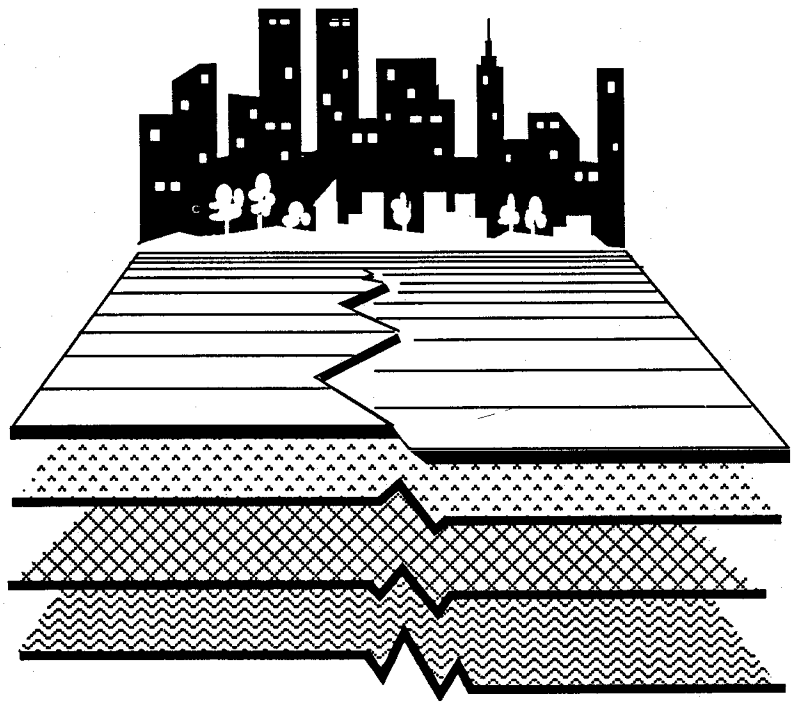
FEDERAL EMERGENCY MANAGEMENT AGENCY FEMA-176 / JUNE 1989

Estimating Losses From Future Earthquakes

Panel Report

(A Non-Technical Summary)



EARTHQUAKE HAZARDS REDUCTION SERIES 50

Issued by FEMA in furtherance of the Decade for Natural Disaster Reduction.

FEDERAL EMERGENCY MANAGEMENT AGENCY

Estimating Losses From Future Earthquakes

Panel Report

(A Non-Technical Summary)

Panel on Earthquake Loss Estimation Methodology
Committee on Earthquake Engineering
Commission on Engineering and Technical Systems
National Research Council

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

This study was supported by the Federal Emergency Management Agency under contract No. EMW-86-G-2366 to the National Academy of Sciences. Any opinions, findings, and conclusions or recommendations expressed in this report are those of the committee and do not necessarily reflect the views of the Federal Emergency Management Agency.

Limited number of copies available without charge from:

Committee on Earthquake Engineering
Division of Natural Hazard Mitigation
2101 Constitution Avenue, N.W.
Washington, DC 20418
202/334-3312

Printed in the United States of America

COMMITTEE ON EARTHQUAKE ENGINEERING (1985-1988)

GEORGE W. HOUSNER, *Chairman,* California Institute of Technology, Pasadena
CHRISTOPHER ARNOLD, Building Systems Development, Inc., San Mateo, California
JAMES E. BEAVERS, Martin Marietta Energy Systems, Inc., Oak Ridge, Tennessee
RAY CLOUGH, Department of Civil Engineering, University of California, Berkeley
C. B. CROUSE, The Earth Technology Corporation, Long Beach, California
RICHARD DOBRY, Department of Civil Engineering, Rensselaer Polytechnic Institute, Troy, New York
WILLIAM J. HALL, Department of Civil Engineering, University of Illinois, Urbana-Champaign
ROBERT D. HANSON, Department of Civil Engineering, University of Michigan, Ann Arbor
JOHN LOSS, School of Architecture, University of Maryland, College Park
FRANK E. MCCLURE, Lawrence Berkeley Laboratory, University of California, Berkeley
JOANNE NIGG, Center for Public Affairs, Arizona State University, Tempe
OTTO W. NUTTLI, Earth and Atmospheric Sciences Department, St. Louis University, Missouri
ROBERT V. WHITMAN, Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge

Liaison Representatives

WILLIAM H. ALLERTON, Division of Inspections, Federal Energy Regulatory Commission, Washington, D.C.
WILLIAM A. ANDERSON, Program Director, Division of Critical Engineering Systems, National Science Foundation, Washington, D.C.
C. CHESTER BIGELOW, Division of Advanced Technology Development, U.S. Department of Energy, Washington, D.C.
FRED COLE, Office of U.S. Foreign Disaster Assistance, Agency for International Development, Washington, D.C.

JAMES COOPER, Federal Highway Administration, Washington, D.C.

JAMES F. COSTELLO, Division of Engineering Technology, Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, Washington, D.C.

CHARLES CULVER, Center for Building Technology, National Institute of Standards and Technology, Gaithersburg, Maryland

RICHARD F. DAVIDSON, Geotechnical Branch, U.S. Army Corps of Engineers, U.S. Department of the Army, Washington, D.C.

A. J. EGGENBERGER, Program Director, Division of Critical Engineering Systems, National Science Foundation, Washington, D.C.

G. ROBERT FULLER, Structural Engineering Division, Office of Architecture and Engineering Standards, Department of Housing and Urban Development, Washington, D.C.

WALTER W. HAYS, Office of Earthquakes, Volcanoes, and Engineering, U.S. Geological Survey, Reston, Virginia

JAMES R. HILL, Natural Phenomena Hazards Mitigation Program, U.S. Department of Energy, Washington, D.C.

PAUL KRUMPE, Office of U.S. Foreign Disaster Assistance, Agency for International Development, Washington, D.C.

EDGAR V. LEYENDECKER, U.S. Geological Survey, Denver, Colorado

RICHARD D. MCCONNELL, Veterans Administration, Washington, D.C.

JANINA Z. MIRSKI, Structural Division, Veterans Administration, Washington, D.C.

UGO MORELLI, Office of Natural and Technological Hazards, Federal Emergency Management Agency, Washington, D.C.

ROBERT NICHOLSON, Federal Highway Administration, McLean, Virginia

MIKE REED, Strategic Structures Branch, Defense Nuclear Agency, Washington, D.C.

CHARLES F. SCHEFFEY, Federal Highway Administration, Washington, D.C.

JOSEPH TYRELL, Naval Facilities Engineering Command, U.S. Department of the Navy, Alexandria, Virginia

J. LAWRENCE VON THUN, Bureau of Reclamation, Department of the Interior, Denver

SPENCER WU, Air Force Office of Scientific Research, U.S. Department of the Air Force, Washington, D.C.

ARTHUR ZEIZEL, Office of Natural and Technological Hazards, Federal Emergency Management Agency, Washington, D.C.

Staff

Riley M. Chung, Committee Director
O. Allen Israelsen, Consultant
Barbara J. Rice, Consultant Editor
Lally Anne Anderson, Administrative Secretary
Norma A. Giron, Secretary
Denise A. Grady, Secretary

PANEL ON EARTHQUAKE LOSS ESTIMATION METHODOLOGY

ROBERT V. WHITMAN, *Chairman,* Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge
CHRISTOPHER ARNOLD, Building Systems Development, Inc., San Mateo, California
RICHARD N. BOISVERT, Department of Agricultural Economics, Cornell University, Ithaca, New York
GILBERT A. BOLLINGER, Department of Geological Sciences, Virginia Polytechnic Institute and State University, Blacksburg, Virginia
HENRY J. DEGENKOLB, H. J. Degenkolb Associates, San Francisco, California
EDWARD S. FRATTO, Massachusetts Civil Defense Agency and Office of Emergency Preparedness, Framingham
ROBERT P. KENNEDY, Consultant, Yorba Linda, California
FRANK E. MCCLURE, Lawrence Berkeley Laboratory, University of California, Berkeley
ROBIN K. MCGUIRE, Risk Engineering, Inc., Golden, Colorado
ALVIN MUSHKATEL, School of Public Affairs, Arizona State University, Tempe
ROBERT B. RIGNEY, Redlands, California
JEAN B. SAVY, Geosciences Group, Lawrence Livermore Laboratory, Livermore, California
DANIELE VENEZIANO, Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge
DELBERT B. WARD, Architect, Salt Lake City, Utah

Consultants

GREGORY ANDRANOVICH, Cosmos Corporation, Washington, D.C.
ROBERT REITHERMAN, The Reitherman Company, Half Moon Bay, California

Ex Officio Member

GEORGE W. HOUSNER, California Institute of Technology, Pasadena

Project Officer From Sponsoring Agency, FEMA

ARTHUR J. ZEIZEL, Office of Natural and Technological Hazards, State and Local Programs and Support, Federal Emergency Management Agency, Washington, D.C.

Liaison Representatives

WILLIAM A. ANDERSON, National Science Foundation, Washington, D.C.

CHARLES CULVER, Center for Building Technology, National Institute of Standards and Technology, Gaithersburg, Maryland

A. J. EGGENBERGER, National Science Foundation, Washington, D.C.

WALTER HAYS, Office of Earthquakes, Volcanoes, and Engineering, U.S. Geological Survey, Reston, Virginia

GARY JOHNSON, Earthquakes and Natural Hazards Division, Federal Emergency Management Agency, Washington, D.C.

RICHARD KRIMM, Office of Natural and Technological Hazards, Federal Emergency Management Agency, Washington, D.C.

ROBERT WILSON, Federal Emergency Management Agency, Washington, D.C.

Preface

A key question that must be addressed in earthquake hazard reduction is: How much loss might a city or region experience from future earthquakes? The destructiveness of an earthquake depends on its size, its proximity, and the area's state of preparation. When all three of these elements are adverse they combine to produce a great disaster. Some of these great disasters have permanently impressed themselves upon the public consciousness—Lisbon, 1755; San Francisco, 1906; Messina, 1908; Tokyo, 1923; Alaska, 1964; Mexico City, 1985; and Armenian S.S.R., 1988. Other earthquake disasters with thousands of deaths and extensive property damage did not receive such widespread publicity and are now remembered chiefly by the local inhabitants. Examples of these are San Juan, Argentina, 1944; Agadir, Morocco, 1960; Skopje, Yugoslavia, 1963; and Tangshan, China, 1976.

A significant feature of each of the more modern events is that the disaster focused the attention of the government and the general public on the problem of earthquake hazard and led to the adoption of appropriate seismic engineering requirements in building codes to better prepare these cities for future earthquakes. It would, of course, have been better if these cities had assessed the earthquake hazard and taken loss reduction measures before the event.

According to a 1983 Federal Emergency Management Agency (FEMA) report, in the United States as many as 70 million people in

39 states face significant risk from earthquakes and secondary hazards, such as earthquake-triggered landslides. The recent relatively modest Whittier Narrows, California earthquake, with a magnitude of 5.9 and less than 5 seconds of ground shaking, resulted in property damage exceeding $350 million. Loss of life from a single major earthquake, such as those that have occurred in California in the last 150 years, could exceed 20,000, and economic losses could total more than $60 billion. Moreover, many other cities or regions are vulnerable to earthquake threat: Seattle, Washington; Memphis, Tennessee; Charleston, South Carolina; and Boston, Massachusetts. These places are less prepared to withstand earthquake hazards than is California and they would experience devastating consequences if a major earthquake were to occur.

The enactment in 1977 of the National Earthquake Hazards Reduction Act offered the nation for the first time a substantial and organized effort to address the nation's earthquake hazard mitigation issues. Four principal federal agencies (FEMA, U.S. Geological Survey, National Science Foundation, and National Bureau of Standards), in partnership with state and local governments and also with the private sector, are working on several aspects of earthquake hazards: prediction, risk assessment, land-use planning, better building design and construction of earthquake-resistant buildings, promotion of better building codes, regional economic impact assessment, emergency planning and management, training and education programs, and regional workshops aimed at better technology transfer.

Much information has been developed from the national program in the past 10 years. Now FEMA, working with city, county, and state governments, is preparing guidelines on how to assess the earthquake hazard and how to take appropriate steps to counter it. Major questions facing a city, for example, are: What is the maximum disaster that might be reasonably thought to happen? and What is the maximum probable earthquake disaster that has a significant probability of occurring during the time span of a generation?

Assessing potential earthquake losses is a difficult but essential task to stimulate and guide earthquake mitigation actions. A number of methods have been used for making estimates of future earthquake losses, and there are significant inconsistencies among them. At the request of FEMA, the Committee on Earthquake Engineering undertook the present study. It is intended to be a consensus set of guidelines for a recommended loss estimation methodology.

It is not possible, at present, to predict *accurately* when and where major earthquakes will occur, how many people will die or be injured, and what the damaging effect will be on the wide variety of buildings of different ages and conditions. However, it is possible to make approximate estimates that will indicate the nature and magnitude of the problem faced by a city or region. The Panel on Earthquake Loss Estimation Methodology has prepared this report to serve as a guide for those undertaking to estimate earthquake losses. Although the material in the report represents a consensus, it is likely that some differences in the opinions of experts on loss estimation have not yet been reconciled.

The panel has been aided greatly in its work by many people and organizations. In the acknowledgments that follow some of the contributors to the effort are briefly mentioned. For the Committee on Earthquake Engineering, I express gratitude for this help. For myself, I wish to thank Robert Whitman, panel chairman, all the panel members, the liaison representatives from federal agencies, the staff of the National Research Council, the technical consultants, and others who have inspired and facilitated this task.

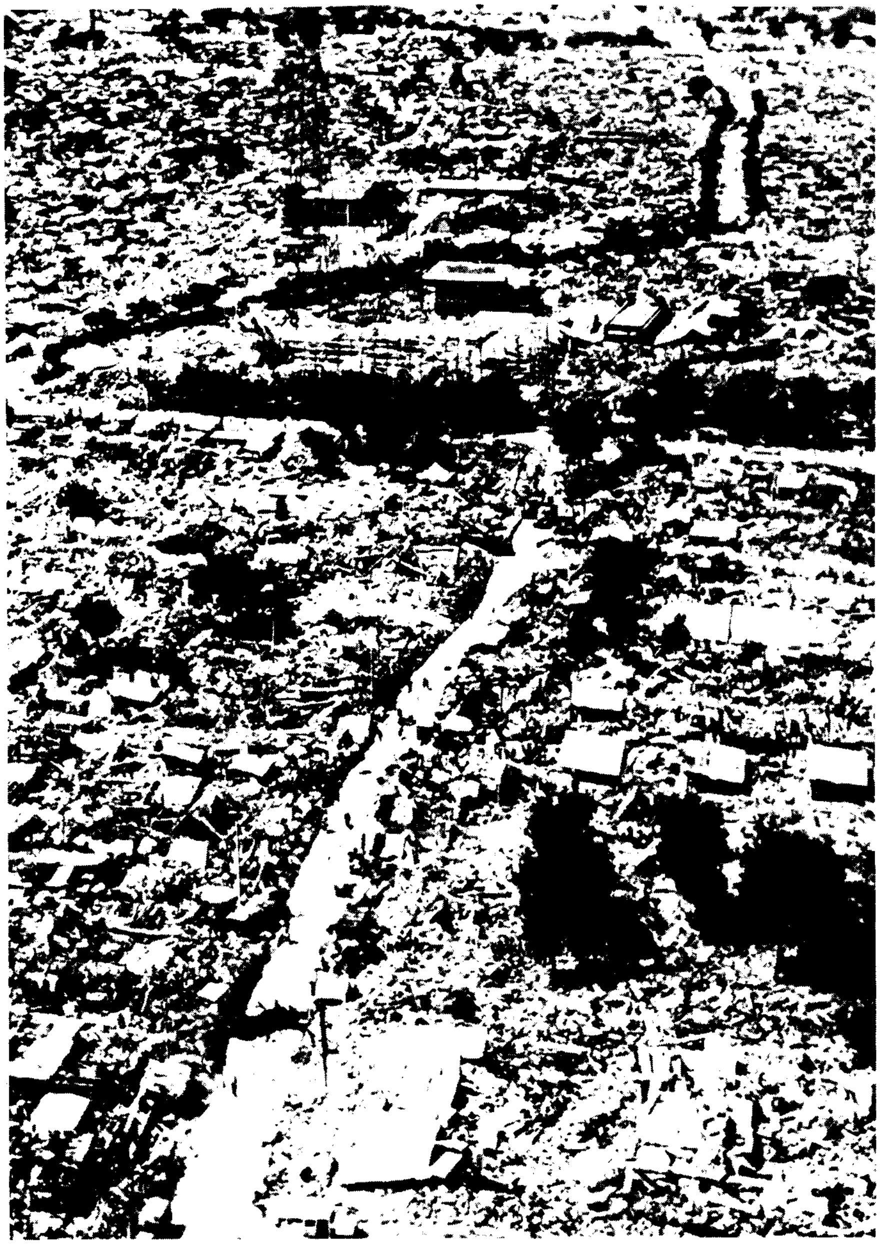
George W. Housner, *Chairman*
Committee on Earthquake Engineering

Acknowledgments

The committee wishes to acknowledge the valuable support of Robert Reitherman, who served as technical consultant to this panel study. It also wishes to thank the following individuals for their assistance in providing materials for the study and in critically reviewing and suggesting revisions to the panel report: S. T. Algermissen, Walter W. Hays, and Gerald F. Wieczorek, U.S. Geological Survey; Neville Donovan, Dames & Moore; Bruce Douglas, University of Nevada; Richard Eisner, Bay Area Regional Earthquake Preparedness Project; Peter May, University of Washington, Seattle; Christopher Rojahn, Applied Technology Council; and David Schodek, Harvard University. In particular the committee wishes to thank Arthur Zeizel, project officer, whose agency, the Federal Emergency Management Agency, sponsored the study, for his management coordination and work with the panel; the COSMOS Corporation, which assisted in developing a survey instrument for the user needs workshop; and the National Research Council staff in completing this panel study.

Contents

Panel Report



Aerial view of a portion of the city of Tangshan, China after the earthquake of July 28, 1976 (M 7.8). The causative fault passed under the city, which had little resistance to earthquakes. This combination led to almost total destruction and very large loss of life. *Photo courtesy of G. Housner.*

Executive Summary

An earthquake loss estimate is a forecast of the effects of a hypothetical earthquake. Depending on its purpose, a loss study may include estimates of deaths and injuries; property losses; loss of function in industries, lifelines, and emergency facilities; homelessness; and economic impacts. This report focuses primarily on loss estimates of the type funded by the Federal Emergency Management Agency (FEMA). They apply to an urban area or region and are intended primarily for use by local and state governments for disaster response and mitigation planning and the formulation of near- and long-term strategies for earthquake hazard reduction. However, the same basic methods, and many of the techniques for carrying out portions of these basic methods, also apply to other types of loss estimates.

Most loss estimates are made for one earthquake or a few earthquakes, specified by magnitude and location. The result is one or more scenarios describing the consequences of the selected earthquake(s). While this is the most common result of a loss study, especially when the objective is disaster response planning, it is not necessarily the most meaningful type of result. When the objective is to select the best allocation of resources for hazard reduction, more information can be derived from a probabilistic risk analysis that considers losses from a spectrum of possible earthquakes, taking into account the relative likelihood of the various magnitudes and locations of the earthquakes.

Even for the type of loss estimate of greatest interest to FEMA, the Panel on Earthquake Loss Estimation Methodology was unable to develop strict standards for conducting loss studies, although such standards might be desirable for the sake of efficiency and consistency. While incorporating some elements of science, loss estimation is still too much of an art for strict standards to be desirable. Instead, the panel has drawn up a general set of guidelines for such studies.

These guidelines first address the planning of a study and the active participation of state and local officials or other intended users. The objectives and scope for a study must be defined carefully, and thought must be given to formation of an inventory of facilities (i.e., buildings and other structures) and networks, so that this inventory can have lasting value, for a variety of purposes, after completion of the study. State and local officials must ultimately disseminate, explain, and make use of a study, and hence must understand the process of preparing the loss estimate. Their early and continuous involvement is essential.

The guidelines also discuss the selection of scenario earthquakes (seismic hazard analysis), the preparation of the inventory, the selection of relationships connecting ground shaking and ground failures to damage and loss, and the evaluation of lifelines, facilities essential for emergency response, and facilities with a potential for causing a very large loss.

Scenario earthquakes should be relatively probable, yet damaging. Use of very large but very infrequent earthquakes for this purpose may cause rejection of loss estimates or a fatalistic attitude. Use of frequent but small events provides little useful information.

Preparation of the inventory should emphasize local sources of data, as much onsite viewing and inspection as the budget allows, and seismically suspicious and critical facilities.

As for motion-damage-loss relationships, valuable information of an empirical nature has been assembled for certain types of buildings in California through the combined efforts of the Insurance Services Office and the large-scale loss estimation projects of the National Oceanic and Atmospheric Administration and the U.S. Geological Survey. An ambitious collection of formalized expert opinion for a broader spectrum of buildings and structures in California has been gathered by the Applied Technology Council, through funding from FEMA. For loss studies in other areas, expert opinion (i.e., a combination of experienced experts, local engineers, architects, building department officials, and lifeline systems operators) or other methods could be used to modify the California-based information for application to the types of facilities found in the areas being studied.

A final recommendation in the guidelines concerns the form of loss estimation reports. It is essential that main findings and conclusions be presented in a way that is useful and understandable to the public and to those who must act on the basis of the report. It is also important to document thoroughly the manner in which the inventory and losses were established. Careful attention must be given to the form and writing of the report to achieve these two objectives.

The guidelines respond to many of the recommendations and desires expressed during an exploratory survey, conducted by the panel, of past and potential users of loss estimates. However, there are two basic areas in which users' desires conflict with the state of the art in loss estimation: (1) the expression of losses as specific numbers, and (2) the identification of individual buildings and other structures likely to be seriously damaged. Loss estimates are approximate, and it is only prudent to report this uncertainty using, for example, a best estimate plus the likely range of losses. Furthermore, a confident prediction of damage to specific facilities requires thorough study, usually beyond the scope of a large-scale loss study, and such predictions may cause legal problems and political controversy.

Even using the best of today's methods and the most experienced expert opinion, losses caused by scenario earthquakes can only be estimated approximately. Overall property loss estimates are often uncertain by a factor of 2 to 3, and estimates of casualties and homeless can be uncertain by a factor of 10. Moreover, the accuracy of estimates will improve only slowly in the future, since a major source for these uncertainties is the very spareness of data on losses during actual earthquakes, as well as the intrinsically difficult inventory problem. Despite these limitations, loss studies—properly conducted and used with an understanding of the methods' strengths and limitations—can be of great value in planning, initiating, and updating programs for earthquake hazard reduction and in emergency planning.

More ambitious than the basic type of loss study is the attempt to evaluate the broader economic impacts of an earthquake, considering such matters as lost revenue and unemployment, on both the directly affected region and a larger area that is linked economically to it. This type of study might also be undertaken to assess the impact of earthquakes on national defense. The panel recognizes the potential value of this type of analysis and recommends the addition of a pilot project to a future loss estimate study.

The panel has also considered the possibility of developing techniques and an operational capability to estimate postearthquake losses within hours after an actual earthquake event, without field reconnaissance, as a basis for better action in disaster response and financial assistance. The panel has little enthusiasm for the prospects of establishing a reliable capability of this kind, because of the large uncertainties in loss predictions and because rapid compilation of actual losses is feasible.

The results of the panel's work are published in two forms: the panel report alone and the panel report with a group of seven working papers. The working papers treat many subjects in detail and are intended for a more technical audience. Chapter 1 of the panel report introduces the issues and discusses the basic underlying method common to most loss estimation studies. The following seven chapters address user needs, ground-shaking hazard, building damage and losses, collateral hazards other than ground shaking, damage and losses to special facilities and urban systems, indirect losses, and rapid postearthquake loss estimates, respectively. Finally, Chapter 9 presents the panel's recommendations on research and development to improve loss estimation capabilities. These are summarized below.

- Compare losses predicted by one or more methods with observed losses, following the next damaging earthquake to strike an urbanized area in the United States.
- Take opportunities to evaluate components of large-scale loss estimation methods (e.g., inventory methods) by comparisons with more accurate small-scale, detailed studies or with available hard data, such as the seismically hazardous building inventories that are now frequently compiled in great detail by local governments in California.
- Perform sensitivity analyses to evaluate the significance, for overall losses, of possible errors at each stage of an analysis.
- With a concerted effort, develop a classification system for buildings and other facilities for use throughout the United States.
- Compare existing inventory methods with the aim of synthesizing their strong points.

- Compare the motion-damage-loss components of various methods with the aim of synthesizing their strong points, and develop a satisfactory quantitative scale for the damaging potential of ground motions.
- Incorporate new developments in the geotechnical field as they become available that will allow more accurate prediction of both the location and severity of ground failures.
- Document precisely how loss studies have been used in hazard reduction and emergency planning efforts.
- Improve the process of collecting loss data of statistical significance immediately after significant earthquakes.

In connection with all of these efforts, special attention should be given to lifelines, emergency response facilities, and storage of hazardous materials.

1
Introduction

An earthquake loss estimate is a description or forecast of the effects of future or hypothetical earthquakes. Loss generally encompasses deaths and casualties; direct repair costs; damage or functional loss to communication, transportation, and other lifeline systems; emergency response and emergency care facilities; the number of homeless people; and the impact on the economic well-being of the region. Earthquake losses may be estimated to:

- Identify especially hazardous geographical areas;
- Identify especially hazardous groups of buildings or other structures;
- Aid in the development of emergency response plans;
- Evaluate overall economic impact;
- Formulate general strategies for earthquake hazard reduction, such as land-use plans or building codes, or evaluate the effectiveness of earthquake programs;
- Support advocacy efforts aimed at establishing priorities and budgets for earthquake programs;
- Aid in obtaining quick estimates, made during the first hours following an actual earthquake, of the approximate impact of the earthquake; and
- Estimate the expected consequences of a predicted earthquake.

The estimation of property losses to assess property insurers' risks has been one of the more common uses of earthquake loss estimates, but is only lightly addressed in this report because the emphasis here is on the broader range of public agency uses.

This report focuses on loss estimates of the type being funded by the Federal Emergency Management Agency (FEMA). They are intended for local and state government use, primarily for disaster response planning and to aid in the formulation of near- and long-term strategies for earthquake hazard reduction. This type of large-scale loss estimate study encompasses a city, region, state, or even the nation, and it looks at more than one type of loss, typically including life loss or casualties, property loss, and functional loss or outages of essential services. A number of such studies have been completed or are under way. Figure 1-1 illustrates the geographic scope of past or in-progress large-scale loss studies, while Table 1-1 lists these major studies.

During the 1970s, the National Oceanic and Atmospheric Administration (NOAA) and the U.S. Geological Survey (USGS) assembled teams of experts, predominantly engineering consultants and federal government geoscientists, who produced large-scale loss studies that set the basic pattern for the scope and methods of others to follow. The first four were devoted to the metropolitan areas of San Francisco (Algermissen et al., 1972), Los Angeles (Algermissen et al., 1973), Puget Sound (Hopper et al., 1975), and Salt Lake City (Rogers et al., 1976). These are sometimes collectively referred to as the NOAA-USGS studies. Some of the more recent studies have been sponsored by FEMA and carried out by consulting firms.

In response to a National Security Council request for an evaluation of potential impacts on the defense industry impacts, FEMA also initiated a recent large-scale effort aimed at modeling the regional economic effects of a major earthquake. This effort involved a study by the Applied Technology Council (ATC) of methods for preparing an inventory of facilities and for estimating damage and functional loss. The result was a report, *Earthquake Damage Evaluation Data for California,* known as ATC-13 (Applied Technology Council, 1985). FEMA also began in-house efforts and supported work by consultants to apply these new methods to selected economic sectors and regions.

Differences exist among the techniques employed in these studies, arising from different levels of earthquake risk in various parts of the country, different objectives and budgets, and different authoring

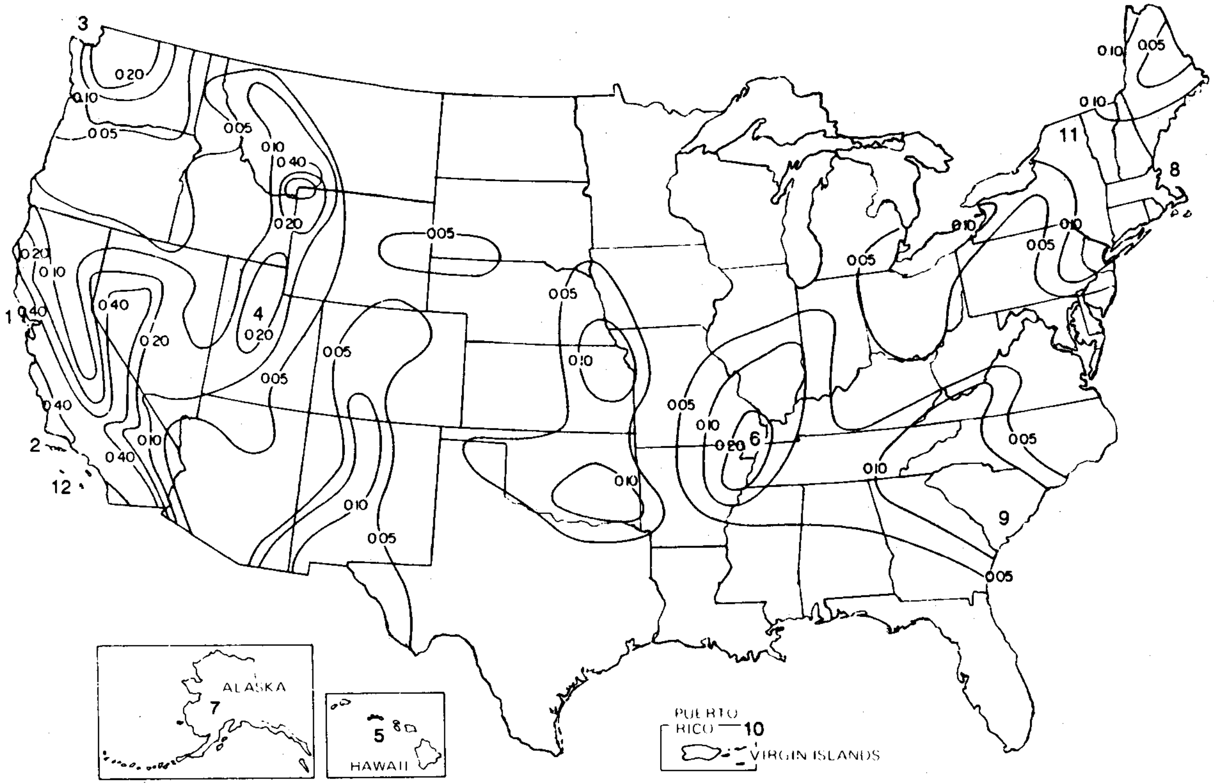


FIGURE 1-1 Areas of the United States where large-scale loss studies have been completed or are in progress (indicated by large numerals, see Table 1-1), shown on a base contour map of effective peak acceleration. Base map source: Building Seismic Safety Council (1985).

TABLE 1-1 Areas of the United States Where Large-Scale Loss Studies Have Been Completed or Are In Progress

Area[a]		Study
1.	San Francisco, California	Algermissen et al., 1972; Davis et al., 1982b; FEMA, 1980; Steinbrugge et al., 1981; Steinbrugge et al., in progress
2.	Los Angeles, California	Algermissen et al., 1973; Blume et al., 1978; FEMA, 1980; Steinbrugge et al., 1981; Davis et al., 1982a; Scawthorn and Gates, 1983; Degenkolb, 1984; California Division of Mines and Geology, in progress
3.	Puget Sound, Washington	Hopper et al., 1975
4.	Salt Lake City, Utah	Rogers et al., 1976; U.S. Geological Survey, in progress
5.	Honolulu, Hawaii	Furomoto et al., 1980; Steinbrugge and Lagorio, 1982
6.	Central United States	Mann et al., 1974; Liu, 1981; Allen and Hoshall et al., 1985
7.	Anchorage, Alaska	Alaska Division of Emergency Services, 1980; URS/Blume, in progress
8.	Boston, Massachusetts	Whitman et al., 1980; URS/Blume, in progress
9.	Charleston, South Carolina	Lindbergh et al., in progress
10.	Puerto Rico and Virgin Islands	Geoscience Associates, 1984 and 1985; Molinelli and Oxman, in progress
11.	Clinton County, New York	Geoscience Associates, in progress
12.	San Diego, California	Reichle et al., in progress

[a]Numbers correspond with studies noted in Figure 1-1.

organizations. Hence, inconsistencies can be found among the results of the various studies, and no clear guidance exists for conducting such studies.

FEMA anticipates the need for future loss estimation efforts. Seeking to encourage studies that are done in a technically sound, efficient, consistent manner that will satisfy the needs of users, FEMA asked the National Research Council to provide "evaluations and recommendations with regard to methodologies which should be used for earthquake loss estimation by FEMA and state and local governments in earthquake preparedness and mitigation planning." This work statement for the council's Panel on Earthquake Loss Estimation Methodology, within the Committee on Earthquake Engineering, required that the applicability of recommended methods be nationwide in scope, or that advice be provided for modifying recommended methods to fit regional variations. In addition to reviewing present methods, FEMA requested recommendations for testing and further development of methods to produce more accurate and comprehensive loss estimates.

The next section of this chapter presents an overview of the basic method used to carry out a loss estimate. This is followed by a discussion in Chapter 2 of the purposes and nature of loss estimates as viewed by potential users, and then by more comprehensive reviews of the techniques and methods available for completing the several parts of a loss estimate. Recommendations for research and development leading to better loss estimates are given in Chapter 9.

Several important points of a general nature must be emphasized:

- The methods examined in this report rely on averaging damage and losses over a large group of facilities, and hence apply to groups of facilities and not to individual buildings. There are techniques for examining in detail the seismic resistance of individual structures, and brief reference will be made to such techniques. However, any such detailed analysis can be expensive and time consuming and therefore generally is not feasible as part of a large-scale study. When methods intended for large numbers of buildings are used to estimate losses for individual buildings, the results may be misleading.
- This report emphasizes large-scale loss estimates, the basic method and some of the detailed techniques of which are applicable to other types of studies.
- No loss estimate prepared today, or in the foreseeable future, can be completely accurate. There are major gaps in our knowledge, both as to the time of occurrence, magnitude, and location of future earthquakes and as to the manner in which the ground and structures will respond to earthquakes. Any loss estimation inherently involves significant uncertainties.
- Despite their limitations, loss studies that are properly conducted and used with an understanding of the methods' limitations can be of great value. These studies have played an important role in developing earthquake programs throughout the country, and are an important tool for initiating effective programs in areas where earthquakes are a significant threat but have received little attention, or where few practical hazard reduction or emergency planning countermeasures exist.

• Loss studies in and of themselves do nothing to reduce seismic risk unless they lead to implementation of hazard reduction or emergency planning measures, or facilitate the development of public policy. Earthquake loss estimation is an important preliminary step toward taking appropriate actions for earthquake loss reduction. This is the most basic purpose underlying earthquake loss estimation. We study earthquake losses so they can be reduced.

BASIC METHOD

As previously noted, earthquake loss estimates may be made for many different purposes. Thus, studies may differ as to the types of losses considered, the extent of the geographical area involved, and the kinds of facilities included. *Facilities* is a term of broad scope that includes buildings as well as other *structures* such as bridges and utility stations and lifeline systems such as water distribution networks and airports. The detail in which the analysis is carried out and the manner in which the losses are aggregated and presented also may vary. Although the techniques used to carry out various types of studies may differ, a basic underlying method is common to almost all loss estimation studies.

The Two Main Components of an Earthquake Loss Estimation Study

Figure 1-2 illustrates two components comprising the basic structure of a loss estimation study. One component, the seismic hazard analysis, involves the identification and quantitative description of the earthquake (or earthquakes) to be used as a basis for evaluating losses. This part of the study falls primarily within the disciplines of geology and seismology, and this geoscience effort must be coordinated with input from the broad field of civil engineering. The phrase *seismic hazard* might seem to refer to all hazards to life and property posed by earthquakes, but the term has a technical meaning restricted to the behavior of the ground, apart from any effects on the built environment.

The second component, the vulnerability analysis, entails analysis of the vulnerability of buildings and other man-made facilities to earthquake damage and the losses that may result from this damage.

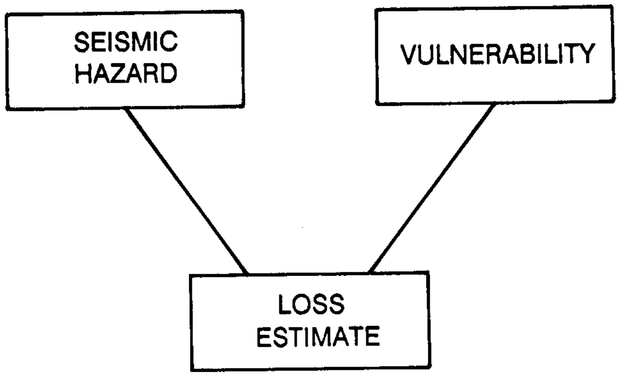


FIGURE 1-2 Basic structure of an earthquake loss estimation study.

This effort primarily involves engineers, architects, and experts in local real estate patterns or socioeconomics, although other disciplines (e.g., utility system operators, urban planners, and disaster preparedness and response specialists) may contribute to identifying steps that can alter the losses caused by damage.

The information assembled from these two components is combined to produce the loss estimate. Close communication among the technical people undertaking the two parts, and with the intended users, is vital to ensure proper coordination.

In most loss estimates, the primary emphasis is on damage and losses caused directly by the shaking of the ground. The bulk of this report deals with the evaluation of the ground-shaking hazard and with the effects of ground shaking on buildings and other facilities. However, other aspects of the seismic hazard, referred to as collateral hazards, often are important. They include fault ruptures, landslides, liquefaction, tsunamis, and seiches.

Landslides may occur in the absence of shaking, but earthquakes often trigger the sliding of susceptible slopes. Liquefaction is the state whereby a normally solid soil (saturated with ground water and usually sands of low density or compaction) turns to a mud-like or fluid consistency when shaken. Tsunamis are seismic sea waves (sometimes popularly called tidal waves). Seiches are sloshing or oscillating waves in bodies of water, generated by earthquakes in reservoirs, lakes, and enclosed harbors. In some earthquakes collateral hazards may be more destructive than the ground-shaking hazard, but the technology for evaluating these hazards and their effects is not as well developed as that relating to the ground-shaking hazard.

In a similar vein, most loss estimates focus on the more or less direct effects of the damage caused by an earthquake: fatalities and injuries, loss of function, and the cost of repairing damage. Various other negative effects are called indirect losses. Other types of indirect but potentially important consequence of damage include fire and flooding from dam failure. Another type of indirect consequence is the economic impact of loss of function on the owners of commercial property, on the region immediately affected by the earthquake, and on a larger region economically linked to the affected area. Again, these losses may be as important as the more direct losses, but the techniques for evaluating them is much more complex and not as well advanced.

The Ground-Shaking Hazard

The basic building block for a description of the ground-shaking hazard is a map displaying the intensities of ground shaking over the study region for an individual earthquake. In general, the intensity will vary over the region, depending on the size and source characteristics of the event, its location, and local geologic materials and topographical conditions. Such a description is a scenario earthquake.

Most loss estimate studies use one or several scenario earthquakes to define the shaking hazard. Loss estimates based on specific earthquakes are relatively easy to understand and explain. In addition, use of specific earthquakes makes it possible to include diverse types of losses, some of which are best described partially by words rather than merely by numbers. The use of several such events allows a range of assumptions and hypotheses to be analyzed and then synthesized in terms of their effects on facilities, without reliance on a single, perhaps unlikely occurrence.

A more comprehensive but difficult to interpret display of the hazard consists of calculating the seismic shaking by considering many possible different earthquakes. Such events can cover a wide range of magnitudes and locations, and each can be assigned a probability of occurrence.

This approach leads finally to probabilities of occurrence for earthquake losses. These results can be presented as loss-frequency curves, which give the annual frequency with which different levels of

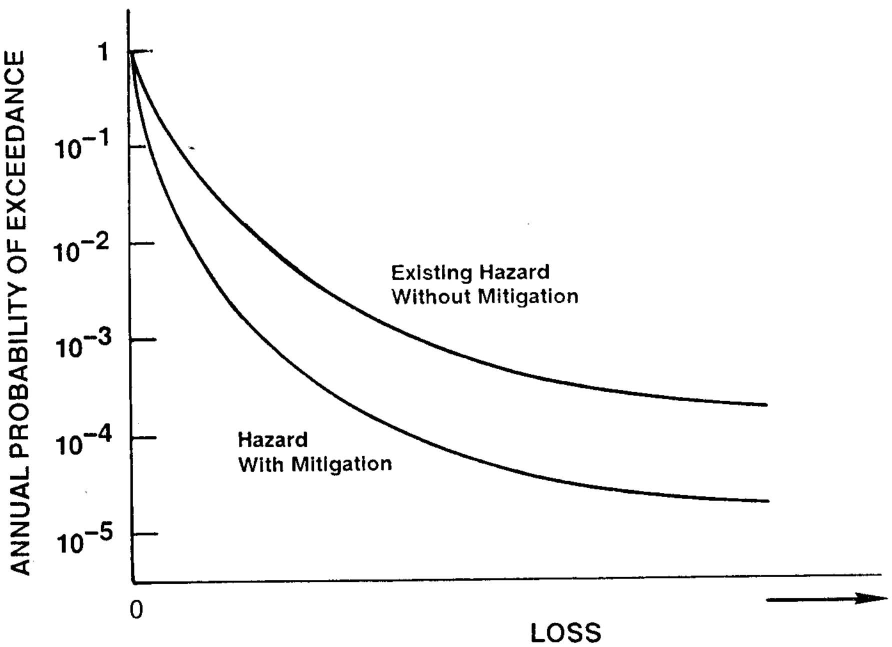


FIGURE 1-3 Loss-frequency curve.

loss are expected to occur (Figure 1-3). Summing these frequencies for levels above a specific value gives, for the study region, the annual probability of exceedance of losses.

Representing the hazard as a loss-frequency curve is ideally suited for study of the relative merits of various mitigative actions. That is, loss-frequency curves corresponding to different possible actions (including no action) may be compared. The method works best when all the consequences of an earthquake can be expressed by a single number, such as dollar loss. When multiple losses of different types are involved, the use of multiple scenario earthquakes finds wider favor.

Regardless of the number of earthquakes used to represent the seismic hazard, there is no single, uncontroversial measure of the damageability of ground motions. For one of the most commonly utilized measures of intensity—Modified Mercalli Intensity (MMI)—there are even basic disagreements as to the interpretation and definition of the scale.

A strong need exists for communication at the beginning of a loss study among those who will evaluate the ground-shaking hazard and ground failures, those who will determine the losses resulting from that seismic hazard, and those who will utilize the results of the study.

Vulnerability

There are two steps in a vulnerability analysis: (1) developing an inventory of the buildings and other facilities to be considered in the study, and (2) establishing for each inventory category the relationships among intensity of ground shaking (and, in some cases, ground failures), resulting damage, and associated losses.

A key step is to develop a list of the categories of facilities to be considered, that is, to select a classification system. Selection of this system requires a compromise between different objectives. On the one hand, a very detailed classification system, with many categories, allows fine distinction to be made among buildings with different seismic resistance. On the other hand, a coarse classification system with only a few categories simplifies the inventory effort and makes it more economical. It is also inappropriate for a classification scheme to divide facilities into many different categories if the underlying state of the art is unable to distinguish among the predicted performance of the categories. Reaching an optimum compromise requires close communication among the parties conducting the loss study.

For purposes of evaluating damage, facilities are usually inventoried by placing them in different groups.

- Buildings that provide working space or residences for people;
- Lifelines, such as transportation, communications, water, sewage, and electricity systems, that are vital to the functioning of an area;
- Essential facilities, such as hospitals, and fire and police stations, that are vital to postdisaster response; and
- Facilities with a potential for large loss, such as large and densely occupied buildings, dams, and chemical plants.

Lifelines must be treated differently than buildings because they form interconnected systems that extend over large areas. Essential facilities, if they are to be included, must receive more careful attention and individual surveys and analyses. Facilities with a potential for large loss pose a very special problem. Clearly their presence and potential for large loss must be noted, but losses cannot actually be estimated without analyses of the likelihood that potential damage will actually occur in a given scenario earthquake, and this requires very detailed study well beyond the scope of a typical loss estimate. It is easier, for example, to map the area that would be flooded if a certain dam were to fail than it is to determine whether the dam actually would fail in various earthquakes.

CONSIDERATIONS OF UNCERTAINTY

The foregoing discussion has presumed that loss estimates take the form of scenarios or a loss-frequency curve. For the former, one or more particular earthquakes are postulated to occur, and the losses expected from each are described. For the latter representation, the probabilities of various levels of loss are indicated. Whichever method is used, the uncertainty in the loss estimates should be indicated, such as by giving a range of possible losses.

The uncertainties in loss estimates derive from several sources. First is uncertainty in the ground-motion intensity and ground failures for a given event. Second is uncertainty in estimating damage given the intensity and ground failures. Third is uncertainty in estimating the losses given damage to the facility. Finally there is uncertainty in the process of inventorying the number of facilities in each building classification and geographic area. Each of these elements could be made more precise with additional effort and resources, but uncertainties are inevitable in any practical study of earthquake losses and should be expressed and quantified.

2
User Needs

In requesting this study, FEMA emphasized the need to learn users' opinions concerning the applicability of loss estimate studies as well as how studies should be conducted and presented in the future. Users were defined primarily as state and local officials responsible for earthquake hazard reduction and disaster response planning.

A user needs workshop was held in September 1986. There was a broad spectrum of invitees from all levels and aspects of government. In addition to discussions in large and small groups, questionnaires were used both before and at the end of the workshop to evaluate the thinking of the participants.

Owing to the breadth of the potential user community and limitations on funds and time, this effort was not a scientifically designed survey or experiment. Nonetheless the undertaking yielded considerable insight into the needs and thoughts of those who ultimately must use the results of loss estimates.

The user group did not consider previous studies to have been as useful as they wished. The discussions also emphasized two questions: Who will use a loss study? and For what purpose? These two questions must be answered prior to selecting methods for producing loss estimates.

CONFLICTS

The study of user needs clearly brought out several important conflicts between what is desired and what is feasible, among different groups within the user community, and between the users and producers of loss estimates.

The Scale of Studies

Loss estimates of primary interest to this study typically are made on a regional basis, that is, they involve an area encompassing a number of political jurisdictions. Actions to reduce hazards must, however, usually be undertaken by the individual jurisdictions. Officials working on this local level consider it vital that loss estimates be disaggregated to the local level—a need that can be in conflict with procedures often used to assemble inventories and compute losses.

Specificity Versus Liability

Local officials also would like to know precisely which buildings or other facilities are most susceptible to damage, so that mitigative actions can be targeted. On the other hand, those making loss estimates fear legal or political reprisals if they are specific in identifying potentially dangerous structures, and consider it essential that they preserve anonymity by lumping together considerable numbers of structures and evaluating losses only for such groups.

The Scenario Earthquake

The user group indicated that loss studies should focus on a relatively probable and yet damaging earthquake, and it was deemed important that losses be estimated separately for different times of the day. Using too large and too improbable an earthquake may decrease the usefulness of a study. However, the group did not indicate a suitable level of probability for a scenario earthquake. There was little enthusiasm for being presented with losses from several different scenario earthquakes having different probabilities.

Accuracy and Uncertainty

Several users indicated that the usefulness and credibility of a study decrease when it gives a wide range of answers to determining potential loss from a scenario earthquake, even though they realized the considerable inevitable uncertainty in loss estimates.

Cost Sharing

Another theme that arose in the discussions involved a basic financial conflict among different levels of government. A recent trend has been the shifting of costs of earthquake programs from the federal government to lower levels, or in other words increasing state and local cost sharing. However, the user group said that funds available for such studies at state and local levels are generally inadequate.

SPECIFIC SUGGESTIONS

Perhaps the most important point to emerge from the discussion of user needs is the need for increased involvement of state and local officials and policymakers in the entire loss study process. This involvement has an educational value apart from the value of the report that is eventually produced. The state and local officials must ultimately use, disseminate, and explain the results of a study and hence must understand just what has been done in preparing the loss estimate. When loss studies are to be used by advocates of seismic policy and planning, officials must be involved in the loss estimation study process, and reports must be understandable and timely. The technical experts involved in producing the study will also benefit from an increased awareness of users' needs and attitudes.

The survey of user needs identified types of facilities about which it is most essential to have reliable loss estimates. High on the list are dams, emergency public facilities (such as hospitals), and electric, water distribution, and highway systems. Also expressed was a need to know the location and vulnerability of facilities containing hazardous materials.

Finally, the user group urged that inventories be prepared in such a way that the information is available to update loss estimates and can be disaggregated for nonearthquake purposes.

3
Ground-Shaking Hazard

This chapter examines the selection of scenario earthquakes. Use of scenario earthquakes is not the only way to address loss estimation, but it is the most common method. There are two general approaches to evaluating scenario earthquakes that are commonly referred to as deterministic and probabilistic methods, although elements of judgment and uncertainty are present in both.

DETERMINISTIC METHODS

In this method, one or more earthquakes are postulated without explicit consideration of the probability that those events will occur. The most common form of this method is use of the largest earthquake known to have occurred in a region, and this event is termed the historical maximum earthquake. This approach is based on a premise that is geologically sound as well as intuitively convincing: if an earthquake has occurred once, it can occur again. Usually this approach is acceptable to both the governmental users of loss estimates and the general public.

Once a decision to adopt this basic approach has been made, various questions must be answered in order to establish a scenario earthquake. For example, will it be assumed that the same earthquake reoccurs with the same extent, location, and type of faulting? The distribution of ground-shaking intensities outward from the earthquake may have been recorded, and can then be used directly. If this distribution was not thoroughly recorded, it will be necessary to use attenuation relationships (derived from analysis of data from many different earthquakes) to calculate some or all of this distribution. Alternatively, it may be decided that a different location should be considered, perhaps closer to the region being studied. In this case, use of attenuation relationships to calculate intensities is essential.

If there are multiple faults near the region being studied, it will generally be desirable to consider separately the historical maximum earthquake for each fault. This is because each of these several earthquakes may produce the largest losses in some portion of the region.

In some studies, two levels of earthquakes have been used: the historical maximum earthquake and a smaller earthquake chosen by judgment. The smaller earthquake has often been taken to have a magnitude one unit less than the historical maximum earthquake. This practice has been adopted when planning for a response to several levels of disaster is deemed desirable, or when a repetition in the near future of a large historical maximum earthquake lacks credibility.

There are also instances where earth scientists present convincing evidence that an earthquake larger or closer than the historical maximum event should be considered. This may happen when there is geological evidence of earthquakes more severe than those that have occurred in historic time.

The proper characteristics of the scenario earthquake for use in planning how to respond to a validated earthquake prediction would be the predicted earthquake's magnitude, location, or other available seismological information accompanying the prediction. Except for the greater potential for controversy concerning predicted earthquakes, the other aspects of loss estimation are the same for nonpredicted scenario earthquakes.

It is clear that this deterministic approach involves some judgment and uncertainty. Even in the most seismic regions of the country, no one knows when the next major earthquake will occur or just what it will be like; almost certainly there will be surprises. There is no clear definition of the largest possible earthquake—some expert can always envision a larger event—and even if there were a well-defined maximum earthquake, it is not obvious that this immense earthquake is the proper basis for hazard reduction planning. As one moves away from use of the actual historical maximum earthquake, and as use of attenuation relationships comes into play, uncertainty increases. As stated earlier, it is desirable that at least a rough indication of the probability of occurrence be attached to all scenario earthquakes, if only to convey to users and the public some indication of the likelihood of such an event.

PROBABILISTIC METHODS

As just noted, there are two situations where attempts to use the historical maximum earthquake run into difficulties. At one extreme is the situation where a very large earthquake has occurred within recorded history, but it is thought unlikely that it will reoccur soon and in the same locale. The other extreme is the situation where it is thought relatively likely that there can be an earthquake larger than the historical maximum earthquake. ("Historical" merely refers to a brief sample of the geologic timespan, up to about 400 years in the eastern United States and 200 years in the West, and some earthquakes that occur only once every several centuries are unlikely to be included.) For such situations, it would be useful to have a systematic method for selecting the scenario earthquakes that meet the criteria of being plausible but damaging.

Probabilistic hazard analysis offers this possibility, and is discussed in a report of the National Research Council (1987). The elements of this method are sketched in Figure 3-1. Information is required concerning: the location of potential sources (such as known faults) of earthquakes, the probability that different magnitudes will occur within or along each source, and the attenuation of intensity away from the source, including uncertainty in the attenuation relation. This information is then formally combined to produce a ground-shaking versus hazard curve (Figure 3-1D), giving the probability that any ground-motion level will be exceeded. An exceedance probability is selected and the associated ground-motion level (target level) is found from the hazard curve.

Finally, the scenario earthquake is defined as the most likely event among those that produce ground motions more intense than the target level. The technology for this type of analysis is well advanced, although there are often problems of statistically inadequate data for evaluating parameters required by the theory.

One difficulty in the use of probabilistic ground-shaking hazard analysis is in selection of the probability of exceedance to be used

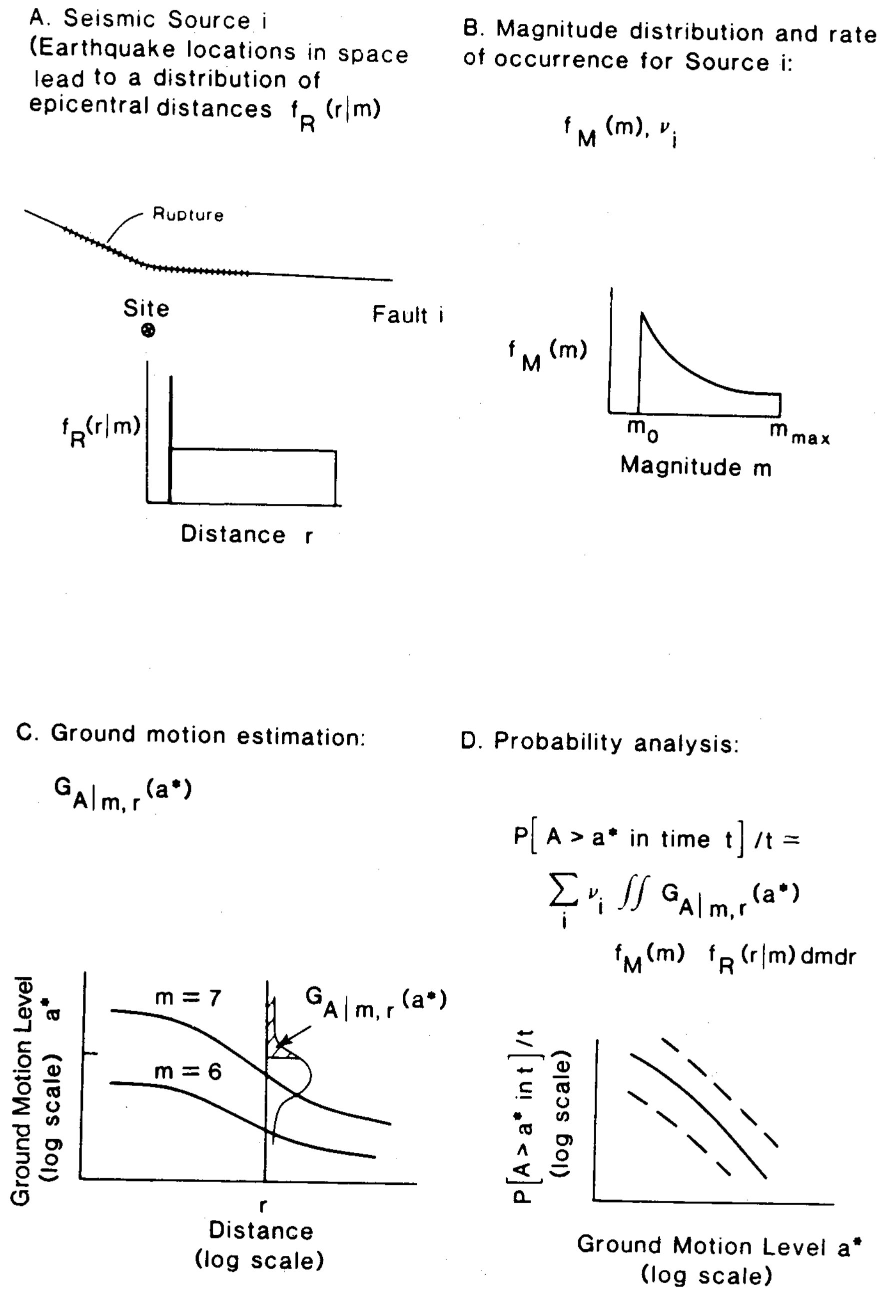


FIGURE 3-1 Graphs indicating probabilistic seismic hazard analysis steps.

for defining a scenario earthquake. There are no generally accepted rules for this purpose. Some of the historical maximum earthquakes used for earlier loss studies have annual probabilities of about .002, which is equivalent to a mean recurrence interval of 500 years.

The panel rejects the notion of a single standard probability at this time, but accepts that, in the absence of a suitable historical maximum earthquake, a scenario earthquake with an annual probability in the range from .001 to .005 is reasonable for disaster response and mitigation planning. Despite the lack of definite criteria, use of probabilistic seismic hazard analysis offers the only rational means for selecting scenario earthquakes for many parts of the country.

DESCRIBING INTENSITY OF GROUND MOTION

As noted earlier, there is no generally accepted, objective, quantitative scale for measuring the damaging effects of strong ground motion. This is because different buildings, structures, or other facilities respond in different degrees to various aspects (e.g., predominant frequency, duration, and so on) of ground motion.

Most U.S. loss estimates have used MMI as a scale for the intensity of ground shaking. This scale involves subjective evaluation of the effects of ground shaking, and its use is subject to abuse and misinterpretation. However, in most parts of the country the historical seismic record is known only in terms of MMI. Instrumentally recorded strong-motion data are much more sparse.

While urging continued research to develop a satisfactory quantitative measure of ground-motion severity, the panel accepts the continued use of MMI as a basis for the usual loss estimate study.

One aspect of MMI that does require careful attention is the meaning and use of intensities XI and XII. The scale's criteria for these levels emphasize observations of ground failure, some of which may occur when other indicators of shaking severity imply a MMI as low as VI. The use of high MMI values in a loss estimate requires explicit explanation to avoid misunderstanding. Some on the panel interpret the MMI scale as implying that intensity X represents maximum possible ground shaking. Others feel that ground shaking stronger than that associated with MMI X is possible, and there have been some instances in which loss estimators have used MMI XI and XII to represent increasingly strong ground shaking apart from ground failures.

The panel recommends that MMI XI and XII *not* be used to indicate increased intensities of ground shaking. If this is nonetheless done, it is essential that the interpretation of these intensity levels be set forth very clearly, and an explicit statement of how the MMI scale was interpreted should be included in any study where it is used.

EFFECTS OF LOCAL SITE CONDITIONS

Local site conditions can have a great effect on earthquake losses. Greater losses often occur because of ground failures, increased intensity of shaking for some soil and topographic conditions, and selective amplification of ground motion at the frequencies critical to structural response. It is important to take site effects into account in a loss estimate. While geotechnical data collected at individual construction sites can be very valuable in this effort, more generalized geologic mapping of districts and zones in a city or region is also useful and can lead to refinements in seismic hazard analyses.

The essential requirement is to make clear whether the intensity in a scenario earthquake applies to the ground as it is locally found (i.e., no further correction for local soil conditions required) or whether it applies to some standard ground condition and must be further modified for actual local conditions. This is a matter requiring good communication among seismologists, geologists, and engineers.

4
Building Damage and Losses

CLASSIFICATION OF BUILDINGS

For loss estimation purposes, the buildings within a region are put into a number of categories according to a construction classification system. This is the starting point in the vulnerability analysis process, as shown in Figure 4-1.

The primary consideration in developing a classification scheme is differences in the resistance of various buildings to damage during ground shaking. Some of the factors taken into account are the type of structural system, the materials of construction, the size of the building, and the degree to which structural features limiting damage have been provided during design and construction. The age of a building is sometimes used as an indirect indicator of seismic design level in areas where seismic codes have been adopted, and it can indicate typical construction practice in a given region.

In the planning stages for a study, the steps of selecting a classification system, developing methods to prepare the inventory, and assembling motion-damage information are all interdependent. That is, the choice of a classification system depends on the availability of information for the inventory and the effort that can be put into carrying out the inventory. The availability of data relating motion and damage for various kinds of construction is also limited, and this similarly restricts the classification options.

This 14-story reinforced-concrete apartment building experienced extensive damage to the spandrel beams during the 1964 Great Alaska earthquake (M 8.3–8.6). Its twin in another location in Anchorage was similarly damaged. Structures that have adequate strength to resist moderate shaking may not be able to withstand strong ground shaking. *Photo courtesy of G. Housner.*

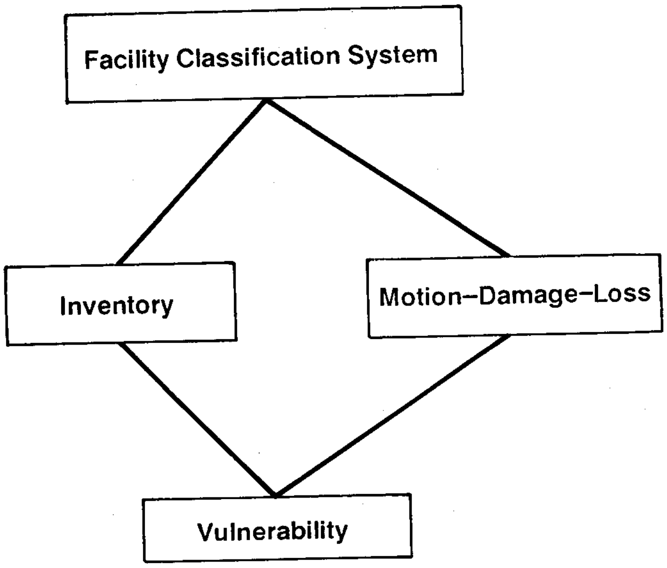


FIGURE 4-1 Structure of the vulnerability analysis portion of an earthquake loss estimate study for buildings, lifelines, facilities with essential emergency roles, and facilities with potentional for large loss.

The most commonly used classification system in the United States for estimation of earthquake loss is that developed by Algermissen and Steinbrugge (1984). As shown in Table 4-1, this scheme has 21 categories, determined primarily by the type of information readily available to property insurance companies. A more recent classification system used in the ATC-13 study (Applied Technology Council, 1985) has over 40 categories, with height emphasized as a factor. Both of these systems have been heavily dependent on the work of experts in California. For loss studies elsewhere in the United States, these basic schemes should be reviewed and possibly modified and simplified to take into account local construction variations and problems of assembling an adequate inventory. For example, in the study of six cities in the midwestern United States (Allen and Hoshall et al., 1985), only eight building construction categories were used.

INVENTORY

Preparation of the inventory is usually the most time-consuming and costly aspect of a loss study. It is also often the most frustrating,

TABLE 4-1 Construction Classes Used in the ISO and NOAA/USGS Methods

Building Class	Brief Description of Building Subclasses
1A-1	Wood-frame and stuccoed frame dwellings regardless of area and height
1A-2	Wood-frame and stuccoed frame buildings, other than dwellings not exceeding three stories in height or 3,000 square feet in ground floor area
1A-3	Wood-frame and stuccoed frame structures not exceeding three stories in height regardless of area
1B	Wood-frame and stuccoed frame buildings not qualifying under class 1A
2A	One-story, all metal; floor area less than 20,000 square feet
2B	All metal buildings not under 2A
3A	Steel frame, superior damage control features
3B	Steel frame, ordinary damage control features
3C	Steel frame, intermediate damage control features (between 3A and 3B)
3D	Steel frame, floors and roofs not concrete
4A	Reinforced concrete, superior damage control features
4B	Reinforced concrete, ordinary damage control features
4C	Reinforced concrete, intermediate damage control features (between 4A and 4B)
4D	Reinforced concrete, precast reinforced concrete, lift slab
4E	Reinforced concrete, floors and roofs not concrete
5A	Mixed construction, small buildings and dwellings
5B	Mixed construction, superior damage control features
5C	Mixed construction, ordinary damage control features
5D	Mixed construction, intermediate damage control features
5E	Mixed construction, unreinforced masonry
6	Buildings specifically designed to be earthquake resistant

SOURCE: Algermissen and Steinbrugge (1984).

since in principle it is possible to develop a perfect inventory, but in practice compromises must always be made. Time and budget constraints lead to shortcuts and extrapolations, but evaluation of building seismic performance necessarily involves the use of reliable building data not obtainable by shortcut methods.

Facility inventories can be maintained and later used both for updating initial loss estimates and in determining follow-up loss estimates for facilities or geographic areas or for other purposes within a study region. Therefore, the panel is persuaded that it is wiser in the long run to compile systematically an inventory that is as accurate as possible under the circumstances and resources available.

There are three interrelated factors to consider at the outset of a project: the content of the inventory, the process of assembling the information, and the manner in which the data are to be recorded or stored.

Content of the Inventory

What information concerning buildings is required? The basic minimum data are:

- Geographic location;
- Category of seismic resistance;
- Economic value of the building;
- Number of occupants, at different times of day; and
- Type of occupancy of the building (e.g., housing, commercial, or essential facility).

Seisimic resistance must be derived from information on such characteristics as construction class, age, height, and so on. The meaning of economic value may differ according to the purpose of the loss study, as discussed below. Other information, such as the function of the building (e.g., office or light manufacturing), may also be desired.

A key problem is the degree of disaggregation or aggregation of this information. At one extreme, the inventory may list only the total economic value and total number of occupants aggregated for all buildings in a given construction class within some geographical area. At the other extreme each building might be listed separately and then aggregated for purposes of predicting losses. Obviously this question is strongly related to how the inventory is to be compiled and how the information is to be recorded.

Another key question is the smallest geographical area to be used. As discussed in the section on user needs, it should be possible to disaggregate losses to any local political unit, which in the case of a large city may mean wards, precincts, or districts. Census tracts or postal zip codes also are convenient minimum geographical units, but if used they may require localized modifications to make the tract or zip code data correspond to other boundary lines.

There are a number of possible definitions for economic value, and the choice depends primarily on the purpose of the loss estimation study. Cash value and replacement cost have both been used. For most studies, it seems appropriate to use replacement cost.

Carrying Out the Inventory

The inventory process is a matter of assembling and using available sources of information, carrying out some amount of onsite inspection, and applying some judgment. Census data are valuable, particularly for housing, and generally some local records are available from, for example, planning departments and assessors' offices. The most difficult information to pin down is the seismic resistance or construction class. Here is where the experience of local engineers, building officials, and architects, combined with judgment, have to play a major role. Field sampling is also useful to define typical local construction patterns.

It might seem ideal to develop a listing of all individual buildings, but this seldom is feasible. While some data files, such as those maintained by assessors, are typically compiled for individual properties, they are unlikely to contain adequate information for assigning seismic resistance. Moreover, for loss estimation purposes it is quite satisfactory to have crude data for the more seismically resistant buildings. Attention should be concentrated on developing a reasonably good inventory of the seismically suspicious buildings of high vulnerability that will incur the bulk of the serious damage (Arnold and Eisner, 1984). Onsite surveys to identify and enumerate these buildings are vital to a satisfactory loss estimate. One example of a seismically suspicious construction class is unreinforced masonry, which is often concentrated in recognizable districts.

ATC-13 describes three methods for assembling an inventory, ranging from situations where detailed information is available in local files to cases where very few data are available. For the common latter situations, a method for abstracting an inventory from socioeconomic data is described. The panel feels that extensive field studies would be necessary to validate this approach, and that the varieties of situations to be encountered make success unlikely. The panel believes that corresponding sums of money spent on direct observation of buildings to discern specific seismic performance indicators would yield more useful results. There appears to be only a weak correlation between socioeconomic characteristics, such as number of employees and the Standard Industrial Classification number indicating economic sector, and construction characteristics relevant to earthquake loss estimation. While a convenient data file, such socioeconomic information is not particularly relevant to the task of producing an inventory of facilities according to construction classes.

Recording the Inventory

There are several reasons for collecting the inventory data in a format consistent with computerization. At a minimum the data should be stored in such a way that losses from several different earthquakes can be evaluated. It is desirable that data be retained so that updated loss estimates can be made in the future. Finally, information in an inventory is potentially valuable for entirely different purposes, such as economic development planning and city planning.

It is vital to include meetings with various potential users of inventory information at the beginning of a loss estimate study. Such discussions will indicate how much effort is justified in obtaining and formatting the inventory so that it can be accessed and used by various governmental agencies. A key question is whether there is the will and the means to maintain the inventory in an updated condition. Where a significant long-term effort appears warranted, use can be made of some impressive digital mapping technology well along in its development by USGS and others (Alexander, 1987; Brabb, 1985; Schulz et al., 1983).

Role for a National Data Base

Creation and maintenance of a complete nationwide data base on the construction characteristics of all buildings is an impractical idea. However, some incremental, less geographically complete projects, or efforts limited to simplified construction classifications, may be feasible and desirable and should be investigated. Modest improvements in the compilation of data might include:

- Comparing classification schemes so that future loss studies collect and organize their data in a format similar to either the ATC-13 or NOAA-USGS construction classes, or to some new scheme.
- Suggesting data that could be reliably collected at virtually no additional cost by the U.S. Bureau of the Census. Noting the height of a building (e.g., placing it in one of three or four ranges of height in terms of numbers of stories) may be such a possibility.
- Investigating the potential of using the FEMA Multihazard Vulnerability Survey method (FEMA, 1985) in connection with large-scale earthquake loss estimation rather than for the field survey of individual essential emergency operation facilities and life support systems, which was the initial purpose for devising this multihazard survey method. Field sampling of buildings previously surveyed by

this method and easy access by earthquake loss estimators to Multihazard Survey data computerized by FEMA, are promising ideas. The applicability of the data collection and analysis components of the FEMA Multihazard Vulnerability Survey method (which includes wind and flood hazards in its scope as well as earthquakes, depending on the site's location) should be evaluated in the context of loss estimation.

MOTION-DAMAGE RELATIONSHIPS

Identifying the relationship between the intensity of ground shaking and the damage experienced by a group of generally similar structures, or a construction class, is essential to vulnerability analyses. One intensity/damage relationship is needed for each type of facility in the classification system.

There are several ways in which this relationship may be expressed and evaluated.

Use of Mean Values

The most common method for presenting the relationship between ground shaking and damage is by a loss ratio curve. Typical curves, developed some years ago by Steinbrugge et al. (1984) for the Insurance Services Office (ISO), are shown in Figure 4-2. The curves truncate at MMI IX because of the interpretation by ISO of the MMI scale: intensities above IX were taken to represent ground failures rather than ground shaking. (The classes of construction are those in Table 4-1.) Percent loss, also called mean damage ratio or mean damage factor, is the cost of damage expressed as a percentage of replacement value. This is a mean value for a large population of buildings of a given class.

Relationships of this form are particularly useful when only the expected value of the dollar cost of damage is evaluated in a loss study.

Information About Distribution of Damage

For some purposes, knowing only the mean level of damage is inadequate. For example, serious casualties and injuries are usually related to extreme damage experienced by a minority of buildings.

Split-level houses that were deficient in earthquake resistance collapsed during the 1971 San Fernando, California earthquake (M 6.6). Well-built houses in the area survived, experiencing only cracks in plaster.

Compton Boulevard between Alameda and Tamarind streets following the March 10, 1933, Long Beach earthquake (M 6.2). So many walls collapsed that the street was completely blocked by bricks. The poor performance of these buildings led to changes in the building code that prohibited the construction of unreinforced-brick buildings.

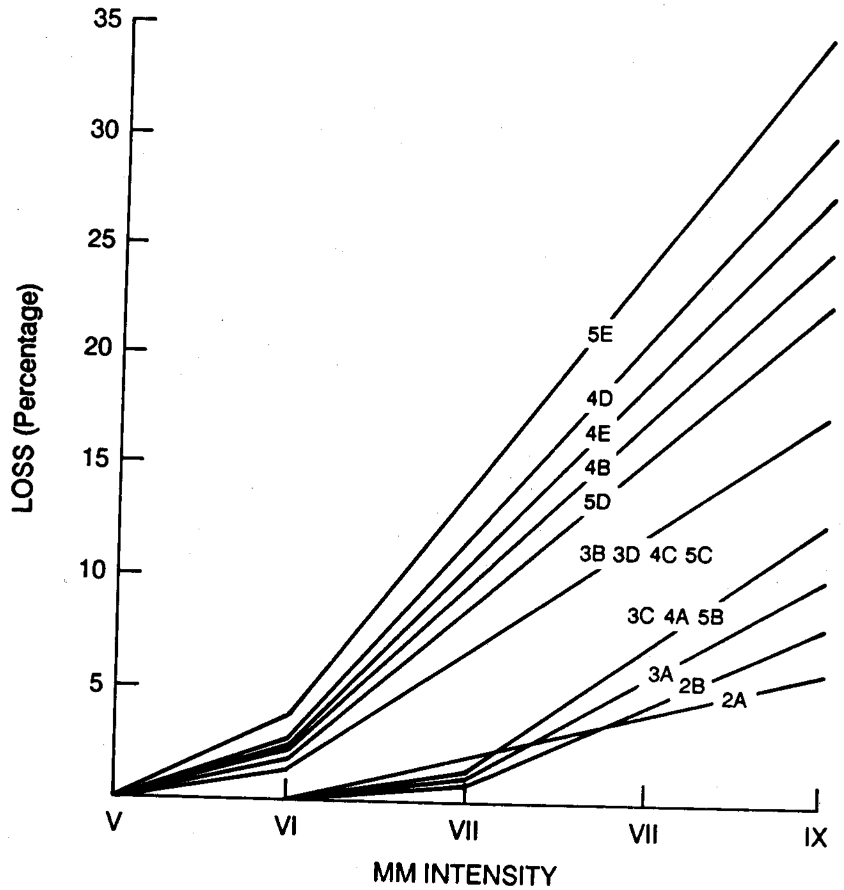


FIGURE 4-2 Loss ratio versus Modified Mercalli Intensity (mean damage ratio curves). Designations on curves refer to Table 4-1 construction classes. Source: Algermissen and Steinbrugge (1984).

One method for expressing the distribution of damage is a damage probability matrix (DPM) (Table 4-2).[1] The spectrum of damage,

[1] In Table 4-2, the original source (ATC-13) used MMI levels XI and XII to represent increasingly severe shaking severities beyond MMI X. As noted earlier, confusion results when this is not explicitly stated, because a literal reading of XI and XII indicates ground failure and at XII "total" damage. In Table 4-2 the DPM has been truncated at MMI X to avoid different portrayals of MMI when definitions for MMI XI and XII may not be clear to the reader.

TABLE 4-2 A Damage Probability Matrix Form

Damage State	Damage Factor Range (percent)	Central Damage Factor (percent)	Probability of Damage (in percent) by MMI and Damage State[a] VI	VII	VIII	IX	X
1--None	0	0.0	95.0	49.0	30	14	3
2--Slight	0-1	0.5	3.0	38.0	40	30	10
3--Light	1-10	5.0	1.5	8.0	16	24	30
4--Moderate	10-30	20.0	0.4	2.0	8	16	26
5--Heavy	30-60	45.0	0.1	1.5	3	10	18
6--Major	60-100	80.0	--	1.0	2	4	10
7--Destroyed	100	100.0	--	0.5	1	2	3

NOTE: These definitions are used as a guideline:

1--None: no damage.
2--Slight: limited localized minor damage not requiring repair.
3--Light: significant localized damage of some components generally not requiring repair.
4--Moderate: significant localized damage of many components warranting repair.
5--Heavy: extensive damage requiring major repairs.
6--Major: major widespread damage that may result in the facility being razed.
7--Destroyed: total destruction of the majority of the facility.

[a]Example values are listed.

SOURCE: Applied Technology Council (1985).

from none to total, is divided into damage states, each of which is described both by words and by a range of damage ratios. For each intensity of ground shaking, numbers in a column give the fractions of buildings experiencing different damage states; the numbers in each column sum to unity.

Fragility curves (Figure 4-3) provide essentially the same information as does a DPM, but in graphical rather than tabular form. Each curve gives, as a function of the intensity of ground shaking, the probability that the indicated damage state is equalled or exceeded. While the curves shown in Figure 4-3 are only for one construction class (wood frame), the general form is typical. The steeper the slope of a curve, the less the variability in expected performance for that damage state. The steep slope of low-damage curves 1 and 2 implies that it is relatively easy to predict that this class will have only slight structural damage or only nonstructural damage at low intensities.

DPMs and fragility curves provide the same information in different formats. Thus, the choice between DPMs and fragility curves is a matter of style and precedent. The DPM originated in connection with loss estimates for buildings. Use of fragility curves developed in studies of the performance of mechanical equipment and have been applied in seismic risk studies for facilities such as nuclear power plants. It is important to note that mean loss ratios may be calculated from the information in DPMs or fragility curves, but the reverse is not true; information about the distribution of damage about a mean cannot be inferred from a mean loss ratio curve.

Evaluating Motion-Damage Relationships

The loss ratio curves in Figure 4-2 were constructed, employing considerable judgment, using loss data gathered during various earthquakes, principally those occurring in California and a few other western states, along with data from foreign earthquakes where construction has been compatible. Actual data of this type are most complete for wood-frame dwellings (these data do not appear in Figure 4-2), and more judgment has been required to construct curves applicable to other buildings.

In a few cases, DPMs have been constructed using data from actual earthquakes, tempered with judgment. A recent report compiled data on earthquake damage from a variety of sources (Thiel and Zsutty, 1987) and indicates the usefulness of hard data about past performance in studies that attempt to estimate future performance. However, for many types of buildings, and especially for those in areas that have experienced few if any damaging earthquakes, actual data are either very sparse or nonexistent. For such buildings, it is necessary to rely on expert opinion to develop loss ratio curves, DPMs, or fragility curves.

A systematized Delphi method approach was used to synthesize diverse expert opinions into the family of DPMs found in the ATC-13 study. The panel examined the method used to develop these DPMs and considered the credibility of the results. Concern was expressed that the ATC-13 DPMs underestimated the dispersion in the damage because zero probabilities were assigned in each column to damage states away from the predominant damage state. However, in the ATC-13 method, each matrix is meant to apply for average California

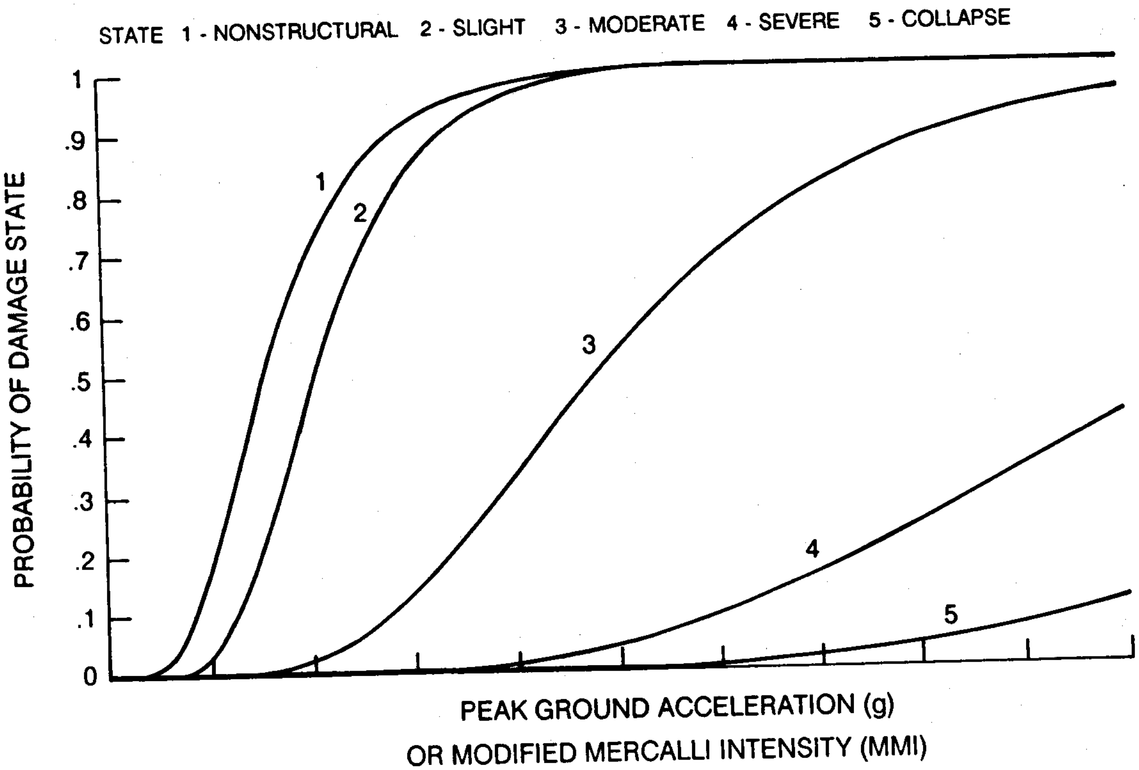


FIGURE 4-3 **Example of fragility curves. Source: Kircher and McCann (1983).**

design and construction, and the ATC-13 report provides a method for combining adjacent columns in a DPM to reflect the dispersion introduced when good, average, and above-average construction are lumped together. The panel recommends the development of new DPMs that incorporate this range of different qualities of construction.

For common building types, loss ratio curves calculated from the DPMs in ATC-13 are very close to the corresponding curves developed by the ISO. For less common buildings (e.g., tilt-up wall construction) for which there are only limited data, the differences in loss ratios expressed by the ISO and ATC-13 methods are within the range of uncertainty in the data. The best use of the ATC-13 DPMs, in the panel's view, is for building types for which there are no ISO curves.

Both the ISO loss ratio curves and the ATC-13 DPMs are intended primarily for use in California. The question then is: How should motion-damage relationships be developed for use in loss estimates for other areas? One answer lies in using expert opinion to modify the California-based information for the types of buildings found in the area to be studied. Analysis of some selected buildings can assist by indicating the general level of seismic resistance of generic examples of building types in relation to the resistance of the buildings forming the data base.

A Look to the Future

It is clear that there are major gaps and uncertainties in the state of the art for evaluating damage from an earthquake. Improvements in this situation can come about only by systematically collecting data from actual earthquakes. More effort should be devoted to this purpose, not only for earthquakes in the United States but also for earthquakes in other countries. In all such future studies, the distribution of damage should be documented—not just the mean loss ratios, and not just by documenting interesting or dramatic individual failures in a reconnaissance overview.

There has been an effort to develop and use empirical relations connecting damage directly to magnitude and distance from an earthquake (Steinbrugge et al., 1984). This approach bypasses the need to evaluate the intensity of ground shaking at sites, and avoids difficulties in using MMI. Initial efforts to establish such relations are under way using data from earthquakes in California. This is an interesting idea and should be pursued, but there are obvious limitations and difficulties. First, different relations will be necessary for different soil and topographic conditions. Second and more important, different relations will be required for different regions of the country according to variations in attenuation of motion with distance.

LOSSES ASSOCIATED WITH BUILDINGS

One form of loss—the cost of repair—has already been discussed in the previous section. The total cost of repair may be obtained by simple summations, such as:

$$\sum_{\text{all building categories}} (\text{dollar value in each category}) \times MDR_I,$$

or

$$\sum_{\text{all building categories}} (\text{average dollar value}) \times (\text{number of buildings}) \times MDR_I,$$

where MDR_I is the loss ratio (or mean damage ratio) for the intensity of the scenario earthquake. Such summations are made for subareas of constant intensity and are then combined.

Considering uncertainties that will inevitably exist in the inventory and the additional uncertainties in motion-damage relations, the accuracy of the estimated loss for a given scenario is not great. A prudent claim would be accuracy to within a factor of 1.5 for the aggregation of single-family, wood-frame California dwellings, 3 for commercial, industrial, and institutional buildings, and an order of magnitude (factor of 10) for an area with no recent earthquake history.[2] However, even such uncertain estimates are still very useful for hazard reduction efforts and emergency planning.

---

[2] These expressions of uncertainty indicate the panel's judgment as to the accuracy with which losses can be estimated. A precise statement about the meaning of these ranges is not possible with the present state of the art, but the following example indicates a reasonable interpretation:

- Statement: "Uncertain by a factor of 3."
- Interpretation: Best estimate, 1,000; high estimate, 1,800; and low estimate, 600.

The estimation of other types of losses–casualties and homelessness–is more complex and difficult.

Casualties

Of all the losses to be estimated, deaths and injuries are perhaps the most important to governmental organizations. Protection of life is a primary function of government and a prime incentive for undertaking hazard reduction. Estimates of casualties are desired for different times of day–typically mid-day, at night, and perhaps at a commuting hour–and sometimes for different seasons of the year.

Unfortunately, the ability to predict casualties is not as good as in the case of property loss. Data on which rational, systematic estimates can be made are very sparse. The early NOAA-USGS studies generally used historical rates of casualties per unit of populaton for wood-frame dwellings and estimated rates for other types of construction, or used city-wide casualty rates from previous earthquakes applied to the population as a whole, adjusted up or down based on changes in construction practice. These estimates were in effect crude extrapolations of the limited data available, primarily from California earthquakes.

A method specifically intended to estimate life safety risk factors for most of the ISO construction classes was devised by McClure et al. (1979) and applied to the problem of prioritizing engineering studies for buildings owned by the State of California.

More recently (e.g., in the ATC-13 project) the tendency has been to relate casualties to levels of damage. For example, Table 4-3 gives casualty rates tied to the damage states described in Table 4-2. These rates are then multiplied by the estimated numbers of people in buildings of varying classes.

This information is based on limited data plus considerable judgment. This does represent a rational approach to estimating casualties, and the panel recommends use of this method combined with careful judgment and comparison with historical data, where comparable cases pertain. It is essential that it be used with a DPM that reflects the considerable dispersion of damage among buildings of any one type, and the recommendations in ATC-13 for noting variations in construction quality should be followed.

TABLE 4-3 Injury and Death Rates in Relation to Damage[a]

Damage State	Central Damage Factor (percent)	Fraction Injured Minor	Fraction Injured Serious	Fraction Dead
1	0.0	0	0	0
2	0.5	3/100,000	1/250,000	1/1,000,000
3	5.0	3/10,000	1/25,000	1/100,000
4	20.0	3/1,000	1/2,000	1/10,000
5	45.0	3/100	1/250	1/1,000
6	80.0	3/10	1/25	1/100
7	100.0	2/5	2/5	1/5

[a]Estimates are for all types of construction except light steel construction and wood-frame construction. For light steel construction and wood-frame construction, multiply all numerators by 0.1.

SOURCE: Applied Technology Council (1985).

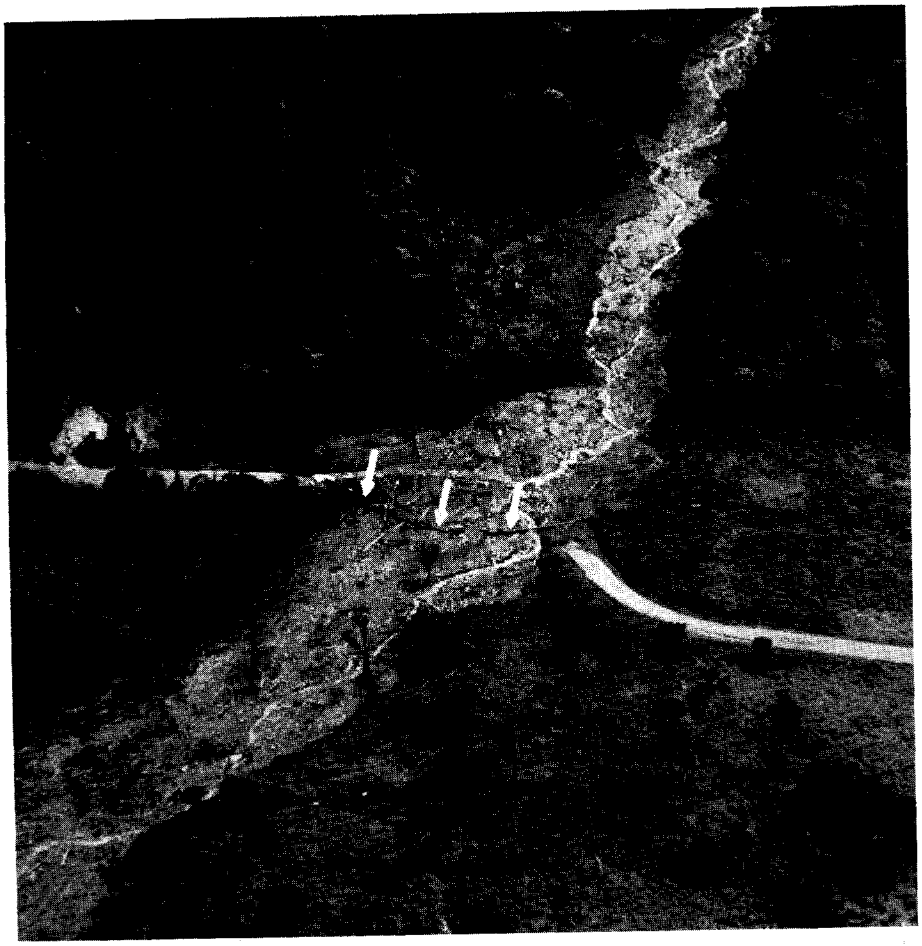
It is evident that estimates of casualties will be very crude and uncertain, and this uncertainty should be represented by, for example, giving ranges of estimates, along with providing the best estimate figures.

Homelessness

Estimates for the number of people requiring shelter by public agencies are also important for planning postdisaster operations. It is even more difficult to make such estimates, partly because data are scarce and partly because potential need is a function of weather conditions and the ability and inclination of the population to find their own shelter, such as with friends and relatives.

The NOAA-USGS studies used a 50 percent dwelling damage ratio as an indicator of the need for alternative shelter. The most complete effort at systematic estimation of homelessness is by Gulliver (1986), who suggested a 20 percent damage ratio as the threshold point past which homelessness results. Clearly, great judgment is required when estimating homelessness, and any estimate will involve a high level of uncertainty.

Estimates of casualties and homelessness should be regarded as having an order of magnitude (factor of 10) uncertainty, although it is possible to provide a tighter range of estimates when a study is restricted to a few well-understood classes of construction. These obviously are both matters for which far more data from actual earthquakes are required to advance the state of the art.



An example of the effects of landslides and debris flows triggered by the March 5, 1987, earthquakes (M 6.1 and 6.9) along the eastern flank of the Andes in north-central Ecuador. Destruction can be seen of the Trans-Ecuadorian oil pipeline (indicated by arrows) and adjacent highway by a debris flow issuing from a minor tributary of the Coca River. *Photo courtesy of R. L. Schuster.*

5
Collateral Hazards

Collateral hazards include fault ruptures, landslides, liquefaction, tsunamis, and seiches. As noted in an earlier section, collateral hazards can cause very significant losses. For example, most of the losses experienced in the Alaskan earthquake of 1964 resulted from collateral hazards, with landslides causing major property loss and tsunamis causing 119 of the 131 fatalities (National Research Council, 1972).

In principle, the overall method for predicting losses that might result from these hazards is much the same as that for losses caused by shaking of facilities. The first question is: How extensive and severe might collateral hazards be? For example, how large an area might be affected by landsliding, and how far and how rapidly might the earth move? These are questions for earth scientists, such as geologists.

The next question is: What damage and losses would result? These primarily are questions for engineers. Where structures are impacted directly by severe collateral hazards, losses may be quite large. Sometimes the effect of a hazard may be indirect. For example, the Hebgen earthquake in Montana in 1959 triggered a landslide that blocked the Madison River, and a lake began to form behind this earthen mass. Considerable effort was expended to alleviate concern about potential downstream flooding when this potentially erodible "dam" eventually overtopped.

FAULT RUPTURE

A surface fault rupture involving several feet of movement will cause major damage (50 percent loss ratio or greater) to almost all houses or small structures sited directly on the fault, and generally even greater damage to larger structures. However, well-built buildings located within only a few feet of a well-defined fault rupture may experience little or no damage. Losses to buildings directly attributable to surface rupture usually are a small fraction of total losses associated with an earthquake, and can be predicted with satisfactory accuracy once the path of the rupture is defined. In the eastern United States, it appears that potential faults are deeply buried and hence fault rupture probably does not extend to the surface. Hence this particular hazard generally can be ignored in this large portion of the country.

LANDSLIDES AND LIQUEFACTION

Landslides and liquefaction are consequences of ground shaking. A rational procedure for evaluating liquefaction and landslide-caused losses as a result of a scenario earthquake is described in ATC-13 and involves the following steps:

1. Identify soil, geologic, and topographic conditions potentially susceptible to such failures as a result of an earthquake.
2. Select relations expressing the likelihood of failure, or the fraction of susceptible area expected to fail, as a function of the intensity of ground shaking.
3. Select additional relations giving loss ratios for buildings and other facilities located at failed areas.

These steps parallel those for the direct effect of ground shaking upon buildings (Figure 1-2).

Identification of areas where these hazards may occur is a major inventory-type problem. The USGS has prepared, or helped prepare, detailed geological hazard maps for several metropolitan areas (e.g., Borcherdt, 1975; Youd et al., 1978; Ziony 1985), and is collaborating in the development of such maps for additional areas. Generally these maps showed areas within which there is a significant likelihood that landsliding or liquefaction might be triggered by an earthquake, and it is not necessarily expected that actual hazards will occur in all such areas or over all of a given area. Preparing a good map of collateral geological hazards is a time-consuming and expensive task.

If these maps are not already available, it is necessary to construct an approximate hazards map using the expertise of experienced local geotechnical engineers and geologists. ATC-13 summarizes the general principles to be followed, and more specific guidance is available in a recent compilation of papers by USGS (Ziony, 1985) and a report on liquefaction by the National Research Council (1986).

Liquefaction

The word *liquefaction* has been used to cover several different types of phenomena associated with the increase in pore water pressures in cohesionless soils during earthquake shaking, with a resulting decrease of strength and/or stiffness. One common manifestation is lateral spreading of nearly level ground toward adjacent dips or other low points. Such lateral spreading can disrupt roadways, canals, pipelines, and so on, and will also damage buildings in the area affected by the spreading.

Liquefaction can also cause more dramatic flow slides from steeper slopes, which occurred at the lower Van Norman Dam during the 1971 San Fernando earthquake (Seed et al., 1975), at mine tailings dams in Chile in 1965 (Dobry and Alvarez, 1967), and at the waterfront in Seward, Alaska in 1964 (Seed, 1973). Obviously such slides are extremely damaging both to any structures on the slide area or in the path of the slide.

Still another manifestation of liquefaction is the appearance of sand boils (small volcanoes emitting sand and water) on the surface of level ground. Where such sand boils occur, there can be excessive settlements of facilities. There may also be large differential horizontal movements between only slightly distant points on the surface, resulting in damage to highway, pipelines, and so on.

Liquefaction has been observed repeatedly during earthquakes in California, but it has also been observed elsewhere. An enormous area was affected by massive liquefactions during the 1811–1812 New Madrid, Missouri earthquakes, and the phenomenon was very evident during the 1886 Charleston, South Carolina earthquake. Liquefaction is a potential problem in any area where a loss estimation is being made.

The liquefaction hazard maps are based on general indicators of liquefaction susceptibility: geological age, the manner in which cohesionless soil is deposited, and the depth to the water table. Detailed procedures involving drilling and sampling have been developed for evaluating the liquefaction susceptibility of specific sites; such efforts are beyond the scope of a loss estimation study, although it may be possible to make good use of pre-existing data to supplement geological information. Approaches developed for California to identify liquefaction susceptible areas (Youd and Perkins, 1978) can be used, with proper judgment and knowledge of local conditions, to guide preparation of approximate maps for areas in other parts of the country.

ATC-13 contains relations giving estimated fractions of liquefaction susceptible areas experiencing different damage states (i.e., degrees of liquefaction) as a function of MMI. These were prepared using expert opinion, and are generally applicable throughout the United States. A very recent paper by Youd and Perkins (1988) presents a method for mapping liquefaction severity index (LSI), which is related to the extent and severity of liquefaction phenomena within liquefaction susceptible soils. The specific relations suggested in this paper are derived from experiences in California, and cannot be extrapolated directly to other parts of the country.

The same ATC-13 report also gives damage ratios for the losses to buildings affected by liquefaction. These clearly are engineering judgments, but they do provide some guidance. Combining this damage information with maps of liquefaction susceptible areas and estimations of extent and severity of liquefaction provides property loss estimates from these collateral hazards. It is essential to keep in mind that different manifestations of liquefaction (e.g., lateral spreading and sand boils) have quite different implications concerning damage.

This method is untried and must be used with caution and judgment and tailored to local situations, but it does permit systematic evaluation of potentially important losses.

Landslides

Here *landslides* is used to cover all permanent earth movements other than those involving saturated cohesionless soils.

In a very comprehensive review of earthquake-induced landslides to date, Keefer (1984) reviewed 40 earthquakes worldwide and ranked the abundance of different types of landslides. He listed disrupted soil slides as very abundant; soil slumps, soil lateral spreads, soil block slides, and soil avalanches as abundant; and rapid soil flows as moderately common. Of these types of landslides involving soils, only soil lateral spreads and rapid soil flows most likely involve liquefaction or failure of sensitive clays. The most notable example of failure of sensitive clays in this country occurred in Anchorage, Alaska in 1964 (Seed, 1973). Technical methods for assessing specific sites are available, but generally are beyond the means of a broad area loss estimate study. Since a combination of very sensitive clay and very strong shaking must be present if such failures are to occur, local geotechnical and geological experts should be able to decide whether or not this particular problem is present.

Soil falls, disrupted soil slides, and soil avalanches can occur as failures of dry, cohesive or cohesionless soils (Keefer, 1984) and were assessed as particularly common to abundant in the 1811–1812 New Madrid (Missouri) and 1906 San Francisco earthquakes. Likewise, landslides in cohesive soils are not restricted to sensitive clays, as shown by Keefer's historic review. Soil slumps, for example, have been at least moderately common in many earthquakes where sensitive clays do not exist.

Landslides in rock (e.g., rockfalls and debris flows) are expected only in steep terrain, in rock formations experiencing a loss of strength during ground shaking. It is very difficult to determine, even with the most careful testing and evaluation, whether or not a slide is likely, in relation to ground-shaking intensity, at a given rock site. Thus it is necessary to rely very heavily on past experience and judgment. ATC-13 contains results from expert opinion concerning the probability of such events. The historical review of 40 worldwide earthquakes by Keefer (1984) formed the basis for developing methods to identify seismically induced landslide susceptibility. These methods have subsequently been applied to several California metropolitan areas, including San Mateo County (Wieczorek et al., 1988) and the Los Angeles Region (Wilson and Keefer, 1985). Of the 40 earthquakes in the review, only 10 were from California. At least a half dozen were from other regions in the United States, including Alaska, Hawaii, Missouri, Montana, South Carolina, and Washington, with the rest of the historical earthquakes from other parts of the world having a variety of geologic and climatic conditions.

ATC-13 also provides estimates for the likelihood of damage to facilities, given that landsliding occurs—again from expert opinion. The warning in the last paragraph under liquefaction applies even more to landslides in rock. Locally steep rock slopes, particularly in closely jointed and weakly cemented rocks, are highly susceptible to seismically induced rockfalls and rockslides as noted by Keefer (1984).

These slopes need not be particularly high; a steep slope 10–20 m high could generate a damaging rockfall. Many metropolitan areas are naturally hilly and in combination with highway cuts, hillside excavations for building foundations create sufficiently hazardous conditions for rockfall and rockslides during earthquakes. Within the United States, Los Angeles, Memphis, Portland, Salt Lake City, San Diego, San Francisco, and Seattle are a few examples of large metropolitan areas with recognized potential for seismically induced landslides involving rock.

TSUNAMIS

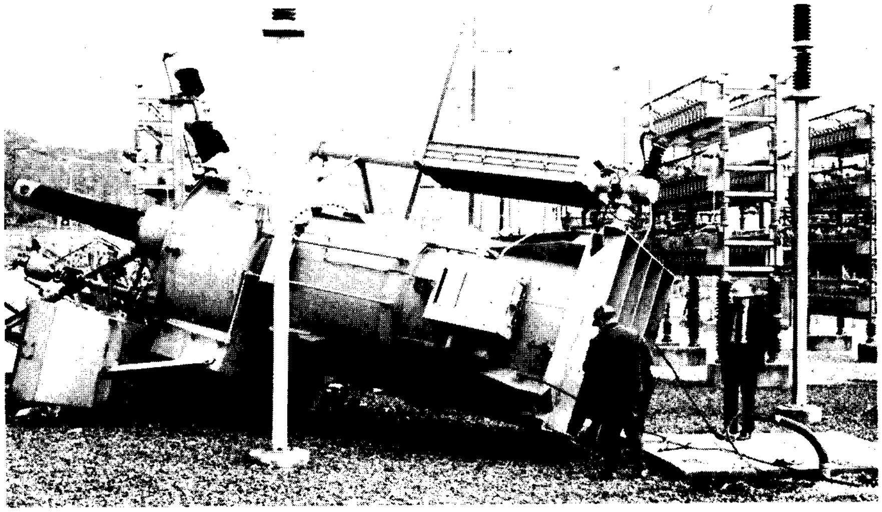
Tsunami inundation areas for the West Coast of the United States, including Alaska and Hawaii, are available in the form of FEMA flood maps (FIRM or Flood Insurance Rate Maps). For the East Coast, the potential hurricane storm surge exceeds possible tsunami heights, and tsunami hazard zones are thus of less importance and are not plotted on FIRMs. Other maps by USGS or the U.S. Army Corps of Engineers are also available and show the extent of expected tsunami run-up for the West Coast. A mean recurrence interval for the tsunami of 100 or 500 years, or both, is commonly used as a basis for developing these maps.

Even though tsunami hazard maps are available, there are two basic difficulties to overcome in estimating losses. First, as with ground failures, one must assess the degree of damage to various structures that might be caused by a range of water heights and velocities. All structures located within the shaded tsunami run-up zones on a map are not expected to be subjected to the same effects. Second, the tsunami map obtained will generally be predicated on a variety of causative earthquakes that may be located thousands of miles away, and thus tsunami losses may be unrelated to the losses associated with a local earthquake scenario. Generally, the major tsunami risk in California, Oregon, Washington, and Hawaii is posed by distant earthquakes, such as large Alaskan or Chilean events. In southern Alaska, a local earthquake could cause a tsunami, and the earthquake and tsunami losses might thus be combined in a particular scenario.

SEICHES

Here *seiches* refers to waves induced in lakes, reservoirs, and so on as a result of ground shaking (or perhaps because of permanent tectonic movement of the underlying earth). If these waves are of sufficient amplitude, facilities along the waterfront may be damaged and there might be overtopping and thus damage to any earth dam retaining a reservoir.

A specialized study is needed to determine whether or not there might be a problem and if so the extent of it. Fortunately, seiches are usually not a problem.



Electrical equipment that is not anchored securely to the foundation can move and fall over, as happened to this unit during the 1971 San Fernando earthquake (M 6.6). This earthquake did extensive damage to electric power facilities, freeway bridges, and water and gas distribution systems. *Photo courtesy of G. Housner.*

Collapse of an airport control tower in Anchorage, Alaska during the 1964 earthquake (M 8.3–8.6). One man was killed in the collapse and one was injured. All air traffic control and advisory services were disrupted in the Anchorage area due to damage to telephone, interphone, and teletypewriter communication lines. *Photo courtesy of G. Housner.*

6
Damage and Losses to Special Facilities and Urban Systems

The methods used to estimate losses for the general population of buildings must be modified for application to lifelines, facilities with essential emergency functions, or facilities with a potential for very large losses.

LIFELINES

Lifelines (or utilities and infrastructure systems) include railroad, airport, motor vehicle, water, telephone, electricity, natural gas or oil pipelines, sewage, port and airport, and communications services. The words ***systems*** and ***services*** are central to the distinction between the loss estimation process for lifelines as compared to buildings.

Service outages are almost always a prominent concern addressed by lifeline loss studies. Property losses are also important, but casualties associated with damage to lifelines usually are small. A lifeline, such as a water or electrical utility's facilities and functions, must be analyzed as a ***system*** rather than as separate, unrelated structures.

Securing the active cooperation and support of local lifeline owners, operators, and regulators is the key to producing a satisfactory loss estimate. An understanding of how the system operates is essential.

The first step in the analysis of lifelines is to estimate the probability that components of the system will fail. Examples of components would be bridges in highway routes, switchyards and transformer stations in power systems, and pumping stations in water and sewage systems. The estimation of losses to the individual components of a system has a less extensive historical loss experience to support the development of construction class motion-damage relationships than with buildings. The most ambitious attempt to date to develop classes that include nonbuilding structures is ATC-13, in which some 30 classes are related to lifelines.

The panel believes that the DPMs in ATC-13 provide the best available guidance, especially for bridges, although adjustments for local conditions will generally be necessary. ATC-13 DPMs should be used with a knowledge of the specific definitions of the classes. For example, a DPM that was devised for the case of seismically anchored electrical equipment should not be applied to a case where the equipment is unanchored.

Buried pipelines are more vulnerable to collateral hazards such as fault ruptures, landslides, and liquefaction than they are to ground shaking. The probability of failure of such a pipeline under these collateral hazards will depend on the detailed characteristics of the ground movement and the material, age, depth of burial, and wall thickness and diameter of the pipeline. There are examples of successful pipeline performance as well as failures for each of these collateral hazards. For any specific pipeline and detailed characteristic of ground movement, an evaluation of pipeline performance can be made. However, such detailed evaluations are beyond the feasible scope for a large geographic loss estimation study that includes many such pipelines. For these studies, the probability of failure of buried pipelines should be treated as being rather high (greater than 50 percent) wherever collateral hazards are postulated to occur.

Similarly, with the exception of bridges, which are potentially vulnerable to both effects, highway and railway networks are also more vulnerable to collateral hazards than they are to ground shaking. The probability of failure of links in such networks due to collateral hazards should be treated similarly to that described above for buried pipelines.

Once the probability of individual components failing has been estimated, the next step is then to evaluate the influence of the failure of components or segments on the performance of the system, as a whole. If analytical models exist for the system (utilities will often have such models), the effect on overall performance of the loss of some components can be estimated readily. Lacking any available system-wide models, expert opinion based on available data must be used to estimate the outages that might be expected. In either case, the result is a scenario describing the state of the lifeline; that is, its ability to provide service following the earthquake.

In addition to degradation in system-wide performance, there may be localized outages. For example, pipes in local distribution systems may fail as a result of ground shaking or ground failures, and streets may become clogged by debris. These local failures contribute to the overall problem of restoring service.

The time needed to restore service is an important factor in planning for disaster response. This is, in part, a matter of the time required to bring components back to a serviceable condition (e.g., to fix breaks in pipelines or to inspect bridges). The ATC-13 report contains time-to-restore-service matrices for a number of lifeline components. Restoring service also depends on the emergency response capability of the lifeline operator or of other emergency response agencies. A utility with an earthquake-resistant radio system, personnel who undergo annual earthquake exercises to test their ability to carry out preassigned tasks, and back-up plans for using emergency bypasses should be much more able to contain the impact of earthquake damage than another utility that does not have these capabilities and experiences the same damage. Considerations such as these must be handled on a case-by-case basis after evaluation of the utilities' emergency preparedness.

Loss estimation studies have seldom incorporated lifelines into the study to the same extent as building losses. Lifeline loss estimation methods are not as mature as for building loss estimation, and the problems are very complex. There has been considerable research into methods for evaluating the performance of interconnected systems in probabilistic terms, but as yet these sophisticated methods have not been used in conventional, multipurpose, regional-scale loss studies. The panel encourages more systematic and sophisticated studies of losses to lifeline systems, partially for the purpose of aiding in the maturing of lifeline loss estimation. However, additional damage statistics will accumulate only slowly, because so many factors affect the behavior of components in lifeline systems.

FACILITIES WITH ESSENTIAL EMERGENCY FUNCTIONS

In general-purpose loss estimates, the main focus of this study, special attention must be given to those facilities most essential to emergency response, such as fire stations, emergency operations centers, and hospitals. The key question is: How well will these facilities be able to perform after an earthquake?

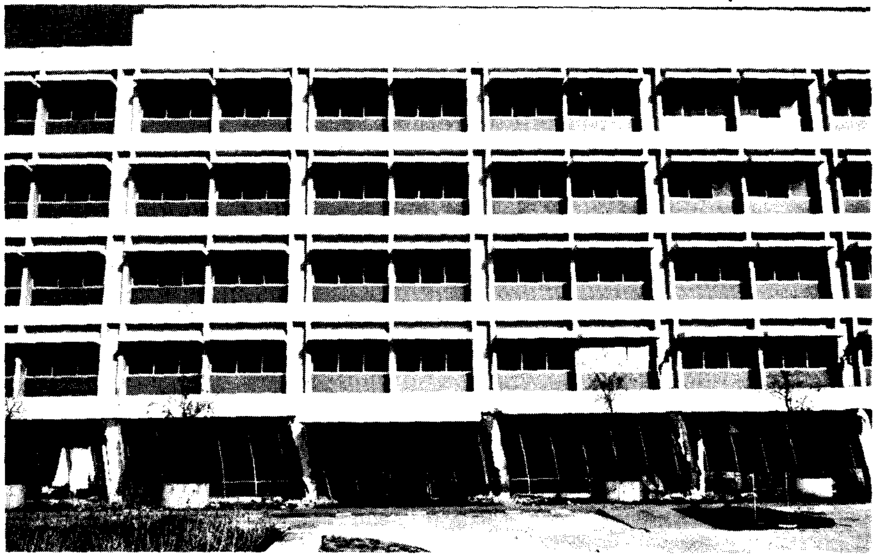
Obviously, if such facilities suffer severe structural damage, their usefulness will be negated or greatly impaired. However, even if there is little or no structural damage, the facility may be unable to function effectively if nonstructural damage causes critical equipment to be dislodged or overturned, or if essential or dangerous chemicals have been thrown down from shelves, or if lifelines services are interrupted.

Nonstructural damage is significant because it is generally more widespread than structural damage. Even a moderate level of ground shaking (such as VI or VII on the MMI scale) can cause nonstructural damage, such as overturned gas cylinders or water heaters and the release of flammable or toxic gas. The inventory task of field surveying nonstructural characteristics for the building population at large has yet to be attempted in a large-scale study, but this effort should be undertaken for the smaller number of essential, emergency function facilities that are within the scope of a large-scale study.

During a loss study, it generally is necessary to walk through each essential facility allowing sufficient time to assess the likelihood of severe structural damage, but it also is essential to ascertain whether critical equipment and supplies have been adequately secured, and whether back-up resources have been arranged to deal with utility outages. This is labor intensive work and requires earthquake engineering expertise, but these are unavoidable costs.

Undertaking a detailed structural analysis of such facilities is generally beyond the scope of a loss study. However, it may be desirable to examine structural drawings and to utilize a rapid assessment method. Critical evaluation of these methods is beyond the scope of this report.

Even though each emergency facility is inventoried, the problem of potential liability to those involved with this work may make it desirable for a number of such facilities to be grouped when stating expected losses. That is to say, the result is a scenario describing the functionality of the emergency response system as a whole and not the functionality of individual facilities.



The flexible, first-story of this hospital building was overstressed during the 1971 San Fernando earthquake (M 6.6). Although designed in accordance with the 1970 building code, this reinforced-concrete structure was so severely damaged that it was torn down. The intensity of ground shaking was much greater than the hypothetical intensity upon which the code requirements were based. *Photo courtesy of P. C. Jennings.*

Aerial view of collapsed hospital buildings in Sylmar, California. The older, weaker buildings collapsed and the newer, stronger buildings survived with only minor damage during the 1971 San Fernando earthquake (M 6.6). *Photo courtesy of G. Housner.*

The ATC-13 report solicited from experts the DPM for mean percentage property loss (termed damage factor by ATC-13 and generally called damage ratio by others) versus the MMI for six classes of equipment (i.e., residential, office, electrical, mechanical, high technology and laboratory, and vehicles). The validity of these relatively gross groupings is unknown and untested at present, although considerable variability is known within these types of equipment. For example, in the mechanical category, many pumps are routinely bolted to concrete slabs and are relatively earthquake resistant, even where earthquakes are not specifically considered in design. Also within this overall category of mechanical equipment is air-handling equipment mounted on springs, and these items are usually quite vulnerable to earthquakes except where special seismic measures are taken. The six classes of equipment analyzed by ATC-13 are also not all-inclusive.

The equipment DPMs were not directly used in the ATC-13 functional loss estimation process. Instead, experts were asked to assign recovery times to the damage states of Table 4-2 (e.g., loss damage state 1 = no damage) for 60 socioeconomic classes of building use. For the class defined as health care services, for example, each expert had to decide how a given damage state (that now included structural plus equipment damage in its definition) affected the facility's functionality in terms of time to restore service to 30 percent, 60 percent, and 100 percent. Loss of function resulting from lifeline service outages were included as a separate step. To be valid, these relationships (of MMI to equipment damage, and of combined structural and equipment damage state to functional loss) must be defined more specifically than to say they represent "typical" California practice.

It should be clearly recognized that there is less certainty and less maturity in such techniques for estimating functional loss than for estimating property loss. For essential facilities, individual field visits rather than reliance on general relationships are recommended.

Considerable potential exists for improving estimates of the performance of essential facilities through research into the earthquake performance of nonstructural items and identification of typical nonstructural conditions in different parts of the country. While the state of the art of quantitative nonstructural loss estimation is not well developed, guidance for identifying and reducing nonstructural vulnerabilities is available in works such as those by McGavin (1981, 1986), Reitherman (1985, 1986), Stratta (1987), and the Veterans

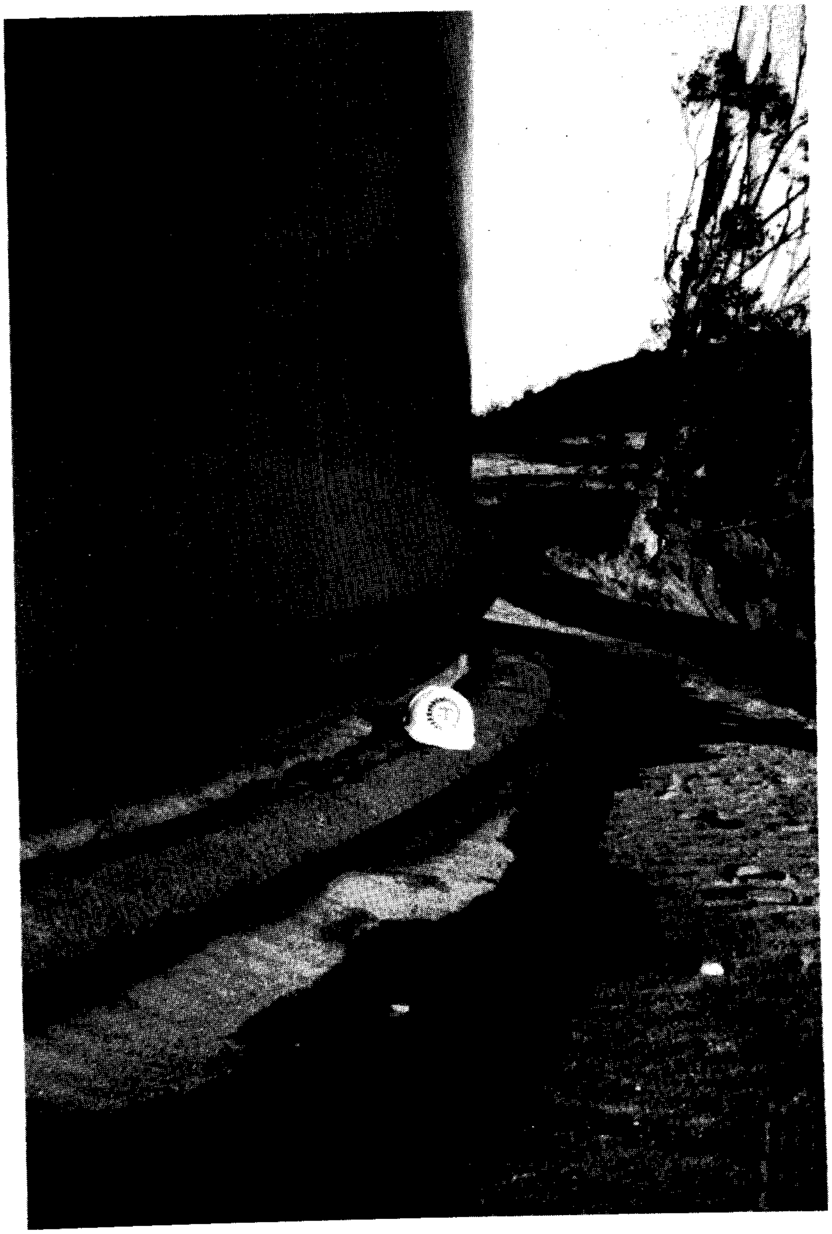
Administration (1976, 1981). For emergency planning purposes, references documenting functional losses (e.g., Arnold and Durkin [1983] concerning hospitals) or other reports in the postearthquake reconnaissance and research literature are useful for pointing the way toward improving emergency response capabilities, even though quantitative response dysfunction can only be very approximately predicted.

FACILITIES WITH A POTENTIAL FOR LARGE LOSS

In this category are large and densely occupied buildings and other facilities such as tank farms, refineries, dams, liquefied natural gas (LNG) plants or storage areas, chemical plants, nuclear plants, and pipelines containing hazardous materials. The characteristic feature of these facilities is that failure could cause an enormous number of casualties as well as very large property losses.

Except possibly for large and densely occupied buildings, there may be only a few of these facilities in a given study area. Thus, the loss estimator cannot take advantage of averaging out uncertainty in performance over many facilities, as can be done for the ordinary building stock. Unless the loss attributable to a facility can be stated with great confidence, including it may completely bias the projected overall losses for the region. Since the loss from an individual building or other facility cannot be estimated reliably except through very detailed and expensive analysis, it follows that possible losses from such facilities should not be quantitatively included in the overall estimated loss.

Obviously, however, the existence of such potentially hazardous facilities cannot be ignored. They should be highlighted in the inventory, and the cognizant regulatory bodies should be urged to require that detailed studies be made. A large-scale multipurpose study can educate local officials and staff personnel about the potential threat and the need to map the location of such facilities.



Damage to a liquid storage tank during the 1971 San Fernando earthquake (M 6.6). The sloshing of the fluid contents overstressed the wall of the tank. Sometimes such overstressed tanks collapse and combustible contents ignite. *Photo courtesy of P. C. Jennings.*

7
Indirect Losses

Indirect losses follow from the direct effects of an earthquake. They may be very important, but are difficult to evaluate.

FIRE

Most loss estimates in the United States have not included losses from fire in a formal, quantitative way. While fire has not been a major factor in recent earthquakes in the United States, more than 100 ignitions occurred in the 1971 San Fernando earthquake, and a shopping center fire was the single largest loss in the 1984 Morgan Hill, California earthquake (M 6.2). Thus, the specter of fire loss following earthquakes, similar to the 1906 San Francisco earthquake, is always present.

Scawthorn et al. (1981) and Oppenheim (1984) have made starts toward a formal procedure for evaluating expected losses from fires. The discussions of this topic in ATC-13 and Steinbrugge and Lagorio (1982) are also useful. More recently, Scawthorn (1987) has provided estimates of losses due to fire following earthquakes in the Los Angeles and San Francisco regions. Data for the initiation of fires following earthquakes in the United States, and especially for the different conditions in Japan, exist. Models can include consideration of time lags in reporting fires and responding to them as well as weather conditions to estimate the possible spread of fire.

However, such models should be used with caution in a generalized loss study because major work remains to advance the state of the art. Inherently, the problem is very complex. A recent reminder that the state of the art of forecasting earthquake-caused fires is poorly developed is provided by the work of Hansen et al. (in progress) on the 1906 San Francisco earthquake. A much larger number of ignitions has been documented than was previously reported, and other previous data, concerning casualties especially, are also being significantly revised.

Possible losses from fire, and the implications to disaster response planning, certainly must be recognized. Property losses from fire are of great concern to the insurance industry, and attempts to quantify possible fire-related losses will certainly continue. From the emergency planning standpoint, information concerning the expected performance of the water supply, communication, gas distribution, and highway and street systems can be used as a basis for devising emergency response plans. Postearthquake fire modeling is also useful to identify general areas of high conflagration potential (e.g., concentrations of wooden buildings) or special risk factors unique to the postearthquake situation (e.g., telephone, transportation, or water system outages).

RELEASE OF HAZARDOUS MATERIALS

Concern about potential releases of hazardous materials was emphasized in the user workshop. Laws in many states and communities have required that an inventory of hazardous substances be maintained at the local level, and Title III of the Superfund Amendments and Reauthorization Act of 1986 imposed nationwide inventory requirements. Lacking legal sanction for having such an inventory, it may be impossible to secure the cooperation of industrial facilities in preparing one.

In general, there is only a limited amount of data from earthquakes upon which to judge the likelihood that releases will occur, as a function of ground-shaking intensity. The manner in which substances are contained will be the major factors affecting the probability of releases. For some general types of components, such as tanks, considerable earthquake performance data and analytical or test findings are already available. Even here, however, this is little direct information as to the likelihood of a release given that a tank has overturned. Development of methods for evaluating the seismic resistance of a range of storage arrangements is an important task for the future.

ECONOMIC IMPACTS

Many economic impacts are associated with earthquake damage. These include loss of production capacity in individual manufacturing facilities, loss of income to commercial enterprises where functionality is destroyed or impaired, the loss of jobs, economic impacts on other undamaged businesses within a region, and losses to industry and commerce located outside the affected region but linked economically to it. In some instances, economic benefits may be associated with an earthquake, such as an influx of federal aid and the creation of new types of jobs. The need to undertake such an analysis was a major motivation for FEMA's sponsorship of the ATC-13 effort.

If such losses are to be considered, the inventory must include considerable information. The economic function of buildings must be identified, and commercial and industrial activities categorized. The 35 basic social function categories in the ATC-13 report are reasonable. However, given the inadvisability of assigning buildings to construction classes based only on socioeconomic data, the panel estimates that about 25 to 50 percent more effort would be needed to include this level of classification of uses in an inventory. In addition, considerable effort by economists will also be needed to develop the economic models that link various commercial and industrial activities inside and outside the region.

The panel recognizes the potential value of analyses of this type, and encourages them. It recommends that a pilot study of this type be added to a future loss estimation study.

8

Rapid Postearthquake Loss Estimates

In establishing the scope of this panel's study, FEMA cited the potential value of being able to estimate losses quickly after an actual earthquake, as a basis for planning disaster response and financial assistance. The panel was specifically asked whether cruder techniques of rapid loss estimation might be developed for this purpose.

An early study by Algermissen (1978) was inspired by this desire for a technique to evaluate earthquake losses rapidly. It resulted in a method for estimating earthquake losses that was much the same as the NOAA-USGS method discussed in this report, and it assumed that the inventory was reasonably up-to-date.

The inventory and other information assembled for any loss estimate may be used very quickly once the magnitude and location of an earthquake are established, *provided* the inventory is current, the computer software is current, and the computer is operating and available. If this approach were to be tried, the data bank and computer software must be maintained in an active condition outside all potentially affected areas. In addition, the crudeness of loss estimates based on the best of today's technology must be kept in mind.

Reports from the affected area based on field reconnaissance usually will provide a more accurate picture of the extent of losses than the best of theoretical loss estimate calculations, and obviously this will be even more true for the cruder estimation techniques.

The panel recommends that low priority be given to developing approaches that rely on projections rather than on field reconnaissance and actual damage reports after earthquakes.

9
Conclusions and Recommendations

SUMMARY GUIDELINES FOR MULTIPURPOSE, LARGE-SCALE EARTHQUAKE LOSS ESTIMATES

This chapter presents the panel's conclusions and recommendations for conducting general loss estimate studies of the type currently being funded by FEMA and primarily intended for use by local and state governments for disaster response and mitigation planning, and to aid in the formulation and implementation of near- and long-term strategies for earthquake hazard reduction.

Study Preparation and Planning

The objectives and scope of a study must be defined clearly and early in a study. Potential users for the study must be identified and plans made for the ultimate dissemination and utilization of the report. Specific plans should be made for the involvement of key local and state personnel throughout the study.

One very important decision at this stage concerns the scope and detail of the inventory and the form in which it will be prepared. Discussions should be held with a spectrum of potential users for the inventory, to identify interest in and commitment to developing and maintaining an inventory in a computer-based format.

Scenario Earthquakes

Earthquakes selected for scenarios should be relatively probable and yet damaging. Using too large and improbable an earthquake may lead to a loss of credibility in the loss estimate or create a feeling of hopelessness in dealing with the high-loss estimate. No standard exists for selecting scenario earthquakes. For the more seismic portions of the country, use of the historical maximum earthquake is often reasonable. For less seismic areas, probabilistic hazard analysis is useful. There also is no standard for the choice of a mean recurrence interval for a scenario, but intervals of as long as 1,000 years may be reasonable for disaster response planning, depending on the intended use. As in seismic design, the more essential or potentially hazardous the facility or system, the longer the recurrence interval that is considered. It is desirable that at least a rough indication of the probability of occurrence be attached to all scenario earthquakes to convey to users and to the public some indication of the likelihood of the events.

Despite the problems associated with the use of Modified Mercalli Intensity (MMI) scale to prescribe the strength of ground shaking, it still is the best available measure of intensity for use in loss estimates. More complex representations of ground shaking, for example, through a filtered "effective" peak motion, a single-degree-of-freedom linear response spectrum, a nonlinear spectrum, a time history of motion, and the duration of strong shaking, have the ability to be more accurate predictors of damage and loss. There is less agreement, however, on how to estimate these functions for a future earthquake, how to quantify the single- or multidimensional hazard associated with them, and how to derive an accurate predictor of damage from them.

However, use of MMI XI and XII should be avoided, or at least the meaning of these intensities should be carefully defined if used. The ground conditions for which prescribed intensities apply must be stated clearly, together with rules for taking into account below- or above-standard ground conditions.

Classification System for Buildings

The primary purpose of a classification system is to group buildings according to their seismic resistance for loss estimation purposes. Choice of a classification system depends on the availability of information relating ground motion to damage and on the funds available for compiling an inventory. Several standard classification systems have been developed, primarily for California construction, but in general it is necessary to tailor the system to suit local conditions.

Inventory

Inventory preparation is generally the most time-consuming and expensive aspect of a loss study. It is an exercise in locating and using available sources of information, carrying out some onsite inspection, and applying considerable judgment. The most difficult step is identifying the seismic resistance category for a building or group of buildings. Methods have been developed for abstracting an inventory from socioeconomic data in national data bases, but the panel believes that loss estimation efforts are better spent on field surveys and compilation of harder, more accurate construction class data.

It generally is not feasible to inventory all buildings individually, and attention is better focused on buildings that are seismically suspicious or are important to emergency response following an earthquake. Even when buildings are inventoried individually, they may subsequently be grouped regarding estimated losses, to help avoid legal and political problems that may result from singling out specific buildings as being hazardous. On the other hand, failure to disclose information about hazards may increase liability exposure, so the issue of specificity of an inventory should be handled with legal advice.

It is important to disaggregate the loss estimates to the smallest relevant political unit, except where this results in a small number of facilities that would compromise either the anonymity or statistical validity of the results.

Motion-Damage Relationships

The best information relating ground motion to damage are the statistics developed by the Insurance Services Office (ISO) from actual earthquake experiences. This information takes the form of average property loss ratios for selected classes of buildings versus intensity of ground shaking. The available data are best for single-family, wood-frame dwellings, and apply directly only to construction in California and some other western areas.

Because actual data of this type are so limited, and because for some purposes it is important to estimate the distribution of damage as well as the mean damage, damage probability matrices (DPMs) and fragility curves have been developed as alternatives to mean loss curves. Using a formalized procedure for obtaining and processing expert opinion, the Applied Technology Council (ATC) has published DPMs for a wide range of types of structures found in California. When the construction classes of ISO and ATC overlap, mean loss ratios deduced from the ATC DPMs are very similar to the curves of ISO.

The ambitiousness of the ATC-13 project has led to impressive accomplishments although the panel identified some criticisms of the method used to develop the ATC DPMs and of the manner in which they are portrayed. The final report of ATC-13 combines in one volume more data, a more complete methodological review, and more discussion by experts of the various tasks involved in the earthquake loss estimation process than any other single publication.

A major question is: How should motion-damage relationships be developed for use in loss estimates in areas other than California? The panel recommends that expert opinion be used to modify the California-based information for the types of buildings found in the area to be studied. Limited analysis of some selected archetype buildings can assist in this effort.

Evaluation of Losses

Combining the inventory with motion-damage relations leads directly to estimates for property losses, although it is necessary to be careful and explicit as to what value of buildings—replacement cost or market value—is used in the calculation. Usually, however, it is also necessary to estimate numbers of casualties. The data on which to predict deaths and injuries are very sparse, and considerable judgment is necessary in organizing available information to estimate casualties. The panel prefers a method set forth by ATC in which casualty rates are linked to degree of damage and class of construction; this is a rational approach but must be used with considerable judgment.

Estimates for the number of people requiring shelter are also important for planning of postdisaster operations, and for this purpose as well as for casualty prediction it is necessary to forecast the amount of severe damage rather than just the mean overall loss.

Any study should give a realistic assessment of the uncertainty in all loss estimates, such as by giving both best estimates and likely ranges.

Collateral Hazards

In addition to losses caused by shaking of buildings founded on stable ground, there may be losses caused by collateral hazards such as fault ruptures, landslides, liquefaction, tsunamis, and seiches. Losses from collateral hazards can be very important, in some cases dominating the overall loss. The key to evaluating these losses is in the identification of areas where such hazards will occur as a result of the scenario earthquake(s). Unfortunately, to do this systematically is a major and expensive task, and it may be necessary to rely on the judgment of experts. ATC has developed a rational sequence of steps for developing DPMs for structures affected by ground failure, once such areas have been identified by geologists and geotechnical engineers.

Lifelines and Emergency Facilities

In addition to buildings for residence and work, many other types of facilities are potentially important in loss estimates. Lifelines (e.g., railroads, highways and streets, water, electricity and sewage systems, and communication services) are vital to the functioning of a region and its emergency response capabilities following an earthquake.

Evaluation of lifelines involves the study of the possible failures of components (e.g., bridges or segments of pipelines) and the analysis of the effect of such individual failures on the overall performance of the system. The ATC-13 report has DPMs for various types of lifeline system components, which are the best available guidance, and the recent reports by the Building Seismic Safety Council (1987) are useful as well. For many lifelines, computer models for evaluating the effect on overall performance of the loss of some components will be available from utilities or agencies responsible for the lifelines, and the active cooperation of such utilities and agencies is the key to a satisfactory lifelines loss estimate. The final result is a scenario describing the ability of each lifeline to provide service following the earthquake.

Special attention must be given to those installations most essential for emergency response, such as fire stations and hospitals.

Susceptibility to structural damage must be assessed, but even if there is no structural damage a facility may be unable to function effectively if critical equipment has been dislodged or if important or dangerous contents have been damaged. It generally is necessary to visit each facility to assess structural resistance, and also to view the state of nonstructural conditions. ATC-13 contains organized expert opinion as to the time required to restore functionality of facilities, but the panel feels that these quantitative estimates contain more uncertainty than most other aspects of the overall process.

Even though each emergency facility is inventoried, legal and political difficulties generally require that a number of such facilities be grouped when stating expected losses. Thus, the result is a scenario describing the functionality of the emergency response systems as a whole, broken down by subareas, and not the state of individual facilities.

Facilities with a Potential for Large Loss

These facilities are not numerous and failure could cause enormous casualties as well as major property loss. Unless the loss and its likelihood can be stated with confidence as the result of detailed (and expensive) analysis, it should not be included in a large-scale loss estimate. However, the existence of such potentially hazardous facilities should be highlighted in the report.

Indirect Losses

It is not yet possible to make reliable quantitative estimates of the potential losses from fire following an earthquake, but a study should emphasize the functionality of the water supply system and the highway and street infrastructure as they relate to firefighting capability. It should also note high-risk areas or factors, such as time of year and weather. This has generally been done in the studies conducted by the National Oceanic and Atmospheric Administration and the U.S. Geological Survey. Precise quantitative loss estimates are not always necessary to point the way toward improvements in hazard reduction and emergency planning efforts.

An inventory of hazardous materials is desirable, but its preparation will depend on state and local inventories and existing programs of environmental health agencies and fire departments. There is no satisfactory method for evaluating the likelihood that storage systems will fail and cause release of these substances, and so this problem should be treated similarly to the topic of fires.

Evaluation of economic impacts other than damage is usually not part of a general-purpose loss estimate.

The Report

The report of a loss estimate study should meet two objectives. First and foremost, it should present results in a manner understandable to users in state and local government and to the public. Second, it should document the technical procedures used to compile the inventory and to calculate or otherwise evaluate losses, so that in the future the loss estimate can be updated. Careful design of the report is essential to achieve these two different and often conflicting objectives.

Independent Guidance and Review

Experts unaffiliated with the organizations conducting a loss study should provide independent guidance and review of an earthquake loss study. This policy is recommended for budgeting and implementation in future federally funded loss studies. The guidance and review might best proceed in steps—a review of the user-defined goals for the study, a review of the seismic hazard analysis, a review of the design for the inventory process, and so on. The final results of the study should also be reviewed.

This independent review is not suggested out of concern over the quality of past projects but to increase confidence in the results of future studies, to ensure better documentation of the methods used, and to conform to validation procedures generally accepted in the scientific and engineering disciplines.

User Needs

The foregoing guidelines respond to several of the identified user needs: involvement of local personnel, selection of the scenario earthquake(s), establishment of inventories with continued use for multiple purposes, disaggregation of inventory and losses to the smallest political unit consistent with the principle of averaging losses over an adequate number of facilities to ensure statistical validity and anonymity, and the reporting of the loss study results.

Several user recommendations conflict with the state of the art:

• Presenting a single number loss estimate rather than presenting a range of possible losses. Loss estimates are quite approximate, and it is considered essential that the uncertainty in any estimate be reported.

• Identification of specific, seismically suspicious buildings, structures, or facilities. In the absence of enabling legislation, identifying specific buildings as being likely to sustain damage could expose a loss estimator to legal suits or political repercussions. To be confident about the likely performance of a specific building involves a thorough study beyond the scope and budget of most loss estimates.

• Identification of expected releases of hazardous substances. In addition to the difficulties mentioned above, experiences during actual earthquakes are too limited to permit confident predictions.

At the outset of any study, the potential users and those performing the loss estimate must agree on compromises between what is desired and what is feasible.

Cost and Commitment Sharing

The panel is unable to provide guidelines as to the appropriate cost of a loss estimation study. It has been noted that a larger loss study budget can be justified on technical grounds because it leads to more accurate results. Another appropriate criterion for gauging how much should be spent on loss estimates is how extensively the information will be used. The political ramifications of cost sharing are also beyond the scope of the panel's review, but the related idea of commitment sharing should be considered in any debate over cost sharing.

While no one can promise that a loss study will lead to the passage of improved building or land-use ordinances, it is possible to schedule statewide conferences, as well as legislative briefings, for building officials and city planners following the completion of a loss study to consider its implications. State and local offices of emergency services can be expected to take a new loss study's findings into account in their earthquake disaster response planning, and this emergency plan revision effort can be scheduled to begin when the loss study is completed. Distribution of copies or summaries of the study and public information efforts can also be budgeted and planned prior to completion of a study. In the words of one observer and participant in the process of producing and implementing a loss estimate study, "Users should be required to commit themselves to the use of the information" (Buck, 1978).

RECOMMENDATIONS FOR RESEARCH AND DEVELOPMENT

Validation of Loss Estimation Methodologies

A strong need exists to demonstrate the validity of the components of the current loss estimation technology as well as the technology as a whole. Therefore, the panel makes two recommendations.

1. Following the next damaging earthquake to strike an urbanized area in the United States, after-the-fact "predictions" should be made using one or more predictive methods and results compared with the actual losses. The goals are to establish confidence in the use of the methods and to learn how the methods might be improved. The comparisons should be made for the methods as a whole—from magnitude and location to loss—and also for various components, such as losses estimated vis-à-vis a given intensity.

2. Opportunities should be seized for evaluating components of the overall methodology. Two examples from the inventory part of the problem are:

- Where an exact inventory exists, such as with unreinforced masonry buildings in Los Angeles, compare these hard data with the inventories established by approximate methods;
- Where an approximate loss estimation inventory has been prepared for a region, and this inventory can be disaggregated to small areas, prepare for comparison a complete inventory of one or more categories of buildings for a small area.

Corresponding opportunities will occur for other components of an overall methodology, for example, predicted and actual intensity of ground motion, or comparison of maps showing probable ground failure zones with maps locating actual failures prepared after an earthquake.

Sensitivity Analysis

For one or more methods, the panel recommends conducting sensitivity analyses to identify the significance of various possible errors on the overall loss estimate at each stage in the process. Such a study will give greater understanding of the uncertainty in loss estimates and will identify the parts of the overall process that contribute most essentially to this uncertainty. Such studies should be done using methods involving different degrees of approximation, and the resulting differences in the mean and ranges of estimated losses contrasted with the effort to prepare the estimate.

Development of Improved Methods

The ATC-13 report and other recent studies have made excellent contributions toward development of improved methods for evaluating losses. Continuation of this work will lead to improved methods with wide applicability. Thus, the panel recommends:

- A concerted effort should be made to develop a construction classification system applicable throughout the United States.
- Existing inventory methods should be compared to synthesize their strong points, rather than developing another new method. The NOAA-USGS method has featured the use of experienced earthquake engineers and locally knowledgeable real estate consultants or building officials to field sample a study area and relate the samples to land-use maps. The inventory method that would be most commonly used in the ATC-13 approach (Level 2), while not generally recommended by the panel, may be promising in combination with some field data to produce preliminary inventory outlines that would be used to design the detailed inventory process. The Gauchat and Schodek (1984) study of Boston housing, and the work by Jones et al. (1986) in Wichita, Kansas, incorporated aerial photography into the inventory process. While the panel does not recommend the use of aerial photography alone, it may be usefully combined with other data sources.
- The motion-damage-loss component of various methods should be compared to synthesize their strong points, rather than developing another new method. ATC-13 is innovative in its structured use of expert opinion and its development of relationships for new construction classes. The NOAA-USGS method has capitalized on historical loss data as well as judgment. The Central U.S.-Six Cities study (Allen and Hoshall et al., 1985) and the study of Boston housing earthquake vulnerability (Gauchat and Schodek, 1984) are notable for their explicit description of the archetype buildings that

represent each construction class, allowing experts to analyze thoroughly and debate the vulnerability of each class with the definition of the class held constant.

While work aimed at developing improved methods for estimating building losses should continue, special emphasis should be given to collateral hazards, such as ground failure and water effects, including the damage caused by such hazards, and to lifelines and emergency facilities.

As part of this effort, there should be a renewed attempt to develop a satisfactory quantitative scale for the damaging potential of ground motion. It is likely that using more than a single ground-motion parameter will be necessary. The panel accepts the use of MMI, but sees the possibility of developing an improved substitute.

Users' Needs and Study Uses

Research should be conducted to document exactly how previous loss studies have been used. For example, in what precise ways is a city's disaster response plan different because of the existence of a loss study? What public policy decisions were directly affected by a study?

In parallel with the development of improved loss estimate methods there should be improved utilization of study results. The problem is not just lack of information, but also lack of use of information.

Collection of Earthquake Loss Data

The process of collecting loss data immediately after significant earthquakes needs to be improved. For example, while reconnaissance efforts are common, collection of good-quality damage data and information on casualties, property loss, and functional loss requires noting the performance of all buildings of a given type in a given area. Documenting the performance of only the small number of buildings that experience dramatic damage does not provide the needed statistics.

As long ago as the 1923 Yokohama and Tokyo earthquake in Japan, or the 1933 Long Beach, California earthquake in this country, thorough field surveys of damage have been conducted. The techniques are readily available, but the administrative program to fund and publish this statistical type of data has often been lacking.

In addition, emphasis must be placed on collecting data for the occurrence and nonoccurrence of collateral hazards, the performance of lifelines, nonstructural components, and emergency facilities, and the containment or release of hazardous substances.

References

Alaska Division of Emergency Services. 1980. Greater Anchorage Area Earthquake Response Study. Anchorage, Alaska: State of Alaska.

Alexander, R. H. 1987. Recent developments in digital map data bases and geographic information systems (GIS) as they may apply to earthquake loss estimation. Synopsis of presentation to the Earthquake Loss Estimation Panel, January 8, 1987, National Academy of Sciences, Washington, D.C.

Algermissen, S. T., W. Rinehart, J. Dewey, K. V. Steinbrugge, H. J. Lagorio, H. J. Degenkolb, L. S. Cluff, F. E. McClure, S. Scott, and R. F. Gordon. 1972. A Study of Earthquake Losses in the San Francisco Bay Area: Data and Analysis. Washington, D.C.: National Oceanic and Atmospheric Administration (NOAA).

Algermissen, S. T., M. Hopper, K. Campbell, W. A. Rinehart, D. Perkins, K. V. Steinbrugge, H. J. Lagorio, D. F. Moran, L. S. Cluff, H. J. Degenkolb, C. M. Duke, G. O. Gates, D. W. Jacobson, R. A. Olson, and C. R. Allen. 1973. A Study of Earthquake Losses in the Los Angeles, California Area. Washington, D.C.: NOAA.

Algermissen, S. T. 1978. Development of a Technique for the Rapid Estimation of Earthquake Losses. Open-File Report 78-440. Washington, D.C.: U.S. Geological Survey (USGS).

Algermissen, S. T., and K. V. Steinbrugge. 1984. Seismic hazard and risk assessment: Some case studies. The Geneva Papers on Risk and Insurance, vol. 9, no. 30, January 1984.

Allen and Hoshall, Jack R. Benjamin and Associates, Inc., and Syston, Inc. 1985. An Assessment of Damage and Casualties for Six Cities in the Central United States Resulting from Earthquakes in the New Madrid Seismic Zone. Washington, D.C.: Federal Emergency Management Agency (FEMA).

Anderson, L. R., J. R. Keaton, J. E. Spitzley, and A. C. Allen. 1986. Liquefaction Potential Map for Salt Lake County, Utah. Final report to the U.S. Geological Survey by Utah State University, Logan. Contract No. 14-08-0001-19910.

Applied Technology Council (ATC). 1985. Earthquake Damage Evaluation Data for California (ATC-13). Redwood City, Calif.: ATC.

Arnold, C., and M. Durkin. 1983. Hospitals and the San Fernando Earthquake. San Mateo, Calif.: Building Systems Development, Inc.

Arnold, C., and R. K. Eisner. 1984. Planning Information for Earthquake Hazard Response and Reduction. San Mateo, Calif.: Building Systems Development, Inc.

Blume, J. A., R. E. Scholl, M. R. Somerville, and K. V. Honda. 1978. A Program for Predicting the Structural Effects of a Major Earthquake in the Region of the Palmdale Uplift. Washington, D.C.: USGS.

Borcherdt, R. D., ed. 1975. Studies in Seismic Zonation of the San Francisco Bay Area. Professional Paper 941-A. Washington, D.C.: USGS.

Brabb, E. 1985. Analyzing and Portraying Geologic, Cartographic and Hydrologic Information for Land Use Planning and Decisionmaking. Menlo Park, Calif.: USGS.

Buck, R. A. 1978. The Puget Sound Earthquake Preparedness Project: Communicating Earthquake Hazards Reduction Information. Open-File Report 78-933. Washington, D.C.: USGS.

Building Seismic Safety Council. 1985. NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings. Washington, D.C.: FEMA.

Building Seismic Safety Council. 1987. Abatement of Seismic Hazards to Lifelines: Proceedings of a Workshop on Development of an Action Plan. Washington, D.C.: Building Seismic Safety Council.

California Division of Mines and Geology. In progress. A study of the impact of a major earthquake on the Newport-Inglewood fault zone in the Los Angeles area. Sacramento: California Division of Mines and Geology.

Davis, J. F., J. H. Bennett, G. A. Borchardt, J. E. Kahle, S. J. Rice, and M. A. Silva. 1982a. Earthquake Planning Scenario for a Magnitude 8.3 Earthquake on the San Andreas Fault in Southern California. Special Publication 60. Sacramento: California Division of Mines.

Davis, J. F., J. H. Bennett, G. A. Borchardt, J. E. Kahle, S. J. Rice, and M. A. Silva. 1982b. Earthquake Planning Scenario for a Magnitude 8.3 Earthquake on the San Andreas Fault in the San Francisco Bay Area. Special Publication 61. Sacramento: California Division of Mines.

Degenkolb, H. J. 1984. Summary Report of Structural Hazards and Damage Patterns: Pre-Earthquake Planning for Post-Earthquake Rebuilding. San Francisco, Calif.: H. J. Degenkolb Associates.

Dobry, R., and L. Alvarez. 1967. Seismic failures of Chilean tailings dams. *ASCE Journal of the Soil Mechanics and Foundations Division* 93(SM6):237–260.

Federal Emergency Management Agency (FEMA). 1980. An Assessment of the Consequences and Preparations for a Catastrophic California Earthquake: Findings and Actions Taken. Prepared from analyses carried out by the National Security Council Ad Hoc Committee on Assessment of the Consequences and Preparations for a Major California Earthquake. Washington, D.C.: FEMA.

FEMA. 1985. National Multihazard Survey Instructions (TR-84). Washington, D.C.: FEMA.

Furomoto, A. S., W. Lum, N. N. Nielsen, and J. T. Yamamoto. 1980. A Study of Earthquake Losses in the Honolulu Area: Data and Analysis. Honolulu: State of Hawaii Civil Defense Division.

Gauchat, U. P., and D. L. Schodek. 1984. Patterns of Housing Type and Density. A Basis For Analyzing Earthquake Resistance. Cambridge, Mass.: Department of Architecture, Harvard University.

Geoscience Associates. 1984 and 1985. Phase 1 Report: Hazard Analysis (1984); Phase 2 and Phase 3 Report: Vulnerability Analysis (1985). Bernardsville, N.J.: Geoscience Associates.

Geoscience Associates. In progress. A study of Clinton County, New York, earthquake losses. Bernardsville, N.J.: Geoscience Associates.

Gulliver, R. 1986. Estimation of Homeless Caseload for Disaster Assistance Due to an Earthquake. Washington, D.C.: FEMA.

Hansen, R., G. Hansen, E. Condin, and D. Fowler. In progress. The San Francisco Earthquake Research Project. San Francisco: California Academy of Sciences.

Hopper, M. G., C. J. Langer, W. J. Spence, A. M. Rogers, S. T. Algermissen, B. C. Olsen, H. J. Lagorio, and K. V. Steinbrugge. 1975. A Study of Earthquake Losses in the Puget Sound, Washington, Area. Open-File Report 75-375. Washington, D.C.: USGS.

Jones, B., D. M. Manson, C. M. Hotchkiss, M. J. Savonis, and K. A. Johnson. 1986. Estimating Building Stocks and Their Characteristics. EPA Materials Distribution Workshop, September 8–11, 1986, Hanover, New Hampshire.

Keefer, D. K. 1984. Landslides caused by earthquakes. *Geological Society of America Bulletin* 95:406–421.

Kircher, C. A., and M. W. McCann. 1983. Development of fragility curves for estimation of earthquake-induced damage. Proceedings of Conference XXIII: A Workshop on Continuing Actions to Reduce Potential Losses from Future Earthquakes in Arkansas and Nearby States. Open-File Report 81-437. Washington, D.C.: USGS.

Lindbergh, C. In progress. A study of Charleston area earthquake losses, funded by FEMA, to be produced by The Citadel Military College of South Carolina.

Liu, B. C., C. Hsieh, R. Gustafson, O. Nuttli, and R. Gentile. 1981. Earthquake Risk and Damage Functions: Applications to New Madrid. Boulder, Colo.: Westview Press.

Mann, O. C., W. Howe, and F. H. Kellogg. 1974. Regional Earthquake Risk Study. Memphis, Tenn.: Mississippi/Arkansas/Tennessee Council of Governments (MATCOG) and Memphis Delta Development District (MDDD).

McClure, F. E., H. J. Degenkolb, K. V. Steinbrugge, and R. A. Olson. 1979. Evaluating the Seismic Hazard of State Owned Buildings. Sacramento: California Seismic Safety Commission.

McGavin, G. 1981. Earthquake Protection of Essential Building Equipment. New York: John Wiley & Sons.

McGavin, G. 1986. Earthquake Hazard Reduction for Life Support Equipment in Hospitals. Riverside, Calif.: Ruhnau McGavin Ruhnau Associates.

Molinelli, J., and B. Oxman. In progress. A study of San Juan area losses for the Puerto Rico Department of Natural Resources. Puerto Rico.

National Research Council. 1972. The Great Alaska Earthquake of 1964: Oceanography and Coastal Engineering. Washington, D.C.: National Academy of Sciences.

National Research Council. 1986. Liquefaction of Soils During Earthquakes. Washington, D.C.: National Academy Press.

National Research Council. 1987. Probabilistic Seismic Hazard Analysis. Washington, D.C.: National Academy Press.

Oppenheim, I. 1984. Modeling earthquake-induced fire loss. Proceedings of the Eighth World Conference on Earthquake Engineering. El Cerrito, Calif.: Earthquake Engineering Research Institute.

Reichle, M. S., J. F. Davis, J. E. Kahle, T. G. Atkinson, E. H. Johnson, R. A. Olson, H. J. Lagorio, K. V. Steinbrugge, and L. S. Cluff. In progress. Earthquake planning scenario for a magnitude 6.8 earthquake on the Silver Strand Fault, San Diego-Tijuana area. Sacramento: California Division of Mines and Geology.

Reitherman, R. 1985. Reducing the Risks of Nonstructural Earthquake Damage: A Practical Guide, 2d ed. Oakland, Calif.: Bay Area Regional Earthquake Preparedness Project.

Reitherman, R. 1986. Nonstructural Earthquake Hazards Mitigation for Hospitals. Washington, D.C.: FEMA.

Rogers, A. M., S. T. Algermissen, W. W. Hays, D. M. Perkins, D. O. Van Strien, H. C. Hughes, R. C. Hughes, H. J. Lagorio, and K. V. Steinbrugge. 1976. A Study of Earthquake Losses in the Salt Lake City, Utah Area. Open-File Report 76-89. Washington, D.C.: USGS.

Scawthorn, C. 1987. Fire Following Earthquake: Estimates of the Conflagration Risk to Insured Property in Greater Los Angeles and San Francisco. San Francisco, Calif.: Dames and Moore.

Scawthorn, C., and W. E. Gates. 1983. Estimation of Earthquake Losses in Los Angeles. San Francisco, Calif.: Dames and Moore.

Scawthorn, C., Y. Yamoda, and H. Iemura. 1981. A model for urban post-earthquake fire hazard. *DISASTERS, the International Journal of Disaster Studies and Practice* 5(2); London: Foxcombe Publications.

Schultz, P. 1983. California Division of Mines and Geology, Environmental Systems Research Institute, MESA-2, San Bernardino County, Southern California Association of Governments, TEMJAM Corporation, Pilot Project for Earthquake Hazard Assessment. Los Angeles: Southern California Earthquake Preparedness Project.

Seed, H. B. 1973. Landslides caused by soil liquefaction. Pp. 73–119 in The Great Alaska Earthquake of 1964. Washington, D.C.: National Academy of Sciences.

Seed, H. B., I. M. Idriss, K. L. Lee, and F. I. Makdisi. 1975. Dynamic analysis of the slide in the lower San Fernando dam during the earthquake of February 9, 1971. *ASCE Journal of the Geotechnical Engineering Division* 101(GT9):889–911.

Steinbrugge, K. V., and H. Lagorio. 1982. Earthquake Vulnerability of Honolulu and Vicinity: Secondary Threats and Credible Surprises. Honolulu: Civil Defense Division, State of Hawaii.

Steinbrugge, K. V., S. T. Algermissen, and H. J. Lagorio. 1984. Determining monetary losses and casualties for use in earthquake mitigation and disaster response planning. Proceedings of the Eighth World Conference on Earthquake Engineering. El Cerrito, Calif.: Earthquake Engineering Research Institute.

Steinbrugge, K. V., J. H. Bennett, H. J. Lagorio, J. E. Davis, G. Borchardt, and T. R. Topposada. In progress. Earthquake planning scenario for a magnitude 7.5 earthquake on the Hayward Fault in the San Francisco Bay area. Sacramento: California Division of Mines and Geology.

Steinbrugge, K. V., S. T. Algermissen, H. J. Lagorio, L. S. Cluff, and H. J. Degenkolb. 1981. Metropolitan San Francisco and Los Angeles Earthquake Loss Studies: 1980 Assessment. Open-File Report 81-113. Washington, D.C.: USGS.

Stratta, J. 1987. Manual of Seismic Design. Englewood Cliffs, N.J.: Prentice Hall.

Thiel, C., and T. Zsutty. 1987. Earthquake Parameters and Damage Statistics. San Francisco, Calif.: Forell/Elsesser Engineers.

URS/Blume Engineers. In progress. Boston and Anchorage studies, under way. Washington, D.C.: FEMA.

U.S. Geological Survey. In progress. A study of seismic hazard and losses in Utah is under way.

Veterans Administration. 1976. Study to Establish Seismic Protection Provisions for Furniture, Equipment, and Supplies for VA Hospitals. Washington, D.C.: Veterans Administration. (Developed by Stone, Marraccini and Patterson.)

Veterans Administration. 1981. Seismic Restraint Handbook for Furniture, Equipment, and Supplies. Washington, D.C.: Veterans Administration. (Developed by Reid and Tarics Associates.)

Whitman, R. V., N. S. Remmer, and B. Schumacker. 1980. Feasibility of Regulatory Guidelines for Earthquake Hazards Reduction in Existing Buildings in Northeast. Cambridge: Massachusetts Institute of Technology.

Wieczorek, G. F., R. C. Wilson, and E. L. Haup. 1985. Map showing slope stability duirng earthquakes in San Mateo County, California. Miscellaneous investigation map I-1257-E. Washington, D.C.: USGS.

Wilson, R. C., and D. K. Keefer. 1985. Predicting areal limits of earthquake-induced landsliding. Pp. 317–345 in Evaluation of Earthquake Hazards in the Los Angeles Region—An Earth-Science Perspective, J. I. Ziony, ed. Professional Paper 1360. Washington, D.C.: USGS.

Youd, T. L., and D. M. Perkins. 1987. Mapping of liquefaction severity index. *ASCE Journal of Geotechnical Engineering* 113(111):1374–1392.

Youd, T. L., J. C. Tinsley, D. M. Perkins, E. J. King, and R. R. Preston. 1978. Liquefaction potential map of San Fernando Valley, California. Pp. 268–278 in Proceedings of the Second International Conference on Microzonation for Safety Construction-Research and Applications, Vol. 1. Washington, D.C.: National Science Foundation.

Ziony, J. I., ed. 1985. Evaluating Earthquake Hazards in the Los Angeles Region—An Earth-Science Perspective. Professional Paper 1360. Washington, D.C.: USGS.

☆U.S. GOVERNMENT PRINTING OFFICE:1998-617-995/90586