Research and Implementation Plan for Earthquake Risk Reduction in California 1995 to 2000

A report of the
California Seismic Safety Commission
1900 K Street, Suite 100
Sacramento, California 95814
(916) 322-4917
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Contents

Foreword

This *Research and Implementation Plan for Earthquake Risk Reduction in California, 1995-2000* responds to 1990 and 1991 California legislation[1] that requires the Seismic Safety Commission to develop a strategy to coordinate and prioritize earthquake research to provide new understanding that can be used to reduce losses from earthquakes. The legislation also required the Commission to conduct an earthquake research conference to review and critique the draft earthquake research plan.

These legislative requirements created an opportunity for the Commission to strengthen its existing mandate to encourage advances in knowledge that can be used to reduce seismic risk. Development of the research plan has provided the first opportunity for the Commission to consider California's short-term and long-term needs for earthquake research, and formulate a comprehensive policy. The research aim is to meet the State's seismic safety needs to support our goal of significantly reducing earthquake risk by the year 2000.

The Commission gave its Research Committee the responsibility of developing such a policy. The Committee members and advisors included experts in the earth sciences, engineering and architecture, and social science and public policy. In addition, the Committee worked with representatives of the State Legislature, local governments, private industry, professional organizations, and the research community in formulating the research plan.

After review by the Seismic Safety Commission in March 1993, the *Draft Preliminary Five-Year Research Plan* was distributed to users and experts in the related scientific and public policy disciplines. More than one hundred professionals attended an Earthquake Research Evaluation Conference in May 1994, which was co-sponsored by the Lawrence Livermore National Laboratory and the California Trade and Commerce Agency. The attendees reviewed, evaluated, and recommended revisions to the draft plan. The Research Committee considered the contributions of the conference, and produced this *Research and Implementation Plan for Earthquake Risk Reduction in California, 1995-2000*. The Plan was adopted by the Commission on November 9, 1994, and will guide state, federal, and private research funding.

Lloyd S. Cluff
Chairman, Research Committee
Seismic Safety Commission

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[1]Senate Bill 1835, Chapter 782, Statutes of 1990; Senate Bill 1245, Chapter 901, Statutes of 1991.

Executive Summary

Moderate earthquakes in California during the past five years were directly responsible for more than $30 billion in damage. Although other states also may be seriously affected, California has by far the greatest earthquake risk in the United States. There can be little doubt that efforts to reduce the catastrophic consequences of earthquakes are vital to the health, safety, and welfare of the citizens California. Such loss reduction efforts have obvious economic benefits to the rest of the nation, as well.

The field is replete with examples of earthquake research that has "paid off." In fact, earthquake losses during the past five years would have been much worse had we not applied the lessons learned from past experience and research efforts. However, now a more specific and focused research plan is needed. In spite of the enormous potential benefits to California, support for earthquake research has not kept pace with the demand for solutions to our earthquake problems.

Financially, capabilities at this time in California and in the country are limited. This scarcity of funding requires that California make the most cost-effective use of every research dollar. We can ill afford research projects that do not focus on California's highest priorities, lack relevance, duplicate other efforts, or are not translated into practice.

To improve the way in which earthquake research is now conducted and its results implemented in California, the Research Committee of the Seismic Safety Commission was charged with developing and implementing a research plan. Specifically, the charge, which is stated in Initiative 5.1 of *California at Risk*, the State's earthquake risk reduction program, asks those research investigations that will do the most to reduce California's earthquake risks be identified, funded, carried out, and the results disseminated to users.

The Research Plan

This Plan has been designed to meet the objectives set forth in *California at Risk*. The goal of the Plan is to **reduce damage, casualties, and interruptions caused by California earthquakes.**

The objectives of the Plan are:

- To improve the performance of man-made structures through better hazard assessment and engineering,
- To improve the effectiveness of emergency response, and
- To improve the speed and effectiveness of post-earthquake recovery.

The Plan incorporates and provides a focus for all workers in the field—earth scientists, engineers, architects, social scientists, emergency responders, and policy makers. The Commission stresses interdisciplinary cooperation to achieve the greatest benefit from the earthquake loss reduction efforts. The various research activities have been grouped into three broad disciplines:

- Earth sciences, to provide greater understanding of seismic hazards as they affect man-made structures and systems,
- Engineering and architecture, to improve the resistance of structures to damage, and
- Social sciences and public policy, to improve the effectiveness of the implementation, response, and recovery processes.

To accomplish the goal and objectives, the Commission took seriously the last request in Initiative 5.1: *that the results be disseminated to users*. The initiation, conduct, and conclusion of research projects must involve active communication with likely users, to ensure relevance. The Plan requires that existing and new knowledge be put to work reducing earthquake risk. **Research projects funded under this Plan shall incorporate a strategy for the implementation of results.**

Implementation of the results of past research also is called for, because much that has been done has not been put into practice. A sustained effort to **use existing knowledge more effectively** to enhance what we are doing now can achieve risk reduction in many ways that are comparatively cost effective. By emphasizing relevance to needs, and systematically pursuing translation, transfer, and use, we can assure full value from the research recommended in this Plan.

This Plan also recognizes that significant advances in earthquake risk reduction have come from **research on new and emerging technologies** in other fields—ones that may not have seismic safety as their focus. **Defense conversion** from military to civilian applications is another resource not previously considered in earthquake research that may have application. The Commission urges consideration of these opportunities.

Administration—Given the current climate of high risk of future earthquakes, shortcomings in existing seismic safety efforts, and the scarcity funds, a responsible organization is required to manage the many aspects of cost-effective research to ensure success. **The implementation of this Plan depends on the establishment of plan management**.

Initially, the Commission will provide for the Plan's oversight by appointing and working through a "Research Plan Implementation Committee." The

Research Plan Implementation Committee will include researchers and practitioners from the appropriate fields, and major users. The Committee will be chaired by a Commission member, and supported by Commission staff.

The Commission will seek funds from appropriate sources to implement management of this Plan. We envision its management activities will expand to require that the Commission solicit competitive proposals from qualified professionals or organizations for the purpose of establishing a California Center for Earthquake Risk Reduction to provide appropriate plan management. A similar center was envisioned by dormant 1986 legislation,[1] and would be a reasonable result of successful growth and maturation of this Plan.

The charge given the Center for Earthquake Risk Reduction is expected to include:

- Promote the Plan,
- Encourage researchers to make relevant proposals,
- Seek new funds to support applied research,
- Encourage agencies having responsibilities for earthquake risk reduction and research to support the research priorities outlined in this Plan,
- Assure the products of research are successfully disseminated to the user community,
- Assist the Seismic Safety Commission in coordinating the research efforts called for in bond issues relating to seismic safety,
- Cooperate with funding organizations to help them assure effective use of funds in accordance with their grants and contracts, and
- Revise the Plan annually to reflect changing priorities and new knowledge, and see that the Plan is distributed to appropriate funding agencies, researchers, and users.

The Research

The Plan identifies the following priority research in the three disciplines:

Earth Sciences—The greatest need for earth-science research is in systematic seismic hazard mapping. Such mapping is vital to the development of earthquake-specific damage and consequence scenarios for engineering and public policy research.

We need to be able to estimate more reliably *where*, *how large*, and *how often* earthquakes will be in the future

[1]Chapter 12.3, Statutes of 1986

by gaining a more accurate understanding of regional tectonics and patterns of seismicity. Within this broad spectrum, evident after the 1994 Northridge and 1983 Coalinga earthquakes, is the better understanding of blind thrust faults—those thrust faults that are not exposed at the ground surface and therefore not readily studied using traditional field methods.

Also important, especially evident following the 1989 Loma Prieta earthquake, is the better understanding of how earthquake shaking is affected by different types of geologic materials and topographic conditions. Research on how different sites amplify ground motions, as well as systematic mapping of soils, rock types, and landslide and liquefaction potential are critical to effective land-use planning and engineering design to accommodate future California earthquakes.

The basic physics of the fault-rupture process needs to be better understood. The detailed mechanics of the ways in which faults rupture and release seismic energy have varied from earthquake to earthquake, surprising scientists and engineers alike. The relationship between faults exposed at the surface and what takes place at depth is a key to estimating the seismic hazard more effectively.

A "core" need in the earth sciences—one that has the potential to contribute to all seismic studies, risk mitigation, response, and recovery—is the continuation and modernization of seismic instrumentation in the State.

Engineering and Architecture—A high priority for engineering and architecture studies is the development of realistic, comprehensive, earthquake-specific damage scenarios using seismic hazard mapping from the earth sciences. The damage scenarios would be based on accurate compilation of structure and systems inventories and realistic assessments of their expected earthquake performance.

Another priority for engineering studies is the evaluation and retrofit of existing vulnerable structures. We need procedures for identifying their expected seismic performance, and consensus standards and cost effective methods to improve the performance of deficient structures.

To achieve desired performance for new construction, we need a better understanding of the behavior of various engineering systems and materials, including steel, concrete, wood, and composite systems. A better understanding also is needed of the performance of nonstructural systems.

We need a better understanding of the nature of ground response and the interactions between the ground and foundations. We need to quantify the ground-motion characteristics relevant to design.

Research is needed to develop cost-effective means for improving the quality of design and construction.

There is a need to be able to rapidly assess the post-earthquake safety of buildings and critical or hazardous facilities, and to develop methods to rapidly stabilize damaged structures to prevent collapse.

A "core" need that would contribute greatly to engineering investigations is an improved experimental capability. Needed are facilities where material and small assemblage experiments on structures or equipment can be performed, and where larger elements and full- or near-full-scale sections of structures or equipment can be evaluated.

Social Sciences and Public Policy—A high priority for social scientists and policy makers are scenarios of the consequences of future damaging earthquakes. These earthquake-specific consequence scenarios would use earth-science hazard mapping and engineering and architecture damage scenarios to gain insight for improved emergency response and recovery.

Informed social science research and public policy are needed to change behavior and achieve measures that reduce earthquake effects. The earth-science and engineering fields especially need this interdisciplinary assistance, and follow-through mechanisms to achieve the risk-reduction ends of this Plan. A vigorous cooperative attitude is a high priority.

Study of the economic and policy implications of recent earthquake damage is essential to guide critical review of building design, code enforcement, land-use planning, and construction. Strategies are needed to assure that design professionals are employing state-of-the-practice earthquake engineering methods. Continuing education programs must be developed to instruct contractors and builders on new seismic codes and earthquake-resistant design concepts.

Engineering and policy research should be combined to explore ways to educate the public, owners, and occupants about realistic alternative performance levels, or "acceptable risk." The public needs better tools to be able to weigh life safety, protection of property, uninterrupted operation of some businesses, systems, and structures, and cost.

Investigations of the resources, including insurance and disaster-recovery financing, needed to help people and communities get started again after an earthquake are a priority. We also need to identify populations that have special needs or are unusually vulnerable. Such studies will help in the development of more effective aid programs and economic and social recovery policies.

Research is needed to identify realistic incentives and penalties to motivate decision makers to embrace risk reduction. We also need to identify influences working against risk reduction, and clarify earthquake-damage liability issues.

Emerging technologies—California legislation[1] requires that the earthquake risk reduction program consider emerging technologies in developing risk mitigation measures. Emerging technologies are multidisciplinary. The most promising overarching areas of new and emerging technology development for earthquake risk mitigation are communication and information technology, and sensor technology. These areas have seen rapid recent advances, but they have not yet been fully brought to bear on problems related to earthquake risk mitigation.

There are many other new technologies that have high potential for application to earthquake risk mitigation. One of these is "intelligent buildings," a technology that aims to provide tools for monitoring and controlling stresses and motions caused by environmental loads on structures. This technology could profit greatly from defense research that is undergoing conversion to civilian purposes.

Conclusion

This Plan sets out a program to cost-effectively reduce earthquake risk to acceptable levels by defining the most needed research and assuring that it is implemented through effective management. The Plan is compatible with the State's defining document on earthquake risk reduction, *California at Risk*, and a logical response to 1990 and 1991 California earthquake safety legislation.[1, 2]

Every effort has been made to include the essential areas where knowledge is required, and areas of previously untapped opportunity. The Commission believes this is a structure in which all organizations and professionals undertaking research on earthquake problems in California can find a helpful role.

The Commission will distribute this Plan to the appropriate federal, state, and local agencies, universities, major users, and private-sector organizations and associations. Any organization having a responsibility for or interest in earthquake risk reduction in California must be made aware of our priorities and encouraged to address them.

[1]Senate Bill 1835, Chapter 782, Statutes of 1990

[2]Senate Bill 1245, Chapter 901, Statutes of 1991.

Introduction

Damaging earthquakes can strike almost anywhere in California, have occurred relatively frequently in California's past (Table 1), and are certain to recur in the future. There is more than a 90 percent chance that at least one major earthquake will strike an urban California area within the next decade. We can also expect smaller, but still damaging, earthquakes to strike every other year or so. Time grows short for significant corrective measures.

Moderate earthquakes in California during the past five years are directly responsible for more than $30 billion in damage. Although these recent earthquake losses have been locally devastating, they could have been much worse. Fortunately, we have applied the lessons learned from past experience and have put research results to use to reduce the effects of those earthquakes.

We stopped building unreinforced masonry buildings more than a half-century ago. Building codes and design practices continue to improve, and modern structures generally perform well during strong ground shaking. The potential for damage to new buildings due to surface fault rupture has been reduced due to setbacks required by the Alquist-Priolo Act. Public schools built under the Field Act have performed remarkably well in earthquakes, and school children are taught how to protect themselves.

Emergency response capability has improved significantly in the past decade, and since the early 1970s, hospital construction has been regulated in a manner similar to that of public schools. We have an improved understanding of how to translate and communicate technical information, and of the kinds of information and methods of delivery that are likely to lead to changes in behavior. This has resulted in improved individual response during earthquakes, during their immediate aftermath, and during aftershocks, thereby reducing life loss and injuries.

Despite this progress, the recent earthquake losses show that California still remains vulnerable, and the risk that remains is unacceptable. The vast majority of structures that will fail in future earthquakes have already been built; many do not meet current engineering standards. Older, unretrofitted highway structures and unreinforced masonry

buildings fail even in moderate seismic shaking, and the 1994 Northridge earthquake has shown us that some steel-framed buildings have structural weaknesses in heavy shaking. Many casualties, major damage, and long disruptions must be expected when larger earthquakes strike any of California's urban and industrial concentrations.

In spite of the potential benefits to California, support for earthquake research has not kept pace with the demand for solutions to our earthquake problems. There is no question that the State's economic conditions are inhibiting progress. However, the Seismic Safety Commission believes that significant earthquake loss reduction can be achieved with only modest expenditures if the available resources are well managed and properly focused.

Since 1986, the Commission has developed five-year programs that have the goal of reducing California's earthquake risks by the year 2000. *California at Risk: Reducing Earthquake Hazards 1992-1996*, describes the current five-year program, which consists of 42 activities, or initiatives. This *Research and Implementation Plan for Earthquake Risk Reduction in California, 1995-2000* was developed in accordance with Initiative 5.1 of that program, which states:

5.1—Implement a Research Plan. Research investigations that will do the most to reduce California's earthquake risks should be identified, funded, carried out, and the results disseminated to users.

This Plan has been designed to meet the objectives set forth in *California at Risk.* It also responds to California legislation,[2] which finds that:

A cohesive plan to optimize current and emerging earthquake research is critical to protect the health and safety of the citizens of California.

California's government agencies, universities, professionals, consulting firms, and businesses have the capacity and ability to pursue and successfully complete the required investigations. These capabilities need to be activated, organized, and supported. To that end, this document provides a framework for their investigations and analyses.

The Commission will use the Plan to review and promote relevant research from all quarters, including researchers located outside California. The awarding of research grants will be guided by the needs outlined in the Plan. Integration of the multi-faceted research efforts will assure optimum value from the limited funds available. The Plan will be reviewed regularly and revised as necessary to ensure the

[2]Senate Bill 1835, Chapter 782, Statutes of 1990; Senate Bill 1245, Chapter 901, Statutes of 1991

most economical use of available resources in promoting seismic safety.

The record is clear that key earthquake studies in California have involved major support from the federal government and the private sector. Although a financial commitment from California is essential, it is recognized that a significant portion of funds aimed at earthquake risk reduction will come from non-state sources. The Commission asks that research institutions recognize the priority research discussed in the Plan when formulating their own research programs for California. This request is directed in particular to the U.S. Geological Survey, the National Science Foundation, the Federal Emergency Management Agency, the National Oceanic and Atmospheric Administration, and the National Institute of Standards and Technology.

To meet the challenge of reducing the State's earthquake risk, California must make wise use of its resources and influence the direction and pace of essential earthquake risk reduction research. The scarcity of research dollars makes it essential that California adopt a comprehensive, cost-effective earthquake research plan. The aim of the Plan described in this document is to meet the State's most pressing seismic safety needs.

Table 1
SIGNIFICANT CALIFORNIA EARTHQUAKES

Location	Date	Magnitude	Deaths	Injuries	$ Property Damage
Northridge	January 17, 1994	6.7	57	?	20 Billion
Big Bear	June 28, 1992	6.6	0	402	91.1 Million
Landers	June 28, 1992	7.5	1		
Cape Mendocino	April 25, 1992	7.1	0	356	48.3 Million
	April 26, 1992	6.2, 6.5			
Joshua Tree	April 22, 1992	6.1	0	10	34,000
Sierra Madre	June 28, 1991	5.8	1	30+	33.5 Million
Upland	February 28, 1990	5.5	0	38	10.4 Million
Loma Prieta	October 17, 1989	6.9	63	3,757	5.9 Billion
Imperial County	November 23, 1987	6.2			
	November 24, 1987	6.6	0	94	2.7 Million
Whittier	October 1, 1987	5.9	8	200+	358 Million
Chalfant Valley	July 21, 1986	6.0	0	N/A	436,500
Oceanside	July 13, 1986	5.3	1	28	720,000
Palm Springs	July 8, 1986	5.9	0	0	5.3 Million
Morgan Hill	April 24, 1984	6.2	0	27	10 Million
Coalinga	May 2, 1983	6.4	0	47	31 Million
Eureka	November 8. 1980	7.0	0	8	1.75 Million
Owens Valley	May 25, 1980	6.l, 6.0, 6.1	0	9	
	May 27, 1980	6.2	0	4	2 Million
Livermore	January 24, 1980	5.5	1	44	11.5 Million
Imperial Valley	October 15, 1979	6.4	0	91	30 Million
Gilroy/Hollister	August 6, 1979	5.9	0	16	0.5 Million
Santa Barbara	August 13, 1978	5.7	0	65	7.31 Million
Oroville	August 1, 1975	5.9	0	0	Minor
Point Mugu	February 21, 1973	5.9	0	Several	1 Million
San Fernando	February 9, 1971	6.4	58	2,000	511 Million
San Francisco	March 22, 1957	5.3	0	40	1 Million
Eureka	December 21, 1954	6.6	1	Unknown	2 Million
Bakersfield	August 22, 1952	5.8	2	35	10 Million
Kern County	July 21, 1952	7.7	12	18	50 Million
Santa Barbara	June 30, 1941	5.9	0	Unknown	250,000
El Centro	May 18. 1940	7.1	9	Unknown	6 Million
Long Beach	March 10, 1933	6.3	115	Hundreds	40-50 Million
Santa Barbara	November 4, 1927	7.0	Unknown	Unknown	Unknown
Santa Barbara	June 29, 1925	6.3	12-14	Unknown	6.5 Million
San Francisco	April 18, 1906	8.3	700-800	Unknown	400 Million
Owens Valley	March 26, 1872	8.0	27	56	250,000
Hayward	October 21, 1868	6.8	30	Unknown	Unknown
San Francisco	October 8, 1865	6.3	N/A	Unknown	500,000
Fort Tejon	January 9, 1857	8.3	1	Unknown	Unknown
San Francisco	June 1838	7.0	0	Unknown	Unknown
San Francisco	June 10, 1836	6.8	Unknown	Unknown	Unknown
San Juan Capistrano	December 8, 21, 1812	7.0	50+	Unknown	N/A
San Diego	November 22, 1800	6.5	Unknown	Unknown	Unknown
Orange County	1769	N/A	0	Unknown	N/A

Source: *California Geology*, February 1986, California Department of Conservation; *Earthquake History of the U.S.*, 1982, U.S. Department of Commerce and Department of Interior; and State of California, Office of Emergency Services records.

The Research Plan

The Goal

The major goal of this *Research and Implementation Plan for Earthquake Risk Reduction in California* is **to reduce damage, casualties, and interruptions caused by California earthquakes.** The general relationship between research, implementation of the results of research, and the goal of reducing earthquake casualties and property losses is illustrated on Figure 1.

The Objectives

The Plan has the following objectives:

- To improve the performance of man-made structures through better hazard assessment and engineering,

- To improve the effectiveness of emergency response in the short term following damaging earthquakes through better understanding of the earthquake risks, and

- To improve the speed and effectiveness of post-earthquake recovery and reconstruction in the long term through better understanding of the social and economic effects of earthquakes.

The Approach

Research activities

As shown on Figure 1, the various research activities that will be guided by this Plan have been grouped into three broad disciplines: Earth Sciences, Engineering and Architecture, and Social Sciences and Public Policy. Research in the earth sciences provides better assessments of the causes, nature, and severity of earthquakes, better forecasts of their occurrence, and helps to identify adverse site conditions. Research in engineering and architecture guides improvements in resistance to damage of buildings and other structures, aids in mitigating adverse site conditions, and helps assure avoidance of future risks. Social science and policy research is essential to better understand, anticipate, and prepare for the social, economic, and human consequences of damaging earthquakes. Such research also aids the development, adoption, and successful application of risk-reduction measures. A fourth activity, Emerging Technologies, is an interdisciplinary resource that is explicitly included in this Plan. Research activities are linked in Figure 1 to the translation and transfer of knowledge.

Information Translation And Transfer

Central to this Plan is the requirement that research projects incorporate a strategy for implementation of the results of the research. In the past, there has been a lack of effort to apply new knowledge to loss-reduction activities. A major aim of this Plan is to put existing and new knowledge to work reducing earthquake risks.

Although this Plan is focused on research, it is vital that aggressive efforts be made to directly reduce losses; therefore, communication,

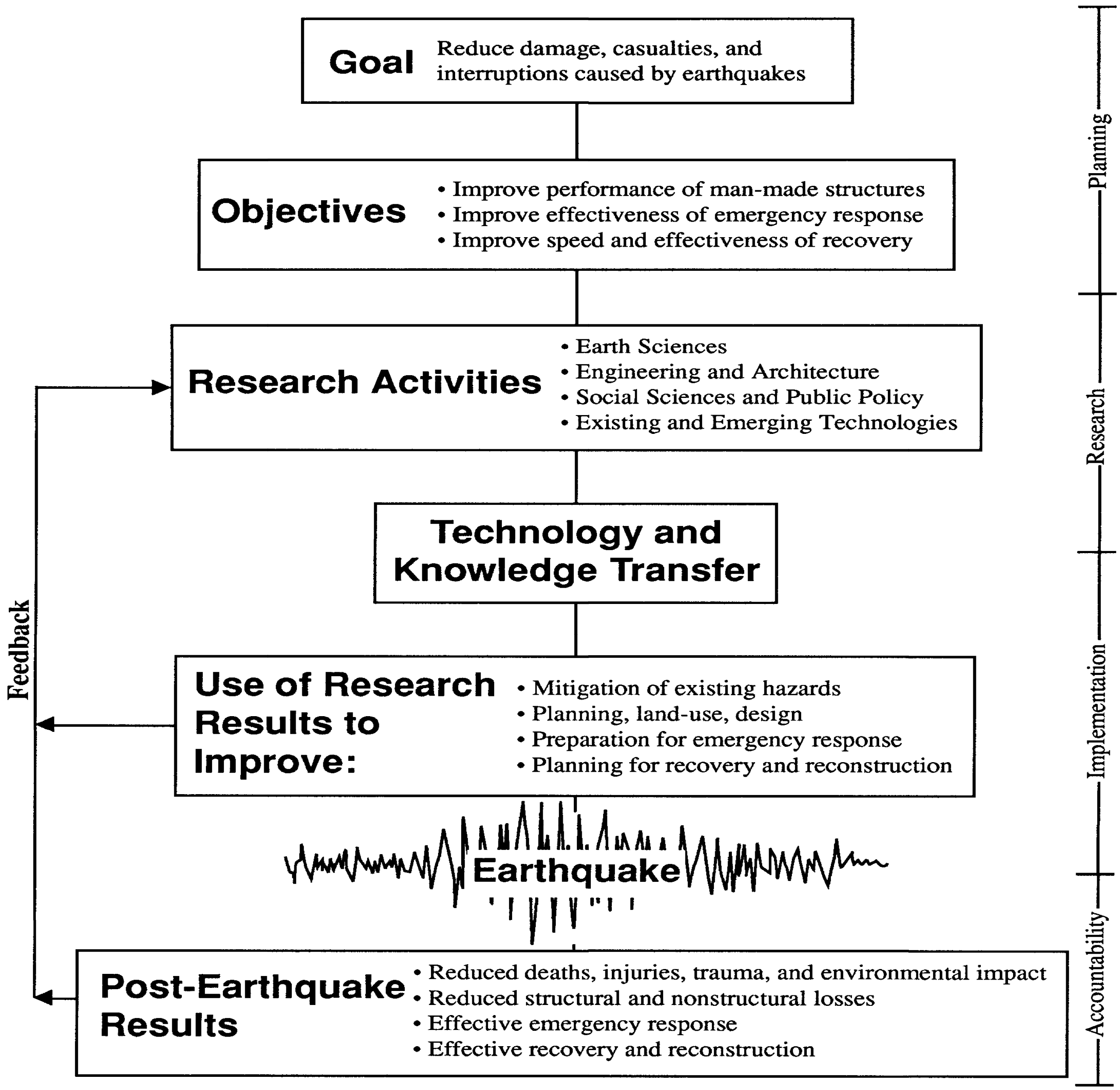

Figure 1. Earthquake Research and Implementation Program

education, application, implementation, and enforcement, as appropriate, shall be included in the research planning and budget. Realistic measures like these can facilitate the transfer of research findings to solve practical problems. They are essential to circumvent an all-too-frequent pattern of research that lacks relevance.

Researchers who fail to ask the correct questions at the outset or do not provide for adequate translation and transfer of their findings, frequently produce products of little use to society. Society, on the other hand, may either be unaware of the end results of research, or fail to understand its potential. To correct this, the initiation, conduct, and conclusion of research projects under this Plan must include active involvement with probable users, whose advice should be sought regarding relevance and applicability of research results.

As it is managed now, peer reviewing of research projects is too closed, limited in the pool of peers, and heavily academic. The peer-review process needs to be more open and include practicing professionals who are knowledgeable in social sciences and public policy. Emphasizing relevance to needs, and systematically pursuing translation, transfer, and use, can break the prevailing pattern and help realize full value from the research recommended by this Plan.

As things stand, efforts to put existing research into practice are under-funded and depend heavily on volunteers. This haphazard process often fails to tap the full potential of researchers, advanced practitioners, and users who have had to learn through experience. We want to stimulate government, industry, and academic partnerships to make effective use of human as well as financial resources. Applied research projects can challenge researchers, attract well-qualified students for training and research, promote professional development, and contribute significantly to future technological and economic growth.

Researchers can capitalize on well-developed public, private, state, and local processes for enhancing connections between research and the State's goals. California's Division of Mines and Geology, the Governor's Office of Emergency Services, Caltrans, the Division of State Architect, the Division of Safety of Dams, and the Seismic Safety Commission are only a few of the many state agencies that can actively apply new knowledge through their programs. Many local government programs also use new information; an example is the City of Los Angeles' pioneering work on retrofitting codes, emergency response, and plans for economic recovery.

Further, California's universities and private-sector organizations can be voracious users of knowledge, and vigorous generators of research and development opportunity. In earthquake studies, such university-based organizations as California Universities for Research in Earthquake Engineering, the Southern California Earthquake Center, the Coordinating Organizations for Northern California Earthquake Research and Technology, and Research in Earth Science/California Universities provide vehicles for organizing existing information and dispensing new knowledge. Universities also offer opportunities to train professionals, maintain libraries, publish journals, and otherwise aid in information transfer.

Active organizational links between practicing professionals include the Structural Engineers Association of California, California Building Officials, the Association of Engineering Geologists, the California Emergency Services Association, the League of California Cities, the County Supervisors Association of California, the California Chapter of the American Institute of Architects, the American Society of Civil Engineers, the Technical Council on Lifeline Earthquake Engineering, the Earthquake Engineering Research Institute, the Seismological Society of America, and the International Conference of Building Officials. These organizations foster close ties among their members, who represent both research and practice. Most of these organizations publish professional journals and reports and sponsor meetings that are vehicles for information dissemination and transfer. Through some of these or similar organizations, new seismic safety knowledge could be made a part of continuing-education requirements for all appropriate professionals, including medical personnel.

This Plan is intended to build on the existing capacity described above, and to increase its effectiveness in earthquake risk reduction. Too much knowledge presently lies fallow, in part from a lack of promoting its active use. Moreover, it is believed that only a minority of practicing professionals are truly and fully current with the state of the practice. Seemingly, the clear self-interest of professionals would motivate them to stay abreast of their fields, so as to practice with the full professional competence adequate knowledge makes possible. The drive to compete and succeed, profit motives, liability concerns, professional ethics, and public safety are powerful reasons to keep current. Nevertheless, these motives do not seem sufficient in themselves. Multiple, often conflicting, demands impinge on professionals, and the incorporation of new information may suffer. Facilitating information dissemination and transfer is an excellent way to help counter the negative influences.

In short, there are many persuasive reasons why translation, transfer, and use of research findings and technical information deserve a high priority in this Plan. The Plan is based on the current and anticipated real needs of California's ready market of users, who can put valid new information and processes to use through risk-reducing measures if we raise the earthquake literacy of all Californians.

Motivated recipients are essential, however, if information transfer is to be effective. Potential users need to understand the severity of the earthquake threat and the probable consequences, including effects on facilities and interests of direct concern to them. To achieve this, information must be "user-friendly" and not intimidate prospective users with unnecessary scientific terminology or technical jargon. It should be translated into forms that can be readily presented and explained to facility owners, clients, students, policy makers, and constituents. More cost-effective ways should be sought to make information available in useful forms, to the proper persons, and in a timely manner.

This Plan has been prepared in cooperation with representatives of organizations regularly involved in putting information to work. The result is a problem-focused and results-oriented Plan aimed at generating relevant new knowledge and putting it to use.

Application of Existing Knowledge

Many individuals responsible for accomplishing improved seismic safety in the public and private sectors are frustrated by the lack of effort to apply existing technologies to expand damage reduction activities. It can be argued that significant loss reduction could be achieved using the limited available resources to apply the technologies we have at hand. A sustained effort to use existing knowledge more effectively to enhance what we are doing now can achieve risk reduction in many ways that are comparatively cost-effective.

Specific suggestions include dissemination of information in forms that are readily used by qualified practitioners. For earth scientists this might include the mapping of seismic hazard zones, accurately depicting the hazards, and describing options for their effective mitigation. For engineers and architects, this might include preparation of design guidelines, state-of-the-art assessments of topics, and codes and other aids in language familiar to the practitioners. Similar efforts can be made by social scientists to communicate effectively with public officials and administrators, contractors, builders, homeowners, and other users.

Another example of existing knowledge that merits expanded application and support is the strengthening and restraining of nonstructural elements in all buildings. Nonstructural hazards continue to pose a significant threat to life and business function even in modern and retrofitted buildings, because owners apparently are unaware of their exposure. As much as 80 percent of the total cost of many large buildings is nonstructural, and nonstructural damage can disable buildings that are otherwise safe. Following the Northridge earthquake, nonstructural losses were unprecedented, economically unacceptable, and almost entirely preventable through application of existing knowledge. Deaths and injuries from nonstructural hazards would have been much greater, especially in schools, had the earthquake occurred during normal working hours.

Existing geotechnical and engineering knowledge can be applied to upgrade the quality of the information in the Safety Elements of General Plans. The Loma Prieta and Northridge earthquakes demonstrated to many local officials that their Safety Elements had not adequately anticipated the effects of the earthquake because they had cursory geotechnical information and little or no building vulnerability information.

Some lifeline components are known to be vulnerable. We could upgrade these with current off-the-shelf equipment that is more earthquake resistant.

We could increase the quality of future buildings by improving the performance objectives of building codes. The knowledge and ability exists to design and construct buildings to withstand higher levels of ground motion, and the incremental cost for new structures is not believed to be prohibitive.

We could also improve our buildings by increasing and enforcing quality control in building construction. Better training and certification of building inspectors could be implemented, as well as rigorous design review, plan checking, and construction inspection. Designers of buildings also could be enlisted in inspections to assure the structure is being built as designed. Contractors could be educated as to the importance of details known to improve seismic performance, and encouraged to use them.

We could use the existing recovery research knowledge base to modernize our relief and recovery programs and make them more effective in promoting and supporting community recovery.

Consideration of Emerging Technologies and Defense Conversion

The California legislation[1] that calls for a comprehensive earthquake Research plan also specifies that it integrate risk mitigation with emerging technologies. We consider an “emerging technology” as one having high promise of contributing to earthquake risk mitigation, but that has not yet been fully tested or proved successful or been accepted for that application.

In its relatively short history, seismic risk mitigation has been a field that has been almost totally dependent on ongoing research, usually not earthquake-related, simply because the field is young and has changed rapidly. There are many examples of such research that has been applied and “paid off” in terms of savings of lives and property. Following are just a few:

The fundamental basis of all seismic hazard assessment by geologists and seismologists is deeply rooted in the concept of plate tectonics. Yet that concept dates only from the 1960s, when a true revolution came about in the thinking of earth scientists regarding mountain-building processes and the causes of earthquakes, virtually none of which had its origin directly in seismic hazard assessment. Indeed, much of the critical information and imaginative thinking originated from topographic and magnetic-field data gathered from the deep ocean floors in connection with WW II naval operations.

The design of virtually all modern earthquake-resistant structures has been directly affected by data on the quantitative nature of earthquake ground shaking derived in recent decades by strong-motion seismographs. Yet the development of this instrumentation was first spearheaded primarily by an insurance company executive. It was carried out mainly in academic and government research institutions. Deployment has been primarily by state and federal agencies, with California leading the way. Design and production of a new generation of strong-motion instruments is now being carried out through university/industry collaboration.

Study of the response of structures to earthquake shaking is totally dependent on the concepts of structural dynamics. Yet the early development of this important area of engineering was stimulated not so much by earthquake-related interests as by basic concerns in fields such as applied mechanics and aeronautical engineering.

Liquefaction is now recognized as a major earthquake hazard, as was dramatically illustrated in the Marina District of San Francisco during the 1989 Loma Prieta earthquake. Yet virtually all we know quantitatively about this phenomenon is the result of basic studies—largely university

[1] Senate Bill 1835, Chapter 782, Statutes of 1990

based—carried out in soil mechanics research that started mainly in the 1930s and continues actively today. A single Harvard University professor is commonly regarded as the "father" of the field, which was initially concerned mainly with landslides and soil stability problems rather than with earthquakes.

One of the major reasons the United States is a world leader in the fields of earthquake science and engineering is its commitment to discovering and developing new technologies. This commitment has created new jobs and new markets for U.S. industry and has provided greater safety for California's earthquake-threatened citizens. California, through its research universities and high-technology industry, has been at the forefront of emerging technologies in all fields, including earthquake risk mitigation. It is vital that we maintain this position of pre-eminence in the field of earthquake risk mitigation by pursuing a vigorous program of research, development, and application of emerging technologies.

Such research is at the cutting edge of earthquake risk mitigation. In many cases, a "new technology" is not guaranteed, but the potential benefit is so high that the research is justified. This type of research must not only continue but must be expanded. It is important that our best young researchers be attracted to the field of earthquake technology development. One way to do this is to support cutting-edge research in this field.

Administration of the Plan

Given the current climate of high risk of future earthquakes, the shortcomings in existing seismic safety efforts, and the scarcity of funds, a responsible organization is required to manage the earthquake research and implementation effort to ensure success. We cannot afford research projects that do not focus on California's highest priorities, lack relevance, duplicate the efforts of others, or are not translated into practice. The implementation of this Plan depends on the establishment of plan management.

Unfortunately, no existing institutional mechanism exists at the state level of government to plan and administer a multidisciplinary, needs-focused, earthquake risk management research program. Existing organizations and funding levels are not solving California's earthquake problems at a rate that corresponds to the risk. New funding and leadership are needed to provide reasonable assurance that the right research is being supported to reduce earthquake risks and effects more quickly.

Initially, the Commission will provide for the Plan's oversight by appointing a new committee. The "Research Plan Implementation Committee" will be selected to include end users, and researchers and practitioners from the earth sciences, structural engineering and architecture, and social sciences and public policy. The committee will be chaired by a Commission member interested in research, and supported by Commission staff.

The Research Plan Implementation Committee will promote the Plan, influencing the goals of funding organizations having responsibility for earthquake risk reduction. It will be empowered to fund and guide loss-reduction activities that address the research objectives detailed in this Plan. It will not only represent the concerns and views of the Commission, it will act as a cohesive force between researchers, practitioners, users, and public policy makers.

To be effective, the Plan will have to be carried out competently and expeditiously. We envision its management activities will expand and soon overwhelm a volunteer committee and the abilities of the Commission staff. Yet, it is essential for the vitality of the Plan that a generally acceptable body offering experience, balance, and influence provide firm, critical, and informed management and support.

The Commission will seek funds from appropriate sources to implement professional management of this Plan. When funds are secured, the Commission, with help from the Research Plan Implementation Committee and other advisors, as necessary, will develop a Request for Proposals. It will solicit competitive proposals from qualified professionals, organizations, or consortia for the purpose of establishing a focus for Plan management activities, called the "Center for Earthquake Risk Reduction." With help from the Research Plan Implementation Committee and other advisors, as necessary, the Commission will evaluate the proposals and select a Plan manager. The Plan manager can be an individual and supporting staff, an organization, or group of individuals or organizations. Whether separate facilities for housing the Center will be part of the initial request will depend on need and the level of funding.

The Commission believes a California Center for Earthquake Risk Reduction would be a reasonable result of successful growth and maturation of this Plan. In 1986, legislation[1] was passed mandating the establishment of a center for earthquake engineering research. The legislation recognizes it is in the interests of the safety of all Californians that there be a center to develop new and improved risk-reduction measures through research and application that will reduce the potential for death, injury, and damage. Although this law has not yet been funded or implemented, we believe the interests of this Plan, and thus the

[1] Chapter 12.3, Statutes of 1986

interests of the State in earthquake risk reduction, would be best served by working towards establishing a center at this time. The Center for Earthquake Risk Reduction would serve an important role in the *California at Risk* implementation scheme.

The responsibility of the Center will be to manage the Plan. The Center will not conduct research itself, but will direct funding to universities, agencies, and private-sector researchers and practitioners who are both capable of high-quality work and interested in solving high-priority earthquake problems. The Center will select, fund, and review research and implementation projects, and assure that research findings are translated and transferred to users, practitioners, and policy makers. Its purpose would not be to centralize research in the State or to exclude any current research facilities. In fact, it would take advantage of facilities throughout the State to enhance earthquake loss reduction by supporting research that addresses the priorities in this Plan.

Although the priorities right now necessarily are geared toward applied research and implementation, we recognize that basic research also is important. The benefits of investments in research allow future direct loss-reduction expenditures to be more cost effective.

It will be important for the Center to work with California government agencies, universities, and existing private and public institutes and organizations, such as California Universities for Research in Earthquake Engineering, the Southern California Earthquake Center, Research in Earth Science/California Universities, the Structural Engineers Association of California, the Coordinating Organizations for Northern California Earthquake Research and Technology, and the Applied Technology Council. We realize that earthquake research will be funded and will continue outside the purview of this Plan, and there is no intention to manage such existing or future research activities. Only research funded partially or wholly under this Plan will be subject to the goals and priorities of the Plan. However, it is the Commission's intention to influence the direction of outside research funding to address California's most pressing seismic safety needs.

Management of the Plan can be an ever-broadening responsibility. It is not hard to imagine a facility, perhaps a portion of an existing military facility converted to civilian use, where contractors could come for information or hands-on displays of seismic safety methods, where builders could come for evening classes, where engineers could use new testing facilities that complement university facilities, where homeowners could find information on emergency preparedness. The evolution of the Center will be based on experience. A perception of success in the first few years will be important to its future.

The Center will be accountable to the Commission, through the Research Plan Implementation Committee. It will submit reports of its progress and activities to the Commission bi-annually. Annually, it will hold a workshop for the purpose of communicating with and receiving feedback from the Commission, researchers, practitioners, users, and anyone else interested in earthquake risk reduction in California. The Commission will monitor the work and the effectiveness of the Center, recommend projects and ways to promote the application of research, help interpret the results of research that could affect state law and policy, and do whatever else is necessary to assure high-quality research and effective operation of the Center.

Effective implementation will result in improved earthquake safety, and success will be measured by post-earthquake results. Following earthquakes that cause significant losses, the effectiveness of the pre-event preparedness activities must be evaluated. The Center will provide a focus for the research and loss-reduction communities in identifying ways in which the lessons learned from future earthquakes can be used to improve pre-earthquake preparedness activities. The research findings from post-earthquake observations and evaluations will feed back (Figure 1) to help policy makers and researchers revise the priorities and update this Plan. This will assure that the Plan is a living, working process that has increasing value.

The charge given the Center for Earthquake Risk Reduction is expected to include:

- Promote the Plan,
- Encourage researchers to make relevant proposals that fill research gaps,
- Seek new funds to support applied research,
- Maintain awareness of direct funding by state and federal agencies, influence the goals of funding organizations having responsibilities for earthquake risk reduction, and encourage them to support the research priorities listed in this Plan,
- **Assure that the products of research are successfully disseminated to the user community,**
- Assist the Seismic Safety Commission in coordinating the research efforts called for in bond issues and legislation relating to seismic safety,

- Identify possible project investigators and encourage and support them in their requests for grants from funding sources for research presented in the Plan,

- Cooperate with funding organizations by reviewing grants and contracts, monitoring their progress, and communicating and coordinating with funders to help them assure effective use of funds in accordance with the grants and contracts,

- Cooperate and coordinate with established research organizations in California and be sensitive to the needs of stakeholders,

- Cooperate and coordinate with private-sector organizations that conduct and support research or create new technologies and materials to solve their own earthquake problems to glean new information and to disseminate it as part of the overall research effort,

- Improve, to the extent necessary, laboratory and testing equipment to assure the capability to conduct adequate studies and experiments, and study the needs for large-scale and innovative experimental and testing facilities to support earthquake research,

- Revise the Plan annually to reflect changing priorities, new knowledge, and findings from future earthquakes,

- Distribute the Plan to all appropriate funding agencies, researchers, practitioners, and users.

The Role of the State

Although other states are also seriously affected, California, by far, has the greatest earthquake risk in the United States. Our unique network of large active faults requires special consideration, and designers of highway bridges, dams, schools, hospitals, and other critical structures in California face specific earthquake threats not seen in other jurisdictions across the country.

Examples of California-specific earthquake programs under the auspices of various state agencies are numerous. Especially important are the responsibilities of Caltrans to achieve earthquake safety of highways and bridges, the Division of Mines and Geology to operate the Strong Motion Instrumentation Program and map active faults and other seismic hazards, the Division of Water Resources, through its Division of Safety of Dams, to maintain dam safety, the Public Utilities Commission to monitor and enforce the earthquake safety of the regulated utilities, and the Division of State Architect to improve the safety of older hospitals, public schools, and state-owned buildings, and to implement gas safety legislation.

There can be little doubt of the ultimate responsibility of the State and its agencies to reduce the dangers from earthquakes and to provide a relatively safe environment for its citizens, industry, and infrastructure. In fact, there has always been a significant contribution by the State of California, at all levels, to support and stimulate basic and applied earthquake research and its implementation. This state involvement has been decisive in advancing earthquake science and in improving building codes and preparation within the State.

An excellent example of how a concentration of effort at the state level has proved valuable is California's support for a statewide network of instruments to measure strong earthquake ground motions. This network has advanced, in a decisive way, the knowledge of the variability of earthquake shaking, and has provided realistic inputs for the design of earthquake-resistant structures. At an earlier time, the federal government had sole responsibility for this activity; the rise and fall of interest in Washington resulted in an inadequate instrumentation program in California for many decades. Then, more than ten years ago, the initiation of the California Strong Motion Instrumentation Program, using fees from construction permits within the State, revolutionized the observation of earthquake ground motions. The program has became a model for such studies throughout the world.

Key earthquake studies in California have involved budgetary and administrative support from the federal government, the state government, and the private sector. The State must participate in partnership with federal agencies and the private sector, demonstrating the seriousness of the earthquake threat by its own active support, or opportunities for funding earthquake research and its implementation can be lost. Significant earthquake risk reduction has aspects so indigenous to California that explicit state support for advanced studies of past and future earthquakes and their consequences is inescapable.

The successful administration of an earthquake risk reduction Plan as ambitious as the one envisioned by the Legislature, described by the Commission, and needed by the State requires a stable commitment of resources. The prevailing paradigm in our society, which protects short-term "bottom lines," is foolhardy when applied to earthquake risk reduction. For every dollar spent on relevant research, the benefits have been shown to be at least ten-fold. Investing now to mitigate future earthquake damage and economic and social disruption will be much more effective than paying huge sums later to clean up the debris, repair facilities, and help victims.

The State has an obligation to deal with our earthquake threat expeditiously. A modest investment of $5 million—one-tenth of one percent of the losses in a moderately damaging earthquake—could fund the initial expenses of the Research Plan Implementation Committee, the selection of professional Plan management, the establishment of the Center for Earthquake Risk Reduction, the activities of the Center for a year, and some research and implementation efforts. The State has mandated a Research Plan and a Center; the Commission needs secure, long-term state funds to fulfill these laws. Once a Center is in place to focus California earthquake research, a mechanism will exist for soliciting additional funding from traditional sources (Table 2). The Center will provide these funders a level of comfort that their research dollars would be well spent.

Table 2

SELECTED EARTHQUAKE RESEARCH FUNDING ORGANIZATIONS*

Federal Agencies

Centers for Disease Control
Department of Energy
Department of Housing and Urban Development
Department of Transportation
Federal Emergency Management Agency
Federal Energy Regulatory Commission
National Aeronautic and Space Administration
National Earthquake Hazards Reduction Program
National Institute for Standards and Technology
National Oceanic and Atmospheric Administration
National Science Foundation
Nuclear Regulatory Commission
U.S. Army Corps of Engineers
U.S. Geological Survey
Veterans Administration

State Agencies

California State University Foundation
Department of Conservation
Department of Transportation
Department of Water Resources
Division of the State Architect
Office of Emergency Services
Office of Statewide Health Planning and Development
Seismic Safety Commission
University of California

Private Sector

American Concrete Institute
American Institute of Steel Construction
American Iron and Steel Institute
American Society of Civil Engineers Research Foundation
Applied Technology Council
Consulting and Construction Firms
Earthquake Engineering Research Institute
Electrical Power Research Institute
Masonry Institute
Portland Cement Institute
Private Universities
Utilities

*The purpose of this table is to illustrate the diversity of research funding organizations.

The Earthquake Research

The following research topics represent the priorities the Commission believes will assist in the accomplishment of the 42 initiatives described in the State's earthquake risk reduction document, *California at Risk*. The challenge to scientific, technological, and policy research is to reduce uncertainties and provide guidance for difficult choices, especially choices in retrofitting old structures and adopting safer building and land-use practices, investment choices in levels of future safety, and a multitude of other economic, social, and political decisions that residents of earthquake country face. Intelligent choices require good state-of-the-art information, which can result from well-focused research. Past progress has been substantial, but a great deal more should and can be done if resources are used wisely. The program of earthquake research outlined here is designed to promote California's greater safety in the large earthquakes to come, and realistic budgets will allow undertaking more than just a few targeted areas in the next few years.

This program represents the Commission's best effort to highlight priority research toward meeting the overall goal of reducing damage, casualties, and interruptions caused by earthquakes. Better knowledge will narrow uncertainty, minimize too-conservative as well as too-liberal assumptions and decisions, increase the reliability of our analytical methods, refine the selection of priorities, and promote our understanding of the social and economic ramifications of earthquakes. This is not intended to be a shopping list, but to illustrate specific, high-priority research goals needed by the State to reduce its earthquake risk.

Priority research in the fields of earth science, engineering and architecture, and social science and public policy has been selected. Also presented is a discussion of potential earthquake research opportunities that could take advantage of defense conversion and emerging technologies not originally intended to address the earthquake problem.

Earth-Science Research

Progress on structural design, land-use planning, and emergency preparation policy is dependent upon reliable geologic and seismological understanding, including the identification and delineation of seismic sources, characterization of strong ground shaking, and the identification of areas of potential ground failure and tsunami inundation. Satisfactory performance of structures can be achieved by avoiding their placement in areas where hazards such as fault rupture or landslides or liquefaction-induced ground failures can cause damage, or mitigating the hazard, and designing the structures to withstand expected ground shaking. These loss-reduction measures are achieved through regulation of land use and construction. Both approaches require knowledge of seismic sources and estimates of the potential contributions of earthquakes along them to the ground shaking that will be experienced during the half-century or so that is the intended lifetime of many structures. Research is necessary to improve our understanding of earthquake potential and, through this, to more safely construct new structures and to strengthen those in existence, where necessary.

Basic seismological observations and results are being demanded by the earthquake engineering, land-use planning, and public-policy sectors. For example, it is now clear that for engineering purposes, not only accelerograms, but time histories of ground velocity, displacement, and duration are important. In addition, the spatial incoherence of seismic ground motions between neighboring points needs to be understood to design and check critical large structures. An illustration is the growth of the use of base-isolated structural systems in seismic regions. For the design and structural analysis of such systems, realistic ground-wave displacements must be defined.

It should be noted that much earthquake research involves enhanced earthquake observations. Instrumentation is a "core" need in the earth sciences—one that has the potential to contribute to all seismic studies, risk mitigation, response, and recovery. Examples are the further development of early earthquake warning systems, the real-time availability of information following damaging earthquakes (including tsunami genesis) to rapidly assess the likelihood of damaging aftershocks and the patterns of their regional effects, and upgraded and well-resolved delineation of the active fault zones within the State through computer-based, three-dimensional graphics.

A major upgrade of the State’s network of earthquake strong motion instruments is a priority. The 1994 Northridge earthquake made clear the great practical use of such readings. This information would allow cities to request assistance from OES and FEMA in a timely manner after a damaging earthquake. As it is now, earthquake loss estimation is based on earthquake magnitude; the actual shaking data are critical to improve the accuracy of these estimates. In addition, post-earthquake building inspections would be greatly enhanced by this information.

There is a danger that much of our present instrumentation is becoming obsolete, particularly with the rapid growth of high technology based on digital recording analysis and dissemination. A capital investment is necessary to expand and maintain Global Positioning System (GPS) networks, broad-band seismic networks, weak-motion seismic networks, free-field strong-motion instrument networks, portable instruments for post-earthquake response, and dense arrays at selected sites. It is essential in California that earthquake data analysis and retrieval be subject to the latest high-tech streamlining, with the widest publicity and education concerning easy availability.

In considering priority research, it became clear that some research efforts were not likely to provide information critical to immediate, cost-effective earthquake risk reduction in California. For example, additional deep geophysical studies probably will not tell us much that we do not already know, unless techniques are dramatically improved. The Commission also feels that research on induced earthquakes is almost irrelevant to California's current needs, and that subduction zone studies should not have a major role, in view of their relative unimportance to California's major population centers. Probabilistic risk assessments, while necessary for critical facilities such as dams, important bridges, and some lifelines, are not efficient for studying urban regions, where earthquake-specific studies can have greater value.

It is clear that a notable research gap involves long-term earthquake forecasting. One general approach to this problem was taken recently by working groups sponsored by the National Earthquake Prediction Evaluation Council. The U.S. Geological Survey[3, 4] published the resulting probabilities of large earthquakes associated with the San Andreas fault system; however, the uncertainties remain very high. The basic studies outlined below will yield information that can be used to develop improved earthquake probability maps along California’s seismogenic zones.

Research Goal: *Statewide, systematic, earthquake-hazard maps.*

There is an urgent need for the systematic development of seismic-hazard maps to identify the parts of urban areas having the greatest potential hazards. Seismic hazards include primary hazards—surface fault

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[3]Working Group on California Earthquake Probabilities, 1988, *Probabilities of large earthquakes occurring on the San Andreas fault*: U.S. Geological Survey Open-File Report 88-398

[2]Working Group on California Earthquake Probabilities, 1990, *Probabilities of large earthquakes in the San Francisco Bay Region, California*: U.S. Geological Survey Circular 1053

displacement and strong shaking—and secondary hazards—liquefaction, lateral spreading, landslides, and tsunami. The effects of strong ground shaking, liquefaction, landslides, or other ground failure account for approximately 95 percent of economic losses caused by earthquakes. Seismic-hazard maps depict the locations of the various hazards so future development or redevelopment can consider them and either mitigate the hazards or avoid them.

Credibly forecasting the distribution and extent of future earthquake damage is important for planning emergency response and recovery, for assessing adequacy of insurance coverage, and for motivating the public and private sectors to invest in loss-reduction activities. Uses include development of realistic, earthquake-specific damage scenarios and consequence scenarios for preparedness planning. To accomplish this, close coordination is needed with engineers and social scientists.

The hazard of surface fault displacement has been systematically mapped during the past two decades by the Division of Mines and Geology under the Alquist-Priolo Act of 1972. Although legislation[5] mandating further earthquake hazard mapping exists, it has not been adequately funded or carried out. We need maps of the locations of potential strong ground shaking and the relative severity of all ground-motion characteristics (acceleration, velocity, displacement, and duration), areas having the potential for liquefaction and associated lateral spreading, and locations of potential earthquake-induced landsliding. The legislation recognizes that areas subject to these processes during an earthquake have not been identified or mapped statewide, despite the fact that scientific techniques are available to do so. We believe high-resolution space images can enhance the mapping process by providing systematic coverage of the state, allowing for better regional mapping of active tectonic zones, and identifying targets for detailed ground studies to characterize previously unrecognized seismic sources.

Maps of coastal areas where there is the potential for tsunami wave impacts also are needed. California is subject to tsunami hazards from distant earthquakes in Alaska, Japan, and South America, as well as from earthquakes near the coast that may induce tsunami waves by offshore fault displacement or massive submarine landslides.

Research Goal: Improved understanding of where in California, how large, and how often earthquakes will strike in the future through a more

[5]Assembly Bill 3897, Chapter 7.8, Statutes of 1990

accurate understanding of regional active tectonics and patterns of seismicity.

Although this is a large order that encompasses many aspects of the earth sciences, those responsible for land-use management, the design of structures, and emergency response and recovery strategies need this information to cope appropriately with future earthquakes. Also, knowledge of high-probability earthquake source zones and likely estimates of earthquake location, size, and effects are inputs to seismic hazard mapping.

Paleoseismic studies, including regional geologic mapping, geomorphic analysis, exploratory trenching, and fault slip-rate and slip-per-event studies, focused on Quaternary deformation, are needed to characterize seismic sources that intersect the surface of the earth. Blind thrusts—those thrust faults that are not exposed at the ground surface and therefore not readily studied using traditional field methods, should be studied using geodetic methods, particularly GPS techniques, and geomorphic field studies to locate and understand active folds. Regional, high-resolution geophysical profiling, including new geophysical imaging of buried thrusts, may help characterize the regional tectonic setting, including young structural features and patterns of stress and strain, and the crustal structure of faults at seismogenic depths. Also needed are the regional characterization of seismicity—the patterns of spatial and temporal clustering—and seismic-source geometries. Studies of the most effective ways in which to portray these data to users must continue and be expanded.

Research Goal: Improved understanding of the geographic patterns and the spectral characteristics of ground motions associated with future earthquakes, and the potential for amplification of ground motions due to site conditions.

Earthquake ground motions are known to be affected by different types of geologic materials and topography. In the recent California earthquakes, surprising differences in the degree of ground shaking were observed at localities very close to one another. Research on how different sites respond or amplify free-field ground motions, as well as systematic mapping to characterize local soil and rock site conditions susceptible to amplification of ground motion are needed. The identification and evaluation of the physical conditions of soil, rock, and topography affecting site response, and delineation of California localities that are susceptible to ground amplification are critical to better land-use planning and engineering design.

We also need to characterize the effects of source and path conditions on strong ground motions. Through analysis of parameters influencing ground motions, using empirical data and theoretical modeling, probabilistic maps of regional ground-motion patterns can be developed. It is important to exploit the information available in recordings of small earthquakes, micro-tremors, and recent well-instrumented moderate to large earthquakes.

Research Goal: Improved understanding of the basic physics of the fault-rupture process.

The detailed mechanics of the ways in which faults rupture and release seismic energy have varied from earthquake to earthquake, surprising scientists and engineers alike. Earthquakes turn out to be very different from one another, and until we understand the range of these differences and their causes, our ability to estimate and plan for earthquake risks will necessarily be limited.

The relationship between faults exposed at the surface and what takes place at depth is a key to estimating the seismic hazard more effectively. Investigation of the physics of fault rupture through basic seismological and geodetic studies are essential in this field, as well as geologic field studies.

Research Goal: Improved effectiveness in the translation and transfer of earth-science research information.

Research is needed to develop strategies to improve the extent and effectiveness of the application of earthquake risk information required for pre-earthquake mitigation actions by engineers and social scientists. Earth-science research results must be effectively communicated to impact land-use decisions and engineering designs. Loss-avoidance estimates, which are important to benefit/cost analyses, also require earth-science research results.

We need to study techniques identified in the social sciences to improve the effectiveness of information translation and transfer of earth-science research results. We must have maps that send the right message, and user-friendly reports in nontechnical language.

Straightforward communication of earth-science information also is important in the development and maintenance of geographic information system centers—centers needed to facilitate transfer, translation, and analysis of data to investigators and users.

Engineering and Architectural Research

The engineering and architectural research goals consider issues related to physically accommodating earthquake forces. They presuppose the details of the hazard for the site are given—research issues that are addressed in earth-science research—

and that the regulatory environment in which the designer works is specified—research issues that are addressed in social sciences and public policy research. Key needs are to reduce earthquake risk to levels generally considered acceptable, and to ensure that important facilities function at acceptable levels after a major earthquake. The research seeks risk reduction through such means as retrofitting and better design, siting, and construction. Underestimation of the risk will result in structural failures; overestimation will require unnecessary restrictions and expenditures.

Life safety is the primary goal of seismic design. A structure is hazardous when it poses an unacceptable risk to its occupants or to the community. Life safety can only be approached indirectly through the control of damage to the structure and its contents. Minimizing loss of function and preserving property are secondary, but important, goals that impact emergency response and recovery.

Observations of earthquake impacts indicate that we do not know nearly as much about earthquakes as we would like. Most estimates of earthquake ground-motion characteristics, using our current mathematical expressions, are uncertain by a factor of two or more, hardly precision in most people's minds. The earthquake magnitude has a strong influence, as does the distance from the source of the energy release, location of the building relative to the fault, and the site response. Each earthquake appears to have its own character: some have high frequency content, others low; one will have higher-than-expected accelerations, another low accelerations. Earthquake duration also varies significantly. The effect of these differences is that the performance of a building can vary widely, leading to the conclusion that magnitude alone is not a good indicator of the likely damage. Furthermore, performance in one earthquake is no guarantee that equivalent performance will be observed in another earthquake, even one of the same magnitude.

Major contributors to building damageability include site characteristics, structural system, and configuration. Site conditions have a systematic influence on damageability. The differences in expected damage for a given building can vary by a factor of more than two, depending on whether the site is rock or alluvium. Similarly, the basic structural system of the building has a large influence on damageability—a factor of four or more. The point of these figures is that site and structural systems have as much influence on damageability as does the earthquake magnitude and distance to the fault. Unfortunately, there are no simple golden rules, not withstanding the desire of many who want or report them.

Some key questions in the process of assessing the vulnerability of a specific structure are: what is its configuration? what is its engineering quality? how well was it constructed? and, what is its condition? Earthquakes tend to find the weak point in a structure. Much of what we know about building performance comes from experience during past earthquakes, and our experience with large earthquakes and their impact on modern society is limited.

Nonstructural damage and the damageability of contents, and thereby the function of the building, is another concern. Much of the injury and life loss that occurs in buildings is caused by the failure of contents. Contents often perform poorly because the building performs poorly. Frequently, contents are badly damaged when the building performs well. Top-heavy equipment topples, bookcases fall, partitions fail, electrical equipment shorts, water pipes fail, ceiling tiles and fixtures fall. Experience indicates that contents and nonstructural systems begin to fail long before the structural system of the building does.

"Core" needs for engineering knowledge and capability are those that must be supported to achieve the basic needs efficiently; they broadly support achievement of all the technical needs. An improved experimental capability in the State is a core need that would contribute greatly to engineering investigations. Better availability of experimental capabilities where material and small-assemblage experiments on structures or equipment could be performed is important to seismic safety research and education. Regional experimental facilities, where experiments on large elements of structures or equipment can be performed also need expansion and improvement. Because small-scale test results do not extrapolate well to field conditions, a full-scale test facility, where full or near-full-scale experiments on large sections of structures or equipment can be investigated should be a long-term goal.

The research goals imply a research program that is large and comprehensive. Given what is now known, how seismic safety is practiced by the design professions today, and extent of the pressing risks faced by the citizens of California, such a program could easily use massive financial and personnel resources.

Research Goal: Realistic, comprehensive, earthquake-specific damage scenarios.

A high priority for engineering and architecture studies is the development of realistic, comprehensive, earthquake-specific damage scenarios using seismic hazard mapping from the earth sciences. The damage scenarios would be based on an accurate compilation of structure and systems inventories, and realistic assessments of their earthquake performance, given the seismic hazard and the structural and damageability characteristics of the facilities. Procedures to measure performance, including casualties, damage, function loss, and cultural values need to be developed.

Field experiments and investigations are needed to help establish base-line information on how sites, structures, and life-line systems are likely to perform in earthquakes, including major aftershocks. Instrumentation should be installed for data collection in structures and facilities in areas where earthquakes are highly likely to facilitate study of the performance of the structures.

Research Goal: To achieve desired performance of existing construction.

Another priority for engineering studies is the evaluation and retrofit of existing vulnerable structures, including common construction, critical facilities, lifelines and industrial facilities, and historically significant structures. Research is needed to develop procedures to identify the expected seismic performance of existing structures. Consensus standards and cost-effective methods to improve performance, if necessary, are needed. Current building codes are essentially focused on construction of new facilities, leaving most jurisdictions at a loss as to the standards that should be required for the seismic retrofit of existing ones.

For all construction, we need to consider material and structural systems, configuration, adjacency, and condition. We need to develop cost-effective methods to improve the performance of structures found to be deficient, including unreinforced masonry, adobe, brick, block, and tile; nonductile cast-in-place concrete; nonductile steel; precast concrete; tilt-up construction; and composite systems (wood and masonry).

We need methods to analyze the nonlinear response of materials and systems under seismic loading. We also need to develop algorithms and computational procedures to predict the earthquake performance of engineered systems. Further research is needed on energy-dissipative and base-isolation devices.

At sites where ground failure is likely, we need improved methods to prevent site failure and to stabilize liquefiable sites.

We need to better understand the performance of and develop methods for upgrading power plants, bridges and freeway structures, dams, lifelines, hospitals, pipelines, communications facilities, and manufacturing, storage and distribution facilities. Research should be conducted on improvement through innovative means, to develop innovative techniques to maintain function during and following earthquakes of hospitals, communications systems, transportation facilities, lifelines, fire stations, and police facilities.

Historically significant structures need special consideration, for both retrofitting before a damaging earthquake, and restoration following earthquake damage, to preserve their architectural, cultural and educational characteristics.

We also need to understand the performance of and develop cost-effective methods for upgrading architectural components, mechanical components, and free-standing mechanical and electrical systems and elements if we are to achieve the desired performance of nonstructural components of structures.

Research Goal: To achieve desired performance of new construction.

Research is needed to develop a better understanding of the behavior of engineered systems: for rigid, semi-rigid, and braced-steel frames, for cast-in-place concrete, for precast concrete, for wood, and for composite systems.

We need to correlate system performance in earthquakes with the codes and practices under which they were constructed and structural characteristics, configuration, construction quality, and condition, relating performance to earthquake demand and structural capacity.

We need improved quality control in building construction, and methods to enforce rigorous design review, plan checking, and construction inspection, including inspections by designers.

We need to design and implement construction and maintenance procedures that provide adequate seismic performance of structures and their contents to maintain acceptable function of systems.

Research Goal: Improved understanding of the nature of ground response and the interactions between the ground and foundations.

To quantify ground-motion features relevant to the design and regulation of structures, we need research on the spatial variations of ground response and the seismological, topographical, geotechnical, and geologic indicators of such variations. Studies are needed of the effects of different supporting materials—soils or rock—on site response, to determine the site and excitation conditions that lead to liquefaction and to site failure, including differential settlement and landsliding.

Research also is needed on the response characteristics of pile foundations, embedded foundations, and buried structures, to determine how site and structure interact to modify the naturally occurring site response. The installation of free-field strong-motion instruments near significant structures is needed to provide reference stations that will record the local input motion. About 2000 sites are needed; however, well-located instrumentation could provide a reference-station record for every damaged structure.

Research Goal: *Improved understanding of the nature and extent of secondary risks caused or enhanced by earthquake damage.*

We need to understand and mitigate by design decisions the triggering of fires and hazardous-materials releases. We need to apply earth-science information to anticipate the occurrences and extent of tsunamis and mitigate their impacts by design decisions .

Research Goal: To rapidly assess the safety of structures based on their damage state and general characteristics, and stabilize damaged structures to prevent subsequent collapse .

Following a damaging earthquake, there is an urgent need to be able to rapidly assess the safety of buildings and critical or hazardous facilities, and to rapidly stabilize damaged structures to prevent collapse. We need research to develop rapidly implementable approaches and methods to achieve the capability to stabilize damaged structures quickly and economically following an earthquake. We also need to research techniques for the restoration of lifeline facilities. Innovative engineering approaches are needed to more rapidly repair structures and recover function.

Research Goal: To apply the knowledge obtained through engineering research.

Application of the engineering research knowledge needs to take place on two fronts. First, engineering design and construction of new and existing facilities should benefit by the development of new codes, standards, and practices to guide the design and construction of earthquake-resistant structures. We need to develop vulnerability assessment guidelines, design criteria, design methods and details of construction, and sophisticated analysis procedures for critical structures.

Secondly, we need to educate individuals and institutions in the use of earthquake risk reduction practices, procedures, and policies. Procedures are needed to archive printed material on earthquake risk reduction and make it available to those who need it. We need to develop easily used computer-based information systems that allow identification and retrieval of information.

Earthquake risk mitigation should be incorporated into the basic course work of higher education institutions, particularly those involved in technical areas related to design and construction. Additionally, we need to develop and conduct training exercises and programs for professionals to bring recently developed knowledge, new practices, and recommended approaches to their attention and train them in their use.

We need to research the best ways to provide lay individuals and institutions with information on the causes and effects of earthquakes, how to identify hazardous conditions, and how to correct such conditions. Working with social scientists, techniques such as using the community-based educational institutions, providing public access to experienced and knowledgeable researchers and practitioners, and conducting demonstration projects of how to mitigate earthquake risks in the home and work place should be explored.

Social Science and Public Policy Research

The Commission has developed this Plan to help improve California's ability to cope with earthquakes, using research findings and other available knowledge. To be effective, knowledge must be disseminated, understood, and put into general practice. Successful translation and transfer of information is an essential connection between research results and their effective use in reducing earthquake risks. Facilitating research translation, information transfer, and application of scientific and technical information is a major task of social science and policy research. This critical link has hitherto not been given adequate attention and effort. Consequently, strong efforts to use information and apply science and technology in the interest of earthquake safety should be an integral and fully funded part of this Plan.

Realistic anticipation of future earthquake impacts is basic to determining how to reduce risks to acceptable levels. Because all risk cannot be eliminated, agreement is essential on what is acceptable and what is not. Judgments are needed on probable risk incidence, practicality of alternative reduction measures, and equitable cost distributions. Policy judgments and choices among alternatives are illuminated by good sociological and psychological research, economic analysis, and social science investigation.

Much work and thought are needed to define "acceptable" levels of seismic safety and express it in realistic operational terms. Both public- and private-sector property owners alike need to understand the kinds and levels of damage they should expect in various kinds of structures (new, old, retrofitted). Risk must be expressed in terms of life safety/life risk, and post-earthquake service/loss of service. Benefit/cost analyses and determinations of "acceptable" risk will vary from system to system being assessed. For example, high-cost retrofitting of bridges to protect the centers of commerce are justified when failure would cause unacceptable regional or national economic consequences.

Improved data and methods are needed to estimate earthquake losses and evaluate the social and economic benefits of risk reduction. Socioeconomic impact assessment is critical to establishing workable concepts of acceptable risk and desirable levels of seismic safety. "Acceptability" is, in the final analysis, determined by a series of social, psychological, economic, and political judgments regarding impacts, and the costs of avoiding or living with those impacts. Anticipating earthquake impacts and the distribution of losses, as well as risk-reduction costs, among different economic and demographic sectors is critical to developing a sense of what may be acceptable and to whom, who benefits and who doesn't.

Better understanding of the ways various groups perceive earthquake risk will help to reconcile different interests in favor of greater consensus by addressing the main concerns of each principal party. Judgments as to what is acceptable may differ significantly before and after a major earthquake. Beforehand, economic concerns may tend to predominate. Immediately afterward, however, political, social, and life-loss concerns may become paramount.

Pre-earthquake planning for emergency response is a key element in preparedness. Earthquake scenarios and vulnerability projections give a reasonably clear picture of probable earthquake effects on individual communities. In addition to estimating structural failures, it is also important to consider potential nonstructural losses. In a high-tech culture, these may be severe and economically harmful.

Knowing more about earthquake impacts will motivate decision-makers to work on reducing the risks they or their successors will confront when earthquakes strike. Such knowledge will aid in planning more effective and workable disaster preparations, focusing on programs having favorable benefit/cost relationships and showing the greatest promise for reducing future losses and minimizing other adverse effects.

Both primary and secondary economic effects of earthquakes should be anticipated in planning for long-term risk mitigation, recovery, and reconstruction. The effects of very large earthquakes may be widespread (regional, statewide, national, and even international). Whatever their scope, earthquake effects on business and finance need to be anticipated as realistically as possible, using sound methods. Regional transportation facility losses immobilize large populations, limit emergency response, and cause severe economic impacts. The proximity of California's largest urban populations to the State's most dangerous faults sets the stage for compounding earthquake effects.

There is also a need to evaluate the implications of multiple destructive earthquakes striking the same urban area several times within a decade or so (spatial and temporal clustering). Just as recovery seems well on its way, the cumulative effects of another damaging earthquake or two within a few years could have far-reaching impacts on the economy and well as the psychological well-being of the people affected. The scientific data indicate that both Northern and Southern California are in increased cycles of seismic activity, and such planning is not unrealistic.

The potentially severe chronic and acute psychological effects of major earthquakes should be better understood and planned for. This requires identification of those who are most vulnerable, and initiation of effective outreach programs to provide adequate help. Finally, crisis intervention strategies should be evaluated to guide future action.

Lessons learned in recent earthquakes need to be documented and responses evaluated, to guide improvements in future emergency preparation. Disaster management needs to be refined and clarified, guidance materials developed, and programs developed to motivate and help with community and private-sector earthquake preparation. Methods of improving emergency response, providing immediate relief, and facilitating short-term and long-term recovery need to be developed.

Relatively few public or private-sector organizations have carefully planned beforehand for post-earthquake recovery and reconstruction. To do this well, the principal issues should be fully identified and the most important lessons learned about critical post-earthquake needs. These typically include replacement housing, better land-use policies, well-considered redevelopment objectives, revised building standards, and other safeguards that can materially reduce the remaining risks. The research suggested here will help California's communities bridge these gaps.

Research Goal: *Statewide, systematic, earthquake-specific consequence scenarios.*

A high priority for social scientists and policy makers is the development of scenarios of the consequences of future damaging earthquakes. These earthquake-specific consequence scenarios would use hazard mapping from the earth sciences and damage scenarios from engineering and architecture to characterize the economic, social, and community impacts of an earthquake. A realistic anticipation of the earthquake effects, together with a critical evaluation of existing programs and policies, can provide insight for improving emergency response and recovery.

Research is needed to anticipate more precisely the kinds of physical-plant and infrastructure damage to be expected, as well as the ways in which communities, businesses, governments, and individuals may be affected. We need to estimate the distribution of the damage and the economic impacts in a community, as well as injuries and deaths. Observations of past earthquakes—what worked and what did not—should be used to improve the data bases and strengthen our understanding of the benefit/cost of risk-reduction measures.

The consequence scenarios need to describe the potential physical and socioeconomic disruption in realistic terms, identifying areas and types of facilities affected. The functionality of emergency operations centers, fire and police stations, and communications facilities need to be projected. The vulnerability of the major economic sectors should be evaluated, as well as transportation and utility service interruptions, and loss of food supplies, medical services, and other essential services. Widespread and cumulative earthquake effects need to be considered, such as numerous fires leading to conflagration, multiple fuel-line ruptures, and interruptions of water and other utilities. The adequacy of regional transportation advance planning to prepare for disaster impacts and for response and recovery needs, including the availability of back-up facilities and alternative modes, needs to be evaluated.

The scenarios also need to project earthquake impacts on various demographic groups, including occupants of collapse-hazard structures and the homeless. Special and unusually dangerous effects such as releases of toxic and other hazardous materials (solid, liquid, and gaseous) need to be anticipated, as well as how local and state government will be affected, and their ability to manage plans for emergency response and recovery.

Research also is needed to anticipate the secondary economic effects of damaging earthquakes on regions, the state, and the nation. We need to analyze the probable effects on distribution systems, private-sector performance and competitiveness, inter-industry trade, and exports and imports.

Effective planning will be based on understanding the patterns of damage and dysfunction that are likely to be associated with future earthquakes, and developing strategies to cope with them. Research is needed to evaluate the earthquake scenarios, and loss/damage estimation techniques and methods. Vulnerability studies and impact projections should be developed based on probabilities and an understanding of the uncertainties.

Research Goal: *Effective techniques to facilitate information transfer and use of earthquake risk reduction information.*

The progress made in the professions and by university researchers offers new, more certain, and often less expensive ways to reduce earthquake risk. Getting that knowledge into use by the thousands of practitioners in earth science, engineering, emergency response, and recovery, and well as in local government land-use plans and private-sector building decisions remains a challenge. We need to use social science and policy research to help achieve the goals of earthquake engineering and good seismic design.

Improved research translation and knowledge transfer techniques are needed to promote the use of appropriate state-of-the-art methods to make geologically and environmentally prudent site decisions, and to design structures that will be seismically resistant. We need research to develop and test new translation and transfer methods, including the transfer of new technologies.

The informational needs of practitioners and policy makers must be determined, and strategies to promote collaboration among scientists, practitioners, and policy makers in seeking better responses to earthquake risks must be formulated. Factors influencing effectiveness of communication and application of research findings should be identified.

We need to improve methods of integrating hazard information into local and state plans, and policies and programs dealing with public safety, transportation, utilities, community facilities, land use, redevelopment, and the economy. We also need to develop policies promoting use of geologic, geotechnical, and earthquake engineering knowledge in decisions on planning, zoning, siting, and design.

Research is needed to develop methods of evaluating the effectiveness of the translation and transfer of earth-science and engineering research information to the media and the public. We need to compare and evaluate educational techniques and agents to identify factors that motivate behavior and contribute to their success, and obstacles to their effectiveness.

It is important to develop tools to enhance the transfer and application of knowledge at all educational levels and in various sectors of society. This can be accomplished through school curricula, teaching materials and other publications, professional society programs, seminars, workshops, conferences, field trips, exhibits, and continuing education.

Because most of the public gets its information from the media, we need to improve local and national media coverage, background information, balance, and coordination. There is a need to explore ways of integrating earthquake preparedness and mitigation into the "culture" of communities. It is important to examine risk-communication activities for evidence of effectiveness or ineffectiveness, and identify methods most likely to change behavior.

We need to examine the collection and use of post-earthquake information to identify any impediments and obstructions to the flow of information to researchers, professional organizations, and practitioners. In particular, we need to identify any features of law, litigation, and jurisprudence that promote or discourage the free flow of necessary damage-related information. Ways to improve the collection, analysis, and transmission of such information should be sought.

There is also a need for research to improve systems for issuing and responding to predictions, advisories, forecasts, and warnings. Earthquake-warning systems should be compared with those for other natural hazards such as floods and hurricanes for guidance on success, obstacles, adaptability of methods, cost, and effectiveness. We need to document and evaluate the social, political, economic, and policy implications of recent earthquake predictions, advisories, and warnings for guidance in handling similar announcements in the future.

Research Goal: *Facilitate the process of achieving reduced risks through seismically adequate construction.*

Studies are needed of the economic and policy implications of recent earthquake damage to guide critical review of building design, code enforcement, and construction. Review of the causes of the damage is necessary to find evidence of ways to improve performance, including review of methods of building design and construction, peer-review, inspection, and use or absence of other measures.

We need to promote seismically adequate construction by improvement and consistent use of quality control methods such as peer review, work inspection, and observation. Research is needed to recommend ways to improve inspection of building construction, including education and certification of building inspectors. Building designers should be required to be involved with the inspection process to insure the structure is being built as designed.

Study is needed of ways to improve architects' and engineers' knowledge of designing earthquake-resistant new and retrofitted structures. Existing continuing-education programs should be reviewed and improvements recommended. We need ways or incentives to ensure participation by all practicing professionals in effective continuing-education programs on new seismic design and seismic retrofitting.

We also need to develop programs to improve the performance levels of contractors and construction personnel, and educate them with regard to new seismic codes and earthquake-resistant design concepts. Strategies to promote the use of state-of-the-art knowledge, and incentives, such as scholarships, credit for participation, and recertification should be evaluated.

Research is needed to develop consensus standards for seismic evaluation and retrofit. The lack of standards probably is the most significant barrier to improved seismic safety in existing facilities. Now, when a building is evaluated for seismic retrofitting, design professionals must use their judgment about what to do and how—needless to say, professional judgments can differ.

We need to develop policies promoting the use of building materials and design methods that reduce vulnerability, and to identify potentially risk increasing technologies and practices, and formulate measures to avoid the adverse effects of such technological development.

Research Goal: *Improve the process of seismic safety decision-making to include realistic assessments regarding the level of safety that is acceptable.*

Because a risk-free world is impossible, it is essential to reach a reasonable consensus on the kinds of risk that are considered unacceptable, and the amount of effort and resources that should go into reducing earthquake risks in California. What levels of risk are acceptable, given the relationship between risk reduction and cost? Where should society draw the line between risk levels that we must learn to live with, and those that should be reduced?

We need to identify past and current levels of risk considered acceptable, and study factors influencing changes in perceptions of what is acceptable among different population groups.

We need to study individual risk perceptions in various circumstances, and consider policies, actions, and information that could facilitate more effective risk management.

We need to study risk perception and management in large and small public and private organizations, and identify factors influencing organizational motivation to mitigate risks.

We need to develop policies and processes for reconciling groups having different and potentially conflicting interests and concerns in risk-reduction programs, and explore ways to reduce conflict and promote consensus on risk-reduction strategies.

We need to evaluate the concept of acceptable risk in terms of life safety, survivability, and property loss, and explore the merit of defining loss of serviceability and functional capability as unacceptable risks for some facilities.

The linkage between long-term earthquake risk reduction and financial policies promoting recovery and reconstruction should be studied, with special attention to possible incentives and disincentives for prudent risk avoidance and mitigation.

We need to evaluate earthquake damage liability, malpractice, and business recovery insurance for potential risk-reduction formulas that include increasing incentives and reducing penalties for owners, contractors, and practitioners taking special measures.

We need to conduct policy research aimed at reducing risks of potentially unsafe structures and critical facilities through various techniques: strengthening, converting, or removing through condemnation, demolition, and relocation, or by retrofitting, anchoring, bracing, and securing nonstructural components and building contents.

Research Goal: *To facilitate both short- and long-term earthquake risk reduction, preparedness, emergency response, and recovery.*

We need to evaluate the effectiveness of risk-reduction programs, including financing and other policies, and identify factors contributing to success as well as obstacles and ways of overcoming them. Policy research is needed to improve and extend legislation and regulations for grading, density control, seismically resistant design and construction, subdivision, land use, special hazard studies, and site investigation.

We need to study household-level preparedness and response in search of techniques to encourage the more wide-spread practice of earthquake preparedness.

We need to identify influences working against risk reduction, and study the use of incentives to counter such influences. We also need to identify legal obstacles to risk reduction, clarify liability issues, and recommend curative legislation.

We need to formulate risk-reduction strategies that will minimize negative impacts and preserve architectural and community cultural values.

We need to identify funding sources to provide incentives for risk reduction and compensation for negative impacts.

In connection with the Division of Mines and Geology's Seismic Hazards

Mapping Program, we need to study the use of zoning restrictions to limit building in hazardous areas, develop model land-use plans and model building and foundation construction ordinances, and conduct case studies of a range of community conditions from undeveloped to highly developed.

We need to improve strategies and techniques for avoiding high-risk land uses in hazardous areas, using risk disclosure, public notice, liability, financial incentives and disincentives, utility service restrictions, lending and insurance policies, and establishing linkages with eligibility for disaster relief funding.

We need to evaluate and improve methods of risk-reduction financing to facilitate lowering risk to acceptable levels.

We need to investigate the need for resources to help people and communities get started again after an earthquake, and evaluate the resources likely to be available, including insurance and disaster-recovery financing.

We need to identify the populations that need particular attention, such as occupants of unsafe structures, the disabled, young, poor, elderly, non-English-speaking, and institutionalized. The main threats to these populations should be characterized, and cost-effective measures for risk reduction and advance preparation should be developed that are culturally acceptable and appropriate to the special needs of each group. Thoughtful efforts to prepare people for these risks will significantly reduce casualties and losses, and speed recovery from damaging earthquakes.

We need to investigate the use of new technologies and risk management in minimizing hazards of technological change, including ways to deal with new and hazardous materials. We need to develop new processes, substitute less-hazardous materials, and use inventory control, equipment replacement scheduling, and automation to remove workers from hazardous areas.

We need to study the nature and scope of psychological and social-psychological impacts of major earthquakes, and evaluate the need for and availability of professional guidance to assist victims.

We need to examine the effectiveness of immediate post-earthquake crisis intervention and counseling on personal and organizational recovery. We also need to examine the roles of normal support groups in crises, and evaluate their relative effectiveness and seek ways of improving their performance in crisis intervention.

The performance of governmental, private-sector and volunteer organizations in providing relief and aiding recovery should be evaluated.

Earthquake warning procedures need to parallel progress by earth scientists on making scientifically supportable forecasts and predictions. Research of this kind is essential to the future of California's emergency response capability, and to more effective disaster preparations.

We need to review basic legal and practical considerations encountered in emergencies, including such issues as “bulldozer” tactics, the independence of adjusters, roles of loan companies, attorneys, movers, storage and repair companies, and contractors. A review of ethical and due-process questions and incidence of scams is needed.

We need to evaluate existing programs and further develop emergency preparation techniques, including disaster training, response plans, direction and control, and warnings and other communications for emergencies.

We need to evaluate and develop methods of expediting prompt and effective use of volunteers and early responders to earthquake disasters.

We need to evaluate and improve disaster management and emergency response techniques, including disaster and resource management, incident command, search and rescue, traffic control, demolition, evacuation, medical services, triage, temporary shelter, food supply, and transportation.

We need a system to collect comprehensive, consistent and comparable post-earthquake information after each damaging event to augment existing data bases for use in comparative longitudinal studies over time. Focus especially should be placed on recording and preserving perishable information, such as direct and indirect personal economic losses, injury types and rates, victim characteristics, unemployment incidence and impact, and hazardous-material releases. We also need to collect information on pre-earthquake risk-reduction policies and their implementation and effectiveness.

We need to collect information on kinds and patterns of structural and non-structural damage, with particular attention to improving design practice and construction, in the interest of achieving a more fully earthquake-resistant physical plant.

We need to evaluate recovery efforts in search of needed modifications in public finance, redevelopment, and other public assistance that could speed post-earthquake recovery. We must formulate new and creative redevelopment and reconstruction approaches that can be implemented promptly and without the delays often observed.

Existing legal and regulatory constraints that inhibit restoration of the economy and community activities need to be identified, and recommendations for their modification need to be formulated.

We need to catalog existing programs, evaluate ways in which they could contribute to recovery and reconstruction, and recommend practical approaches for decision-makers responding to earthquake disasters.

We need to analyze the experiences in previous earthquakes for guidance in evaluating preparation for early response and long-term recovery, and identify what has worked well and not so well, seeking guidance for improvements in recovery and reconstruction policies.

We need to study the range of private-sector recovery efforts and evaluate the effectiveness of various techniques and methods. We also need to consider the impact of public agencies and utilities on private-sector recovery.

We need to study the role of post-disaster assistance from outside California, and evaluate the out-of-state contribution to total response.

We must develop model plans and guidance materials to promote pre-earthquake planning for post-earthquake recovery and reconstruction.

Emerging Technologies

The California legislation[6] that calls for a comprehensive earthquake research plan also specifies that it integrate risk mitigation with emerging technologies. We consider an "emerging technology" as one having high promise of contributing to earthquake risk mitigation, but that has not yet been fully tested or proved successful or been accepted for that application.

Some of the most significant advances in earthquake risk reduction have come from research on new and emerging technologies. One of the major reasons the United States has been a world leader the fields of earthquake science and engineering is its commitment to discovering and developing new technologies. This commitment has created new jobs and new markets for U.S. industry, and has provided greater safety for California's earthquake-threatened citizens.

California, through its research universities and high-technology industry, has been at the forefront of emerging technologies in all fields, including earthquake risk mitigation. This has resulted in many benefits for the State and its citizens beyond increased safety. For example, California researchers were among the first to apply the emerging computer technology to problems of earthquake

[6]Senate Bill 1835, Chapter 782, Statutes of 1990

structural response, and have developed much of the pioneering software in this field. More recently, they have played a crucial role in the development of structural isolation systems (base isolation) for important or inherently weak structures. California researchers also are applying new and emerging technologies to the study of geophysics and the causes of earthquakes. They are leading the way in the use of satellites to measure crustal deformation associated with the buildup and release of stress within the crust of the earth and thereby to better understand earthquake mechanisms and potential.

It is vital that we maintain this position of pre-eminence in the field of earthquake risk mitigation by pursuing a vigorous program of research related to emerging technologies. One way to insure that the best young researchers will be attracted to earthquake hazard assessment and risk mitigation is to support cutting-edge research in this field. To promote the use of emerging technologies for earthquake risk reduction, the legislation called for and funded the Office of Competitive Technology to award one-time grants to five California companies to conduct feasibility studies on technologies that will improve the understanding of impending earthquakes and their effects. The research results were reported at the Earthquake Research Evaluation Conference in May 1994.

These efforts represent a good start, but more needs to be done. Additional steps could include direct funding of research on emerging technologies, legislation encouraging the use of emerging technology in certain applications, periodic workshops to help identify and apply emerging technologies to earthquake hazard assessment and risk mitigation, partnerships between government, universities, and industry to develop emerging technologies, efforts to facilitate the "rummaging" of new and emerging technologies through both electronic and conventional means, and creation of a board to provide a focal point for new technology applications related to earthquake risk mitigation to set goals and monitor programs.

At the present time, it is believed that the most promising overarching areas of new and emerging technology development for earthquake risk mitigation are communication and information technology, and sensor technology. Both of these areas have seen rapid recent advances, but they have not yet been fully brought to bear on problems related to earthquake risk mitigation. Following is a brief discussion of those new and emerging technologies that have particularly high potential for application to earthquake risk mitigation.

Communication and Information Technologies—The needs for earthquake risk reduction share key information requirements. Information not only must be collected in the process of research, it must be stored, managed, and made accessible. New technologies, such as on-line information systems, the World Wide Web (WWW), digital libraries, and advanced, high-speed digital networks will be important in meeting these needs. These technologies and their descendants can enable researchers to sort information and share results with their colleagues more quickly and efficiently.

Usage of the WWW has exploded since the introduction of Web browse software in August 1993, and its use should continue to grow. The coupling of new information technologies with other technologies, such as archival data storage systems, data management systems, geographical information systems, and other spatial data management systems can further expand their usefulness, not only for pre-earthquake research, but also for response and recovery phases. For example, networks and on-line information systems may be useful in earthquake response operations to collect and exchange early damage assessments.

Sensor Technologies—Surface and subsurface sensors for earthquake mitigation before and during an earthquake consist primarily of seismic monitoring sensors for weak and strong ground motions. Emerging technologies in seismic instrumentation include the development of broad-band, force-balance sensors for weak-motion monitoring, and the development of micro-accelerometers that can be used for strong-motion monitoring at a potentially dramatic cost savings.

Sensors in the post-earthquake environment can be applied to search and rescue, event monitoring, and non-destructive evaluation. Examples of emerging sensor technologies include chemical sensors that can help locate individuals who are buried in buildings, real-time chemical/atmosphere monitoring of dangerous atmospheric releases associated with earthquake events, and mobile sensor systems for bridge and road evaluation following earthquakes.

Geodetic Measurement of Crustal Deformation—Geodetic measurements of crustal deformation are playing an increasingly important role in earthquake research, especially Global Positioning System (GPS) geodetic networks. They provide very precise determination of the positions of points on the earth, and make it possible to characterize the continuous accumulation of strain in the earth's crust. Recently established permanent and continuously operating GPS arrays in central Japan and in California permit frequent (daily) measurements of crustal deformation. Technological improvements in GPS receiver and antenna technology, communications, and data analysis are still required to allow operation of very dense GPS arrays.

High-Resolution Space Images— High-resolution space-shuttle and satellite images can be used to further advance our understanding of California's seismic hazards. They can provide the basis for systematic mapping of California and the surrounding area, important to an understanding of the active tectonics affecting the State. Space images can be used for detailed review of active tectonic zones, and the development of hazard maps for local governments and land-use planners. New imaging could be compared with historical photographs to document changes and provide a data base for urbanized areas.

The application of high-resolution imaging capabilities to civilian mapping and research can provide faster and more accurate damage data to emergency providers. In post-earthquake damage surveys, space images could be taken at any time—through cloud cover and during daylight hours to show the regional extent and concentration of damage; at night they would reveal areas having no power or on fire. Near-real-time images could be obtained from properly placed and instrumented satellites and supplemented by timely space-shuttle images. Reviewed and analyzed digital images could be electronically distributed to all interested parties within minutes to hours following the event.

Real-Time Monitoring of Ground Motions—Real-time seismology can be used to (1) increase the effectiveness of emergency response, recovery of lifelines, and estimation of damage and losses, (2) estimate the likelihood and locations of damaging aftershocks, and (3) provide timely information to the public, government, and other agencies. It is presently possible to know the location and magnitude of an earthquake within minutes of its occurrence. Moreover, with available modern, high-dynamic-range and broad-band instrumentation, earthquake source parameters and the distribution of damaging ground motions can be estimated with an accuracy that is limited only by the geographical distribution of the instruments. This is controlled by the costs of the instrumentation and data transmission. Increased effort is necessary to develop more-affordable sensors, reliable and affordable digital communications, enhanced processing capabilities, information distribution systems, and user-oriented tools to apply the real-time information. Also needed is research on the analysis and interpretation of real-time data.

Innovative Materials—Significant research is currently underway into the development of new construction materials that can lead to safer and more economical structures. Promising technologies include the application of composite materials in conjunction with reinforced-concrete structures. More distant goals include the development of self-healing materials.

Construction Automation—The use of robotics for improving the efficiency and quality of the construction process is an emerging technology that is starting to be used in Japan, abut has not been explored yet in the United States in conjunction with civil infrastructures.

Soft Computing—Soft computing embodies several important emerging approaches in computer science, including fuzzy logic, neural networks, genetic algorithms, expert systems, and algorithms that exploit massively parallel computers. This technology is invaluable in virtually all areas of earthquake risk mitigation and underlies the development of safer and more efficient earthquake-resistant structures.

Health Monitoring—Health monitoring of civil infrastructure systems is an emerging technology that has wide application to all types of structures—before, during, and after earthquakes. Many results of this technology are ready for immediate application to existing structures, provided there is a sufficiently strong incentive for owners of structures to implement this technology.

Intelligent Buildings—Structural control is an emerging interdisciplinary technology that aims to provide tools for monitoring and control of stresses and motions caused by environmental loads such as earthquakes, microtremors, and man-made actions. Significant elements of this technology have been implemented in Japan, but not the United States This technology could profit greatly from defense research that is undergoing conversion to civilian purposes. Structural control research and implementation warrants relatively high priority in this five-year Plan.

Conclusion

This Plan sets out a program to cost-effectively reduce earthquake risk to acceptable levels by defining the most needed research and assuring that it is implemented through effective management. The Commission believes a California Center for Earthquake Risk Reduction is important to achieve the goals of this Plan, and would be a reasonable result of the successful growth and maturation of the Plan. The Plan builds on and is compatible with the State's defining document on earthquake risk reduction, *California at Risk*, and is a logical response to 1990 and 1991 California earthquake safety legislation.[1]

Every effort has been made to include the essential areas where knowledge is required, and areas of previously untapped opportunity. The Commission believes this is a structure in which all organizations and professionals undertaking research on earthquake problems in California can find a helpful role.

This Plan is designed to seek both short-term and long-term goals in reducing the earthquake risk in California. Although major earthquakes will always pose geologic threats to human affairs in this state, thoughtful and persistent effort can reduce earthquake damage due to large seismic events to acceptable levels. Achieving this goal requires observation and collection of data, research, education, and implementation to develop and carry out earthquake risk-mitigation programs.

The long-term goal includes maps that classify all significant seismic sources; land-use policies based on reliable maps delineating all earthquake hazards; consistent, high levels of earthquake engineering design practice; adequate building codes for the design and retrofit of structures; adequate advance preparation for emergency response and rapid recovery when earthquakes strike; and wide dissemination of earthquake knowledge among government agencies, communities, industries, and individuals.

The Commission is responsible for distributing this Plan to the appropriate federal, state, and local agencies, universities, major users, and private-sector organizations and associations. Any organization having a responsibility for or interest in earthquake risk reduction in California must be made aware of our priorities and encouraged to address them.

[1]Senate Bill 1835, Chapter 782, Statutes of 1990; Senate Bill 1245, Chapter 901, Statutes of 1991