchers from around the world to develop database resources for ground motion research and model development. Prior to NGA, databases were assembled by individual researchers and were unavailable for broader use. NGA introduced openly available community databases from which engineering models for ground motion prediction (i.e., Ground Motion Prediction Equations, GMPEs) are derived. This has had a transformative impact on scientific discovery and its implementation in practice. Given the sustained work that is needed to maintain and grow database resources, and the substantial pace of improvement in ground motion prediction, we recommend sustained baseline funding for consortia of researchers engaged in this work. No investment in earthquake hazards reduction is likely to have greater long-term impact.



Since Northridge we have seen many examples of physics-based simulations of various phenomena in earthquake source dynamics and wave propagation. This is a vital development because simulations can provide important insights into aspects of source, path, and site effects that cannot be adequately evaluated from empirical data (recordings). We recommend that this practice continue through formal collaboration between the Southern California Earthquake Center (SCEC), which is deeply involved in the development of simulation procedures, and PEER, where the focus is on the development of engineering tools for risk assessment.

As with earthquake ground motion research, studies of ground failure rely to a great extent upon case histories. Case histories of ground failure or non-ground failure from past earthquakes are either used directly to develop predictive tools or they are used to validate or calibrate engineering physics-based models. However, the ground failure research community has not yet adopted the openly shared database approach that has had such transformative impact for ground motion studies. Accordingly, we recommend the establishment of a major research program to develop this community database, with the goal that the database support development of the next generation of engineering models for ground failure prediction. Such models should be capable of distinguishing between liquefaction of sands, cyclic softening of clayey soils, and seismic compression of unsaturated soils—each of which caused damage during the Northridge earthquake and other international events since 1994.

A problem in earthquake engineering practice in relation to ground failure is that the hazards are too often not recognized during engineering design. This problem has been highlighted by the recent development of large buildings very near the Hollywood fault in Los Angeles. Fortunately, two California state laws provide a solution by requiring evaluation of common ground failure hazards as part of routine geological/geotechnical studies when the site is within a mapped hazard zone. Unfortunately, many densely developed and highly seismically active parts of the state have not been mapped. In several cases, especially in relation to liquefaction, the methods used to evaluate the presence of the hazards are in need of updating. We recommend accelerating and updating the mapping program by the California Geological Survey.

Transportation Systems

TOM OSTROM, MARC EBERHARD, AND TOM SHANTZ

CALIFORNIA DEPARTMENT OF TRANSPORTATION (CALTRANS), UNIVERSITY OF WASHINGTON, AND CALTRANS

FINDINGS

Damage to transportation systems during the Northridge earthquake was largely limited to freeway bridges. The earthquake provided the first major test of emerging bridge design and retrofit strategies at that time. Of the over 2500 state-owned bridges in Los Angeles County, 7 collapsed, 39 had major damage, and 194 had minor-to-moderate damage. All recently retrofitted bridges performed well.

KEY LESSONS FROM DAMAGED OR COLLAPSED BRIDGES

- ▲ Highly skewed bridges have a tendency to unseat if the seat length is inadequate.
- ▲ The lateral stiffness of bents should be roughly equal (short columns, particularly if they are shear critical, should not be combined with tall columns).
- ▲ Architectural column flares can act to reduce the effective column height.

IMPACT ON BRIDGE DESIGN

- ▲ Consideration of ground-motion amplification due to near-fault and thrust faulting effects was adopted into design practice.
- ▲ Design criteria focusing on use of energy absorbing ductile columns, balanced substructure stiffness, and large seat capacity were quickly adopted. These principles have been widely adopted both nationally and internationally.

TRAFFIC IMPACTS

Traffic impacts were relatively modest, with most routes quickly returning to near pre-event levels. In two routes, each incorporating segments where bridge collapses occurred, traffic flows of approximately 40% of pre-event levels were achieved through the use of detour routing.

PROMISING INNOVATIONS FOR TRANSPORTATION SYSTEMS

Advanced Column Systems

Several new column systems have been developed that promise to enhance seismic performance and accelerated construction, which can reduce traffic congestion. All of these systems utilize pre or post tensioning to promote re-centering at the end of shaking. Recent shake-table comparison tests demonstrated the new systems' superior seismic performance relative to conventional cast-in-place column design. The comparison tests also showed that the seismic performance of the various alternative systems would be roughly similar.

Rocking Foundations

Designing foundations to rock under strong shaking represents a dramatic departure from the current design approach of utilizing the creation of plastic hinging in the column to act as an energy-absorbing fuse. The rocking foundation approach offers the advantage of lower foundation costs, better re-centering, and less overall damage to the substructure. The performance of bridges utilizing rocking foundations has been investigated at small scale utilizing the geotechnical centrifuge, at near full scale on a large shake table, and numerically using both simple and complex simulation techniques.

Rapid Estimates of Seismic Damage to Distributed Facilities (SHAKECAST)

Following the Northridge earthquake the density of seismic instrumentation increased substantially, first in Southern California and then later in Northern California. This increased density, along with both advancements in transmission and processing technologies, have enabled the rapid generation and dissemination of maps depicting levels of ground shaking (ShakeMaps).

The information available from these maps can be combined with information about the system infrastructure to allow for rapid assessment of possible infrastructure damage. For application to state bridges, a system called ShakeCast has been developed to alert early responders to potential bridge damage. ShakeCast provides both an aerial map of shaking intensity and a list of potentially affected bridges.

RECOMMENDATIONS

- ▲ Caltrans should review innovative column systems for cost, constructability, and maintenance issues. A preferred system should be identified and design details and specifications developed.
- ▲ Detailed design guidelines for rocking foundations should be developed.
- ▲ Develop improved fragility relationships that are consistent with the results of research and with field observations of damage. Special focus should be placed on skewed bridges given their generally poorer performance in past earthquakes.
- ▲ Develop component-by-component (e.g., columns, decks, bearings) fragility curves, so that inspectors will know what component is predicted to contribute most to the likely damage of a bridge.
- ▲ Develop methodologies for incorporating the importance of the facility to the network in the ranking procedures.
- ▲ Utilize ShakeCast to perform scenario-based studies that focus on system resilience and ways to improve it.
- ▲ Develop fragility curves for a wider range of facilities (buildings, pipelines, unstable slopes, etc.).
- ▲ Perform periodic screening of existing infrastructure to assess potential vulnerabilities using the latest seismic source information, ground motion prediction models, and seismic performance models.
- ▲ Develop, refine, and test infrastructure screening algorithms. For systems with thousands of components, it is critical to be able to assess and find vulnerable components.
- ▲ Develop the information technology tools and infrastructure description schema to allow for rapid assessment and identification of vulnerabilities.

Lifelines and Utilities

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LOS ANGELES DEPARTMENT OF WATER AND POWER, UNIVERSITY OF CALIFORNIA, DAVIS, AND LAURIE JOHNSON CONSULTING

FINDINGS

The 1994 Northridge earthquake significantly affected most lifeline systems serving the Los Angeles region, including water, wastewater, natural gas, electric power, liquid fuels, and telecommunications systems. System damages disrupted services to more than a million people and were a major cause of the 110 fires that erupted across the region, just as fire-fighting capacity was simultaneously impaired by water system damages in many affected areas. Images of the fire raging in the midst of a water-logged and sunken Balboa Boulevard remains an iconic illustration of the vulnerability of buried infrastructure to strong shaking and ground failures due to liquefaction.



Lifeline system interdependencies due to colocations and other complex system interactions resulted in service disruptions as well as delays in restoration and recovery. Lifeline providers did an outstanding job restoring services and repairing damage. Most lifeline customers had services restored within days to weeks; however, response times were delayed by communications, transportation, materials, human resources, coordination, and prioritization decisions. System repairs and a return to full-system functionality took nearly a decade to complete on some lifeline systems. Repairs and improvements to damaged facilities required extensive planning, engineering design, financing, environmental and historical considerations, and community involvement.

Some major lifeline system improvement programs were either ongoing or already completed before the 1994 earthquake struck and helped to reduce system damages. Most of these were designed and initiated based upon lessons learned from the 1971 San Fernando earthquake. Since 1994, the earthquake resiliency of Southern California's lifeline systems has continued to improve with advances in technologies, engineering, preparedness, operations, response capabilities, regulations, and policies. Billions of dollars have been spent by lifeline providers to seismically strengthen and add redundancy and dispersion within their systems. For example, some significant enhancements were made to materials (e.g., installation of earthquake-resistant ductile iron pipes), equipment seismic qualification criteria (e.g., IEEE 693), design criteria (e.g., water pipe seismic design guidelines), system modeling [e.g., software such as GIRAFFE (Shi and O'Rourke, 2008) and SERA], emergency response capabilities and planning (e.g., use of ShakeCast and ShakeMap, spare equipment, and material inventories), and regulations (e.g., requirements for water heater straps, regulations on mobile home gas meter assemblies, and state mandates for gas earthquake valve installations).

Additionally, major weaknesses in systems have been further studied and identified, including the potential for surface rupture from a major earthquake along the San Andreas fault that would disrupt many of the major lifeline systems serving Southern California. For example, such an earthquake could damage the region's aqueducts and impede 70% of the water delivery to about 20 million people, and it could take more than 18 months to restore. Two such efforts include (1) the American Society of Civil Engineers' (ASCE) Technical Council on Lifeline Earthquake Engineering (TCLEE), which created a Lifeline Interdependency Committee in 1994, and (2) the American Lifelines Alliance created in 1998, which made important progress in demonstrating the need for and the development of lifelines system design and performance guidance before it was disbanded in 2006.

RECOMMENDATIONS

- ▲ A “Water Supply Task Committee” should be formed by the region’s water supply agencies (LADWP, MWDSC, and DWR) to coordinate their efforts in identifying water supply vulnerabilities, mitigation solutions, and planning for emergency response and recovery. The Southern California water supply is too critical to fail, and the estimated minimum 12 to 18 month timeframe to repair earthquake-damaged aqueducts is too long.
- ▲ A “Lifelines Council” should be formed by the City of Los Angeles to develop and expand collaboration among lifeline providers serving the City and its residents. This council could improve the understanding of inter-system dependencies, share information, and establish coordination processes to enhance mitigation, emergency planning, and system restoration and reconstruction following a major disaster.
- ▲ An interdisciplinary “council” should be established to better link together water supply agencies and fire departments to address post-earthquake ignitions and ensure that there are adequate firefighting capabilities and water supplies for firefighting. Considerations should be given to state-wide standards for portable water supply systems, a LA-area high-pressure system using sea water, and requirements for gas shutoff valves.
- ▲ All lifeline providers should advocate for and collaborate in developing and implementing an Earthquake Early Warning System for California.
- ▲ The California Legislature should continue to support and authorize funding to provide dam owners resources to repair dams to withstand earthquakes. California should also support legislation for a National Dam Safety Rehabilitation Act to provide grants for rehabilitation of the most critical publically-owned dams. In addition, dam owners should prepare Emergency Action Plans to minimize risks to the public.
- ▲ The California Department of Public Health should change its “Boil Water Notice” to a “Tap Water Purification Notice,” as has recently been implemented by the LADWP. The “Boil Water Notice” makes many recommendations for water purification and should not encourage lighting of fires in a disaster situation.
- ▲ Consistent performance and restoration goals should be developed for all lifeline systems. Community-level lifeline system performance and restoration goals need to be created and applied consistently by all operators. Lifeline specific guidelines and standards for community resilience also should be developed.
- ▲ The regional economic impacts from major lifeline system disruptions should be assessed and quantified on a sector level and include system interdependencies.
- ▲ Lifeline system modeling and vulnerability analyses should be performed with the participation of critical infrastructure operators. The results could be used to implement prioritized mitigation plans consistent with asset management programs. Enhanced visualization results are needed for communicating with decision makers, city councils, and local governments. Maps identifying potential ground displacement hazards should be prepared because ground failure causes the greatest disruption to all lifeline pipes and cables.
- ▲ Telecommunications providers should standardize methods to ensure cell site power is continuously available after an earthquake.
- ▲ All lifeline operators should prepare emergency response plans consistent with known system vulnerabilities. Emergency response activities should be rehearsed and updated annually.
- ▲ Additional research is needed in the areas of dam safety and the role of utilities in making resilient communities.
- ▲ There needs to be funding and support for lifeline operators to continue learning and implementing lessons from other disasters (e.g., Christchurch, New Zealand, Tohoku, Japan).

Steel Structures

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FINDINGS

Looking back 20 years later, we know that the 1994 Northridge earthquake was a wake-up call for all involved in the design and construction of steel buildings in seismic applications. Up until that time, systems, practices, and methods had evolved based upon good intentions, but faulty assumptions. The innocence of those assumptions ended as the nature and extent of damage to the code-prescribed steel moment frame connection was realized. While there was no collapse of steel moment frame buildings in Northridge, the reality that the pre-Northridge welded flange/bolted web moment connection thought to be bulletproof was in fact flawed required answers and action.

The engineering profession and steel construction industry collaborated and the Federal Emergency Management Agency (FEMA) funded a very significant project, called the SAC Steel Project, as a joint venture of the Structural Engineers Association of California (SEAOC), the Applied Technology Council (ATC), and the Consortium of Universities for Research in Earthquake Engineering (CUREE). This project was extensive and successful, determining the root causes of the unexpected damage, advancing the understanding of what performance is needed, and developing systems, practices, and methods to achieve that performance.

FEMA's SAC Steel Project changed the landscape for steel design and construction in high-seismic applications. The SAC research and conclusions, which were documented in the FEMA 350-series publications, influenced and improved two parallel and complementary activities. First, there was direct collaboration with the activities of the Building Seismic Safety Council (BSSC) in their development of the National Earthquake Hazard Reduction Program (NEHRP) Provisions, a seismic design pre-standard in which system design requirements also were coordinated with load and system requirements in ASCE 7. Additionally, there was extensive coordination by SAC and NEHRP with the American Institute of Steel Construction (AISC) and their development of the AISC Seismic Provisions, AISC 341, which serves as the basis of building code requirements for design and construction of steel systems in seismic applications. The integrated, collaborative work done by these groups is a model of efficiency for all who seek to do such work in the future.

Today, steel seismic systems are designed and constructed in accordance with the AISC Seismic Provisions. The state-of-the-art today is very different from the very basic style of the information used before the Northridge earthquake and SAC Steel Project. Furthermore, this is true not only of steel moment frames. The AISC Seismic Provisions address many other systems as well, including concentrically braced frames, eccentrically braced frames, steel plate shear wall systems, buckling-restrained braced frames, and cantilevered column systems; systems of steel, and composite framing are addressed.

Special and intermediate moment frame systems have a supplemental document called AISC 358, which provides prequalified connections for use in routine design. It also is an option to use the results from project-specific testing or relevant tests performed by others as a basis for seismic steel moment frame design and construction. There are many choices of moment connections, most of which are in the public domain. AISC 358 also includes some proprietary moment connections as well.

The impact of the SAC Steel Project on steel design and construction today cannot be understated. With virtually every aspect of design and construction practice from before Northridge recognized as having contributed to the unexpected and unacceptable performance of these steel structures, many improvements have been made:

- ▲ Steel materials have been improved. Current steel materials and welding filler metals and processes provide improved seismic performance.
- ▲ Details of steel frames and their connections have been improved. The understanding of detailing requirements in the design phase, and the importance of proper configuration and adherence to procedures and processes in the construction phase, are both now well understood.
- ▲ Steel moment frames have been improved. Their member and connection requirements now are based on thorough research, first conducted by the FEMA-funded SAC Joint Venture and subsequently by others, including AISC.
- ▲ Steel braced frames have been improved. Braces perform better because current requirements better address the impact of wall slenderness and net section effects at slots in braces. Also, system performance is better because brace connections develop the strength of the brace, and our current analyses account for the effects of brace buckling.
- ▲ Many other systems also are now available, such as steel plate shear walls and buckling-restrained braced frames.
- ▲ Current inspection practices have improved through standardization of requirements in building codes and improved certification programs for fabricators and erectors.
- ▲ Education and awareness have been improved. Today, seismic steel design requirements are nationally disseminated in freely available standards like AISC 360, AISC 341, and AISC 358. Additionally the purpose, intent, and importance of the requirements in these documents are better understood.

Work continues to advance the state-of-the-art. The NEHRP Provisions continue to be developed, and the AISC Seismic Provisions continue to advance the capabilities and performance of steel seismic systems. AISC and others also continue to fund the research that drives the safety, quality, economy, and ease of design and construction of seismic systems in steel.

RECOMMENDATIONS

Ongoing research and development is needed to:

- ▲ Improve our understanding of the correlation between the seismic performance of individual components in tests and that in actual structures.
- ▲ Improve our understanding of the seismic behavior of tall steel buildings and steel buildings with heavily loaded columns.
- ▲ Improve our understanding of multi-tier braced frame behavior.
- ▲ Develop performance-based standards for seismic design of steel structures.

Additionally, the quality process needs to be understood when fabricators and erectors perform inspections instead of a third party with the waiver of third-party inspections now permitted in the 2012 International Building Code (2013 California Building Code).

Concrete Buildings

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FINDINGS

Significant damage to reinforced concrete (RC) buildings was reported following the 1994 Northridge earthquake despite the fact that shaking intensities were generally less than expected for code-level design earthquakes and that the fault rupture extended to the north, away from regions with the largest concentrations of older, more vulnerable, RC buildings. Damage included the partial collapses of the Kaiser Permanente building in Reseda, the Bullock's Department store in the Northridge Fashion Mall, and a relatively new 4-story parking structure at Cal State Northridge, as well as severe damage to the Barrington building and substantial damage to buildings at Saint John's Health Center in Santa Monica.

The magnitude MS 6.7 earthquake occurred under the San Fernando Valley community of Northridge, with strong shaking lasting in the range of 10 to 20 seconds. The earthquake occurred on a previously unknown fault with no observed surface rupture. According to the EERI Reconnaissance Report (EERI, 1994), over 60,000 buildings required inspection in Los Angeles, whereas estimates of red-tagged and yellow-tagged buildings in the affected region exceeded 2100 and 7000, respectively.

Design improvements for RC buildings implemented following the 1971 San Fernando earthquake very likely led to a reduction in damage to newer buildings, although significant vulnerabilities were exposed in these newer buildings, leading to important changes in RC building codes. For newer buildings, key observations included the need to develop improved design approaches to account for the interaction between lateral (earthquake) force resisting elements/systems and elements/systems used to resist gravity loads (commonly referred to in building codes as "deformation compatibility"), and to address issues associated with load paths, connections, and realistic strength demands (or over-strength) for floor systems (diaphragms) transferring loads to lateral-load-resisting elements, such as shear walls. The ground shaking in the Northridge earthquake also exposed vulnerabilities in older RC buildings, accelerating the development of recommendations for seismic rehabilitation of existing buildings (e.g., FEMA 273/274, FEMA 356, ASCE 41, and ATC-40). Senate Bill (SB) 1953, an amendment to and furtherance of the Alfred E. Alquist Hospital Seismic Safety Act of 1983, was introduced on February 25, 1994, to require evaluation and possible seismic upgrade of existing acute-care hospital facilities within a specified timeframe. The development of retrofit guidelines, the implementation of



Cal State Northridge parking structure after 1994 Northridge earthquake. (source: unknown)



Precast parking structure at Northridge Fashion Mall after 1994 Northridge earthquake. (source: unknown)



Damage to the north wing of Saint John's Healthcare Facility, Santa Monica, CA (source: J.W. Wallace)

SB-1953, as well as voluntary upgrades, has provided owners and engineers with numerous opportunities to evaluate and improve existing guidelines/standards to develop economical and innovative retrofit strategies.

Although significant progress has been made over the last 20 years to reduce the vulnerability of RC buildings subjected to strong shaking, major challenges still exist and recent observations from earthquakes in Chile (February 2010), New Zealand (2010–2011), and Japan (2011) suggest the potential for severe consequences despite this progress. Coordinated efforts to further assess and reduce the vulnerabilities associated with RC buildings should be aggressively pursued. Given this need, there are several important action items recommended.

RECOMMENDATIONS

- ▲ Expand efforts to improve standards for seismic retrofit of existing buildings (e.g., ASCE 41). These standards provide engineers with the background and tools needed to assess building vulnerabilities and to develop cost-effective strategies to mitigate these vulnerabilities.
- ▲ Increase resources to continue and expand the development of simplified assessment tools that can be used to identify buildings that pose significant collapse risk. These tools are currently being developed under the ATC-78 Project; however, current efforts are limited in scope and have not addressed buildings that include structural walls. Buildings with structural walls have typically been less susceptible to collapse; therefore, expanding the ATC-78 effort to address this deficiency should be a high priority.
- ▲ Continue support for research focused on improving our understanding of building collapse, including shake table tests of complete building systems, and the development and validation of analytical tools that capture experimentally observed behavior.
- ▲ Allocate resources to prepare comprehensive inventories of existing buildings. These inventories should then be used to assess risk, develop mitigation strategies, and to track progress on risk reduction.
- ▲ Prepare standards that focus on limited or incremental retrofit, i.e., cost-effective approaches that address vulnerabilities associated with buildings that pose the highest risk, by allowing deficiency-only retrofit of the most vulnerable building elements (e.g., wrapping of moment frame columns, strengthening of columns under discontinuous walls, and retrofit of weak first-story conditions).
- ▲ Promote development of a Building Rating System similar to the LEED certification and restaurant-rating system, to be used for property transfer, insurance, mortgage, building users, and tenants. In parallel, develop and implement an education and community outreach plan for business and community leaders, building owners, and the general public.
- ▲ Establish deadlines for completion of limited and comprehensive retrofit of vulnerable buildings.
- ▲ Identify financial incentives, such as low-interest loans, tax relief, and zoning relief, or eliminate costly requirements for ADA and other building improvements that impede progress toward risk reduction.
- ▲ Establish mechanisms to take advantage of the City of Los Angeles building instrumentation program and identify funding sources to develop integrated sensor networks to study issues associated with complex buildings and system interactions that focus on service-level and collapse-level shaking, as well as sustainability issues.

Wood-Frame and Soft-Story Buildings

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FINDINGS

The January 17, 1994, Northridge earthquake impacted wood-frame construction to a degree greater than experts had anticipated. The only collapses were of weak-story apartment buildings and hillside homes, i.e., buildings with significant irregularities. However, the overall amount of damage, and thus economic losses, to wood-frame buildings was far higher than experts had anticipated. Specifically:

- ▲ 24 of the 25 fatalities were caused by building damage that occurred in wood frame buildings.
- ▲ At least half of the \$40 billion in property damage was due to damage to wood buildings.
- ▲ 48,000 housing units, almost all in wood-frame buildings, were rendered uninhabitable.

A major outcome of the 1994 Northridge earthquake was the way it changed how wood research projects were funded and organized. Previously, both USDA and NSF funded individual projects that, while productive, lacked the synergy that can be developed by larger more professionally diverse groups. The first of these projects was the CUREE-Caltech Wood Frame Buildings Project, which was funded by the state and FEMA. Its goal was to “advance the (seismic) engineering of wood frame buildings and improve the efficiency of their construction for targeted performance levels.” It had five elements: Testing and Analysis; Field Investigations; Codes and Standards; Loss Estimation; and Education and Outreach. It advanced the state of knowledge of wood-frame construction and our ability to predict and improve performance, and led the way by setting a blueprint for projects that used project teams made up of engineering professionals and analysts.

The NEESWood and NEES-Soft projects followed, as well as efforts in Canada by University of British Columbia and FPInnovations, with additional efforts as far away as Chile. Broader implications resulting from the Northridge earthquake and the CUREE-Caltech project were: (1) development of better testing approaches for wood (CUREE Protocol); (2) the first consensus standard for wood published in 2001 (SDPWS); (3) wood-frame construction was benchmarked and found to provide life safety but sustain significant damage, and; (4) projects leading to the development of performance-based seismic design for wood-frame construction.

The results of these research programs have led to the development of several design guidelines for wood-frame construction and retrofitting, including:

- ▲ FEMA 232, *Homebuilders Guide for Earthquake Resistant Design and Construction*, which provides guidance on the seismic provisions of the International Residential Code.



Northridge earthquake soft-story failures
(source top: unknown; bottom: FEMA News Photo)

- ▲ FEMA P-50, *Simplified Seismic Assessment of Detached Single Family Wood Frame Dwellings* and FEMA P-50-1, *Seismic Retrofit Guidelines for Detached Single Family Wood Frame Dwellings*; originally developed for Los Angeles but since nationalized to provide a residential rating system and a related retrofit guide.
- ▲ FEMA P-807, *Seismic Evaluation and Retrofit of Multi-Unit Wood Frame Buildings with Weak First Stories*, which was the basis for the recent San Francisco mandatory retrofit ordinance for weak-story multi-story residential buildings.

RECOMMENDATIONS

As engineers look to the future, improvements are still needed to guide earthquake research and its translation into engineering practice for wood-frame design and retrofit to close the gap between state-of-the-art analysis tools and full building performance to provide reliable prediction of strength, deflection, and collapse. These include:

- ▲ Better guidance for seismic evaluations and retrofits for existing buildings.
- ▲ Comprehensive testing of floor diaphragms.
- ▲ Design guidance for selection of systems to achieve the desired levels of performance.
- ▲ Simplified rules for designers to distribute force and achieve certain levels of performance.
- ▲ Improved calibration of nonlinear time history models and incorporation of pinched wood hysteresis.
- ▲ Development of performance-based seismic design guidelines for wood buildings.
- ▲ Investigate hybrid systems, including developing technologies such as cross laminated timber.
- ▲ Testing of archaic building materials and pre-engineered moment frames.
- ▲ A better understanding of soft-story wood buildings through numerical analyses and experimental testing.
- ▲ Develop improved models of wood-frame collapse mechanisms to better estimate the margin against collapse.
- ▲ Further development of displacement-based design methodologies.

From the perspective of design guidelines, we need simplified design tools that capture actual building behavior that can communicate anticipated performance to nontechnical community in a responsible and realistic fashion. We also need screening tools to quickly identify vulnerable building configurations that rise to the level of requiring detailed evaluation. In addition, quality of construction and resulting building performance issues also remains a significant concern.

Further, there needs to be a consolidation of the guidelines that address various aspects of seismic protection, and from that develop a consensus standard that can then be referenced in model building codes. Such a standard would encourage seismic retrofitting programs and allow for more consistent enforcement of the codes. This is the goal of a recently announced ATC project funded by the California Earthquake Authority and FEMA.

From the public policy side, our greatest risk is from the vast population of structures that were built prior to current building codes. Our primary recommendation is to encourage seismic retrofitting of at-risk structures, particularly of weak-story wood-frame buildings, using guidelines such as FEMA P-807. However, it is important that building owners also understand that: (1) the building code is only a minimum standard that is designed to protect life safety but may not prevent damage and the possibly loss of use of the structure; and (2) some seismic retrofitting techniques will not necessarily bring their building up to new code-level performance.



The NEES-Soft Project's four-story soft-story building specimen prior to testing on the NEES@UCSD shaking table (source: M. Gershfeld)

Performance-Based Earthquake Engineering

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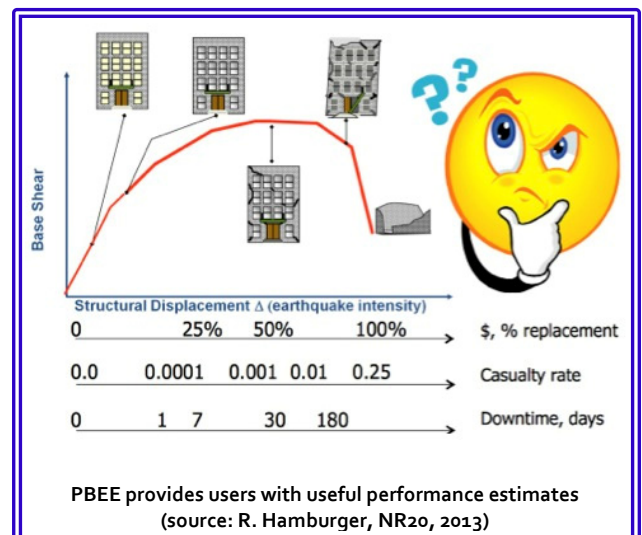
FINDINGS

Performance-based earthquake engineering (PBEE) is one of the most transformative earthquake engineering concepts to emerge during the past two decades. Traditionally, structures are designed using prescriptive building codes. These codes are intended to achieve buildings that have an acceptably low probability of collapse during future earthquakes. Although these codes contain provisions to mitigate excessive damage during small, frequent events, and the public often has the impression that code-compliant buildings are “earthquake proof,” modern seismic codes are not intended to limit damage or maintain function in the event of major ground shaking. As such, the performance of new structures during the 1994 Northridge and other earthquakes varied greatly from one building to the next. Moreover, the prescriptive nature of modern codes does not easily allow for evaluation of their likely behavior nor for the design of structures for which enhance performance is desired. PBEE procedures have been developed to meet these and similar challenges.

PBEE provides a systematic, scientifically sound framework for integrating information about earthquake hazards, structural response, damages and consequences, and characterizing seismic risk in a form useful to a wide range of stakeholders. For instance, design engineers may be concerned about technical response quantities such as forces and displacements, while owners or public officials may want information on likely downtime, repair costs, or casualties. Such performance-oriented information can be used to make sound decisions related to the need for seismic retrofit of existing structures, the potential costs and benefits of alternative designs for new construction, the need for and proper cost of earthquake insurance, and so on. At its simplest, PBEE lists performance goals for different levels of seismic hazard, identifies specific engineering or loss-related quantities to be checked to insure that a performance goal is achieved (acceptance criteria), and stipulates appropriate engineering methods to carry out the required calculations.

The Northridge and other earthquakes demonstrated the risk posed by existing buildings constructed before the advent of modern seismic codes. As such, one of the first applications of PBEE concepts was the evaluation and rehabilitation of existing buildings. As described by Robert Pekelnicky, ASCE 41 was developed to provide nationally applicable performance-based standards for assessing existing buildings. Building owners, regulatory officials, and other stakeholders can now use these standards in a logical and transparent manner to decide on the seismic performance desired for an existing building.

PBEE methods have also found widespread use in designing new structures that do not conform to the narrow prescriptive requirements of current building codes. For example, codes limit the height and other features of tall buildings compared to current architectural trends. Farzad Naeim and Jack Moehle discussed specific applications of PBEE methods to develop special PBEE guidelines for seismic evaluation of tall buildings. These presentations highlighted the power of PBEE methods and results in guiding the design of new or unusual classes of buildings. John Hooper examined actual cases where new buildings were designed using PBEE (ASCE 41) methods by demonstrating that the structures would achieve performance comparable or better than stipulated by building codes. Ronald Hamburger and Vesna Terzic examined



recent extensions to PBEE methodologies included in Seismic Performance Assessment of Buildings (FEMA-P-58). The use of PACT, a Performance Assessment Computation Tool (FEMA-p-58-3.1), to estimate structural and nonstructural damage, repair costs, down time, business interruption costs, and so on was described for scenario events or over the life of a structure. Such PBEE methods provide attractive ways to compare the cost and performance of alternative designs.

CONCLUSIONS AND RECOMMENDATIONS

Performance-based earthquake engineering provides design professionals with a practical framework and set of tools for characterizing the performance of structures subjected to future earthquakes. As such, PBEE has found considerable use where traditional prescriptive building code based approaches are not applicable. In particular, PBEE concepts have found increasing application in (a) evaluating and retrofitting of older, potentially vulnerable buildings, (b) evaluating, repairing and upgrading buildings damaged by earthquakes, (c) designing new structures that do not conform to the limitations imposed by prescriptive design codes, and (d) designing new structures for enhanced levels of performance. By expressing performance in terms such as the likelihood of post-earthquake functionality, collapse, repair costs, downtime, casualties, and so on, PBEE provides a direct and effective means of communicating performance expectations among the relevant stakeholders. To advance the use and effectiveness of PBEE, several high-priority actions are recommended.

- ▲ The use of PBEE in real world applications should be expanded to better achieve targeted performance goals and to improve understanding of the benefits and limitations of the PBEE methodology.
- ▲ Continued research and development efforts are needed to benchmark and improve the predictive capabilities of PBEE procedures, to improve accuracy and reduce unnecessary conservatism where possible, and characterize more fully the uncertainties involved. Thus, coordinated and integrated efforts are needed to:
 - ▼ Improve the ability of computer analysis procedures and related numerical models to accurately predict the full range of behavior observed during earthquakes and laboratory tests. To this end, seismic instrumentation should be installed in buildings, especially those designed or retrofitted using PBEE methods, to speed improvement of PBEE methods following future earthquakes.
 - ▼ Gather data from laboratory experiments, and, especially, actual buildings following earthquakes, to extend and improve relationships between structural response quantities and the damage to various structural and nonstructural elements, and contents, and between damage and losses (e.g., costs associated with repair, business interruption, etc.).
 - ▼ Benchmark current PBEE tools against actual performance observed in recent earthquakes.
- ▲ Systematic studies are needed to better identify the types and characteristics of structures and nonstructural systems that can easily and economically lead to improved performance.
- ▲ Similarly, PBEE methods have already been useful in developing specific evaluation techniques for special classes of structures, such as existing buildings, tall buildings, etc. Similar efforts might develop more detailed guidelines for evaluating and enhancing the performance of other types of structures, such as essential or hazardous facilities or buildings with special or high-value occupancies.
- ▲ Although PBEE is frequently used to show performance equivalent to current code expectations, or to demonstrate adequate performance for temporary or non-critical facilities, greater emphasis is being placed on increasing seismic resilience, reducing damage, and improving sustainability. PBEE should play a major role in developing new systems and design methods to achieve enhanced levels of seismic performance.
- ▲ Because PBEE involves advanced analysis methods and other procedures not included in traditional code based design, improved educational resources and training courses are needed to fully realize its potential.
- ▲ PBEE concepts and tools should be extended to include non-building structures, communities and lifelines.

Business, Insurance, and Financial Implications

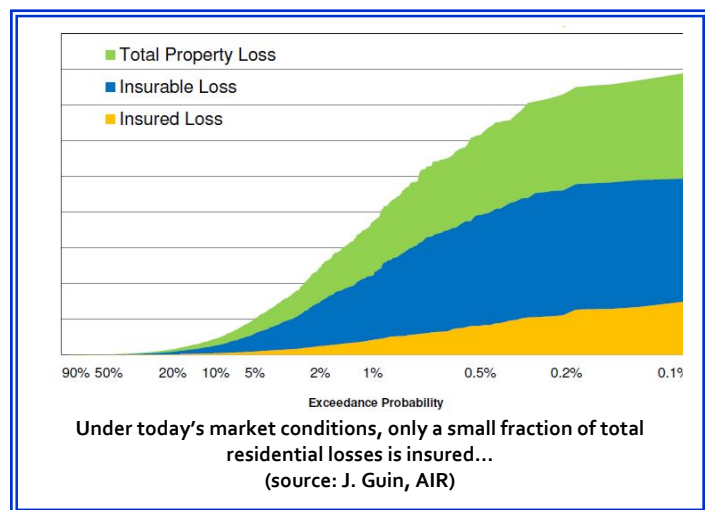
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FINDINGS

At the time of the 1994 Northridge earthquake, catastrophe risk modeling was in its infancy; few property insurers used catastrophe models, and most earthquake risk assessment was based on previous loss experience. Further, the data available to model exposures was incomplete or inaccurate.

The Northridge earthquake caused a significant amount of damage and economic loss to the Los Angeles area. Total economic losses have been estimated to be on the order of \$40 billion dollars. Documented insured losses reached \$12.5 billion (\$8.4 billion residential, and \$4.1 billion commercial). At the time of the earthquake, approximately 40% of the impacted homeowners had residential earthquake insurance; today, statewide that figure is less than 10%. The low demand for earthquake insurance is due, in part, to the fact that there is no mortgage requirement for earthquake insurance, unlike wind, fire, and in some cases, flood coverage. Price and high deductible also play a role in the low take-up of insurance. However, ample capacity is available through the reinsurance and capital markets as they have learned how to re-supply capital quickly after a large event (such as after Katrina) to back up primary insurers that provide natural catastrophe insurance. Sufficient capacity is available for earthquake insurance: increased take-up could result in more efficient delivery of insurance and reinsurance products that could ultimately increase access for all property owners at risk.



The Northridge earthquake spawned a myriad of research on earthquake hazards and vulnerability leading to improved catastrophe models, including:

- ▲ Improved seismic hazard maps.
- ▲ Major engineering studies, such as the SAC Steel Project, the CUREE-Caltech Wood Frame Project, and the Tall Building Initiative (TBI), which are discussed in more detail in other parts of this report.
- ▲ Lessons learned from earthquakes in other countries (1995 Kobe, Japan, 1999 Chi-Chi, Taiwan, 1999 Izmit, Turkey, and more recently the 2011 Honshu Japan and 2010–2011 New Zealand earthquakes).
- ▲ Lessons learned from other perils, including loss amplification.
- ▲ Improved treatment of fire following earthquake, industrial exposures, business interruption, and demand surge.

Using current catastrophe modeling techniques, participants have estimated potential losses in a repeat of a Northridge-type event include:

- ▲ Economic losses ranging from \$90 - \$155 billion (\$32 - \$76 billion residential, and \$59 - \$82 billion commercial/industrial).
- ▲ Insured losses ranging from \$12 - \$24 billion (\$4 - \$8 billion residential, \$8 - \$17 billion commercial/industrial).

These predicted losses fall somewhere in the range of a 50 to 100 year return period loss for the Los Angeles area, meaning that we have at least a 2% probability of a loss of this size every year. When such an event occurs, due to the lower take-up rates the amount of uninsured loss will be much greater than from the Northridge event. While much planning focuses on larger, regional events, moderate urban events like Northridge and Christchurch can pose significant risk in terms of their frequency of occurrence and ultimate economic loss.

Clearly businesses in Los Angeles have done a better job in addressing the challenge of earthquake catastrophes. This is especially the case for medium and large businesses, as they have a heightened awareness of the risks, both physical and fiscal, that are faced in the aftermath of a significant urban event. Risk managers must understand that earthquake risk must be managed using a combination of insurance, mitigation, and recovery planning. Panelists recognized that no single method can answer all of requirements of a thriving business, especially if that business needs to maintain market share in a competitive environment. Several panelists noted that small businesses, similar to residential property owners and tenants, under recognize the importance of addressing earthquake risk, as evidenced by the low insurance take-up rates in both sectors.

The panelists did not reach consensus on the most appropriate role for government. While all parties agree that a primary role for Federal and State government is the provision of innovation and incentives for mitigation and recovery planning, others assert that a limited federal guarantee for post-event bonds issued by eligible state programs would reduce the cost of earthquake insurance and increase the funding for mitigation and education. The benefits of these investments will be numerous, including easing the burden on communities for emergency response, avoiding job losses, avoiding displaced populations, avoiding environmental impacts from building debris and other pollution releases, and avoiding capital destruction. Insurance rates that reflect the actual risk posed by the hazard and the likely performance of buildings will continue to help individuals and businesses see the economic and life safety benefits of mitigation. An objective, risk-based focus, coupled with government incentives (e.g., property tax breaks for mitigation investments) and financial preferences (e.g., better loan rates for mitigated buildings), will enable communities to deal with the largest element of the catastrophe risk problem: buildings that are already built, but in their current state will not perform well in significant earthquakes. We only need to look at the aftermath of the Christchurch earthquake to understand the destructive effects of urban earthquakes to the historical, cultural, and financial center of a city.

KEY RECOMMENDATIONS AND NEXT STEPS

- ▲ Develop and promote tools to help California residents understand, evaluate, and mitigate their risk of loss from damaging earthquakes.
- ▲ Continue to increase the awareness, affordability, and value of earthquake insurance.
- ▲ Develop and promote mitigation opportunities for California residents, including structural and non-structural retrofits.
- ▲ Encourage government to prioritize mitigation of private buildings through funding, code development, financing, etc.
- ▲ Establish a statewide working group to fulfill the Northridge 20 recommendations and promote seismic resiliency.

Resilience Case Studies and Tools

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FINDINGS

This session defined seismic resilience as the ability of the city to: (a) contain the effects of earthquakes; (b) carry out recovery activities in ways that minimize social disruption; and (c) rebuild in ways that mitigate the effects of future earthquakes.

Since the 1994 Northridge earthquake, major cities and institutions in California have made significant efforts in lowering risk through building code improvements, developing programs to mitigate the impacts of earthquakes on privately owned buildings, upgrading or replacing government-owned properties and hospitals, and planning for recovery. In addition, federal agencies, such as the Federal Emergency Management Agency (FEMA) and the National Institute of Standards and Technology (NIST) have funded the development of tools for mitigating the impacts of earthquakes on the built environment.

The City of Los Angeles experienced six presidentially declared disasters between 1991 and 1994, including wildfires, floods, and the 1992 civil unrest. As such, the city developed a well-organized response to emergencies, including the establishment of an Emergency Management Department in 2000. Post-Northridge, Los Angeles developed creative approaches to rebuilding multi-family housing with inclusionary affordable units, proposed voluntary guidelines for repair of steel frame and soft-story buildings, and began a program for installing 30,000 gas shut off valves per year. Other city programs, such as the Adaptive Reuse of downtown industrial buildings for residential lofts, added to the overall resilience of the city, as the change of use triggered seismic retrofits.

San Francisco has taken a pro-active stance in planning for resilience, as evidenced by the San Francisco Planning and Urban Research (SPUR) efforts to (1) Define the concept of resilience in the context of disaster planning and recovery; (2) Establish performance goals for the “expected” earthquake that supports the definition of resilience; (3) Define transparent performance measures that help reach the performance goals; and (4) Recommended next steps for San Francisco’s new buildings, existing buildings, and lifelines. Reports and recommendations can be found at SPUR’s website: <http://www.spur.org/spur-program/disaster-planning>. In addition, the city created the Community Action Plan for Seismic Safety (CAPSS), which resulted in a mandatory seismic retrofit ordinance for soft-story apartment buildings of three or more stories and with five or more units, and organized neighborhood groups to plan for post-event recovery.

Institutions such as universities and hospitals have also made great strides in resilience planning. Cal State Northridge (CSUN) shared its experience with other institutions, including many from overseas. The University of Canterbury in Christchurch, New Zealand, learned a great deal from CSUN. As such, they were prepared for the 2010–2011 earthquakes, and they were able to help the larger city during the emergency. Similarly, after the poor seismic performance of older hospitals and widespread damage to nonstructural components in newer hospitals during the Northridge earthquake, the state of California enacted Senate Bill (SB) 1953, which updated the building standards program of the Office of Statewide Health Planning and Development (see http://www.oshpd.ca.gov/fdd/seismic_compliance/SB1953/) to “address the issues of survivability of both nonstructural and structural components of hospital buildings after seismic events.” The act applied to all 470 general acute-care hospital facilities statewide (comprised of approximately 2700 hospital buildings). Subsequent legislation has provided for additional time to comply, and the final date for all hospital buildings to be reasonably capable of providing services to the public following strong ground motion is January 1, 2030.

Tools that can be used by many communities have been developed by cities and technical organizations. San Francisco's CAPSS program has led to the creation of the Earthquake Safety Implementation Program—a 30-year plan for improving resilience in the city. Retrofit ordinances, coordination among city agencies, and public outreach are critical to the approach. The Applied Technology Council (ATC) developed engineering procedures in FEMA P-807 for evaluating and retrofitting weak-story wood-frame residential buildings. Another tool, also developed by ATC, is the FEMA P-50 report, *Simplified Seismic Assessment of Detached, Single-Family, Wood-Frame Dwellings*, and the companion FEMA P-50-1 report, *Seismic Retrofit Guidelines for Detached, Single-Family, Wood-Frame Dwellings*. These publicly available tools can be used across the United States to grade houses and give owners and/or potential buyers an understanding of seismic hazards and provide retrofit recommendations.

Overall, resilience is a long-term effort by governments, communities, and institutions to prepare for the next disaster with pre-event mitigation and with planning for post-event recovery strategies.

CONCLUSIONS AND RECOMMENDATIONS

- ▲ Individual preparedness is the most critical step; and preparedness education need to be relevant, understandable, and in many cases, personal.
- ▲ A community is stronger if organizations and institutions contribute by being independently prepared; this attitude should be supported and fostered.
- ▲ Disaster risk reduction is the concept and practice of reducing disaster risks through:
 - ▼ Systematic efforts to analyze and reduce the causal factors of disasters.
 - ▼ Reducing exposure to hazards.
 - ▼ Lessening vulnerability of people and property.
 - ▼ Wise management of land and the environment.
 - ▼ Improving preparedness and early warning for adverse events.
- ▲ "It takes a village," that is, local government, civic groups, and neighborhood organizations all need to be involved in recognizing risks and planning for a more resilient future.
- ▲ Mandatory seismic hazard reduction programs, developed with the input of local stakeholders, work; voluntary programs don't.
- ▲ Technical tools exist to reduce the seismic hazards of a broad range of vulnerable structural types, including residential wood-frame buildings with weak first stories.

Risk Communication: Tools and Resources for Policymakers

LESLIE CHAPMAN-HENDERSON AND LUCY JONES

FEDERAL ALLIANCE FOR SAFE HOMES AND U.S. GEOLOGICAL SURVEY

FINDINGS

In the ongoing effort to make California communities more resilient to the effects of damaging earthquakes, the Northridge 20 Symposium hosted two risk communication panels that offered insights and fostered discussion on achieving greater seismic safety education and awareness. The panels were represented by experts in seismology, social science, communications, emergency management, education, and disaster safety.

The first panel focused on opportunities to advance earthquake awareness and policy based on lessons learned and best practices in strategic communications research. The panel included Dr. Lucy Jones, Seismologist with the U.S. Geological Survey; Dr. Roxane Cohen Silver, University of California, Irvine; and Chris Nance, Chief Communications Officer with the California Earthquake Authority (CEA).

IMPORTANCE OF CLEAR, SIMPLE MESSAGES IN TIMES OF DISASTER

Dr. Lucy Jones, who was responsible for much of the public communication following the 1994 Northridge earthquake, stressed the value of presenting scientific information in a manner that is not just technically correct, but is perceived correctly and informs people what they need to be safe in a way that is meaningful and relevant based on research on how people perceive risk. Specifically, she referenced work in the psychology of risk perception that has shown that several factors make effective communication more difficult, including misunderstanding of probabilities, widespread innumeracy, and how uncertainty contributes to fear. Scientists and engineers express uncertainty to be technically correct, but the general public perceives the discussion of uncertainty as demonstrating lack of knowledge. According to Dr. Jones, effective risk communication is grounded in clear and simple messages that (1) concentrate on consensus understanding shared by the technical community and (2) minimize discussion of the areas of dissent in the scientific community. In times of crisis, emphasis on what is not understood increases fear. Long-term education outside of a crisis is the time for helping the public understand the scientific process. She specifically pointed to the global groundswell of participants in the Great ShakeOut, an innovative research project and public awareness campaign she initiated in 2008 for California.

The research of Dr. Roxane Cohen Silver, an international expert in the field of stress and coping, suggests that it is easier to design effective and targeted messages if we pay closer attention to how the public responds following a disaster. Based on more than 30 years of research on the psychological impacts of various disasters, including the Southern California firestorms and the 2006 and 2010 earthquakes in Indonesia and Chile, respectively, the psychological effects of disasters often extend beyond those directly impacted. In her research on residents experiencing post-traumatic stress disorder (PTSD) following the Chile earthquake, 18.6% of residents at the epicenter reported PTSD symptoms and more than 250 miles away, 17.6% of Santiago residents reported similar levels of symptomatology. Dr. Silver noted there are several factors that predict resilience to disasters, such as community support and solidarity, experience in coping with stressful events, and confidence in authorities. She also shared that those who develop disaster plans and are prepared are typically older, more educated, and have prior experience with a natural disaster. Those who are more educated and have children living at home practice them.

IMPORTANCE OF MESSAGING THAT COMBINES WHAT TO DO WITH HOW TO DO IT

Chris Nance based his presentation on three recent game-changing research studies. The first study recommended distribution of messages that combine what to do with why to do it, saying the same thing through different organizations, and saying the same thing through different campaigns that work together. The second study reported that over 80% of California residents receive information about earthquake preparedness from television anchors, that (previous) messages on earthquake preparedness and mitigation developed for California have low market penetration, and recommended coordination of content and dissemination efforts for delivery of an ongoing stream of communications across time and targets.

Mr. Nance then discussed the third research study that identified the emotional values (why to do it) that should be central to future preparedness communications. He showed how the same values-based messages can be shared effectively through both short-term (kits, plans, be informed; drop, cover, and hold on) and long-term (insurance, structural mitigation) preparedness campaigns that appeal to emotional demands for survival, recovery, and returning to normal activities after an earthquake strikes.

Mr. Nance showed how the CEA, American Red Cross, and Earthquake Country Alliance have been working together to share values-based messages through coordinated preparedness campaigns. Specifically, they've produced public service announcements featuring different TV news reporters on 21 stations, representing five networks in six markets statewide, who are reading the same values-based script. Mr. Nance revealed CEA's new campaign for 2014 called California Rocks!, which aligns with shared, values-based calls-to-action coordinated with other campaigns through a double entendre—California Rocks as a cool place to live, yet California Rocks with earthquakes, too.

The second panel focused on creating a culture of prevention and highlighted tools and tactics for enhancing earthquake preparedness and mitigation. Panelists included Barbara Harrison, Project Manager for the Federal Alliance for Safe Homes (FLASH)®; Mark Benthien, Global Coordinator for Great ShakeOut Earthquake Drills and Executive Director of Earthquake Country Alliance; and Carmen Mackey, Community Services Liaison for Division V of the Los Angeles County Fire Department.

IMPORTANCE OF COMMUNICATION TACTICS THAT ARE CONSISTENT AND FREQUENT, INCLUDE MULTIPLE PARTNERS AND ENGAGE COMMUNITY LEADERS

Mark Benthien presented an overview of the Great ShakeOut Drill, an annual multi-state, multi-country all sector preparedness event during which millions of people learn how to protect themselves by practicing "Drop, Cover, and Hold On!" The drill originated from the "ShakeOut Scenario" created by USGS and many partners for a 7.9 magnitude earthquake. The core practices of the ShakeOut incorporate and validate research by Mileti, Bourque, and others to promote consistent information about what to do—and do it frequently—in many forms and from many sources; allow participants to see others like them getting prepared; encourage them to talk about preparedness with people they know; and learn potential consequences and how to avoid them. The ShakeOut involves both public and private partners working together to improve preparedness, mitigation, and resilience by using a whole community approach with customized information for more than 20 categories of participants on www.shakeout.org.

Barbara Harrison presented an overview of the outreach activities associated with the promotion of the QuakeSmart Business Toolkit (FEMA P-811). The toolkit, also translated into Spanish, explains the risks for structural and nonstructural damage, contains useful business continuity information, and provides specific instructions on how to mitigate earthquake losses. FLASH has promoted the toolkit through professional associations, reaching 150 association executives and nearly 14,000 small businesses.

FLASH has also undertaken the development of the Mitigation Outreach Academy with two levels of activation for volunteer advocates and leadership advocates. The academy will provide volunteers with an outreach toolkit containing messaging in multiple formats, which include talking points, social media messages, PowerPoint slides, training videos,

FLASH cards, and resource lists. Also contained in the toolkit are Volunteer Playbooks/Guidebooks specific to a community's needs post-disaster to help volunteers easily incorporate mitigation into the repair and retrofitting of homes.

Carmen Mackey shared the success of the QuakeSmart Mitigation Inspection Program recently undertaken by the L.A. County Fire Department. The program incorporates earthquake mitigation inspections into annual fire inspections of the community's small businesses. The inspections are voluntary and provide the business owners with tips and tools to help them prepare their businesses and their employees for an earthquake by using the checklists found in the QuakeSmart Business Toolkit. The department is in Phase II of the pilot and plans to expand the program to additional fire departments in Antelope Valley.

CONCLUSIONS

In summary, key recommendations from Risk Communication panelists include:

- ▲ Using clear and simple messages in times of crisis.
- ▲ Helping the public better understand technical, scientific information through long-term educational efforts.
- ▲ Designing and targeting messages that combine what to do with why to do it, and then consistently and frequently disseminating those messages through different organizations.

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