SECURING SOCIETY AGAINST CATASTROPHIC EARTHQUAKE LOSSES

A Research and Outreach Plan in Earthquake Engineering

JANUARY 2003

EARTHQUAKE ENGINEERING RESEARCH INSTITUTE

EXECUTIVE SUMMARY

Earthquakes are a threat to the United States, capable of causing levels of destruction and loss in the built environment that equal or exceed those due to the terrorist attacks of September 11, 2001. The average annual financial loss associated with U.S. earthquakes is $10 billion for buildings, transportation networks, other lifeline systems, and business disruption. A single large earthquake could cause losses in excess of $100 billion to the built and human environment, more than twice the loss in the 1994 Northridge earthquake, the most costly U. S. earthquake to date.

THE RESEARCH AND OUTREACH PLAN

The Research and Outreach Plan proposed in this report presents a vision for a society that is aware and concerned about the vulnerability of its built environment. Earthquakes are catastrophic risks that need to be addressed in a more concerted way than they have been to date. Doing so provides benefits for society through safeguards from earthquakes as well as the preparedness and technology to address other catastrophes. The investment in this Plan will be paid back many more times through the security of the nation's citizens and the protection of the economic vitality of the United States from disasters.

In 1977 the United States Congress established the National Earthquake Hazard Reduction Program (NEHRP) in response to the threat of large earthquakes. Much has been accomplished under NEHRP in the past 25 years. Nevertheless, the incremental approaches to improvements in the past will not protect society in the future. The protection of human lives, which was central to the goals of NEHRP, is necessary but not sufficient to minimize the social and economic impacts of major earthquakes because of population growth, very rapid economic expansion, and the increasing interconnectedness of society and its infrastructure.

We have the unprecedented opportunity to build on the existing knowledge gained from past research, to create new knowledge that will address the reasons for increasing losses, and to use revolutionary advances in information technology to develop the means for preventing catastrophic losses from earthquakes. The proposed Plan will provide the tools for protecting against catastrophic earthquake losses. The Plan comprises the following five research and outreach programs:

Understanding Seismic Hazards: developing new models of earthquakes based on fundamental physics.

Assessing Earthquake Impacts: evaluating the performance of the built environment by simulating performance of structures and entire urban systems.

Reducing Earthquake Impacts: developing new materials, structural and non-structural systems, lifeline systems, tsunami protection, fire protection systems, and land use measures.

Enhancing Community Resilience: exploring new ways to effectively reduce risk and improve the decision-making capability of stakeholders.

Expanding Education and Public Outreach: improving the education of engineers and scientists from elementary school to advanced graduate education, and providing opportunities for the public to learn about earthquake risk reduction.

The research tasks will develop the science, engineering, and societal approaches necessary for making better risk management choices to prevent catastrophic losses. The outreach tasks for each program will facilitate the transfer of research findings into practice, an essential step to the implementation of successful risk management.

This Plan was prepared by a panel of earth scientists, earthquake engineers, and social scientists involved in research and professional communities throughout the United States. The Earthquake Engineering

Research Institute (EERI) formed this panel with financial support from the National Science Foundation. EERI is a national, nonprofit technical society of engineers, geoscientists, architects, planners, public officials, and social scientists.

BUILDING SAFER COMMUNITIES

Achieving the goal of catastrophic loss prevention rests not only on breakthrough technologies but also on the incorporation of research results into professional practice and decision-making. The translation of research knowledge into practice is not simply a question of disseminating research findings. The advances discussed in this report entail fundamental changes in engineering practice and in decision-making about seismic risks.

Much of the attention in earthquake engineering is focused on individual structures and systems—a building, bridge, or water supply system—and decisions that are made about the seismic integrity of these structures and systems. From a societal perspective, however, more is involved than these decisions to improve earthquake risk management for a community. Loss-reduction strategies that address specific structures and systems are important, but protecting the social fabric of our communities against earthquake losses necessitates more comprehensive and holistic approaches. Seismic safety is a matter of public welfare, involving the potential for loss of life or injury, disruption of lifeline systems, and costs to insurers, property owners, and governments for earthquake losses and recovery. These issues make it important to consider the extent to which communities are resilient to the damaging effects of earthquakes.

THE REVOLUTIONARY ROLE OF INFORMATION TECHNOLOGY

A central focus of earthquake engineering research in the next twenty years will be to merge current and future information technology advances—including significant adaptations and new developments—into the practice of earthquake engineering, with the objective of radically reducing the currently large uncertainty associated with hazard, performance, damage, and loss prediction of the built environment. Relevant technologies include inexpensive, accurate, and low-power sensors communicating in distributed, wireless networks to collect data on performance of the built environment; new simulation tools utilizing high-end computing systems; and data visualization, data fusion, and decision support systems. Each of these technologies has important applications for pre-event mitigation and post-event response, in addition to providing new tools to help communities understand the impacts of earthquakes and other disasters as well as examine the effects of mitigation decisions.

Information technology is already being adopted in earthquake engineering. It is perhaps most apparent in two applications central to the Plan's vision: the George E. Brown, Jr., Network for Earthquake Engineering Simulation (NEES) and the Advanced National Seismic System (ANSS). These two initiatives promise to provide a major impetus for achieving the goal of this Plan. NEES is a new major research equipment, computation and networking initiative of the National Science Foundation, whose main goal is to expand the state of knowledge in earthquake engineering through new methods for experimental and computational simulation. ANSS is an initiative of the U.S. Geological Survey, acting in collaboration with scientists from universities, private industry, and state governments, to modernize strong motion seismographic networks in the United States.

THE COSTS AND BENEFITS

We have estimated that the funding for the Plan will require \$358 million per year for the first five years of a twenty-year program. The plan includes funding for current activities within the NEHRP agencies. The total estimate for the twenty-year plan, including capital investments, is \$6.54 billion. We expect that the funds would ramp up at a 15% annual rate over the first five-year period of the Plan. After the ramp-up, it is estimated that the annual cost of research using the NEES facilities will be about \$75 million, which is included in various items in the detailed budget breakdown.

The successful accomplishment of this Plan will require a high level of coordination among the NEHRP agencies as well as other federal agencies and state and local government organizations, the earthquake engineering research community, organizations responsible for promulgation of building codes, engineering professionals, and government officials.

The benefits of the proposed Plan are not limited to preventing catastrophic losses from earthquakes. Plan outcomes will also provide substantial benefits for homeland security and other initiatives to increase the resilience of communities to extreme events. Through advances in the design of buildings and facilities, planning measures for addressing population growth and land use, and technologies which address emergency management and recovery, the initiatives presented in this report complement and enhance programs to reduce the threat of terrorist attack and harmful effects of other extreme events such as blast, wind, flood, and fire.

The breakthrough opportunities in earthquake engineering presented in this report hold the promise of preventing catastrophic losses from major earthquakes in the United States. More comprehensive and systematic approaches to managing earthquake risks will be fostered by use of performance-based engineering to guide not only engineering decisions but also financial decisions about earthquake risks. Improved emergency response and recovery will be advanced through breakthrough technologies in risk management that will enable rapid evaluation of damage and enhanced management of relief and recovery processes. The knowledge developed through the experiments and simulation methodologies provide the essential scientific base for improving codes and guidelines. Social science and education research will help to better understand and communicate the societal implications and choices involved.

SUMMARY

The Research and Outreach Plan proposed in this report provides a vision for the future of earthquake engineering research and outreach focused on security of the nation from the catastrophic effects of earthquakes. While the comprehensive and long-term Plan builds upon previous accomplishments, it is fundamentally different from many previous incremental and fragmented activities. The earthquake engineering community is poised for a fundamental shift in the mitigation of earthquake risks by developing new ways of thinking about the performance of structures and new societal choices about seismic safety. The time is now to launch a new, bold initiative to provide security for the United States from the effects of catastrophic earthquakes.

ACKNOWLEDGMENTS

This Research and Outreach Plan was prepared by a panel of earth scientists, earthquake engineers, and social scientists involved in research and professional communities throughout the United States. The Earthquake Engineering Research Institute (EERI) formed this panel, under the direction of President Chris D. Poland and Executive Director Susan Tubbesing, with financial support from the National Science Foundation. Dr. Paul Somerville chaired the panel, which included the following members:

Ian Buckle,[1] University of Nevada, Reno
Ricardo Dobry,[2] Rensselaer Polytechnic Institute
Ronald Eguchi,[3] ImageCat, Inc.
Gregory Fenves,[1] University of California, Berkeley
Steven French,[4] Georgia Institute of Technology
Anke Kamrath,[5] University of California, San Diego
Ronald Hamburger,[1] Simpson Gumpertz & Heger Inc.
William Lettis,[6] William Lettis & Associates
Peter May,[7] University of Washington
Keith Porter,[8] California Institute of Technology
Adam Rose,[9] Pennsylvania State University
Paul Somerville,[10] URS Corporation
Kathleen Tierney,[11] University of Delaware

The panel thanks the many individuals who contributed their time and expertise to review, critique, and suggest improvements to the drafts of the plan, especially Dan Abrams, Robert Bachman, William Holmes, Doug Honegger, Howard Kunreuther, Bruce Kutter, Jack Moehle, Tom O'Rourke, Andrei Reinhorn, Charles Scawthorn, and Solomon Yim. EERI Staff Susan Tubbesing, Victoria Costello, Eloise Gilland, Juliane Lane, and Xena van de Walle assisted the work of the panel. Susan Rathbun helped arrange the two panel meetings that were hosted by Anke Kamrath at the San Diego Supercomputer Center, and Lelio Mejia arranged the two meetings at the URS Office in Oakland. The members of the panel gratefully acknowledge the contributions of all these individuals.

The Plan was reviewed in detail by representatives of the Consortium of Universities for Earthquake Engineering Research (CUREE). A special committee of CUREE and EERI members, including Ian Buckle, Ricardo Dobry, Andre Filiatrault, William Holmes, Bruce Kutter, Tom O'Rourke, Robert Reitherman, Paul Somerville, Susan Tubbesing, and Andrew Whittaker worked to incorporate CUREE recommendations in the Plan. Their contributions are gratefully acknowledged.

The Earthquake Engineering Research Institute is a national, nonprofit technical society of engineers, geoscientists, architects, planners, public officials, and social scientists. EERI members include researchers, practicing professionals, educators, government officials, and building code regulators. The objective of EERI is to reduce earthquake risk by advancing the science and practice of earthquake engineering, by improving the understanding of the impact of earthquakes on the physical, social, economic, political and cultural environment, and by advocating comprehensive and realistic measures for reducing the harmful effects of earthquakes.

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[1] Structural Engineering
[2] Geotechnical Engineering
[3] Lifeline and Systems Engineering
[4] Planning and Geographical Information Systems
[5] Information Technology
[6] Geology
[7] Public Policy
[8] Panel Recorder, Structural Engineering
[9] Economics
[10] Panel Chair, Seismology
[11] Sociology

PREFACE

The creation of the National Earthquake Hazard Reduction Program (NEHRP) in 1977 was a milestone event in earthquake engineering research. It provided significant funding for earth science research, and stimulated research in engineering, emergency response, and social science research. It was structured as an earthquake prediction program with a life-safety goal. The promise was that if we could predict where and when earthquakes would occur, then we could focus the needed risk reduction activities in those few areas. Much has been accomplished over the last 25 plus years, and we can point to substantial accomplishments in identifying and mitigating earthquake hazards. Nevertheless, we now recognize that earthquake prediction is not the key to risk reduction, and life-safety performance levels are not sufficient to minimize the social and economic impacts of major earthquakes. Furthermore, our current design, evaluation, and rehabilitation techniques are too conservative to make significant risk reduction economically feasible and politically viable.

In recent years, the Earthquake Engineering Research Institute (EERI) has been deeply concerned about the eroding levels of funding available for earthquake engineering research. Without exception, requests to expand NEHRP funding levels have failed to capture sufficient long-term attention, even though the cost of earthquakes is soaring and our country's vulnerability to loss is steadily increasing. It has become clear that the need for expanded research is being largely ignored because there has been no holistic plan or common voice to present all the needs together in a balanced and prioritized manner.

The EERI Research Policy Committee deliberated on how NEHRP should be updated to meet the needs of the community of earthquake engineers and their stakeholder constituency for three years. This effort was greatly facilitated by a grant from the National Science Foundation (NSF). This report represents a holistic, balanced, and comprehensive statement about how to augment NEHRP so that the growth in earthquake losses in the United States can be arrested and brought to acceptable levels over the next twenty years. The cost is estimated to be $330 million per year, almost four times the current level of spending, but still less than one twentieth of the annual projected losses from earthquakes in the United States. We believe that this Research and Outreach Plan provides the essential basis for seismic risk reduction by providing tools that will be easily understood, feasible, cost beneficial, adaptable and successful. Accelerated seismic risk reduction activities are expected to follow at a rate sufficient to meet the 20-year goals of the program.

EERI represents the user community in its entirety and is well-positioned to craft this "common voice" statement about what needs to be done. This plan began with the careful deliberations of the panel, and has been prepared with the counsel of the NEHRP agencies. It has undergone careful scrutiny by our membership, and represents a comprehensive and concise statement from the entire earthquake engineering community about what needs to be done. We have already received endorsements from the Consortium of Universities for Research in Earthquake Engineering (CUREE), the Seismological Society of America (SSA), and the Structural Engineers Association of California (SEAOC) (see the following pages). We fully intend to carry this plan to other organizations and to the local, state and federal levels for endorsement and support. We expect that the largest funding source will come from the Federal government, most probably through an expansion of the current National Earthquake Hazard Reduction Program.

Chris D. Poland, President, EERI, 2001-2003
Thomas D. O'Rourke, President, EERI, 2003-2005
September 2002

CUREE **Consortium of Universities for Research in Earthquake Engineering**

CUREE, a non-profit organization established in 1988, is devoted to the advancement of earthquake engineering research, education, and implementation.

December 17, 2002

Chris Poland
President, EERI
Degenkolb Engineers
225 Bush Street, Suite 1000
San Francisco, CA 94104-4207

Subject: CUREE Support for EERI Research and Outreach Plan

Dear Mr. Poland:

On behalf of the Consortium of Universities for Research in Earthquake Engineering, I would like to convey to EERI the resolution of our Board of Directors to support the research and outreach plan, *Securing Society Against Catastrophic Earthquake Losses*. We realize the importance of implementing the plan and commend EERI for its effort in bringing together so many constituencies and viewpoints within the earthquake engineering community.

Now that CUREE has grown to 29 university members, we feel a greater responsibility to give that university-based engineering sub-community of the overall earthquake engineering community a voice on matters of importance to them, and the national-scale plan crafted by EERI was thus a topic of great interest to our members. Thank you for the opportunity afforded to CUREE to become involved in a detailed review process of the drafts that preceded the November, 2002 document. We realize the additional meetings and efforts to incorporate CUREE comments increased the work load of Paul Somerville and the EERI panelists, and we appreciate their openness in considering comments that could strengthen the report. Thanks also go to Tom O'Rourke for devoting the time to convene the CUREE-EERI discussions in a timely way.

If CUREE can be of assistance in supporting the plan as EERI meets with agencies and Washington legislative staff members, please let us know.

Sincerely,

André Filiatrault

Professor André Filiatrault, UC San Diego
PRESIDENT

cc: Paul Somerville, Tom O'Rourke, Susan Tubbesing, Bob Reitherman

1301 S. 46th Street, Richmond, CA 94804-4698 ■ tel.: 510-231-9557 ■ fax: 510-231-5664 ■ web: www.curee.org ■ email: curee@curee.org

Seismological Society of America

201 Plaza Professional Building | El Cerrito, CA 94530-4003 | (510) 525-5474 FAX (510) 525-7204

November 14, 2002

Susan Tubbesing
Executive Director
Earthquake Engineering Research Institute
499 14th Street, Suite 320
Oakland CA 94612-1902

Dear Susan:

I am writing to formally notify you that SSA has endorsed the EERI Research Plan. The resolution enacted by the Executive Committee after consultation with the Board of Directors is as follows:

> The Board of Directors of the Seismological Society of America has reviewed with great interest the July draft of the EERI Research Plan entitled "Securing Society against Catastrophic Earthquake Losses: A Research and Technology Transfer Plan for Earthquake Engineering for the Next Two Decades." The Society endorses the plan's comprehensive commitment to preventing catastrophic earthquake losses through intelligent risk management, continued research, and use of such current technology applications as ANSS (Advanced National Seismic System) and EarthScope.

Sincerely,

Susan

Susan Newman
Executive Director

Structural Engineers Association of California

1730 I Street, Suite 240 ▪ Sacramento, CA 95814-3017 ▪ (916) 447-1198 ▪ (916) 443-8065 fax
info@seaoc.org

January 24, 2003

Mr. Chris Poland, President
Earthquake Engineering Research Institute
499 – 14th Street, Suite 320
Oakland, CA 94612-1934

Subject: SEAOC Support for EERI Research and Outreach Plan

Dear Mr. Poland:

On Behalf of the Structural Engineers Association of California (SEAOC), I would like to convey the support of our Board of Directors for the EERI developed research and outreach plan, *Securing Society Against Catastrophic Earthquake Losses*.

As design engineers we are concerned about public safety and we realize the importance of goals and needs described in the plan.

We commend EERI for its effort in bringing together so many constituencies and viewpoints within the earthquake engineering community.

Our view is that the basic and applied research proposed in the plan will provide practitioners with the tools to improve safety for our communities throughout the United States. SEAOC desires to remain involved in the development of the research activities as they evolve. Thank you for the opportunity afforded to SEAOC to be part of these activities. Our special thanks go to the thoughtful development of the plan by the EERI team.

Please feel free to contact me on any assistance SEAOC can provide to support the EERI plan.

Sincerely,

William Staehlin
President

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1. THE CHALLENGE OF GROWING EARTHQUAKE VULNERABILITY

The terrorist attacks of September 11, 2001, on the World Trade Center in New York City and the Pentagon in Virginia vividly demonstrate the vulnerability of even the most monumental and robust elements of the nation's built environment. These attacks resulted in approximately 3,000 lives lost and an estimated $100 billion in economic losses. In this regard, earthquakes and terrorist attacks have much in common. But whereas political and social processes may eventually eliminate the threat of terrorism, earthquakes will remain a global threat to society, capable of causing large-scale loss of life and catastrophic destruction to the built environment, equaling or exceeding the tragedy of September 11. Indeed, recent estimates of earthquake risk in the United States project the average annual financial loss (repair costs, inventory loss, and business interruption) to be on the order of $4.4 billion, in residential and commercial buildings alone.[i] This figure does not include indirect economic losses or the social costs of death and injuries. If these are estimated, along with the direct and indirect losses suffered by the industrial, manufacturing, transportation, and utility sectors, the total annual average financial loss is expected to exceed $10 billion.[ii]

THE CHALLENGE

Earthquakes remain one of the world's major problems. They occur frequently and result in high death tolls, thousands injured, and crippling economic losses. On average, there are more than 1,000 earthquakes of magnitude 5 (M5) or greater every year worldwide, 100 M6 or greater, 10 M7 or greater, and one M8 or greater earthquake.[iii] In the twentieth century, more than 100 earthquakes each resulted in a loss of more than 1,000 lives. For very deadly earthquakes, the loss of life exceeds that recorded in other events by an order of magnitude. Nine earthquakes in the twentieth century each resulted in the loss of more than 50,000 lives. Several, in China, Italy, Japan, and the Soviet Union have individually resulted in more than 100,000 lives lost.[iv] Economic losses have also been catastrophic and particularly so in highly developed countries. The recent 1995 Hyogo Ken Nanbu (Kobe, Japan) earthquake (M6.9) caused damage with a repair cost estimated to be $100 billion, about 2% of the country's Gross Domestic Product, and caused over 5,500 fatalities.[v]

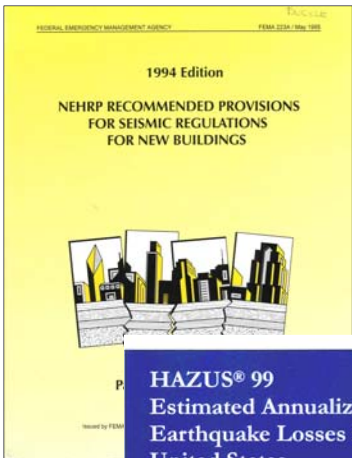
The United States is not immune to these disasters. Large earthquakes, many with magnitudes approaching or in excess of M8, have struck Alaska, California, the Mississippi River Valley, and Charleston, South Carolina, in the past 200 years. There is ample paleoseismic evidence of the repeated occurrence of large earthquakes prior to the European settlement of the United States, as well as similar large events in the Pacific Northwest, Utah, and other parts of the United States. That the nation has not experienced massive loss of life and large economic loss from past earthquakes is largely due to a sparse population at the time, a situation that has changed dramatically in the intervening centuries. It is a geological certainty that large earthquakes will strike the United States in the future with the potential for catastrophic damage, loss of life, and severe economic consequences.

A single large earthquake could cause losses in excess of $100 billion to the built and human environment, more than twice the loss in the 1994 Northridge earthquake, the most costly U.S. earthquake to date. The Northridge earthquake was catastrophic, not because of lives lost (approximately 60) but because the economic loss exceeded $40 billion, the affected region was overwhelmed, and interregional assistance was essential for recovery.

In 1977 the United States Congress established the National Earthquake Hazard Reduction Program (NEHRP) in response to the threat of large earthquakes in the U.S. NEHRP has provided significant funding for earth science research, and it stimulated research in earthquake engineering, emergency response, and the social sciences. Originally, NEHRP was structured as an earthquake prediction program with a life-safety goal. The promise was that, if science could predict where and when earthquakes will occur, attention could then be focused on reducing the risk in those areas alone.

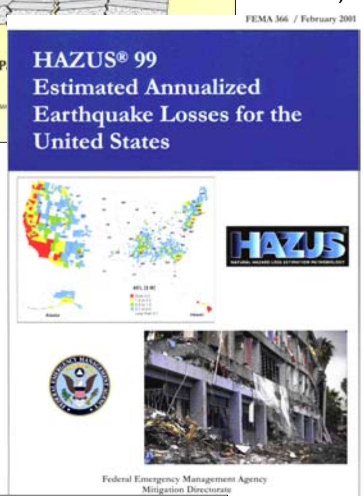
ACCOMPLISHMENTS OF THE NATIONAL EARTHQUAKE HAZARDS REDUCTION PROGRAM

The United States Congress established the National Earthquake Hazards Reduction Program (NEHRP) in 1977 largely in response to the threat of damaging earthquakes in the U.S. For 25 years NEHRP has provided significant funding for earth science research, and has stimulated research in earthquake engineering, emergency response, and the social sciences. Originally, NEHRP was structured as an earthquake prediction program with a life-safety goal. Time has shown that earthquake prediction was an unrealistic goal, but real progress has been made towards the life-safety objective through the sustained efforts of the research and practicing communities alike.



Much has been accomplished under NEHRP, and earthquake engineering has made significant advances since the program's inception. Our ability to design the built environment to resist earthquakes is vastly greater than it was even ten years ago.

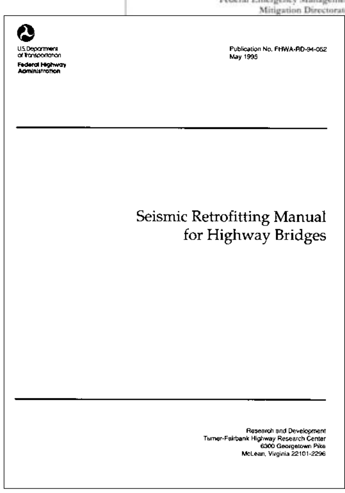
Major NEHRP products include national hazard maps (USGS), seismic design provisions for new buildings (FEMA), guidelines for the rehabilitation of existing buildings (FEMA), loss estimation methodologies (FEMA, FHWA), and performance-based design methodologies (FEMA, FHWA).



Many of these products are based on fundamental research sponsored by the National Science Foundation. Advances in earthquake mechanics, model-based simulation of structural and geotechnical systems, lifeline networks, control technologies, and hazard mitigation policies are directly attributable to NSF's commitment to fostering the development of new knowledge and advancing the state of the art in science and engineering.

Today the goals of NEHRP include

- Accelerated implementation of earthquake loss-reduction practices and policies,
- Improved techniques for the reduction of seismic vulnerability of facilities and systems,
- Improved seismic hazard identification and risk assessment methods and their use, and
- Improved understanding of earthquakes and their effects and consequences.



Other federal agencies have also contributed to the goals of NEHRP, including the Federal Highway Administration, the Department of Energy, the Nuclear Regulatory Commission, the General Services Administration, the Department of Housing and Urban Development, the Department of Defense, the Department of Interior, and the National Oceanic and Atmospheric Agency. These departments and agencies are expected to continue to play major roles in reducing seismic vulnerability, particularly in those areas in which they have specific responsibilities, e.g., defense installations (DOD), nuclear power plants and nuclear waste storage (NRC and DOE), highways and bridges (FHWA), federal buildings (GSA), housing (HUD), dams and reservoirs (Department of Interior and Army Corps of Engineers), and coastal regions subject to tsunamis (NOAA).

In addition State, county, and municipal departments of transportation, water utilities and districts, electric power and telecommunications companies, and operators of other lifelines have played significant roles in reaching the life-safety objectives of NEHRP.

Much has been accomplished under NEHRP[vi] over the last twenty-five years. Earthquake engineering has made significant advances, and our ability to design the built environment to resist earthquakes is vastly greater than it was even ten years ago.

Nevertheless, we now recognize that earthquake prediction is not the key to risk reduction, and that the protection of human lives is a necessary but not sufficient goal to minimize the social and economic impacts of a major earthquake. Recent data from U.S. natural disasters (Figure 1) show that, despite the advances to date under NEHRP and other natural hazard mitigation programs, economic losses due to natural hazards in the U.S. are escalating at an alarming rate, particularly over the last 25 years.

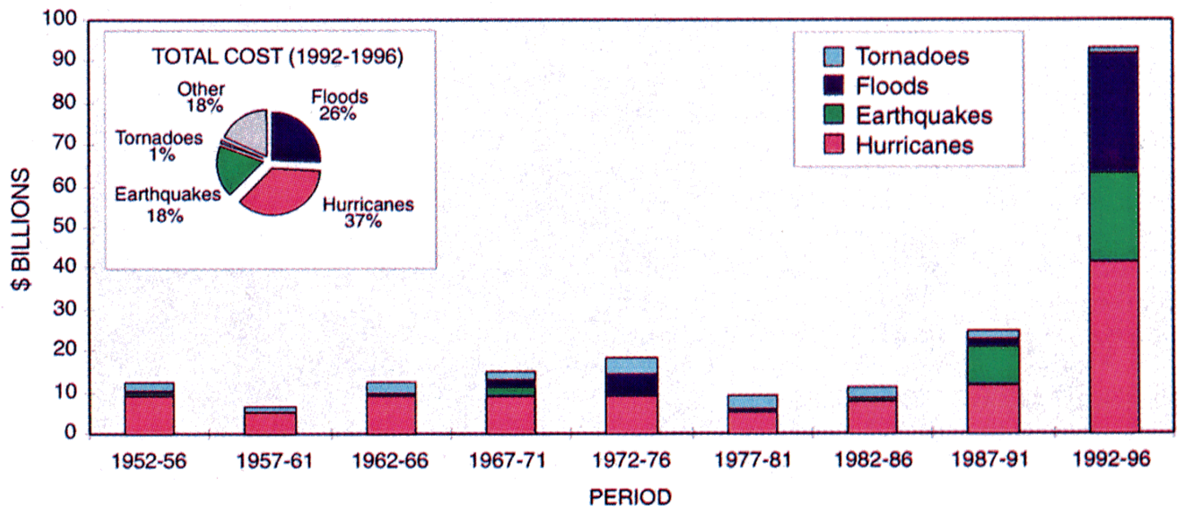


Figure 1. Direct Costs of Structural Repair and Replacement for Natural Disasters in the United States, 1952-1996 (van der Vink et al., 1998[vii])

Although a number of factors are believed responsible for these increasing losses, a prime factor is the continued population growth of the United States and the corresponding economic investment necessary to sustain the nation's quality of life.[vii] Population and economic growth in turn lead to an escalation in the extent, complexity, and interconnectedness of the built environment (homes, schools, office buildings, factories, industrial plant, highways, bridges, mass transit systems, dams, reservoirs, wastewater systems, electric power, and telecommunication systems). This growth results in an ever-increasing number of lives at risk and a rapidly expanding inventory of construction that is exposed to earthquake hazards.

Although new construction is typically less vulnerable to damage than older construction because of advances due to NEHRP and other programs, the exposure of the nation to catastrophic loss continues to grow because of the following factors:

- The primary objective of building codes and regulations is to protect the lives of occupants, rather than avoid future economic loss. Whereas new facilities are expected to protect human life, they also present significant economic risk to their owners and society at large. Furthermore, despite recent advances, current building codes are based on incomplete knowledge about structural and foundation performance, resulting in the construction of facilities that, while code-compliant, may have significant vulnerability.
- The knowledge of earthquake hazards and their impact is still evolving, and we continue to design and construct new facilities without fully understanding the potential hazards.
- The cost of using current technology to rehabilitate older construction is often high, as is the cost of improving new construction to minimize risk. Decision makers either do not completely understand the risk, or do not perceive adequate economic incentives to warrant sufficient investment. They lack the decision-making tools necessary to identify these incentives.

- The growing interconnectedness of society, enabled by extensive transportation systems and modern communications, greatly expands the impacted area of a damaging earthquake far beyond the epicentral region. Global trade, commerce, and defense may all be affected if a critical link in a communications or distribution network is taken out of service by an earthquake. A local disaster can quickly become a national one, which in turn can lead to an escalation in financial loss not seen in earthquakes of a decade ago.

The National Earthquake Hazards Reduction Program has achieved important goals, including significant reduction in the loss of life and injuries sustained in recent U.S. earthquakes, but the time has come to focus on controlling the economic and social losses from future earthquakes to prevent a catastrophe. The achievement of this goal requires a major new research and outreach plan to develop the necessary knowledge and tools. This report presents such a plan.

THE PLAN

This report presents a Research and Outreach Plan that will develop the tools for protection against catastrophic earthquakes. Today, we have the unprecedented opportunity to build on knowledge gained from past research, create new knowledge that will address the reasons for increasing losses, and use revolutionary advances in information technology to develop the means for preventing catastrophic losses from earthquakes.

This Plan comprises four integrated research programs that will develop the science, engineering, and societal approaches necessary for making intelligent management choices to protect society against catastrophic earthquakes. The Plan also includes four outreach programs, one for each of the research programs, to transfer research findings into practice. A timeframe of twenty years was used for developing this Plan.

The four research programs will provide the tools to understand and quantify the earthquake hazard in the U.S., assess and reduce the impacts of this hazard, and enhance community resilience. An education and public outreach initiative is also proposed to equip present and future generations with the expertise and awareness to live safely with earthquakes.

The Plan is built on recent technology applications, including the Advanced National Seismic System (ANSS), EarthScope, and the George E. Brown Jr. Network for Earthquake Engineering Simulation (NEES). In turn, these applications would not be possible without the ongoing revolutionary growth of high-end computing as well as inexpensive sensing and telecommunication technologies. The hierarchy of societal needs, our vision to address these needs, and the programs of research and outreach, including applications of revolutionary technologies, are summarized in Figure 2.

This Plan was developed by a multidisciplinary panel of members of the Earthquake Engineering Research Institute (EERI), with the financial support of the National Science Foundation. Through several draft stages, the Plan was reviewed and debated by earth scientists, engineers, architects, planners, public officials, and social scientists involved in research, professional practice, education, government, and building code development and regulation. Throughout this report the term *earthquake engineering* is intended to be inclusive of this broad interdisciplinary activity.

Constructive comments were also provided during the review stages by the NEHRP agencies (the Federal Emergency Management Agency, the U.S. Geological Survey, the National Science Foundation, and the National Institute for Standards and Technology).

Figure 2. Vision of the Proposed Plan

THE OUTCOME

The overarching goal of this Plan is protection from catastrophic earthquakes and related loss of life and economic disruption. To achieve this goal many steps are required, from hazard quantification to impact assessment and reduction, each with outcomes that together contribute to this goal. To illustrate the potential outcomes of the Plan, two scenarios are given in this section, which look forward to 2022 and imagine two different risk management tools being used to minimize earthquake losses.

Scenario 1 relates to the *risk certification* of buildings based on performance-based engineering and new loss-resistant technologies. Earthquake engineering is used to estimate potential losses to individual elements of the built environment, and the community as a whole, and then to limit these losses to desired levels in a reliable manner. The development of performance-based approaches is already an important goal of NEHRP.[viii] The research and outreach programs recommended in this Plan directly support these initiatives.

Scenario 2 imagines how information technology will revolutionize the management of emergency response by 2022, offering vast improvements in damage assessment, response times, and recovery following an earthquake. Accelerating recovery times is recognized as one of the most important steps towards reducing catastrophic economic losses.

The breakthrough opportunities included in the above two scenarios hold promise for protecting lives and increasing the resilience of communities subject to earthquakes and other extreme events. This investment will provide important benefits to society, such as

- comprehensive and systematic approaches to managing earthquake risks by building owners, the financial community, and officials concerned with engineering structures and lifelines;
- a vastly improved understanding of the broad range of factors that contribute to societal vulnerability and the ways in which vulnerability can be reduced in both pre- and post-event contexts;
- improved emergency response and recovery from earthquakes and other catastrophic events, including other natural disasters as well as terrorist events; and
- a more scientific and credible basis for developing and testing codes and other guidelines for improving seismic safety.

Comprehensive and systematic approaches to managing earthquake risks will be fostered by use of performance-based approaches to guide not only engineering decisions but also financial decisions about earthquake risks. Sources of community and societal vulnerability will be examined through research to improve loss-estimation methodologies. A range of strategies to reduce vulnerability will be developed, including both pre-event and post-event strategies. More rapid and effective emergency response and recovery will be developed through the use of breakthrough technologies for disaster management, such as rapid damage evaluation and enhanced decision-support systems for the management of post-earthquake response, restoration, and recovery. Research conducted under this Plan will provide the essential scientific knowledge base for making building codes, guidelines, and public policy more effective.

Achieving the goal of catastrophic loss prevention rests both on the breakthroughs presented in this report and on the incorporation of research results into professional practice and decision making. The translation of research into practice is not simply disseminating research findings. The advances required for the Plan's success entail fundamental changes in engineering practice and in decision-making about seismic risks.[ix] Bringing about these changes will require concerted efforts and ingenuity, including

- engaging building owners, civil infrastructure managers, the financial community, public officials, and the public at large in confronting choices about seismic safety;
- equipping the design professions to make use of advances in earthquake engineering methods of design, new building technology, and advanced simulation tools;
- modernizing regulatory systems to address advances in earthquake engineering; and

- understanding and communicating the societal implications of different choices about seismic safety to a diverse set of audiences.

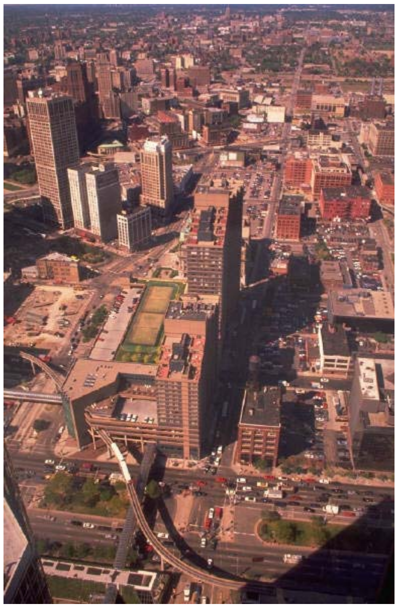
Steps to achieve these changes are presented as outreach tasks under each of the research programs in this Plan.

The outcome of the proposed Research and Outreach Plan is not limited to preventing catastrophic losses from earthquakes. Substantial benefits accrue to homeland security, for example, and other efforts to protect communities from extreme events. Through advances in the design of buildings and facilities, planning measures for addressing population growth and land use, and technologies that address emergency management and recovery, the Plan's initiatives will complement and enhance programs to reduce the threat of terrorist attack and the traumatic effect of other disasters such as blast, wind, flood, and fire.

SCOPE OF REPORT

Chapter 2 gives an overview of the proposed Research and Outreach Plan, together with a summary of the Plan's enabling technologies. In particular, the revolutionary role of information technology is discussed in this chapter. Subsequent chapters present research and outreach programs for major activities of the Plan: understanding seismic hazards, assessing and reducing earthquake impacts, enhancing community resilience, and expanding education and public outreach. A final chapter on turning opportunities into reality, including a twenty-year budget, concludes this report. Additional budget information is given in the appendix.

SCENARIO 1: Reduction of Earthquake Impact Using Informed Risk Management



In 2022, new buildings, bridges and other structures will be *risk-certified*, a process that will explicitly state the

- probable annualized loss of life per occupant-day,
- damage repair cost per square foot, and
- loss of service hours due to various hazards including earthquake, hurricane, tornado, fire, and blast.

A variety of building technologies, ranging from conventional materials to intelligent control systems, will be available for achieving a range of risk certifications, either in new construction, or in rehabilitated existing construction.

Performance-based building codes will set minimum criteria for risk compliance, based on intended structure occupancy and use, life-safety protection, and the economic hardship due to facility loss on the individual user as well as society at large. Certification will be obtained as part of the standard building occupancy permit process, based on simulation-based mapping of seismic hazards, building department audit of the building site, performance-based engineering design, construction, and maintenance. *Risk certification* will be part of the permanent building record and will be subject to review based on building damage and maintenance history. The finance and insurance industries will set lending and underwriting rates, governments will set property tax rates, and landlords will set rental rates, in part, on the basis of risk certification.

An individual, business, institution, or government agency, desiring to locate in a new community, will be able to review the risk certifications of lifeline services in the community, including roads, power, water, telecommunications, health care, and education, to determine if the community is suitably disaster-resilient. Once a community is selected, the individual will be able to examine the risk certifications of individual real estate considered for occupancy. The cost of potential losses, as evinced by the risk certification, can be balanced against the relative lease costs, insurance costs, and other business costs associated with each prospective property. If no suitable property is found, the costs of upgrading existing properties or building new properties to suit the desired risk tolerance can be evaluated.

When new facilities are commissioned, or older facilities rehabilitated, the owner/developer will routinely specify the desired level of risk certification to be obtained, subject to minimum standards, based on consideration of finance and insurance costs, the marketability of space conforming to different standards, the potential financial losses resulting from facility damage, and the initial construction costs. Under market economics, communities will gradually evolve to a disaster-resilient state.

SCENARIO 2: Reduction of Earthquake Impact Using Rapid Response

A repeat of the 1811 New Madrid earthquake occurs in the Mississippi Valley in 2022, causing intense ground shaking, liquefaction, and lateral spreading through a broad region that includes Arkansas, Illinois, Missouri, and Tennessee. Railway and highway bridges spanning the Mississippi River collapse. Oil and gas pipelines transiting the region from Texas to Chicago and the northeastern U.S. are severed and thousands of buildings are damaged, including many complete collapses.

Within minutes, many thousands of ground motion and other types of sensors located throughout the Midwest have transmitted data to the National Earthquake Center in Golden, Colorado, where the United States Geologic Survey produces ground-shaking intensity and ground-failure maps. These data are immediately fed to the Federal Emergency Management Agency, together with health-monitoring instrumentation telemetry obtained from many thousands of sensors mounted on buildings, bridges, dams, pipelines, and power control systems throughout the stricken region. At FEMA the data are instantly fed into national disaster simulation software and used to produce early estimates of the magnitude and distribution of life and property losses, and the extent that essential lifelines remain in service.

In less than an hour, the President of the United States and the governors of the affected states have sufficient information to declare an official disaster, to mobilize the National Guard, emergency medical, rescue, and hazardous materials personnel, and to begin dispatching aid to the most severely impacted zones. Hospitals and airports immediately outside the heavily affected region are notified to make all preparations necessary to transport and care for casualties. Communities downstream of a major dam, which has become unstable and which may fail, are notified immediately to evacuate low-lying areas.

Within hours, power and water utility managers in each of the affected states have an accurate picture of the extent of damage to their systems and the extent that aid is available from out-of-region providers. State departments of transportation have a reliable assessment of the extent to which highway systems have been disrupted and how to best direct traffic to and around the affected bridges and damaged roads.

In the days and weeks that follow, engineering and construction resources are mobilized from around the nation, and are efficiently assigned to emergency stabilization, repair, and restoration tasks in a manner that assures minimization of loss and optimal recovery from the disaster.

2. PROTECTION FROM CATASTROPHIC EARTHQUAKES

Earthquake engineering stands at the threshold of potentially rapid advances made possible by revolutionary technologies and technology applications. To take advantage of these breakthroughs, the proposed Plan comprises five integrated research and outreach programs for developing the science, engineering, and societal tools necessary to protect against catastrophic earthquake losses. These five programs are:

1. Understanding Seismic Hazards,
2. Assessing Earthquake Impacts,
3. Reducing Earthquake Impacts,
4. Enhancing Community Resilience, and
5. Expanding Education and Public Outreach.

The relationships among these programs and the major tasks within the programs are shown in Figure 3.

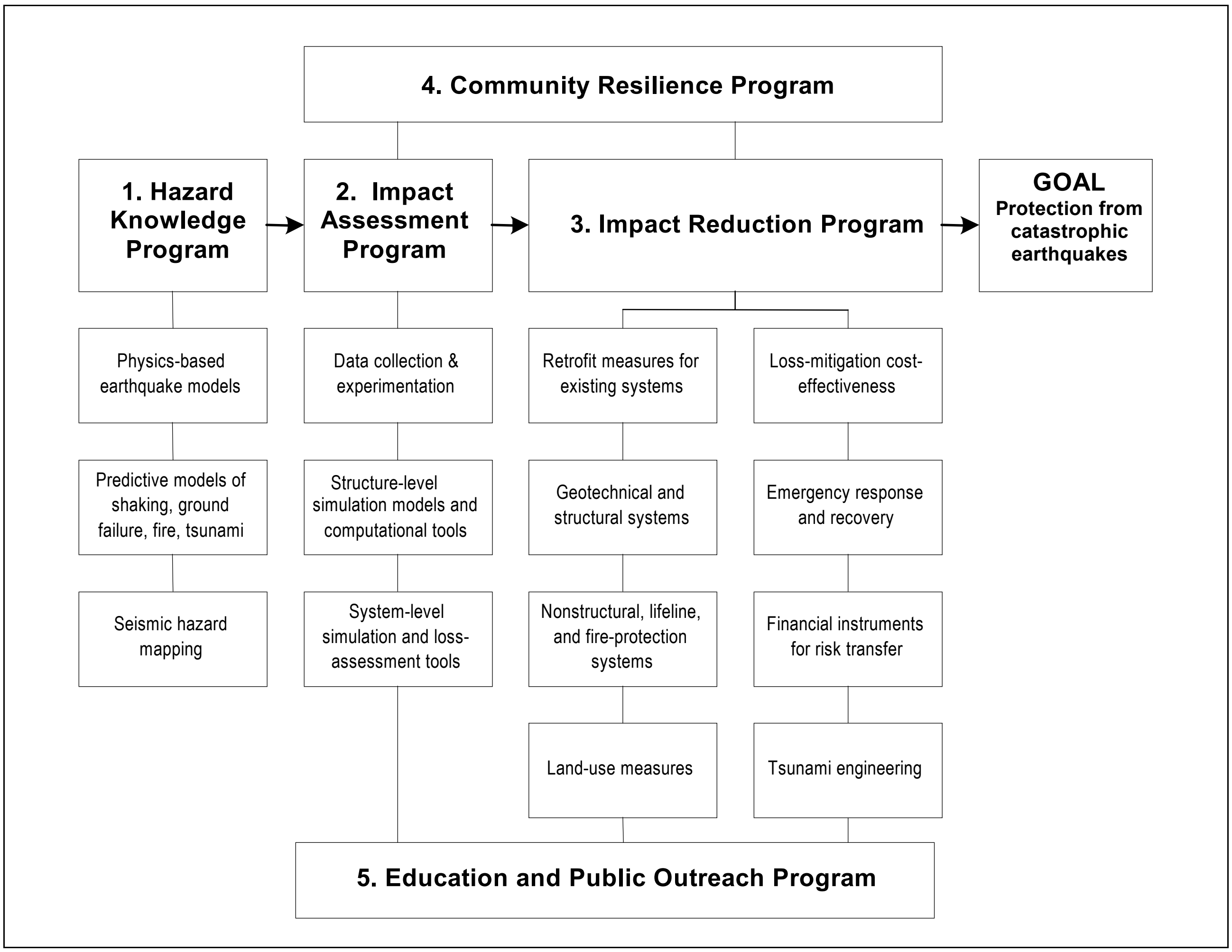


Figure 3. Programs and Major Tasks in Research and Outreach Plan

There is a natural progression in the programs from left to right in Figure 3. Characterizing and quantifying the hazard is followed by impact assessment and impact reduction, leading to the goal of protection from catastrophic earthquakes and their related losses. The programs in community resilience and education are essential for the successful execution of the Plan, and they interface with the other programs as shown in

Figure 3. The activities proposed within each program are identified in the relevant boxes and are described in more detail in the following chapters of this report.

The Plan outlined in Figure 3 embraces the main thrusts of the Southern California Earthquake Center (SCEC) and the three NSF-funded earthquake engineering research centers. The major emphases of SCEC[x] include earthquake rupture and fault system dynamics, and predictive models and mapping of seismic hazards. The central focus of the Pacific Earthquake Engineering Research Center (PEER)[xi] is performance-based earthquake engineering, which involves facility- and system-level simulation models and computational tools for assessing and reducing earthquake impacts. The Mid-America Earthquake Center (MAE)[xii] has a major focus on consequence-based engineering, which involves system-level simulation and analysis for assessing and reducing impacts. A major focus of the Multidisciplinary Center for Earthquake Engineering Research (MCEER)[xiii] is the use of advanced and emerging technologies for reducing impacts and developing methodologies to quantify community resilience.

BREAKTHROUGH OPPORTUNITIES

The success of the Plan depends heavily on the following breakthrough technologies and applications:

- High-end computing and information technology
- Intelligent sensors and network communications
- Remote sensing technologies
- Information management and visualization
- The Advanced National Seismic System (ANSS)
- The Network for Earthquake Engineering Simulation (NEES)

Table 1 lists key technologies and programs, and indicates the role they are expected to play in the Research and Outreach Plan. Applications for impact reduction are divided into pre- and post-event activities because of the very different nature of preparation for a large earthquake compared with the response and recovery after an earthquake occurs. Advances in information technology and their role in this Plan are further described in the next section.

Research alone will not achieve the benefits from these breakthrough opportunities because they entail fundamental changes in engineering practice and in decision-making about seismic risks. Educating new generations of earthquake engineers, equipping existing professionals to use these new tools, and improving decision-making about risk mitigation are also required to bring about these changes. These societal and educational issues are also addressed in this Plan.

THE ROLE OF INFORMATION TECHNOLOGY

The goal of preventing catastrophic losses from earthquakes and other extreme events will require more data about the earth and the built environment, continued improvement in the design and construction of the built environment, and new tools for emergency response and recovery management. Information technology (IT), including sensing and imaging, network and wireless communication, high-end computing systems, information management, and human-computer interaction, plays an important role in achieving this goal.

Table 1. Breakthrough Opportunities Enabled by New Technologies and Related Applications

TECHNOLOGY AND APPLICATIONS	HAZARD KNOWLEDGE PROGRAM	IMPACT ASSESSMENT PROGRAM	IMPACT REDUCTION PROGRAM	
			PRE-EVENT	POST-EVENT
High-end computing, information technology	Dynamic fault-rupture simulation, simulation of basin response, and permanent ground deformation	Simulation of soil, foundation, and structure systems; Loss-estimation models	Simulation of innovative materials, concepts, and systems	Near-real-time damage-estimation models
Sensors and network communications	Validation of liquefaction prediction and permanent ground deformation models	New understanding of field response of the built environment	Remote sensing for building and lifeline inventory development	Remote sensing of damage for emergency-response decisions; Rapid diagnosis of structure damage
Information management and visualization	Data management and visualization of large geological structures	Built-environment inventory, vulnerability, and loss databases; Integration of sensor data with structure-level simulation	Visualization of earthquake consequences using experimental and numerical simulations	Processing post-disaster information Emergency-response decision support
Advanced National Seismic System (ANSS)	Source, path, basin and site characterization; Predictive ground-motion models	Recordings of structural response for validation of structure-level simulation	Regional strong-motion characterization	Rapid shakemaps and early warning for emergency response
George E. Brown, Jr., Network for Earthquake Engineering Simulation (NEES)	Validation of predictive models of permanent ground deformation and soil/structure interaction for both transient and permanent ground movement	Scientific understanding of component, structure level, and system-level behavior Validation of component, structure level, and system-level behavior models	Scientific understanding of retrofit, new materials, structural, geotechnical, and coastal systems Validation of models for the above systems	Scientific understanding of repair techniques; Validation of models for repair techniques

Advancement and recent applications of IT indicate that there will be fundamental changes in earthquake engineering, construction, and loss prevention. Information technology is revolutionary not only because it will predict how the ground shakes during an earthquake, or make buildings perform better during the shaking, or speed recovery after an earthquake, but also because IT has the potential to improve how communities accomplish the necessary tasks to reduce vulnerability to earthquakes and prevent catastrophic earthquake loss.

A central focus of earthquake engineering research in the next twenty years will be to merge current and future information technology advances (including significant adaptations and new developments) into the practice of earthquake engineering, with the objective of radically reducing the large uncertainty currently associated with hazard, performance, damage and loss prediction of the built environment. Table 2 summarizes five IT applications to earthquake engineering, which can be broadly described in three major categories. The first uses inexpensive but accurate, low-power sensors communicating in distributed, wireless networks to collect data on the performance of the built environment. The second is based on new simulation tools that utilize high-end computing systems. The third category is data visualization, data fusion, and decision support systems. Each of these technologies has important applications for pre-event mitigation and post-event response. These developments will provide new tools to help communities understand the impacts of earthquakes and other disasters, and examine the effects of mitigation decisions.

Implementation of information technology for earthquake engineering takes several forms. Commercialization of new technology is the most effective driving force, particularly with the rapid reductions in the cost of sensors, communication, and other hardware. For software, many developments occur through commercialization (such as geographic information systems, databases, and virtual reality). For simulation, loss estimation, and decision support systems, an effective implementation strategy is for the earthquake engineering community to develop a modular approach by defining standards and protocols for software components. In this way, new developments — through research and commercialization — can be integrated into software and technology systems for earthquake engineering applications.

Information technology is already being adopted in earthquake engineering. It is perhaps most apparent in two applications central to the Plan: the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) and the Advanced National Seismic System (ANSS). These initiatives promise to provide a major impetus for achieving the goal of this Plan. As

NEES
Network for Earthquake Engineering Simulation

A Major Reseach Equipment Project at NSF

The George E. Brown, Jr. Network for Earthquake Engineering Simulation is the first Major Research Equipment and Facilities Construction Project in the Engineering Directorate at the National Science Foundation. Congress has authorized $82 million for the developmental phase (2000-2004) of NEES: construction or enhancement of engineering laboratories at fifteen universities; an advanced networked and grid-enabled experimental, data, and computational infrastructure, and a consortium that will operate the facilties in the 2004-2014 timespan. Operation, maintenance, and research funding in that decade to realize the potential of the NEES investment is expected to be in the range of $75 million per year.

Large-scale Structural Testing
University of Nevada-Reno

A New Way to Do Earthquake Engineering Research

The distributed laboratories will offer shared usage to researchers unaffiliated with the host universities, thus involving a broader circle of researchers around the country. Under a concept known as a "collaboratory," researchers can remotely interact with each other and with their experimental and simulation work via "telepresence" tools. The NEES experimental capabilities will lead to new tools for modeling, simulation, and visualization of site, structural, and nonstructural response to earthquakes. A curated data repository will provide an advanced level of access to researchers, university and K-12 educators, practitioners, and the general public.

Tsunami Wave Tank
Oregon State University

Moving University Research Into Engineering Practice

NEES will provide an unprecedented engineering capability for attacking major earthquake problems with coordinated multi-organizational teams ("grand challenge" research projects), producing convincing results that can be adopted into building codes and engineering practice. As of this writing, a National Research Council panel is developing for NSF a long-range research agenda for NEES.

Mobile Shaker-Monitoring Lab
University of Texas-Austin

For further information: http://www.nees.org described in the sidebar, NEES is a new major research equipment, computation, and networking initiative of the National Science Foundation, whose main goal is to advance the state of knowledge in earthquake engineering through new methods for experimental and computational simulation. The Phase I and II deployments of NEES equipment sites, to be completed in 2004, provide new experimental earthquake engineering equipment in laboratories connected by high-bandwidth network communication, curated data repositories, and collaboration facilities. The NEES Consortium will operate the NEES Collaboratory (distributed resources shared by researchers and other users) through at least 2014. The system architecture of NEES is based on grid computing that enables coordinated, flexible, secure resource sharing and problem solving among dynamic collections of individuals, institutions, and resources. Through this architecture, NEES will provide a revolutionary resource for earthquake engineers to conduct advanced experiments, collect data, collaborate in improved simulations, and use all this information to improve design.

The Advanced National Seismic System (ANSS) is an initiative of the U.S. Geological Survey, acting in collaboration with scientists from universities, private industry, and state governments to modernize strong motion seismographic networks in the United States. Funding of ANSS has been authorized, but appropriations are proceeding at one-tenth the planned rate. ANSS will provide scientists with high quality data to understand earthquake processes and solid earth structure and dynamics, to provide engineers with information about building and site response, and to provide emergency response personnel with near-real-time earthquake information. ANSS will consist of 6,000 new instruments concentrated in high-risk urban areas to monitor ground shaking and the response of buildings and structures, together with upgraded regional and national networks and data centers. When fully deployed, ANSS will provide the means to generate rapid ground shaking maps to facilitate emergency response following damaging earthquakes.

THE ROLE OF THE SOCIAL SCIENCES

The breakthrough opportunities discussed above are a major step towards the vision of securing society from the effects of catastrophic earthquakes. As noted, many of the engineering and earth science research programs will benefit directly from these technologies, but these efforts, by themselves, will not assure protection from loss. Translating knowledge to action continues to frustrate loss reduction efforts in this and other hazard mitigation efforts. A significant ground-breaking effort is also required to understand the underlying societal factors that contribute to vulnerability and inhibit efforts intended to reduce this vulnerability.

Recent advances in social science research hold particular promise in this regard. These include the challenging areas of risk perception and communication, societal inertia to change, decision-making, effective fiscal instruments, and quantification of economic impacts. Consequently, a major component of this Plan is the complementary role of the social sciences, working in partnership with engineering and earth sciences, to achieve the goal of community resilience and protection from loss.

Table 2. Information Technology Applications to Earthquake Engineering

SENSING AND IMAGING

Earthquake engineering knowledge has been hobbled by the lack of data about strong ground motion, permanent ground deformation, and structural performance. New developments in micro-electromechanical sensors for acceleration, strain, pore water pressure, and other quantities will significantly enhance our ability to collect the large volumes of data that would greatly accelerate progress in earthquake engineering. Imaging technology spans video, infrared, ultrasound, and laser, which all have applications to damage assessment of individual buildings. Satellite imaging, remote sensing, and high-resolution aerial photography provide new capabilities to capture and update inventory information on the natural and built environment prior to an earthquake, and to provide near real-time damage assessments after an event.

COMMUNICATION

Advances in networking and communication technologies and rapid decreases in their cost will directly impact earthquake engineering in areas such as sensor networks, grid-based computing, sharing of resources and data, and collaboration environments. The most important earthquake engineering application relies on potentially revolutionary opportunities for utilization of large numbers of sensors and the related large-scale data collection. Wide-area wireless networking will be a key technology to link sensors to modern communication networks. Earthquake engineering is already an early adopter of this technology through programs such as the TRINET System in southern California. In addition to providing rapid maps of ground shaking following an earthquake, prototype systems for early warning of strong ground shaking are being tested. For example, the HPWREN (High-Performance Wireless Research and Education Network), a prototype network that enables field scientists to send and receive continuous real-time data from remote stations, has been linked with the ANZA Seismic Network and is used by TRINET. Extending these concepts, a city fully instrumented with networked sensors could include tens of thousands of sensors providing the data needed for radically improving the knowledge base of earthquake response; video or other imaging systems could also be used in damage assessment, emergency response, and disaster recovery.

COMPUTING AND SOFTWARE

Advances in high-end computing systems are creating new opportunities for significant impact on the way buildings and bridges are designed, for developing new theories in earth sciences and earthquake engineering, and for application to real-time crisis management and decision-making. High-end computers will likely realize petaflop scale (10^{15} floating point operations per second) computing well before 2010. Computers of this scale will have fundamental implications for earthquake engineering applications. For example, high-end computers will allow computational simulation of the ground motion in an entire region, unprecedented accuracy in simulation of physical behavior, and interpretation of data collected through sensors. Ensuring the effective utilization of high-end and grid computing systems by the earthquake engineering community will require improving and accelerating the software development process and the adoption of methods for efficiently creating and maintaining high-quality software, including the creation of a component-based software system for earthquake engineering.

INFORMATION MANAGEMENT

The ability to acquire knowledge and insight from vast amounts of data is transforming numerous scientific and engineering disciplines. The opportunities in earthquake engineering for information management include fusion of data from sensors with models, data mining, large-scale data repositories, significantly improving the flow of information for decision-making and emergency response and management. Managing data on this scale will be very challenging, requiring many advances in data analysis, data management, and the merging of information from diverse sources.

HUMAN-COMPUTER INTERFACES

New modes of human interaction with computers are being developed to enrich and simplify the way we communicate with computers. The fields of human-computer interfaces and scientific visualization have advanced dramatically in the past decade. It is now possible to visualize and interactively explore complex systems and high-resolution, time-series data. Leveraging new and existing capabilities and developing community-based visualization capabilities will be vital to realize benefits for improving earthquake engineering science and knowledge, and effective loss mitigation.

3. Understanding Earthquake Hazards

The first step towards protecting society from catastrophic losses requires a major effort to improve the understanding and quantification of the earthquake hazard in the U.S. This chapter presents a research and outreach program for this purpose based on recent developments in physics-based earthquake models and predictive models for seismic hazards.

RESEARCH TASKS FOR UNDERSTANDING EARTHQUAKE HAZARDS

Rapid advances in our knowledge of earthquake science, together with planned new data gathering programs, provide opportunities for breakthrough advances in the utility of earthquake science for earthquake engineering. These opportunities lie in three broad areas: physics-based earthquake models, predictive models of seismic hazards, and seismic hazard mapping for performance-based seismic engineering. They are summarized in Table 3. Accomplishment of these objectives requires the use of many more sensors of different types, including full development and in some cases significant expansion of new data acquisition systems that are now planned or in the formative stage: the fledgling Advanced National Seismic System (ANSS),[xiv] the efficient archiving of seismological data (IRIS),[xv] and elements of the NSF planned Earthscope,[xvi] including geodetic measurements of deformation of the active plate margin of the west coast (PBO using GPS, and InSAR), drilling the San Andreas fault (SAFOD), and delineating the structure of the United States using USArray. The timely accomplishment of these objectives also requires the use of data and knowledge, gained from the many earthquakes that occur overseas, that are relevant to seismic hazards in the United States.

Table 3. Research and Outreach Tasks for Understanding Earthquake Hazards

RESEARCH TASKS FOR EARTHQUAKE HAZARDS
Physics-Based Earthquake Models • Physics-based models of fault mechanics and earthquake rupture dynamics • Physics-based models of fault systems and fault interactions and the earthquake cycle
Development of Predictive Models of Seismic Hazards • Predictive models of ground shaking • Predictive models of permanent ground deformation
OUTREACH TASKS FOR EARTHQUAKE HAZARDS
Application of Predictive Models of Seismic Hazards • Incorporation of predictive models into codes and guidelines • Dissemination of predictive models to practicing professionals
Seismic Hazard Mapping • Earthquake source characterization • Seismic zonation of urban regions • Rapid shakemaps and ground deformation maps • Tsunami inundation mapping and warning

Although the kinematic model of plate tectonics provides the framework for understanding and predicting the long-term occurrence of earthquakes, it cannot predict the sequence of occurrence of future earthquakes, or the detailed characteristics of an individual member of the earthquake sequence. The ability to do those things requires the development of physics-based models of earthquake rupture dynamics of individual earthquake occurrences, and of the interaction between fault systems that produce earthquake sequences. Our ability to predict the ground motions of future earthquakes will be greatly enhanced by the development of dynamic models of fault rupture. Preliminary models have already been tested, but the key problem is how to constrain the parameters that describe the driving stress and the frictional properties of the fault, which change radically once rupture begins. The realistic dynamic models that are needed for improved earthquake source characterization for strong motion prediction will depend on in-situ measurements (such as SAFOD), laboratory measurements of rock mechanics, and the analysis of strong motion seismograms from ANSS.

ADVANCES IN SEISMOLOGY AND PHYSICS OF THE EARTH

Plate tectonic theory was first proposed in 1960's and since that time has provided the basis for increasingly sophisticated descriptions of dynamic geological processes. These kinematic descriptions include

- relative motions on faults that form the boundaries between the plates comprising the earth's outer shell,
- slip rates on faults within these plates, and
- distribution and orientation of slip on the fault plane that occurs during individual earthquakes.

The measurement of these motions has been enabled by geodetic measurements of strain using new technologies such as VLBI, GPS and InSAR; geological measurements of surface faulting slip rates; and seismological measurements that can be related to the fault motions. The elastodynamic representation theorem has provided the key to using recorded seismic waveforms to infer the geological parameters of earthquakes (the amount, orientation, and spatial and temporal distribution of slip on the fault that produces the earthquake).

Our ability to relate seismic waveforms to details of earthquake faulting processes has grown rapidly over the past three decades, making theoretical and computational seismology directly applicable to the understanding, characterization, and prediction of strong ground motion for engineering applications.

The capability to kinematically model relative rates of plate motion has provided the basis for the probabilistic prediction of earthquake hazards. The landmark 1996 USGS National Seismic Hazard Maps integrated a large body of information about the seismic potential of faults, historical seismicity, and strong ground motion characteristics to produce probabilistic ground motion maps representing long-term earthquake probabilities. In addition, research during the past 10 years has provided the technology to develop microzonation maps of permanent ground deformation during earthquakes, including surface fault rupture, liquefaction, and earthquake-induced landslides, as well as the location and magnitude of tsunamis.

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[1] Living on an Active Earth: Perspectives on Earthquake Science. Review Draft Report, NAS–NRC Committee on the Science of Earthquakes, Dec. 7, 2001

Research is needed to develop improved predictive models of earthquake hazards that serve as design tools for engineering application. The strong horizontal variations in near-surface geology that are caused by undulations in bedrock topography and by lateral changes in the composition and distribution of overlying sediments in structures, such as sedimentary basins, give rise to large variations in ground motion characteristics. To reduce the large uncertainty in the prediction of ground shaking hazards, we need predictive models for site response whose validation is based on measured seismic velocity profiles at strong motion recording sites, including downhole seismic arrays, and that extend beyond simple flat layered models to include the complex effects of near-surface geological structures, such as sedimentary basins. This new generation of models should use ground motion parameters that are optimally predictive of damage, and should reliably describe the variability in the ground motions in addition to their expected values. We also need to develop data-validated predictive models for other seismic hazards. These include accurately predicting the location, magnitude, and geometry of permanent ground deformation resulting from earthquakes, including tectonic fault rupture; tilting, warping, and folding of the Earth's surface due to fault slip at depth; tsunamis; and liquefaction (settlement, lateral spreading) and slope failure induced by strong ground motion. Improved engineering models of material properties for predicting non-linear behavior, including both liquefaction-induced ground deformation and shaking hazards of shallow soils, and for predicting soil-structure interaction effects, will form the basis of computer simulation tools that provide more reliable predictions than do current empirical methods.

OUTREACH TASKS FOR UNDERSTANDING EARTHQUAKE HAZARDS

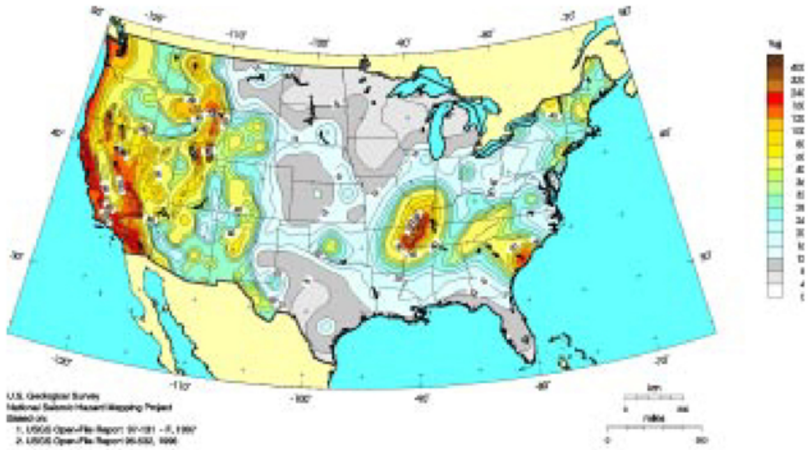
The predictive models of seismic hazards that are developed through the research described above need to be incorporated into building codes and provisions, and disseminated to the community of practicing professionals as user-friendly design tools. These predictive models also need to be used in the preparation of more reliable maps of earthquake hazards throughout the United States. For ground shaking hazards, the USGS National Seismic Hazard Maps need to be systematically updated as more information on earthquake potential and earthquake source characteristics becomes available from programs such as Earthscope, and as improved hazard prediction models are derived from ANSS data. The usefulness of these maps will be greatly enhanced through the seismic zonation of urban regions based on seismic velocity profiles of soils and sedimentary basins.

Earthquake-induced liquefaction and associated permanent ground deformation are hazards responsible for significant economic losses in earthquakes. They commonly occur in saturated soft cohesionless soils of young geologic age. Current geologically-based liquefaction susceptibility maps portray areas where future liquefaction may occur. Specific predictions of liquefaction and ground deformation for engineering projects use more detailed geological and geotechnical information and mostly empirical or semi-empirical prediction methods based on compilations of case histories in past earthquakes. These predictions of ground deformation involve great uncertainty and are limited by the available databases of case histories. In the next two decades, detailed probabilistic ground deformation maps will be prepared in digital format for all urban areas of the country exposed to seismic activity. These maps, as well as site- specific computational procedures, which can both refine the ground deformations provided by the maps and obtain estimates for modified or improved ground, will be developed using the physics-based, data-calibrated computational tools for ground deformation discussed in the next section. These maps will provide the basis for community planning, preliminary retrofit strategies, and real-time emergency response.

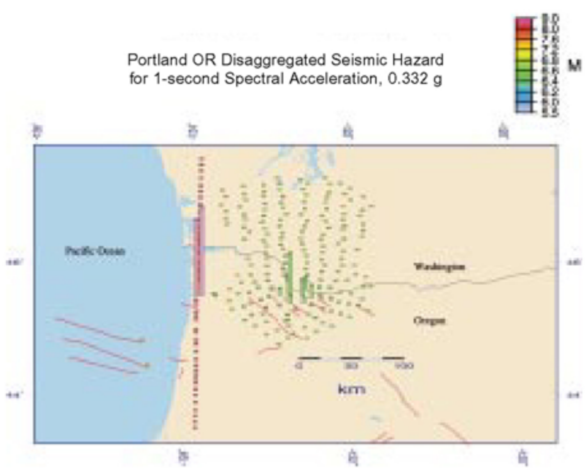
The effective response to the threat of earthquakes requires more accurate, more complete, and more rapid information on seismic hazards. Over the next two decades, information technology will greatly expand our ability to map seismic hazards, including ground shaking, tsunamis, and sensor- and satellite-based observations of ground deformation. Examples of these emerging applications include the rapid generation of ground-shaking and ground-deformation maps immediately following the earthquake, and early warning of imminent shaking. The products of this program, including the reduction in uncertainty in the characterization of seismic hazards and the rapid provision of hazard information following an event, will substantially improve our knowledge of earthquake hazards.

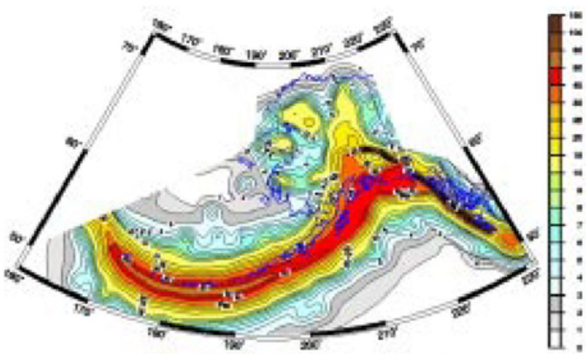
USGS National Seismic Hazard Maps

Our current knowledge of earthquakes, active faults, crustal deformation and seismic-wave generation and propagation must be integrated and translated before it can be effectively used to mitigate earthquake losses. The national seismic hazard maps produced by the U.S. Geological Survey (USGS) accomplish this critical information transfer. In 1996, the USGS developed new national seismic hazard maps based on a state-of-the-art probabilistic methodology and the latest findings of research conducted under the National Earthquake Hazards Reduction Program (NEHRP). An open, consensus-building process was instituted, consisting of several regional workshops and extensive feedback and review by experts. The 1996 seismic hazard maps are the basis of the probabilistic portion of the seismic design maps in the NEHRP Recommended Provisions, a resource for model building codes developed by the Building Seismic Safety Council and published by FEMA. These design maps were adopted by the International Building Code, which is currently used in jurisdictions in 37 states, and the ASCE national design load standard. Thus, the national seismic hazard maps affect billions of dollars of new construction. In addition, the USGS maps are used in seismic retrofit guidelines, loss estimation, earthquake insurance, and the design of highway bridges, dams, and landfills, among many other applications that help to reduce the losses of lives and property from earthquakes. The USGS has recently released updates of the national seismic hazard maps based on new research findings from NEHRP.

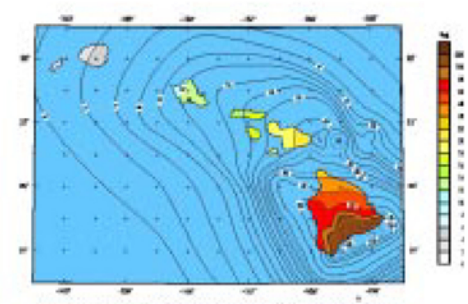


Horizontal Spectral Response Acceleraton (%g) for 0.2 Sec Period (5% of Critical Damping)
with 2% Probability of Exceedance in 50 Years
Firm Rock - 760 m/sec shear wave velocity





Peak Ground Acceleraton (%g) with 10% Probability of Exceedance in 50 Years



Peak Ground Acceleraton (%g) with 10% Probability of Exceedance in 50 Years

Vulnerability of Buildings and Infrastructure to Soil Liquefaction

The Problem

Extensive liquefaction damage to port facilities in 1995 Kobe, Japan, earthquake, due to tilting and displacement of quay walls, caused a US $10 billion loss (Iai, 1996).

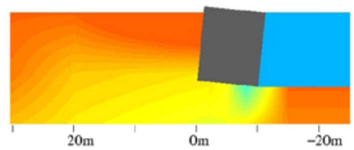
Liquefaction of wet sands causes much destruction in earthquakes. In San Francisco in 1906 and 1989 and in Alaska in 1964, it damaged buried pipes and buildings, crippled bridges, and destroyed waterfronts. The 1811-12 New Madrid earthquakes liquefied large areas from Tennessee to Missouri; a repeat today would have disastrous consequences. During liquefaction, the sand grains are suspended in the pore water, buildings sink into the soil, and the ground cracks, settles and moves laterally.

Structural failure and sinking of an apartment building in San Francisco Marina District, 1989 Loma Prieta earthquake (Nakata, 2002).

Research Tools and Accomplishments

The flow failure of the upstream slope of the Lower San Fernando Dam in 1971 nearly caused overtopping, which could have killed thousands. It has been reconstructed and analyzed by Seed, et al. (1975) to provide an understanding of the mechanics of flow failures and to develop engineering procedures to evaluate post-liquefaction soil shear strength.

Geotechnical centrifuges with in-flight shakers, such as the 9-meter radius unit at UC Davis, play a role in understanding and quantifying liquefaction effects.

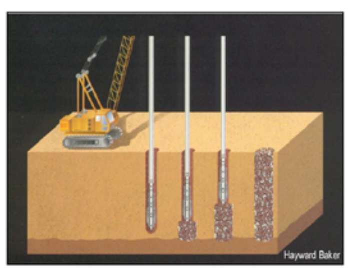


Visualization of data measured during shaking of waterfront structure centrifuge model, RPI, Troy, NY. (Colors: blue = ocean, black = quay wall, red = liquefied sand with high positive pore water pressure, yellow = sand with some positive pressure, green = sand with negative pore water pressure).

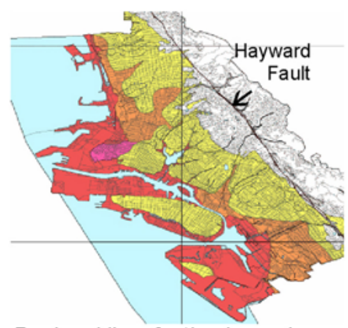
Liquefaction involves complex phenomena, and its characterization is subject to uncertainties in determining the relevant properties of a natural soil mass. Observations in earthquakes, case studies, correlations with *in situ* soil measurements and groundwater conditions, field and laboratory soil investigations and measurements, centrifuge model tests, and computer simulations have been used to clarify many aspects of liquefaction. Research provides the means of producing effective design procedures and advanced ground stabilization technologies to remove or substantially reduce the risk of liquefaction.

Research Applications

Empirical and semi-empirical methods have been developed for mapping of areas at risk and prediction of liquefaction and ground deformation at specific sites. Engineering analyses and computational simulations calibrated by field observations or centrifuge tests are used to evaluate effects of liquefaction on ground deformations and foundations. They are also used to develop new retrofitting and site remediation techniques, such as stone columns, compaction grouting, and deep soil mixing.



Vibroreplacement stone column construction at Mormon Island Auxiliary Dam east of Sacramento, California (1993). Stone columns are one new method to improve the resistance to liquefaction. They work by densifying and reinforcing the sand, and by drainage of earthquake-induced pore water pressures.



Regional liquefaction hazard map showing the California communities between Berkeley and Oakland for a 7.1 magnitude earthquake. Blue areas represent water. 73% of the red area is predicted to show surface manifestations of liquefaction, (Holzer, et al., 2002).

4. ASSESSING EARTHQUAKE IMPACTS

The pressing need to reduce the expected losses from future earthquakes and other disasters requires focused research programs on evaluating the impact of disasters on the built environment and society at large. The NEHRP program has greatly enhanced our ability to assess the impacts of earthquakes. However, the current state of knowledge and technology for assessing performance in such terms as damage, risks to human life, and economic losses does not readily enable individual decision-makers and public officials to make informed choices regarding appropriate levels of safety, business operations, and minimum regional and national standards.

The task of reducing the impacts of an earthquake is fundamentally hampered by uncertainty about the earthquake hazard, the behavior of individual structures and networks of facilities such as lifeline systems, and impacts on an entire region. Large uncertainties reduce our confidence in decisions about how to improve that performance, especially for rehabilitation of existing construction where the cost of rehabilitation hinges on the accurate prediction of performance. Two of the primary sources of uncertainty are the lack of data and the lack of knowledge as represented by limitations in models of behavior and performance of structures, soils, and lifeline systems. The solutions are to develop new ways to collect critically needed data in a cost-effective manner from the field and the laboratory, and to develop improved models and computer simulation methods. Although the past ten years have seen considerable progress in simulation capability, current technology is limited by lack of data, by simplified models, by inadequate representation of uncertainty, and by computational tools that do not harness the potential of high-end computers.

RESEARCH TASKS FOR ASSESSING EARTHQUAKE IMPACTS

Three research initiatives summarized in Table 4a and outlined below are necessary to address these shortcomings and achieve major breakthroughs in assessing earthquake impacts on the built environment.

Evaluation of Performance of the Built Environment through Measurements, Experimentation, and Data Synthesis

This program will focus on generating and interpreting response data obtained from two main sources: (i) extensive instrumentation of ground, buildings, bridges, and other elements of the built environment using many thousands of increasingly available low-cost sensors and wireless technologies for measuring ground, foundation, and structural and nonstructural response in earthquakes; and (ii) systematic experimentation in the field and in the laboratory on the performance of components and complete structures subjected to simulated earthquake loading. The first of these activities will augment the capabilities provided by the Advanced National Seismic System (ANSS), whose focus is on strong motion accelerometers, by deploying other types of sensors to measure significant parameters such as pressure (including water pore pressure in the soil), displacement, and strain. The augmented measurements will take full advantage of the ANSS infrastructure and of experimental facilities and research infrastructure being developed as part of the Network for Earthquake Engineering Simulation (NEES).

The extensive experimental database to be provided by the sensors, both during earthquakes and in controlled field and laboratory experiments, requires research on new methods for data fusion, including maximum use of advanced visualization, system identification and optimization technologies, as well as systematic treatment and evaluation of uncertainty. Expected uses of the experimental data and data fusion include (i) evaluation of individual structure performance based directly on the data and updated as more data become available, including improved estimates of uncertainty associated with each evaluation; (ii) calibration of performance-prediction simulation models and computational tools; (iii) direct indication of damage after an earthquake for prioritizing inspection and repair strategies; and (iv) guiding emergency evacuation of individual buildings and dispatch of emergency response services.

Table 4a. Research Tasks for Assessing Earthquake Impacts

RESEARCH TASKS FOR ASSESSING IMPACTS
Evaluation of Built Environment Performance through Measurements, Experimentation, and Data Synthesis • Improve knowledge of behavior of soil, foundation, and structural and non-structural components of structures through field monitoring with next-generation sensors and experimental research • Improve understanding of behavior of full structural, geotechnical, and structure-foundation-soil systems through field monitoring (including remote sensing) and experiments on complete systems • Produce information, including processing with data fusion, visualization, and system identification, for the development and validation of structure-level simulation tools • Provide diagnostic information about condition and prognosis of expected future performance of structure-foundation-soil systems
Structure-level Simulation Models and Computational Tools • Modeling of complex, heterogeneous materials used in construction • Multi-phase and multi-physics modeling of soils • Models for structural components, non-structural components, and foundation components • Models of assemblies, substructures, and global systems including multi-component combinations, with uncertainties and sensitivities • High-end and grid-based computational methods for simulating seismic performance • Collaborative software development tools and protocols for the earthquake engineering community • Large-scale database and scientific visualization tools for simulation
System Level Simulation and Loss Assessment Tools • Validation studies to calibrate the accuracy of loss estimation models, incorporating the full range of physical and societal impacts and losses for earthquake and other hazards • National models for earthquake hazards, building and lifeline inventories, and exposed populations, and application to other natural and man-made hazards • Improved damage and fragility models for buildings and lifelines based on new and improved structure level simulation tools • Improved indirect loss estimation models

Structure-Level Simulation Models and Computational Tools

The design of a new structure or the assessment and seismic improvement of an existing structure can be improved with the use of computational simulations to assess the seismic performance of the structure. Structure-level simulation is broadly defined to include the development of models and computational tools to determine the behavior of structural systems, foundation, and non-structural components of a building, bridge, industrial plant, wharf, or other constructed facilities in an earthquake. Analysis methods using nonlinear models of behavior are just beginning to be used in practice after many years of research, and the degree to which they facilitate decisions about performance has the potential to increase rapidly. Structure-level simulation includes methods for understanding and evaluating the uncertainty associated with the prediction of performance due to randomness of the earthquake loading level and the actual construction, as well as the uncertainty associated with the models themselves because of lack of data and lack of knowledge. Structure-level simulation, firmly based on and validated by data from sensing and experiments, should provide assurance that a design will achieve its intended performance objective with a much higher level of confidence than possible with today's analysis methods. The reduction in the uncertainty in predicted performance through improved and validated simulation procedures, and the resulting increased confidence, can potentially reduce construction costs by reducing the level of conservatism in design.

The SAC Steel Project: Program for Reduction of Earthquake Hazards In Steel Moment-Resisting Frame Structures

The Loss-Reduction Problem

Prior to the 1994 Northridge earthquake, the engineering field generalized that steel-frame structures were among the very best in their ability to resist earthquake shaking, and when damage occurred, it would be limited to "bending not breaking" (i.e., ductile rather than brittle behavior). However, over 100 large steel-frame buildings in the Los Angeles region suffered fractures in their joints, even though in many cases the ground motion was less than anticipated in building code provisions. (The ability of the beam-column joints to resist the tendency to rotate under lateral loading -- "moment resistance" -- thereby preventing excessive sidesway, is essential for a frame building's structural stability.)

Research Accomplishments

The Federal Emergency Management Agency provided $12.5 million over six years to the SAC Joint Venture, a partnership of the Structural Engineers Association of California, the Applied Technology Council, and the Consortium of Universities for Research in Earthquake Engineering. Researchers funded by NSF and NIST were also involved. There were 120 SAC tests (see illustration) conducted at over a dozen universities (and with tests conducted by industry, 500 test results were catalogued); practicing engineers conducted field stud-computer simulations were conducted to assess proposed improvements; cost and other other socio-economic impacts were assessed.

Beam-column connection tests

Research Applications

The culmination of the project was the production of interim and final guidelines in a form suitable for quickly implementing needed changes in building regulations, engineering procedures, and industry practices.

For further information: http://www.sacsteel.org

Research in structure-level simulation needs to address the complex, heterogeneous, and highly variable nature of materials used in construction. This includes the different types of soils, concrete, metals, and advanced materials increasingly used in construction (such as high-performance metals, high-performance concrete, polymers, and advanced composites). Many of these problems involve multi-phase physics (saturated soils, liquefaction) and complex behavior such as fracture and deterioration. After improved models of material behavior have been developed, interactions among components must be represented in computational models. This includes interface conditions, which are critical in understanding the behavior of piles and connections of structural components. The next step in structure-level simulation is to aggregate component behavior into meaningful models of a complete structure, including foundation and non-structural components, to provide accurate prediction of the performance as a system. Integration of structure-level simulation with the measurement of performance in the field and in the laboratory described above, and data fusion, is necessary to validate computational models. Consideration of uncertainty is a necessary aspect of structure-level simulation, because performance predictions must be associated with ranges of variability and confidence limits.

Computational simulation is driving advancement in other scientific and engineering fields because of the rapid evolution of information technology. A comprehensive initiative by the earthquake engineering community is needed to develop new software tools that take advantage of high-performance computing, including grid-based technologies (e.g. NEESgrid, which forms the basis for NEES system integration), collaborative software development methods, large-scale databases, and scientific visualization to produce a radically improved structure-level simulation capability. This will require the development of software engineering strategies for the earthquake engineering community that will maximize the benefits of research and allow for rapid commercialization of technology.

System-Level Simulation and Loss Assessment

Loss estimation methodologies and tools such as HAZUS have evolved considerably in the past five to ten years, largely due to the introduction of geographic information systems (GIS). Currently, these tools are being used to forecast potential impacts and losses from large and moderate earthquakes, to compare the benefits of various mitigation strategies, and to provide a basis for assessing the effectiveness of existing emergency response plans. However, there are several areas where improvements are needed in order to integrate more effectively loss estimation methodologies into loss assessment programs. These include 1) validation studies to calibrate the accuracy of loss estimation models across the entire range of losses, from physical damage through deaths, injuries, health impacts, and economic and social losses; 2) improved models that can also include information and data on local hazards, regional-specific building and lifeline inventories, and detailed information on exposed populations; 3) much-improved damage or fragility models for buildings and lifelines taking full advantage of the new structure-level simulation tools mentioned above; 4) improved indirect loss modeling, specifically business interruption losses and the impact of lifeline disruptions on short- and long-term economic losses; and 5) more examples of system level integration, such as interdependencies among lifeline systems. The development of these loss estimation tools should be coordinated with parallel work related to other natural and man-made hazards.

This three-component program in impact assessment will provide new data, methods, and software tools to improve the ability to predict the effects of an earthquake, with much less uncertainty than is possible today. New sensor and communication technology and dramatic improvements in computing will enable fundamental changes in impact assessment. The integration of large amounts of new data with simulations of individual structures will provide major advances in understanding performance and the ability to model it. Advances in loss estimation with vastly improved data, data management, and visualization will improve decision making on loss-reduction strategies.

OUTREACH TASKS FOR ASSESSING EARTHQUAKE IMPACTS

Outreach is required to assure that the impact assessment technology can be implemented in practice. These activities, described in the Outreach Plan summarized in Table 4b, will contribute to the goal of preventing catastrophic losses by improving the knowledge of impacts on the built environment and on communities. Furthermore, new impact assessment technology will allow an increased focus on understanding the damage that can be caused by earthquakes and improving loss estimates for better decision making.

Table 4b. Outreach Tasks for Assessing Earthquake Impacts

OUTREACH TASKS FOR ASSESSING IMPACTS
Evaluation of Built Environment Performance Through Measurements, Experimentation, and Data Synthesis • Develop comprehensive research plan for critically needed experiments on structural, non-structural, foundation, and structure-level components to address knowledge shortcomings in our ability to predict performance. • Develop implementation strategy for large-scale deployment of sensors in the ground and in full systems including buildings and other constructed facilities; identify incentives for deploying sensors through policy instruments. • Develop consensus guidelines for deployment of sensors and their use in operation of buildings and other constructed facilities, including interfaces with emergency responders.
Structure-level Simulation Models and Computational Tools • Create new models for representing the behavior of structural and non-structural components for use in computer simulation software. Models will be validated using curated databases of experimental and field data, to be developed by NEES. • Form a consensus-based earthquake engineering organization for the development and promulgation of software standards for earthquake simulation software. Encourage the development of modularized software protocols and standards to maximize the inter-operability of software for earthquake applications. • Develop strategy to utilize national high-end computing resources for challenge problems in earthquake engineering; include practicing engineers in developing and performing challenge problems as a means for disseminating new simulation technology.
System Level Simulation and Loss Assessment Tools • Develop next-generation loss estimation methods utilizing new simulation technologies, databases of performance, and high-end computing and visualization tools. • Develop outreach plan for improving building inventory of communities. • Work with communities in creating databases and specific modules for loss estimation from earthquakes and other hazards.

5. REDUCING EARTHQUAKE IMPACTS

In the past twenty-five years of the National Earthquake Hazards Reduction Program, much has been learned about reducing the impacts of earthquakes on the built environment and on society. The new technologies to be developed as part of this Plan have the potential of developing much more effective tools for improving the performance of new and existing systems within the built environment. These systems include the structural and nonstructural components of buildings, industrial plants, and lifelines (transportation, water, wastewater, electric power, telecommunication, and gas and liquid fuel systems). Pre-event strategies include the exploration and adoption of new materials and innovative structural systems, such as advanced composites and adaptive structural systems. Reduction in the uncertainty in predicting the performance of structures and systems has the potential for greatly enhancing the cost-effectiveness of retrofitting existing vulnerable structures and systems. Major improvements in impact reduction are also expected in aspects of geotechnical engineering, such as soil improvement techniques, and in coastal (tsunami) and fire-protection engineering. Other pre-event strategies include the development of methodologies for assessing the cost-effectiveness of mitigation strategies, land-use measures that restrict exposure or require added engineering measures in hazardous zones to minimize potential losses, and financial instruments to transfer risk. Post-event strategies include advanced and emerging technologies for emergency response and effective recovery. These areas of research are summarized in Table 5a and outlined below. An Outreach Plan is given in Table 5b.

RESEARCH TASKS FOR REDUCING EARTHQUAKE IMPACTS

Materials and Structural Engineering
Two challenges need to be addressed in the materials and the structural systems used in buildings, bridges, dams, and other structures in order to make major advances in impact reduction. The first is to shift the focus of our efforts from structural component behavior to system-level performance, and the second is to develop structural systems that exhibit an enhanced degree of resilience, not only to the earthquake hazard, but also to other extreme events.

Historically, progress has been made by disaggregating the built environment into its component parts, and improving the performance of these parts, one piece at a time. This has been done to simplify an extremely complex problem into tractable pieces and enable progress through incremental discoveries and engineering innovation. This approach has served well so far, but will not by itself eliminate losses from future earthquakes. What is needed is a systems approach, which contains significant intellectual challenges. The current drive towards *performance-based* design of buildings and other structures is a first step in this direction.

Performance-based earthquake engineering provides a logical framework in which to develop and evaluate new materials and structural systems. Structural steel, reinforced concrete, and timber are the most common construction materials and are preferred by the engineering profession because of their reliability and competitive cost. The prescriptive nature of current design codes tends to preserve the status quo and stifles the implementation of new materials and structural systems. Compelling justification is required for any new material to be adopted, but performance-based approaches provide a framework for such justification. The benefit-cost analysis for superior performance (arising from an advanced material or innovative structural system) can be compared against those for conventional design, using explicitly defined performance objectives. The higher costs of meeting stringent objectives for critical facilities, such as hospitals, emergency-dispatch centers, fire-suppression systems, and interstate freeways can be justified within the performance-based framework.

Alternative materials and structural systems, evaluated within the performance-based framework, are required to improve system performance. Promising new materials include high-performance steel and concrete, which deliver higher strengths for less weight, and various composite materials, which not only have high strength-to-weight ratios but also have lower life-cycle costs due to resistance to corrosion and other adverse environmental effects.

Table 5a. Research Tasks for Reducing Earthquake Impacts

RESEARCH TASKS FOR REDUCING IMPACTS
Materials and Structural Systems • Determination of strength, rate dependence, environmental, toughness, and life cycle characteristics of new and existing materials • In-situ characterization of existing materials • Application of high-performance steel, concrete, polymers, and composites in dynamic load environments • Cost-effective strategies for retrofitting existing inventory of buildings, bridges, and lifelines • Innovative structural framing systems for lateral-load capacity and resiliency • Smart structural systems using hybrid control technologies
Nonstructural Systems • Improved design methodologies for nonstructural systems
Lifeline Engineering • Strategic hardening of lifeline systems for optimal system performance
Geotechnical Engineering • Ground improvement to minimize occurrence and extent of liquefaction through soil modification and/or strengthening techniques • Protection of foundation systems from lateral spreading/ settlement due to liquefaction/ soil failure
Tsunami Engineering • Protection of coastal structures (seawalls, breakwaters, docks, buildings, and cranes) from tsunami wave effects, including debris loading • Protection of low-lying coastal areas from inundation due to sea-level rise
Fire-Protection Engineering • Hardening of water-supply systems • Improvements to gas shutoff valves • Advancements in fire-detection technology
Land-Use Measures • Changes in land-use patterns to minimize exposure in hazardous regions such as fault zones, landslide areas, low-lying coastal areas, and areas subject to liquefaction

Table 5a continued next page

Table 5a. Research Tasks for Reducing Earthquake Impacts (continued)

RESEARCH TASKS FOR REDUCING IMPACTS (continued)
Assessment of Cost Effectiveness of Loss Mitigation • Definition of performance measures for lifelines and communities • Improved loss estimation models • Comprehensive direct and indirect loss models • Quantification of uncertainties • More in-depth demonstration studies, involving an integration of disciplinary approaches • Application in post-event settings (i.e., recovery) • Examination of non-linear adaptive behavior in complex organizations
Financial Instruments to Transfer Risk • Systematic collection and dissemination of insured loss data • Studies to assess the efficacy of alternative risk reduction or transfer methods • Analysis of benefits and costs to various stakeholder groups • Analysis of complementary roles of mitigation and insurance • Analysis of safeguards against insurance industry insolvency
Advanced and Emerging Technologies for Emergency Response and Effective Recovery • Real-time earthquake monitoring and ground motion recording systems • Real-time loss estimation tools • Remote-sensing technologies for damage assessment • Advanced decision-support systems for response and recovery • Data-fusion technologies • Advanced communication and networking systems for response and recovery

New structural systems also warrant research initiatives, especially those that are tolerant of large lateral loads for brief periods of time. Structural systems that separate load-carrying functions from those related to energy dissipation and energy absorption show promise for major improvements in earthquake-resistant performance. For example, ductile-end diaphragms for bridges with steel superstructures improve overall system performance without jeopardizing the gravity-load function of the structure. Other devices, such as steel shear links, viscous and friction dampers, visco-elastic devices, buckling-restrained braces, and tension-only shape-memory alloy braces, have all been shown to have a beneficial effect. The challenge is to improve structure performance without adversely impacting function and continued operability. Seismic base isolation is an accepted technology now for protecting structures from earthquakes, but there are many improvements possible in the isolator bearings and the systems for isolation. Energy dissipators and isolators are passive devices that are applied currently to enhance performance during the design earthquake. The next generation of these devices will expand the range of performance that can be achieved with them and will provide a level of protection not presently feasible with current technology. Multi-hazard protection will also be provided for both natural and man-made events. This effort will require the involvement of multidisciplinary teams of researchers and practitioners, including control and structural engineers, experts in experimental and numerical simulation, sensor and instrumentation scientists, seismologists, geotechnical specialists, and experts in flood, wind, and blast loading.

Performance-based engineering is the first step towards understanding the behavior of a building and its component subsystems. But the performance-based approach is not restricted to the design of a single building, and may be applied to complete infrastructure systems, such as transportation networks. Understanding the interdependence of lifelines and their complex interaction with other segments of the built environment and the communities they serve are major challenges that require a system-level approach.

SMART TECHNOLOGIES FOR IMPROVING BUILDING PERFORMANCE

The Problem

Annualized earthquake losses to the building stock in the United States have been estimated at $4.4 billion (FEMA 366, 2001). Whereas this figure includes indirect losses from business disruption, it does not include damage to lifelines and industrial plant. More resilient buildings and lifeline systems are urgently required if these losses are to be reduced, and the development and application of smart devices and systems for improving structural performance are the subjects of this research.

Damage to medical facilities was widespread during the 1994 Northridge earthquake in southern California (right), causing evacuations at 12 hospitals (left) and the temporary loss of 2,500 beds.

Research Accomplishments

With funding from the National Science Foundation, the Federal Highway Administration, the Department of Energy, state and local agencies such as the California Department of Transportation, and the private sector, an innovative class of response modification devices (RMDs) has been developed that significantly improve the performance of buildings, bridges, storage tanks, manufacturing plants, and large items of equipment. These devices include both passive and semi-active devices such as elastomeric and sliding seismic isolators, viscous and hysteretic energy dissipators, and electromagnetic fluid dampers. Computer-based simulations have been validated using experimental studies on shake tables, and field experience obtained on full-scale structures during actual earthquakes has confirmed the merits of this technology.

Research Applications

Over the last decade, applications have been made to hospitals, emergency command centers, hi-tech manufacturing plants, and database centers. In addition to protecting critical facilities, RMDs have been used to retrofit historical buildings, where they are not only a cost effective solution for these fragile structures, but also enable the historical fabric of these buildings to be preserved. Seismic isolation and energy dissipation codes have now been developed and adopted for buildings and bridges in the United States, and the number of applications is steadily growing.

The University of Southern California Teaching Hospital (above) is seismically isolated with 300 elastomeric isolators. It survived the Northridge Earthquake without damage of any kind or interruption to service.

Protection of Nonstructural Components and Systems
Nonstructural systems in buildings include secondary components such as ceiling tiles and internal partitions, and infrastructure systems such as fire-suppression, water and wastewater distribution, electric power, telecommunications, and heating, ventilating, and air-conditioning systems, including chilled water.

Emergency response facilities, such as hospitals and dispatch centers, are critically dependent on these systems for their continued operation, in addition to the integrity of the structural system in which they are housed. Progress in the design of these structures to satisfy extreme performance criteria has improved their overall response. Nevertheless, hospitals have been evacuated in recent earthquakes because their nonstructural systems have failed, despite the survival of the building frame. In fact, direct losses in recent earthquakes are dominated by damage sustained by nonstructural systems, compared to that suffered by the structural frames in which they are housed. Little is known about the performance of nonstructural systems, including their interaction with structural frames. A typical system might be a pressurized water distribution system, including header tanks, pipes of different diameter and stiffness, joints of varying integrity, and a range of hanging and braced supports including snubbers and other control devices. Response is nonlinear for reasons of joint slip, water sloshing, large-displacement geometry, and inelastic snubbers and dampers. Research is required to understand this behavior, and to develop improved design methods that will minimize nonstructural damage and ensure the continued operation of critical facilities.

Lifeline Engineering
Lifeline systems include transportation, water, wastewater, electric power, telecommunication, and gas and liquid fuel systems. Lifelines are major elements of the infrastructure that permit the nation to transport its people and distribute food, provide clean water, control disease, conduct commerce, and defend itself. Outside of California, few lifelines in the United States have been designed for earthquake loads. A notable exception is the bridge component of the national highway system. But more than 70% of the national bridge inventory was constructed before the development of modern seismic codes, and bridge retrofitting is an urgent need. Furthermore, many of the existing lifelines are aged and deteriorating due to a lack of maintenance and/or systematic upgrading. These systems are therefore both fragile and vulnerable. Their continued operation following a major earthquake cannot be assured.

In addition to high-performing nonstructural systems, many critical facilities also depend on uninterrupted access to electric power, water, and the like to provide essential services to the community. Electric power transmission systems are vulnerable because of the fragile equipment in substations. Water supply systems are critically dependent on the seismic performance of dams, reservoirs, and pipelines that store and distribute water to communities. Research is required to find cost-effective means to design and upgrade systems in accordance with earthquake-resistant criteria.

The intellectual challenge is not only to understand how these spatially distributed systems perform under earthquake ground motion, but also to understand their interdependence on each other. Advanced GIS systems hold great promise for characterizing these complex networks and will enable more sophisticated modeling to be undertaken, such as those provided by artificial intelligence, neural networks, and associative memory techniques.

Geotechnical Engineering
Foundations of buildings, buried lifelines, and other parts of the built environment are vulnerable to liquefaction and ground failure due to permanent ground deformation. It is estimated that about $10 billion of the loss during the 1995 Kobe earthquake was caused by liquefaction and ground deformation. There is an urgent need to learn how to prevent liquefaction and to mitigate its effects in a practical and cost-effective manner. Making improvements to foundations, lifelines, and the ground are often very expensive – especially when rehabilitating existing structures – with the degree of improvement and cost being sensitive to the desired degree of expected performance. Therefore, accelerated research is needed on new

and advanced ground improvement and foundation technologies and materials, including full use of existing and new tools to verify and predict with minimum uncertainty the expected performance and reduced vulnerability provided by these new technologies. There are currently a number of strategies for foundation retrofitting and ground improvement (e.g., stone columns, deep dynamic compaction, pressure grouting, deep soil mixing, passive grouting, etc.), and new ones are proposed every year. Many of these foundation and ground technologies are applicable both to buildings and to other parts of the built environment, such as bridges, ports, buried lifelines, and earth structures, including dams and dikes. Structure-level simulation tools developed for natural ground and traditional foundations should be adapted to predicting the performance of improved ground and foundation systems. This will enable full use of performance-based approaches in the practical design of improvements, accounting for construction optimization and expected reductions in earthquake damage costs. Laboratory (especially centrifuge) and field experiments using NEES facilities should be used systematically to evaluate the seismic performance of these improved ground and foundation systems as well as to validate the corresponding structure-level simulation tools. Once the improved new and advanced ground and foundation technologies are implemented in actual engineering projects, these projects should be instrumented with dense arrays of sensors to compare predicted and actual performance when an earthquake occurs.

Tsunami Engineering

Tsunamis are generated by co-seismic fault displacement of the sea floor as well as by submarine landslides triggered by earthquakes. Tsunamis can cause structural destruction and economic losses, and more importantly, cost human lives. Since 1992, sixteen tsunamis have occurred in the Pacific Ocean, resulting in more than 6,000 fatalities, which is comparable to the number of fatalities caused by other earthquake hazards in that region during that time interval. In all cases, these tsunamis struck land near their sources, so little reaction time was available. Ironically and unfortunately, coastal areas that are preferred sites of human habitation have been frequent, vulnerable targets of tsunamis.

To mitigate tsunami hazards, the first priority is to establish reliable warning systems for evacuation and to improve the identification of the zones likely to be inundated by a tsunami. Japan has attempted to minimize the inundation area by construction of tsunami seawalls (often more than 10-m high) along the shoreline. In the U.S., such high coastal seawalls are not considered a tenable approach to hazard reduction. Instead, the National Oceanographic and Atmospheric Administration (NOAA) has launched a comprehensive effort to estimate potential inundation zones along the western states, Alaska, and Hawaii. Once inundation zones are defined, civil defense authorities can design evacuation routes a priori as well as routes for search and rescue, while planners can develop priorities for such measures as relocation of critical and high-occupancy facilities. The next level of a mitigation strategy is the reduction of casualties and property damage within the tsunami inundation zones. Specific tsunami run-up patterns must be predicted, and tsunami-induced forces and scour effects need to be determined to enable better design of waterfront structures and help guide the decision making process for land-use issues. The complex problems associated with tsunami hazard mitigation strategies necessitate interdisciplinary and international research efforts, including modeling and computational simulation, large-scale laboratory modeling, geographical information and communication systems, and social sciences and planning. Comprehensive and integrated efforts for multi-disciplinary tsunami research should be facilitated by the NEES tsunami facilities.

Fire-Protection Engineering

Research is needed to improve fire protection and suppression equipment such as piping, valves, tanks, and smart control systems to avoid and minimize the number of ignitions after an earthquake. Existing models of post-earthquake fire were designed before adequate computational power existed to perform detailed simulations of fire ignition, growth and spread, and fire department response at high resolution. Furthermore, major recent events are not reflected in these existing models. It is now possible to update these models using data from recent earthquakes, most notably the 1994 Northridge, 1995 Kobe, 1999 Turkey, and 2001 Nisqually, Washington earthquakes, as well as non-earthquake conflagrations such as the 1991 Oakland, California fire, and major high-rise building fires. It is also possible now to model fire department response at the detailed level of individual structures and apparatus. With these new data, we can create empirical and analytical models of fire growth and spread within buildings. This information should be used to update models of ignition rate, fire spread, and fire-service response under disaster conditions. The new computational simulations can be employed in decision analyses of pre-earthquake mitigation and post-earthquake emergency response. Pre-earthquake mitigation options include examining the effects of staffing levels, seismic strengthening of fire stations, strengthening of sprinklers, gas shut-off valves, and advanced fire-detection technology. Post-earthquake mitigation alternatives include linking fire departments' GIS systems (for dispatch and display) with real-time aerial imagery and models of urban fire spread.

Land Use Measures

Earthquake vulnerability is fundamentally affected by choices about the location and density of development. This includes decisions about the siting of facilities and infrastructure and the degree of development at particular locations. Land use measures that include prohibitions or restrictions for development in hazardous areas (e.g., steep slopes and liquefaction areas), or require special engineering analyses for such development (e.g., geotechnical reports) are important instruments for addressing this vulnerability. Given the potential value of such measures for reducing future vulnerability, it is important to conduct research that documents the available instruments and their effectiveness. Information technology advances that will facilitate this include new uses of remote sensing and geographic information systems to document land use changes. Consideration of changing land use patterns is also an important component of assessing changes in earthquake vulnerability.

Cost Effectiveness of Loss Mitigation Measures

There are a number of ways to evaluate whether a particular mitigation measure is cost-effective or not. The measure or strategy can be examined after a major earthquake; that is, validated through actual performance. A good example of this type of validation was the performance of highway bridges in the 1994 Northridge earthquake. Another way of validating the efficacy of mitigation measures is to estimate future losses in the absence of the mitigation measure. This technique has been widely used by FEMA to decide which post-

Vulnerability of Woodframe Construction

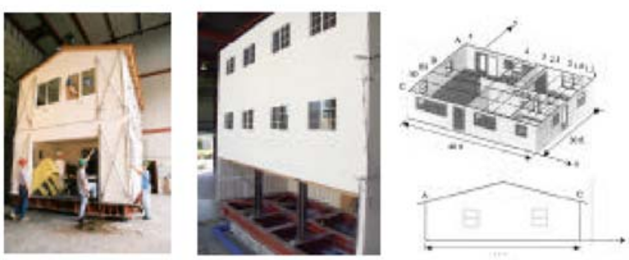
The Loss-Reduction Problem

Collapsed woodframe apartment building, Northridge earthquake

In the 1994 Northridge earthquake, 24 of the 25 fatalities that were caused by building collapse occurred in woodframe ("two by four") construction, and this type of building—which represents about 80% of all buildings in the United States—accounted for half the $40 billion in property damage and virtually all of the 50,000 dwelling units rendered uninhabitable (CUREE, 1998). The project aims were to "make the engineering more scientific and the construction more efficient."

Research Accomplishments

With $5.2 million in Federal Emergency Management Agency funds, and an additional $1.7 million in non-federal matching contributions, the 1998-2002 CUREE-Caltech Woodframe Project engaged a dozen universities and several consulting engineering firms in conducting an experimental and analytical study of wood building seismic performance that is by far the largest to date in this country.



Full-scale shake table testing of a two-story house (left, UC San Diego) and three-story apartment building (center, UC Berkeley). A new engineering analysis method and software package were produced (right).

Research Applications

Consulting structural engineers and building officials have had a prominent role in the project's research, both in guiding the research plan and interpreting the results and producing building code and construction practice recommendations. Recommendations for cost-effective improvements to 23 different codes, standards, and guidelines are now in-press. A loss-estimation method useful for cost-benefit analysis of retrofits and to the insurance industry was produced. Museum exhibits and videos were produced to convey information to the general public.

Hand-operated shake table and collapsible/re-erectable structure model, Riverside County Youth Museum

For further information: http://www.curee.org event mitigation projects to award. In order to implement this procedure, a loss estimation tool that allows users to vary the earthquake-resistance level of a structure or system must be employed. HAZUS, which has undergone significant development and testing over the last several years, can perform this type of analysis, but much more sophisticated tools are necessary to allow decision makers to fully consider the costs and benefits of alternative mitigation strategies.

The application of these methodologies can be performed both before and after a major earthquake. In most cases, they are applied as pre-event mitigation tools. However, in large events, where significant damage has occurred, there are unique opportunities to rebuild or retrofit vulnerable structures or systems. For example, the damage to moment-resisting steel-frame buildings after the 1994 Northridge earthquake led to the FEMA/SAC Steel Project, a comprehensive research program to identify cost-effective methods of retrofitting these structures. Because of the large costs involved with these retrofits, this project included studies to quantify the benefits and costs associated with these retrofit measures. The results of these studies should be used to develop a technology transfer plan that recommends how these retrofits should be carried out, an appropriate time schedule, and ways of accelerating this program should another significant earthquake occur.

Research that must be conducted to improve our ability to determine cost effectiveness includes 1) clearer definition of performance measures and standards, 2) improved loss-estimation tools, 3) incorporation of all relevant direct and indirect loss measures in cost-effectiveness analysis, 4) quantification of how uncertainties affect cost-effectiveness calculations, and 5) better explanations on the use and limitation of loss-estimation results for cost-effectiveness analysis.

Financial Instruments to Transfer Risk

Risk-transfer mechanisms complement mitigation strategies by providing financial compensation to organizations that have suffered a catastrophic loss. Traditionally, this has been viewed as an alternative to governmental funding in the aftermath of damaging events. In making decisions regarding how much insurance to purchase, organizations must determine their level of insolvency and how much financial protection they desire to protect their capital stock and investment. The more risk-averse an organization is, the more it will use risk-transfer instruments to protect itself against large losses, and the more willing it will be to pay for this protection. However, insurance does not usually reduce losses to society as a whole, but simply redistributes across entities, regions, and time periods.

There are several mechanisms available to minimize or transfer this risk, including 1) insurance policies, 2) indemnity contracts, and 3) indexed based or parameterized contracts, commonly known as catastrophe-linked or *cat bonds*. Future research should concentrate on 1) the systematic collection of insured loss data, 2) the efficacy of these types of risk transfer methods under a wide variety of conditions, and 3) more ways of incorporating incentives for loss reduction into insurance.

Advanced and Emerging Technologies for Emergency Response and Recovery

We need to develop knowledge, techniques, and tools that can aid society in becoming more resilient when earthquakes occur. Since resilience entails the ability not only to avoid damage and losses but also to respond and recover rapidly and intelligently, the improvement of post-event response and recovery measures is one important avenue toward achieving resilience.

In the last decade, there has been a tremendous increase in the use of advanced technologies for design, construction, retrofit, and emergency planning. Emphasis must be placed on those technologies that have regional or community benefits and that can be employed following the occurrence of a damaging earthquake to enhance the effectiveness of emergency response and recovery efforts. These technologies include 1) real-time earthquake-monitoring and ground motion systems, 2) near-real-time loss-estimation tools, 3) remote-sensing technologies, such as satellite imagery, light-detection-and-ranging radar

(LIDAR), synthetic-aperture radar (SAR), 4) advanced decision-support systems, and 5) advanced data-management and communication technologies.

These technologies hold the promise of reducing losses in a number of ways. Real-time earthquake monitoring makes it possible to detect earthquakes as they occur, rapidly capture relevant data, and transmit those data to affected communities and responding organizations. With even a short-term warning period, emergency response organizations will be able to protect vulnerable equipment and personnel and respond more rapidly as problems begin to develop. Monitors and remote-sensing technologies can be linked with near-real-time loss estimation tools to provide responding jurisdictions and organizations with information on the location of the most severely damaged areas, sites where building collapses will require immediate search and rescue efforts, areas where the demand for emergency medical services will be greatest, as well as rapid information on secondary hazards such as fires and hazardous chemical releases. The rapid situation assessments made possible through the use of advanced remote-sensing and information technologies will aid emergency response organizations in deploying resources to areas of greatest need, establishing priorities among competing demands, and requesting mutual aid and other outside assistance. Rapid loss estimation tools can also provide decision makers with credible estimates that can serve as the basis for requests for disaster declarations and state and federal aid.

Decision-support tools are needed not only for post-impact response and for system restoration but also for longer-term community recovery. To enhance community resilience, recovery decisions should be made systematically, on the basis of the best available data and models, rather than in an ad hoc manner, so as to speed the recovery process for affected communities. Research is needed to develop comprehensive recovery models so that communities can assess potential recovery trajectories, evaluate trade-offs, and manage the recovery process effectively. For example, until recently, the focus of loss estimation has been on property damage, a measure that is affected by ground shaking, permanent ground deformation, and other factors. However, business interruption, a major source of the losses that result from earthquakes, represents a flow measure that needs to be evaluated over a period of time and that is very sensitive to the timing and pattern of reconstruction. Specific strategies that can be employed during the post-earthquake recovery period to reduce economic losses resulting from business interruption include 1) more effective strategies to restore lifeline service, particularly electric power, water, gas, and telecommunications; 2) use of rationing as a means of providing limited lifeline service; 3) improved allocation of supplies and inventories based on availability and demand; and 4) identifying transportation bottlenecks in routing critical supplies.

After a major disaster, information and data from a variety of sources will begin to fill emergency operations centers (EOCs) and other centers involved with the response effort. These data will generally be disparate in form, quality and comprehensiveness, and will arrive at these centers at different times during the disaster. New data fusion methodologies must be developed that will help to merge and integrate this information so that more intelligent decisions regarding response can be made. Techniques that recognize the common information among these disparate data sets – particularly as they pertain to specific incidents – can be useful in validating the reliability of events requiring some type of response. In past disasters, this lack of validation has led to delayed or impeded response. In addition, technologies that help to convert or translate voice messages into text can be extremely useful in capturing the scope and magnitude of an event in real time. When integrated with geographic information systems (GIS), this type of technology can be extremely effective.

Pilot applications of many of the advanced technologies described above have been made, but not all have made their way into the emergency responder's toolbox. This is due mainly to the reluctance of users to implement these technologies without clear examples that demonstrate their efficacy for planning, mitigation, response, or recovery. Substantial evidence or validation that these technologies do in fact help to improve risk reduction efforts in these areas is a prerequisite for their widespread implementation. More research is needed on overcoming impediments to adoption of individual technologies, and on non-linear, dynamic adaptive responses in organizations and systems.

OUTREACH TASKS FOR REDUCING EARTHQUAKE IMPACTS

Significant reductions in vulnerability can be achieved by reducing the impact of the earthquake risk through better engineering, planning, and risk management decisions. If the performance of the built environment and the resilience of communities to earthquakes and other extreme events are improved to the extent envisioned above, both direct and indirect losses will be significantly reduced. A technology transfer plan to facilitate the implementation of this research is described in Table 5b. This plan comprises four essential elements: 1) developing codes, guidelines, demonstration projects and training in the use of new design and retrofit procedures; 2) developing procedures for assessing the effectiveness of mitigation measures; 3) adopting measures to transfer seismic risk; and 4) using advanced technologies to enhance emergency response and recovery. All these activities have direct benefits in helping to reduce and manage earthquake risks, both before and after the occurrence of earthquakes. This work will be guided by a management plan that directs the research and implementation efforts to ensure that they are responsive to stakeholder need.

Table 5b. Outreach Tasks for Reducing Earthquake Impacts

OUTREACH TASKS FOR REDUCING IMPACTS
Develop Codes, Guidelines, and Demonstration Projects • Develop guidelines, manuals of practice, and model codes for the seismic design and retrofit of buildings and their contents, bridges, lifelines, and coastal structures • Develop products for the implementation of performance-based seismic design, including structural and nonstructural performance products, risk management products, performance-based seismic design guidelines, and a stakeholders' guide[xvii] • Conduct demonstration projects involving researchers, practitioners, owners, and other stakeholders in the assessment and mitigation of risk to buildings, infrastructure, and coastal systems • Conduct short, intensive courses on new technologies, codes, and guidelines
Adopt Financial Instruments to Transfer Risk • Systematically collect insured loss data after every major natural disaster • Develop a comprehensive, publicly accessible database on these losses • Perform research to determine the long-term efficacy of these types of risk transfer methods • Perform case studies to illustrate the long-term benefits and problems associated with this type of risk-transfer strategy
Incorporate Advanced and Emerging Technologies for Emergency Response and Effective Recovery • Integrate loss estimation tools with near real-time ground motion systems, e.g., Shakemap, ANSS • Develop methodologies to update post-event loss estimates with post-event data from field and aerial surveys • Develop methodologies to use satellite imagery (pre- and post-event images) to quantify regional damage and damage to specific structures • Develop decision-support tools that can incorporate data from disparate data sources, update decision making in a chaotic and dynamic environment, communicate effectively between different data centers or hubs, and incorporate a strong visualization element • Incorporate data and networking research being performed for other purposes (voice to text messaging) into disaster or crisis management

6. ENHANCING COMMUNITY RESILIENCE

Much of the attention in earthquake engineering addresses individual structures—a building, a bridge, or an industrial facility—and decisions that are made about the seismic integrity of those structures. From a societal perspective, however, much more is involved than these decisions in order to improve earthquake risk management for a community. Loss reduction strategies focusing on specific structures and facilities are important, but protecting the social fabric of our communities against earthquake losses necessitates more comprehensive and holistic approaches.[xviii] Seismic safety is a matter of public welfare, involving the potential for loss of life or injury, disruption of lifeline systems, and costs to insurers, property owners, and governments for earthquake losses and recovery. These issues make it important to consider the extent to which communities are resilient to the damaging effects of earthquakes.

RESEARCH TASKS FOR ENHANCING COMMUNITY RESILIENCE

Strengthening policymaking for seismic safety requires a better understanding of the societal and economic implications of catastrophic earthquakes. There is a critical need for a full understanding of earthquake vulnerability, including (1) agreement about what constitutes the dimensions and measures of vulnerability; (2) an understanding of the demographic, economic, and other societal considerations that affect vulnerability; and (3) a methodology for assessing vulnerability and changes in vulnerability. As discussed in Chapters 4 and 5, the HAZUS loss estimation methodology is an important tool for documenting aspects of earthquake vulnerability. However, HAZUS does not directly address the factors that contribute to changes in vulnerability. Such understanding requires research.

A second important need is to establish a better understanding of the relative costs and effectiveness of different risk management policies, focusing on insurance, land use, and building standards for mitigating the impacts of such events. In the past, we have been hampered by a lack of systematic data on the impacts of earthquakes. The ability to measure the effectiveness of risk management strategies rests on the availability of reliable and systematic data on damage and losses.

More generally, the progress in understanding vulnerability, cost effectiveness of different mitigation tools, and the resilience of communities requires the development of a comprehensive social science research program that will provide basic information on a broad range of societal impacts of catastrophic earthquakes, including:

- How earthquakes affect households, businesses, and public sector organizations, and what can be done to reduce negative impacts, both through pre-event mitigation and through more effective response and recovery measures;
- Public health consequences of earthquakes, including ways to reduce life loss and injuries and containing their costs;
- Direct and indirect economic losses occurring as a consequence of earthquakes at local, regional, and national levels and optimal approaches for containing those losses, including both pre- and post-event measures;
- Demands that earthquakes place on response and recovery systems, and ways to make those systems more effective;
- Understanding individual, organizational, and community-level decision making about earthquake risk mitigation measures, including attention to earthquake risk perceptions;
- How the social and economic impacts are affected by different means of sharing financial risks (i.e., loans, grants, insurance) and by public and private decisions about recovery from earthquakes; and
- Understanding the factors that affect the adoption and implementation of risk management programs and mitigation measures at all levels of government and among private entities.

Although much insight has been gained in the past twenty-five years about these topics, noteworthy gaps remain in understanding the societal impacts of major earthquakes and how to bring about changes in engineering practice and seismic risk decision-making.[xix] The socio-economic research program proposed below provides the essential knowledge basis for addressing these gaps. These research activities, shown in Table 6, require social-science-led research modeled on the successful NSF-based program in hazard mitigation research.

Table 6. Research and Outreach Tasks For Enhancing Community Resilience

RESEARCH TASKS FOR ENHANCING RESILIENCE
• Methodologies and measurement of progress in reducing vulnerability and enhancing community resilience to earthquakes • Risk management cost-effectiveness methodologies and analyses • Investigation of societal impacts of catastrophic earthquakes, including "learning from earthquakes" • Research on decision making and earthquake risk perceptions • Research on implementation of risk management and earthquake mitigation programs
OUTREACH TASKS FOR ENHANCING RESILIENCE
• Outreach to: – relevant stakeholders and decision tools for these stakeholders – state and local governments regarding risk management policies and programs – design professions involved with earthquake risk management • Stakeholder process for improving regulatory systems • New methodologies and demonstration efforts for communicating societal implications and choices

OUTREACH TASKS FOR ENHANCING COMMUNITY RESILIENCE

The research and outreach programs presented in this Plan contribute to the goals of preventing catastrophic earthquake losses and enhancing community resilience to earthquakes. These goals can be realized if the research results are incorporated into everyday practices and decision making. The outreach programs outlined in the Plan are important steps for ensuring that research findings are provided in ways that can be implemented. This section outlines additional steps that are particularly important in accomplishing the broader goal of enhancing community resilience to earthquakes. The translation of research knowledge into practice is not simply a question of disseminating research findings. The needed advances entail fundamental changes in engineering practice and in decision making about seismic risks.

In addition to the specific programs presented, initiatives are required for enhancing decision making, for equipping the design professions with the knowledge and tools they need to more effectively reduce earthquake vulnerability, for bringing about change in regulatory systems, and for enhancing public understanding of seismic hazards and participation in seismic safety decision making. This is a more diverse and costly set of activities for which a more detailed plan is required to fully assess their costs. A starting point for such a plan is the 2000 *Action Plan for Performance-Based Seismic Design* that sets forth a ten-year engineering research and guidelines development program for performance-based standards and guidelines.[xx] The cost of this limited guidelines development program was estimated to be $20.4 to $27.3 million (in 1998 dollars) over the ten-year period. The outreach program outlined in Table 6 incorporates the non-engineering components of the technology transfer program while also including activities that go beyond performance-based seismic design considerations. These include processes for improving regulatory systems and carrying out outreach programs for the design professions and relevant public and private decision makers concerning earthquake risk management.

Confronting Choices About Seismic Safety

Diverse organizations confront decisions about seismic safety, including private and public entities, large and small firms, firms with single facilities and those with distributed facilities, those with essential and non-essential facilities, and those entities that deliver electric, gas, water, and other lifeline support. Not only do organizations differ in size and revenue base, but they also differ in their time horizons, tolerance for risk and uncertainty, and involvement with the public. Put differently, the stakes in making decisions about seismic safety differ greatly from those of a small business concerned more about tomorrow's sales than about potential earthquake losses, to those of an acute-care hospital whose emergency services must remain functional in the event of a disaster, to those of a school district concerned with protecting the lives of children, to those of an energy utility concerned about reliable delivery of service and exposure of the energy network to seismic hazards. These choices are not made in isolation; rather, they interact with other choices by lenders, insurers, other risk managers, policymakers, and the general public. Market forces, social values, institutional priorities, and legal considerations also affect these choices.

The transformation of earthquake engineering under the performance-based approach necessitates a more active involvement of these stakeholders in making decisions about desired levels of seismic safety. Indeed, the premise of performance-based earthquake engineering is that, subject to minimum standards, relevant stakeholders will choose desired levels of seismic risk management. The methodologies and tools of performance-based earthquake engineering will provide the necessary analyses for evaluating tradeoffs among different options and the costs associated with them. However, providing such analyses does not guarantee that their results will be comprehended or used. How such information is conveyed, comprehended, and used are important issues for research concerning risk communication, perception, and decision making.

The engineering profession will be required to fulfill a broader consultative role in explaining the stakes involved, the relevant choices, and the implications of those choices. Basic tools of risk communication will be important aspects of the skill set for this consultative role, along with technologies for visualizing outcomes of different earthquake risk management choices. Also relevant are improved ways of communicating uncertainties associated with different outcomes and for communicating the distribution of costs of seismic improvements over time.

The choices that governmental officials face in regulating public safety will need to be more clearly identified and articulated. These include establishment of regulatory standards (i.e., minimum performance levels) and performance objectives for lifelines or critical facilities. These are essential aspects of community-level decision making about earthquake risks. The ability to adequately frame these choices is a critical first step in improving societal decisions about seismic safety.

Equipping the Design Professions

The design professions—architects, engineers, and professionals responsible for the design of nonstructural elements and building interiors—will need to be equipped to understand and take advantage of advances in performance-based earthquake engineering and other technological advances discussed in this report. Each will need to understand the philosophy of performance-based design and develop new skill sets specific to their profession. Architects will need to better appreciate the relationships between structural features and nonstructural components of facilities. Interior designers will need to understand how modifications in the use of a structure will affect its ability to withstand earthquake damage and maintain functionality. Earthquake engineers will need to be well-versed in the methodology of performance-based earthquake engineering as applied to new and existing structures.

Additionally, as a consequence of their education and training, most design professionals tend to focus on individual structures and systems and on relatively narrow definitions of performance. Those views will need to be broadened to take into account the functional importance of structures and systems within their community settings, and also to take into account multiple performance objectives, as seen from the perspectives of different stakeholders. For example, the reliability of electrical power systems becomes critically important once it is recognized that other lifelines and numerous community functions are dependent upon electrical power, and that power supply disruption is a significant contributor to earthquake-induced economic losses. Similarly, the seismic performance of a particular hospital assumes greater importance when that hospital is the sole source of trauma care in a region, or when the direct and indirect economic impacts of hospital closure are taken into consideration.

Equipping the design professions for the revolution in earthquake engineering that lies ahead entails more than education. As discussed in previous sections of the report, new analysis tools will need to be developed that bring the power of simulation-based modeling to the desktop of practicing engineers. Visualization tools that bring the power of graphical displays will also need to be developed. In addition, new tools for assessing the social and economic impacts of earthquakes will need to be developed to help practicing engineers fulfill their broader consultative function under performance-based approaches to earthquake engineering.

Modernizing Regulatory Systems

The system for regulating building safety in this country is complex because regulation occurs at the state and local level. Like many regulatory systems in this country, a patchwork of codes and guidelines and a fractured system for overseeing their application has developed over time in response to particular events or new advances in seismic design. Due in large part to a concerted federally funded effort to develop guidelines for seismic code provisions, the private code development process in this country has been very good in incorporating advances in seismic design into code provisions and in producing structurally sound facilities through new construction. Implementation of those advances has often fallen short, however, especially as they relate to the rehabilitation of existing buildings. All too often, building officials or inspectors do not understand key provisions, or are too quick to accept the advice of unqualified engineers.

Attention needs to be given to the way in which the current building regulatory system incorporates the breakthrough advances in earthquake engineering. Mechanisms for improved communication with code writers about engineering advances need to be developed that take advantage of the range of revolutionary tools discussed in this report. New approaches to submittal, review, and processing of permits for structures need to be considered that also take advantage of advances in information technology, results of simulation-based engineering, and new methodologies for performance-based assessments. Equally important, the traditional roles of building officials, inspectors, and third-party engineering consultants need to be addressed to reflect the performance-based approach.

Another important component for modernizing regulatory systems entails confronting the interplay of choices concerning land use, risk management, and seismic engineering decisions within the context of broader policies concerning such topics as disaster relief funding, growth management, and utility regulation. Along with the development and implementation of earthquake-resistant design, seismic safety is also affected by choices concerning appropriate land use, the siting of facilities, and the financial management of risk. As discussed in Section 5, land use regulatory approaches and financial management of earthquake risk are also highly relevant to discussion of seismic safety and to broader visions of performance-based earthquake engineering.[xxi] Like the building regulatory system, land use regulation is a patchwork of state and local regulations. In many seismic-prone regions of the country, little effort has been expended to make effective use of land use management through density and zoning provisions to enhance seismic safety. The visualization and impact tools discussed are also highly relevant for these tasks. Equally important is extending performance-based engineering as a risk management tool that incorporates consideration of financial instruments and tradeoffs when making choices about earthquake mitigation.

Understanding and Communicating Societal Implications

Policymaking for seismic safety in the United States consists of deliberations among code-writing entities, among seismic safety commissions in a handful of states, and among more specialized entities dealing with earthquake risks for nuclear power plants, major dams, or state and federal facilities. Despite the existence of these forums, seismic safety has not achieved the prominence that it warrants on the broader public agenda. Although surveys have shown that residents in high-seismic-risk areas perceive earthquakes as a significant risk and that many at least potentially support stronger seismic safety measures, earthquake loss reduction lacks an organized, broad-based political constituency in almost all U.S. communities.[xxii]

Strengthening policymaking for seismic safety requires a better understanding of the societal implications of catastrophic earthquakes and the social science research called for above. Strengthening policymaking also requires better ways of communicating the societal implications of catastrophic events and improved methods for making collective policy choices for mitigating their impacts.[xxiii] The advances in simulation and visualization of earthquake effects hold promise for elevating discussion of earthquake impacts—especially with respect to the distribution of impacts across different geographic regions, sectors of the economy, and socio-economic groups—and for gaining a better understanding of tradeoffs in seismic safety policy options. Efforts to enhance earthquake safety must also engage the public through 1) education about the earthquake threat and the losses that will occur unless improvements are made in seismic safety; 2) information on effective loss reduction measures for households and businesses and why it is important to adopt those measures; 3) public awareness of new seismic safety techniques and technologies, and how those measures will make communities safer; and 4) encouraging discussions on public expectations concerning seismic safety.

7. EXPANDING EDUCATION AND PUBLIC OUTREACH

Twenty-five years ago most earthquake engineers were trained as structural engineers in university departments of civil engineering primarily on the west coast of the United States. Today earthquake engineers are educated throughout the nation, and include not only structural engineers but also those from the geotechnical, materials, coastal, mechanical, and other disciplines. Furthermore, earthquake engineering as a discipline has grown to include the earth sciences as well as the social sciences, as illustrated by the membership of the Earthquake Engineering Research Institute.[xxiv] Earthquake engineering has become a diverse and multidisciplinary field, and its educational needs are a reflection of this diversity.

The most immediate needs for education and outreach relate to design professionals, stakeholders, and state and local government officials, as described in the Outreach Tasks for Assessing and Reducing Earthquake Impacts in Tables 4b and 5b, and for Enhancing Community Resilience in Table 6. The focus of this section is on educating the next generation of design professionals and the public at large. The most important needs for the education of the next generation of design professionals include:

- attracting and retaining the best and brightest students, and providing special encouragement to underrepresented and minority students,
- recognizing that the Masters degree is becoming the entry-level qualification for many professional positions in earthquake engineering because of the increasing complexity of the issues faced by the discipline,[xxv] and
- providing a performance-based education rather than a prescriptive one; i.e., one that provides the skills necessary to meet the challenges of the future in a discipline that is rapidly changing.

Student enrollments in civil engineering, the major source of earthquake engineers, are falling nationally despite a healthy job market. The reasons for this decline are perhaps two-fold: the perception that civil and earthquake engineering are not hi-tech fields and that the degree is too difficult to attain and not adequately remunerated. For this and other reasons, traditional methods for teaching the discipline need to be reviewed, and a shift towards information and distance-learning technologies should be strongly considered. Curriculum review should also be undertaken to develop critical thinking skills and to emphasize learning by discovery rather than by rote.

Excellent efforts in the education and outreach arena are currently being undertaken by the three NSF-funded earthquake engineering research centers.[xxvi] NSF digital library programs, such as the Electronic Library of Earthquakes being created by SCEC, IRIS, and CUREE, are inventing new ways to allow K-12 and college audiences access to information. EERI is developing similar web-based technology for a Worldwide Housing Encyclopedia and Earthquake Mitigation Center. The education and public outreach program presented below is intended to supplement this work. Table 7 lists the five initiatives proposed in the program.

Pre-college (K-12) Initiative

The pre-college initiative has two main thrusts: first, working with teachers to enhance the curriculum in the earth sciences, and second, providing selected K-12 students early learning experiences in earthquake engineering.

In recent years, teacher workshops have been held across the country to introduce and disseminate curricular materials and classroom exercises for the development of earthquake lessons. FEMA has been a frequent partner in these activities, which have stressed not only science but also safety issues and the importance of school preparedness plans. Curricular materials for K-12 grade classrooms will be further improved under this Plan, and distributed with increased reliance on the Internet, museums, libraries, and others as publicly accessible local point sources. Interactive online learning experiences will be explored as well as instructional use of other emerging technologies, such as NEESGrid. In-service and pre-service workshops for teachers will use distance-learning opportunities to reach wider audiences at less cost. Primary pedagogical emphases will integrate science, mathematics, and engineering with a social science perspective. The Plan will involve national groups addressing systematic curricular reform at the secondary level. Increased effort will be given to the involvement of girls and traditionally underrepresented minorities in science learning experiences. To be most effective in this regard, other groups will be involved, such as those at the NSF-funded earthquake engineering research centers, EERI, SCEC, and IRIS.

Table 7. Education and Public Outreach Initiatives

INITIATIVES IN EDUCATION AND PUBLIC OUTREACH
Pre-College (K-12) Initiative • Curriculum enhancement in seismology and earthquakes • Early-learning experiences for K-12 students, including interactive access (e.g., NEESgrid telepresence), summer internships, and camps **Undergraduate College Initiative** • Curriculum enhancement in earth sciences and earthquake engineering, junior faculty workshops • Interactive projects in simulation for freshman and sophomore students (e.g., NEESgrid telepresence) • Internship programs for junior and senior students • Incentive programs for underrepresented groups, women, and other minorities **Graduate Student Initiative** • Increased scholarship and assistantship funds for masters and doctoral programs • Participation in interdisciplinary research projects and NEESgrid telepresence research projects • Participation in earthquake reconnaissance exercises • Development of practice-oriented masters degrees for practicing professionals • Incentive programs for underrepresented groups, women, and other minorities **Continuing Education Initiative** • Short courses on recent advances in the earth sciences, earthquake engineering, risk management, and emergency response and recovery using web-based interactive formats and other distance-learning technologies • Intensive training courses in emerging technologies using web-based interactive formats and other distance learning technologies **Public Awareness and Outreach Initiative** • Enhanced media relations and communications • Support for national and international conferences, workshops, and major public meetings • Maintenance of public helpline / bulletin board / web site for access to quality information • Authoritative articles for public press and television • Annual public meeting on frontiers in earthquake engineering

Four-day summer camps are proposed for high school students in their junior and senior years to supplement curricula in the physical and earth sciences. The goal of the camp experience is to give students early exposure to earthquake engineering, seismology, computer simulations, and hands-on laboratory experiments. They will take field trips to earthquake faults and visit buildings and bridges that have both traditional and non-traditional defenses against earthquakes. Summer internship programs for gifted 12^{th} grade students will also be established.

Undergraduate College Initiative

At the undergraduate level, opportunities for student participation in funded research programs will be expanded. An academic year internship program, similar to the NSF Research Experiences for

Undergraduate Program (REU), will be established to allow baccalaureate-level students extensive involvement in earthquake engineering research projects. Particular attention will also be given to the participation of women and traditionally underrepresented groups. Expanded use of distance-learning technologies will be explored to increase undergraduate access to earthquake engineering instruction. New faculty may also benefit from summer workshops that introduce the basic principles of earthquake engineering. Methods for teaching such a course in an undergraduate curriculum will be suggested, with teaching aids and sample curricula material offered. The NSF program for Undergraduate Faculty Enhancement (UFE) may be a potential source of support for this activity. We also propose to explore collaborative activities between Plan-supported scientists and engineers and undergraduate education students to enhance the cognitive capabilities of future teachers in the areas of science, mathematics, and technology. Supplemental funding for this activity may be available through NSF's Collaboratives for Excellence in Teacher Preparation Program (CETP).

Graduate Student Initiative

Successful graduate student programs in earthquake engineering have already been established by many universities, including members of the NSF-funded earthquake engineering research centers. These include Master of Science and doctoral degree programs, and both will be strengthened under the Plan. Doctoral programs will continue to be the preferred vehicle for training and developing the nation's future educators in earthquake engineering and the social sciences, and will be sponsored and supervised in the same way, and with the same rigor, as has been the hallmark in earthquake engineering to date.

The educational experience of a graduate student is greatly enriched when he or she works on a multi-disciplinary team alongside faculty and students from other campuses and disciplines. Attendance at research coordination meetings, open interaction in technical debates, and access to a network of the best and brightest minds as well as extended library, computing, and laboratory resources are all benefits to the graduate student when he or she is a participant in a consortium-based project. These opportunities are a cornerstone of the proposed Plan.

The educational experience of a graduate student (and most other students) is also greatly enriched by reconnaissance in the field following a damaging earthquake. Experiences learned in the field cannot be duplicated in the laboratory or classroom and are among the most rewarding opportunities in a student's career. Under this Plan, the number of graduate students that make these visits will be greatly increased, as the opportunities arise. In preparation, pre-event training in reconnaissance work by experienced researchers will be offered.

In response to the pressing educational need of the profession, a Master of Engineering degree program in earthquake engineering will be facilitated. This practice-oriented program will bridge the gap between the baccalaureate degree in civil engineering and the current state of practice in earthquake engineering. Knowledge in the field is rapidly expanding and will continue to do so under the Research Plan. Whereas short courses can satisfy immediate needs for retraining, they are in reality only a quick fix, not a long-term solution to a technology-transfer gap. A 12-month intensive graduate program leading to an M. Eng. degree will meet an important need for the profession.

Recent developments in educational technologies have made it possible to teach courses at a distance. Many universities now have multi-media lecture facilities from which classes can be recorded for delayed transmission or immediately relayed to selected sites. Also, a growing number of institutions have satellite uplinks to multiple user sites nationwide. Emerging Internet infrastructure, such as NEESgrid, offer tremendous potential for applications that provide personalized instruction in a manner not currently feasible by video conferencing or satellite classrooms. Advantage will be taken of these innovative educational methodologies as they become affordable.

Continuing Education Initiative
The outreach program for reducing earthquake impacts includes a comprehensive continuing education program. Short courses on research findings and other relevant topics will give the practitioner an opportunity to stay abreast of discoveries and emerging technologies developed under this Plan. Use of advanced educational technologies will be essential to this effort, with increased implementation of interactive Internet formats and distance-learning techniques, such as asynchronous learning networks. To assure that course offerings meet the needs of the profession, an advisory panel that includes both practitioners and academics will be established.

Continuous assessment and evaluation of methods and outcomes are vital to the success of the various elements of the proposed education plan. This is especially true with respect to the continuing education program and the efficacy of distance education technology as an educational tool. Additional funding may be sought from the NSF program in Advanced Technological Education (ATE) to convene a special workshop to examine distance learning in the engineering profession and possible assessment tools that might be used to measure its success.

Public Awareness and Outreach Initiative
Proposed public awareness and outreach activities include:

- enhanced media relations and communications to improve media coverage and understanding of research findings in earthquake hazard mitigation;
- support for conferences, workshops, and major public meetings;
- maintenance of a public helpline/bulletin board/web site for access to quality information; and
- publications in a variety of formats from archival papers to articles for the popular press.

Every summer, an open three-day research-in-progress meeting is proposed for the earthquake community and interested public. The first two days will feature the results of research in progress or recently completed research, covering the breadth of the Plan's activities. The third day will explore a particular topic in greater depth. A different topic might be chosen each year and will feature a new development, methodology, or debate on a controversial issue.

8. TURNING OPPORTUNITIES INTO REALITY

This report provides a vision for the future of earthquake engineering research and outreach to secure the nation from the catastrophic effects of earthquakes. A comprehensive and long-term Plan is presented that builds on previous accomplishments but is fundamentally different from the incremental and fragmented approaches to research and outreach to date. The earthquake engineering community is poised for a fundamental shift in the approaches for mitigation of earthquake risks that entails new ways of thinking about performance of structures, new societal choices about seismic safety, and a more central role for the engineering profession, all of which are needed to achieve the vision.

This Research and Outreach Plan establishes long-range goals to prevent catastrophic losses from earthquakes and outlines the programs needed to achieve the goals. More research is certainly required, but research alone will not achieve the vision; it is necessary to reinvigorate the research and practitioner communities and to change the thinking of stakeholders about the management of earthquake risks. The actions for accomplishing these changes are outlined in the outreach tasks for incorporating research into day-to-day decision making.

Many of the building blocks to achieve this vision are in place or are planned for accomplishing the breakthrough opportunities that we describe. These opportunities are enhanced by revolutionary technologies in data collection and computing, experimental earthquake engineering, computational simulation, and other aspects of information technology.

While previous initiatives have established important goals for earthquake loss reduction, funding levels have been too limited to provide the momentum that our vision requires. The challenge for federal, state, and other entities that fund earthquake-engineering research is to recognize the benefits of these changes and to adjust funding and other initiatives accordingly.

We have estimated the funding for research and outreach that is required to achieve the goals of this vision. The budget for the Plan, outlined in Table 8 and Figure 4, includes ongoing funded research activities, many of which already support the vision embodied in this Plan. The budget is provided for four consecutive five-year periods, beginning in fiscal year 2004. A more detailed breakout is provided for the first five-year interval in the Appendix. We expect that the funds would ramp up at a 15% annual rate over the first five-year period of the Plan. After the ramp-up, it is estimated that the annual cost of research using the NEES facilities will be about $75 million, which is included in various items in the detailed budget breakdown. Funds required for the development and application of information technology tools in support of the research and outreach tasks are listed in a separate column in the budget breakout for the first five years (see the Appendix).

An important step for translating the Research and Outreach Plan into reality is preparing detailed scopes and refining the budget estimates provided in the Appendix. As a preliminary step, we recommend assessments of the capacity of the earthquake engineering research community to carry out the research, tool development, and educational activities that are needed to achieve the breakthrough advances in knowledge and capabilities.

Most of the existing capacity is at universities throughout the United States, with significant capacities also at federal and state laboratories, in private industry, and in professional practice. The NSF-supported NEES facilities significantly augment the capacity of the universities for performing the research needed to achieve the vision. Participation by federal and state governments reflects their vital responsibilities for ensuring the safety of their citizens from earthquake and other disasters. Participation by industry and practicing professionals will provide critical assistance in the development of research products that can be implemented in practice. The success of the Plan will require ongoing collaboration among all these sectors of the earthquake engineering research community.

Table 8. Estimated Cost of Plan Including Research and Outreach Programs and Related Activities

Activity	Average Annual Cost ($M) FY04-08	FY09-13	FY14-18	FY19-23	Total 20-year cost ($M)
Hazard Knowledge	86	86	70	55	1,485
Impact Assessment	64	67	36	21	940
Impact Reduction	82	92	60	41	1,375
Enhancing Community Resilience	22	33	44	44	715
Education and Public Outreach	20	20	20	20	400
Capital Investments[1]	55	77	80	70	1,410
Information Technology	28	5	5	5	215
Management Plan Development	1	0	0	0	5
PLAN TOTAL	358	380	315	256	$6,545

Note 1. Capital investments include ANSS, NEES and Field Instrumentation

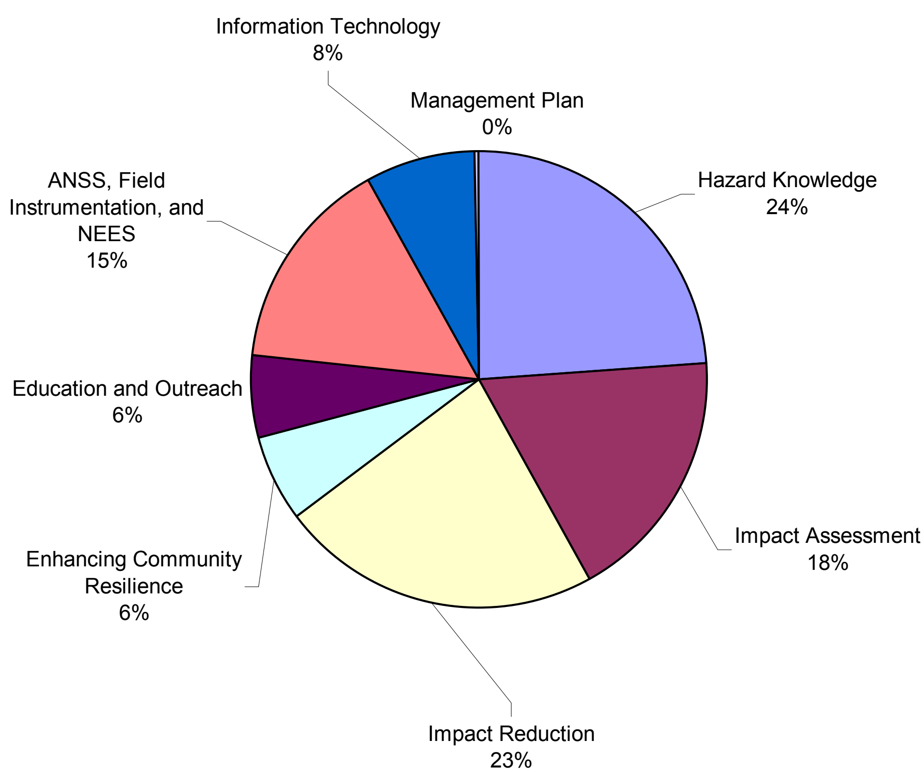


Figure 4. Budget Distribution by Activity for FY2004-2008.

The distribution of budget among the activities of the research and outreach plans for fiscal years 2004-2008 is shown in Figure 4. The budget distribution among the activities, and between research and outreach, evolves as the plan progresses through each five-year period, as shown in Table 9. As knowledge of earthquake hazards and their impacts on the built and human environment increases, the research component decreases from about 50% to 33%, while the outreach component increases and the overall annual costs of the plan decrease. Maintenance of existing sensors and research infrastructure, and deployment of additional equipment, is reflected in a fairly constant level of capital re-investment.

Table 9a. Distribution of Costs Among Research, Education and Outreach Programs, Capital Investment, Information Technology, and Program Management ($M)

Program Description		Average Annual cost ($M)				Total 20-year cost ($M)
		FY04-08	FY09-13	FY14-18	FY19-23	
Hazard Knowledge	Research	36	36	30	25	635
	Outreach	50	50	40	30	850
Impact Assessment	Research	61	61	30	15	835
	Outreach	3	6	6	6	105
Impact Reduction	Research	64	65	38	24	955
	Outreach	18	27	22	17	420
Community Resilience	Research	10	15	20	20	325
	Outreach	12	18	24	24	390
Education / Public Outreach		20	20	20	20	400
Capital Investments		55	77	80	70	1,410
Information Technology		28	5	5	5	215
Management Plan Development		1	0	0	0	5
PLAN TOTALS		358	380	315	256	$6,545

Table 9b. Distribution of Costs Among Research, Education and Outreach, and Other Activities ($M)

Activity	Average Annual Cost ($M)				Total 20-year Cost ($M)
	FY04-08	FY09-13	FY14-18	FY19-23	
Research	171	177	118	84	2,750
Education and Outreach (including Public Awareness and Outreach)	103	121	112	97	2,165
Capital Investments, Information Technology, Management Plan Development	84	82	85	75	1,630
PLAN TOTALS	358	380	315	256	$6,545

Table 9c. Distribution of Effort Among Research, Education and Outreach, and Other Activities (%)

Activity	Average Annual Effort (%)[1]				Total 20-year Effort (%)[1]
	FY04-08	FY09-13	FY14-18	FY19-23	
Research	48%	47%	37%	33%	42%
Education and Outreach (including Public Awareness and Outreach)	29%	32%	36%	38%	33%
Capital Investments, Information Technology, Management Plan Development	23%	22%	27%	29%	25%
PLAN TOTALS[1]	100%	100%	100%	100%	100%

NOTE: 1. Totals may not add to 100% due to rounding

Funding for the Plan's budget in Table 8 is envisaged to come from a partnership between the public and private sectors. In the public sector, the largest share is expected to come from the federal government, through the NEHRP and non-NEHRP agencies; in addition, state and local governments have a significant responsibility to share this burden.

The NEHRP agencies comprise FEMA, USGS, NSF and NIST. The goals of NEHRP include:[xxvii]

- Accelerating the implementation of earthquake loss-reduction practices and policies,
- Improving techniques to reduce seismic vulnerability of facilities and systems,
- Improving seismic hazard identification and risk assessment methods and their use, and
- Improving the understanding of earthquakes and their effects and consequences.

The roles that the four agencies take towards achieving the above goals, as defined in the NEHRP Strategic Plan, are expected to continue, with an enhanced level of coordination, as part of the actions outlined in this report. These roles are as follows:

- USGS and NSF take lead roles in defining and understanding the seismic hazard in the United States;
- NSF supports fundamental research that will provide the knowledge, technology, and educated workforce to improve the performance of the built environment;
- NSF supports the social and behavioral research necessary to understand changes in societal vulnerability, evaluate risk reduction choices, assess economic impacts, and design programs and policies for mitigating earthquake risks and enhancing community resilience;
- FEMA develops implementation products, interacts with stakeholders, fosters public awareness and preparedness, and assists with emergency response and recovery following a damaging earthquake; and
- NIST develops guidelines for seismic design and retrofit and assists in the transfer of knowledge into practice.

Other federal agencies with research and implementation programs in earthquake loss reduction include the Federal Highway Administration, the Department of Energy, the Nuclear Regulatory Commission, the General Services Administration, the Department of Housing and Urban Development, the Department of Defense, the Department of the Interior, and the National Oceanic and Atmospheric Agency. These departments and agencies are expected to continue to play major roles in reducing seismic vulnerability, particularly in those areas in which they have specific responsibilities: e.g., defense installations (DOD), nuclear power plants and nuclear waste storage (NRC and DOE), highways and bridges (FHWA), federal buildings (GSA), housing (HUD), dams and reservoirs (Department of Interior and Army Corps of Engineers), and coastal regions subject to tsunamis (NOAA).

At the state and local levels of government, similar responsibilities for earthquake safety are expected to generate support for the research and outreach tasks in the Plan. State, county, and municipal departments of transportation have historically had the responsibility for local transportation systems, along with FHWA assistance, for the seismic safety of the bridges and highways in their jurisdictions. Water utilities and districts, electric power companies, telecommunications companies, and operators of other lifelines have responsibilities to their customers to provide reliable and safe service. Large industrial and commercial companies that are heavily invested in the built environment, as well as companies that provide insurance, financial, and information technology services, and companies that supply the construction industry, all have strong vested interests in the goals of this Plan and should contribute accordingly.

In summary, the successful accomplishment of this Research and Outreach Plan will require a high level of coordination among the NEHRP agencies as well as other federal agencies and state and local government agencies, the earthquake engineering research community, organizations responsible for promulgation of building codes, engineering professionals, and government officials.

The breakthrough opportunities in earthquake engineering presented in this report hold the promise of preventing catastrophic losses from major earthquakes in the United States. More comprehensive and systematic approaches to managing earthquake risks will be fostered by the use of performance-based engineering to guide not only engineering decisions but also financial decisions about earthquake risks. Improved emergency response and recovery will be advanced through the breakthrough technologies in risk management through rapid evaluation of damage and enhanced management of relief and recovery processes. The knowledge developed through the experiments and simulation methodologies provide the essential scientific base for improving codes and guidelines. Social science and education research will help to better understand and communicate the societal implications and choices involved.

This Research and Outreach Plan encompasses a vision for a society that is aware and concerned about the catastrophic risks it faces. Earthquakes need to be addressed in a more concerted way than they have been to date. Doing so provides benefits for society in providing security from earthquakes and other catastrophes. The investment in this Research and Outreach Plan will be paid back many more times through the security of the nation's citizens and the protection of the economic vitality of the United States from disasters.

APPENDIX: PLAN BUDGET

This Appendix presents the budget for the Plan. For the first five years of the plan, FY04-08, specific tasks and budget amounts are identified. Also for the first five years of the plan, the budget for information technology (IT) is specifically identified by task. Overall budgets are provided for research and outreach programs for subsequent five-year periods.

The twenty-year information technology budget is $215 million, of which $140 million is projected for research tasks in the first five years (FY04-08). The information technology budget for the subsequent years is estimated to be $5 million per year, for an additional $75 million in FY09-23. The capital investment and re-investment over the life of the Plan is $1,410 million.

The following table provides an overall summary of the budget for the Plan. Subsequent tables provide breakdown information on the individual programs and activities.

Table A1. Summary Plan Budget

PROGRAM	Average Annual Cost ($M)					Total 20-year Cost ($M)
	FY04-08	FY04-08: IT[1]	FY09-13	FY14-18	FY19-23	
RESEARCH AND OUTREACH TASKS						
Hazard Knowledge	86	10	86	70	55	1,535
Impact Assessment	64	11	67	36	21	995
Impact Reduction	82	7	92	60	41	1,410
Community Resilience	22	0	33	44	44	715
Education and Public Outreach	20	0	20	20	20	400
CAPITAL INVESTMENTS[3]	55	0	77	80	70	1,410
INFORMATION TECHNOLOGY (FY09-23)			5	5	5	75[2]
MANAGEMENT PLAN DEVELOPMENT	1	0	0	0	0	5
GRAND TOTAL	330	28[2]	380	315	256	$6,545

NOTES:
1. Information Technology
2. Total IT over 20-year life of Plan = $215M = $140M (FY04-08) + $75M (FY09-23)
3. Includes NEES, ANSS and Field Instrumentation

Table A2. Budget for Hazard Knowledge Program

HAZARD KNOWLEDGE PROGRAM	Average Annual Cost ($M)					Total 20-year Cost ($M)
	FY04-08	FY04-08 IT	FY09-13	FY14-18	FY19-23	
RESEARCH TASKS						
Physics-Based Earthquake Models						
A. Physics-based models of fault mechanics and earthquake rupture dynamics	12	1				
B. Physics-based models of fault systems and fault interactions	8	1				
Development of Predictive Models of Seismic Hazards						
A. Predictive models of ground shaking	13	1				
B. Predictive models of permanent ground deformation	3	1				
Subtotal, Hazard Knowledge Research Tasks	**36**	**4**	**36**	**30**	**25**	**655**
OUTREACH TASKS						
Application of Predictive Models of Seismic Hazards						
A. Incorporation of predictive models into codes and guidelines	1					
B. Dissemination of predictive models to practitioners	1					
Seismic Hazard Mapping						
A. Earthquake source characterization	24	1				
B. Seismic zonation of urban regions	11	2				
C. Rapid shakemaps and ground deformation maps	6	3				
D. Tsunami inundation mapping and warning	7					
Subtotal, Hazard Knowledge Outreach Tasks	**50**	**6**	**50**	**40**	**30**	**880**
SUBTOTAL, Hazard Knowledge Program	86	10	86	70	55	$1,535

Table A3. Budget for Impact Assessment Program

IMPACT ASSESSMENT PROGRAM	Average Annual Cost ($M)[1] FY04-08	FY04-08 IT	FY09-13	FY14-18	FY19-23	Total 20-year Cost ($M)
RESEARCH TASKS						
Measurements, Experimentation and Data Synthesis						
A. Improve knowledge of behavior of soil, foundation, and structural and non-structural components of structures through experimental research	20	5				
B. Improve understanding of behavior of full structural, geotechnical and structure-foundation-soil systems through field monitoring and field testing on complete systems	3					
C. Produce information, including processing with data fusion, visualization and system identification, for the development and validation of structure-level simulation tools	3					
D. Provide diagnostic information about condition and prognosis of expected future performance of structure-foundation-soil systems	1					
Structure-Level Simulation Models and Computational Tools						
A. Modeling of complex, heterogeneous construction materials	1					
B. Multi-phase and multi-physics modeling of soils	3					
C. Models for structural components, non-structural components, and foundations	5					
D. Models of assemblies, substructures and global systems, including uncertainty	1					
E. High-end and grid-based computational methods for simulating seismic performance	1	1				
F. Collaborative software development tools and protocols for the earthquake engineering community	1	1				
G. Large-scale database and scientific visualization tools for simulation	1	2				
System-Level Simulation and Loss Assessment Tools						
A. Validation studies to calibrate the accuracy of loss estimation models, incorporating the full range of physical and societal impacts and losses	2					
B. National models for seismic hazards, building and lifeline inventories, and exposed populations, and application to other natural and man-made hazards	10	2				
C. Improved damage and fragility models for buildings and lifelines	7					
D. Improved indirect loss estimation models	2					
Subtotal, Impact Assessment Research Tasks	**61**	**11**	**61**	**30**	**15**	**890**
OUTREACH TASKS						
A. Measurements, Experimentation, and Data Synthesis	1					
B. Structure-Level Simulation Models and Computational Tools	1					
C. System Level Simulation and Loss Assessment Tools	1					
Subtotal, Impact Assessment Outreach Tasks	**3**		**6**	**6**	**6**	**105**
SUBTOTAL, Impact Assessment Program[1]	64	11	67	36	21	$995

NOTE 1: Costs include research expenditures at NEES Equipment Sites, estimated as follows:

FY04-08: $25M / yr FY09-13: $25M / yr FY14-18: $20M / yr FY19-23: $10M / yr

Table A4. Budget for Impact Reduction Program

IMPACT REDUCTION PROGRAM	Average Annual Cost ($M)[1] FY04-08	FY04-08 IT	FY09-13	FY14-18	FY19-23	Total 20-year Cost ($M)
RESEARCH TASKS						
A. Materials and Structural Engineering	**15**					
B. Nonstructural Engineering	**10**					
C. Lifeline Engineering	5					
D. Geotechnical Engineering	15					
E. Tsunami Engineering	5					
F. Fire-protection Engineering	1					
G. Land-use measures	2					
H. Methodologies for assessing cost-effectiveness	2	1				
I. Financial instruments to transfer risk	2					
J. Advanced and emerging technologies for emergency response and recovery	7	5				
Subtotal, Impact Reduction Research Tasks	**64**	**6**	**65**	**38**	**24**	**985**
OUTREACH TASKS						
A. Develop guidelines, manuals of practice, and model codes for the seismic design and retrofit of buildings and their contents, bridges, lifelines and coastal structures	5					
B. Develop products for the implementation of performance-based seismic design including structural performance products, nonstructural performance products, risk management products, performance-based seismic design guidelines, and a stakeholders' guide	3					
C. Conduct demonstration projects involving researchers, practitioners, owners, and other stakeholders in the assessment and mitigation of risk to buildings, infrastructure and coastal systems	5					
D. Conduct short, intensive courses on new technologies, guidelines, and Performance-Based Earthquake Engineering	2	1				
E. Develop methodologies for assessing cost-effectiveness of mitigation measures	1					
F. Adopt financial instruments to transfer risk	1					
G. Incorporate advanced and emerging technologies for emergency response and effective recovery	1					
Subtotal, Impact Reduction Outreach Tasks	**18**	**1**	**27**	**22**	**17**	**425**
SUBTOTAL, Impact Reduction Program[1]	82	7	92	60	41	$1,410

NOTE 1: Costs include research expenditures at NEES Equipment Sites, estimated as follows:
FY04-08: $50M / yr FY09-13: $50M / yr FY14-18: $35M / yr FY19-23: $25M / yr

Table A5. Budget For Community Resilience Program, Education and Public Outreach Program, Capital Investment and Other Activities

PROGRAM	Average Annual Cost ($M)					Total 20-year Cost ($M)
	FY04-08	FY04-08 IT	FY09-13	FY14-18	FY19-23	
ENHANCING COMMUNITY RESILIENCE						
RESEARCH TASKS						
A. Methodologies and measurement of progress in reducing vulnerability and enhancing community resilience to earthquakes	2					
B. Risk management cost-effectiveness methodologies and analyses	1					
C. Investigation of societal impacts of catastrophic earthquakes, including learning from earthquakes	5					
D. Research on decision-making and earthquake risk perceptions	1					
E. Research on implementation of risk management and earthquake mitigation programs	1					
Subtotal, Community Resilience Research Tasks	**10**		**15**	**20**	**20**	**325**
OUTREACH TASKS						
A. Outreach to relevant stakeholders and decision tools for these stakeholders	3					
B. Outreach to state and local governments regarding risk management policies and programs	3					
C. Outreach to the design professions concerning earthquake risk management	2					
D. Stakeholder process for improving regulatory systems	2					
E. New methodologies and demonstration efforts for communicating societal implications and choices	2					
Subtotal, Community Resilience Outreach Tasks	**12**		**18**	**24**	**24**	**390**
SUBTOTAL, Community Resilience Program	22	0	33	44	44	715
EDUCATION AND PUBLIC OUTREACH PROGRAM						
A. Pre-college (K-12) initiative	5					
B. Undergraduate college initiative	5					
C. Graduate student initiative	5					
D. Education program and public outreach initiative	5					
SUBTOTAL, Education and Public Outreach Initiatives	20	0	20	20	20	400
CAPITAL INVESTMENTS / OPERATIONS: ANSS, FIELD INSTRUMENTATION AND NEES						
A. ANSS deployment and operations	30		30	30	30	
B. Field instrumentation, deployment and operations	10		25	25	25	
C1. NEES Phase III Capital Investment	0		7	10	0	
C2. NEES Phase I, II and III Operations	15		15	15	15	
SUBTOTAL, Capital Investments	55	0	77	80	70	1,410
SUBTOTAL, Information Technology		28	5	5	5	215
MANAGEMENT PLAN DEVELOPMENT						
A. Develop a management plan for the Research and Outreach Plan to ensure alignment with stakeholder needs	1					
SUBTOTAL, Management Plan Development	1		0	0	0	5

END NOTES

[i] Hazus 99 Estimated Annualized Earthquake Losses for the United States, FEMA 366, September 2000.

[ii] Estimate is based on expert opinion and empirical data from historical earthquakes (San Fernando, Loma Prieta, Northridge, Kobe, Chi-Chi), which suggest that total losses are about 2.5 times residential and commercial building losses.

[iii] Columbia Electronic Encylopedia, 6th Edition, 2000, www.encyclopedia.com/articles/03908MajorEarthquakes.html

[iv] United States Geological Survey, World Data Center for Seismology, National Earthquake Information Center, wwwneic.cr.usgs.gov/nesi/eqlists/eqsmajr.html

[v] United Nations Centre for Regional Development, 1995, *Comprehensive Study of the Great Hanshin Earthquake,* Nagoya, Japan: UNCRD. The earthquake is variously called the Kobe earthquake, the Great Hanshin earthquake, or, by the official name assigned by the Japan Meterological Agency, the Hyogo-ken Nambu earthquake. The damage cost was estimated at 9.916 trillion yen by the Hyogo prefectural government, which, at an average exchange rate of 100 yen = one US dollar, converts to US $99.2 billion (p. 194). This does not include indirect costs following the earthquake (for example, loss of port revenue and disruption to other business activities). The fatality total was 5,502 (p. 42).

[vi] Abrams, Daniel, 1999. Meeting the challenges of reducing earthquake losses: Engineering accomplishments and frontiers. *Proceedings of the 1999 Annual Meeting of the American Association for the Advancement of Science*, Anaheim, California, January 24.

[vii] van der Vink, G., et al., 1998. Why the United States is becoming more vulnerable to natural disasters, *Eos*, Trans. AGU, 95, 533-537.

[viii] See endnote ix.

[ix] These changes are highlighted in:

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Federal Emergency Management Agency, Office of Earthquakes and Natural Hazards, 1993. *Improving earthquake mitigation, Report to Congress*, Washington D.C., FEMA;

Federal Emergency Management Agency, 1996. *Performance-Based Seismic Design of Buildings, An action plan for future studies, Issue papers*, Report FEMA 283, Washington D.C., FEMA;

and Federal Emergency Management Agency, 2000. *Performance-Based Seismic Design of Buildings, An action plan for future studies*, Report FEMA 349, Washington D.C., FEMA.

[x] SCEC Research Plan, scec.org/scec2/index.html

[xi] peer.berkeley.edu

[xii] mae.ce.uiuc.edu

[xiii] mceer.buffalo.edu

[xiv] Requirement for an Advanced National Seismic System, USGS Circular 1188

[xv] Incorporated Research Institutes for Seismology, iris.edu

[xvi] Earthscope Project Plan: A New View into the Earth, October 2001, earthscope.org

[xvii] Federal Emergency Management Agency, 2000, *Performance-Based Seismic Design of Buildings, An action plan for future studies*, Report FEMA 349, Washington D.C., FEMA. This plan is currently being updated under a contract with FEMA.

[xviii] This perspective is highlighted in:

May, P. J., 2001. Societal perspectives about earthquake risk: The fallacy of "acceptable risk," *Earthquake Spectra*;

Mileti, D. S., 1999. *Disasters By Design, A Reassessment of Natural Hazards in the United States*, Washington D.C.: Joseph Henry Press, National Academy of Sciences; and

Tierney, K. J., 1999. Toward a critical sociology of risk, *Sociological Forum*, 14, 215-242.

[xix] For discussion of research accomplishments see:

Anderson, William, 1998. The history of social science earthquake research: From Alaska to Kobe, in *The EERI Golden Anniversary Volume, 1948-1998*; Oakland, CA: EERI, 29-33; and

Nigg, Joanne, 1993. Societal research under NEHRP: Past accomplishments and future directions, in *Directions for research in the next decade: NSF programs in Earthquake Engineering and Earthquake Related Earth Science*, *Report on a Workshop*, *June 17-18, 1993*; Oakland, CA: EERI, 13-15.

For discussion of gaps in social science knowledge about earthquake impacts see the following results of the Second Assessment of Research on Natural Hazards in the United States:

Burby, Rayond J. ed. 1998. *Cooperating with Nature: Confronting Natural Hazards with Land Use Planning for Sustainable Communities*, Washington, D.C., Joseph Henry Press;

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[xx] Federal Emergency Management Agency, 2000, *Performance-Based Seismic Design of Buildings, An action plan for future studies*, Report FEMA 349, Washington D.C., FEMA. This plan is currently being updated under a contract with FEMA.

[xxi] Also see Burby, Raymond J. ed., 1998, *Cooperating with Nature, Confronting Natural Hazards with Land Use Planning for Sustainable Communities*, Washington D.C., National Academy Press.

[xxii] See: Flynn, J., Slovic, P., Mertz, C. K. and Carlisle, C., 1999. Public support for earthquake risk mitigation in Portland, Oregon, *Risk Analysis*, **19**, 205-216;

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[xxiii] More generally, see: Stern, P. C. and Fineberg, H. V., eds., 1996. *Understanding Risk: Informing Decisions in a Democratic Society*, Committee on Risk Characterization, Commission on Behavioral and Social Sciences and Education, National Research Council, National Academy Press, Washington, DC.

[xxiv] EERI members include those from the engineering disciplines noted above, along with architects, urban planners, geologists, seismologists, emergency responders, preparedness officials, insurance analysts, and social and behavioral scientists.

[xxv] In a parallel development, the American Society of Civil Engineers has proposed (Fall 2001) that the Masters degree be the first professional degree for the practice of civil engineering at the professional level.

[xxvi] Mid-America Earthquake (MAE) Center at University of Illinois, Urbana-Champaign IL; Multidisciplinary Center for Earthquake Engineering Research (MCEER) at University at Buffalo, Buffalo NY; and Pacific Earthquake Engineering Research (PEER) Center at University of California, Berkeley, CA.

[xxvii] Using Knowledge to Reduce Earthquake Losses: The National Earthquake Hazards Reduction Program Strategic Plan, Unpublished Draft, August 2000.