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Plan for Developing and Adopting Seismic Design Guidelines and Standards for Lifelines

PLAN FOR DEVELOPING AND ADOPTING SEISMIC DESIGN GUIDELINES AND STANDARDS FOR LIFELINES

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PREFACE

Although earthquakes are an inevitable hazard, they are not inevitable disasters. Experiences in recent years have shown consistently that lifelines properly designed to resist earthquakes perform well in spite of severe earthquakes; those not so designed are subject to failure. Assessments of earthquake hazards indicate that one or more severe earthquakes can be expected to strike U.S. metropolitan areas in the next decade. Until actions are taken to improve the design and construction of lifelines, failures can be expected to result in substantial losses--estimated at billions of dollars and many lives for a single severe earthquake.

The plan described in this document defines a process that, if activated, will begin the development of seismic design guidelines and standards for both new and existing lifelines. The plan was prepared by the Federal Emergency Management Agency, in consultation with the National Institute of Standards and Technology, in response to Public Law 101-614, the National Earthquake Hazards Reduction Reauthorization Act.

ACKNOWLEDGMENTS

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Funding for developing this plan was provided by the Federal Emergency Management Agency. Additional support was provided by the National Institutes of Standards and Technology. The plan was prepared by Richard N. Wright, Robert D. Dikkers, and Riley M. Chung of the National Institute of Standards and Technology and by Gary D. Johnson, William S. Bivins, and Harold W. Andress, Jr., of FEMA.

EXECUTIVE SUMMARY

BACKGROUND AND OBJECTIVES

Lifelines are the public works and utility systems that support most human activities: individual, family, economic, political, and cultural. The various lifelines can be classified under the following five systems: electric power, gas and liquid fuels, telecommunications, transportation, and water supply and sewers.

This plan for developing and adopting seismic design and construction guidelines and standards for lifelines (hereafter referred to as the Plan) has been prepared in response to Public Law 101-614, the National Earthquake Hazards Reduction Program (NEHRP) Reauthorization Act. The act requires the Federal Emergency Management Agency (FEMA), in consultation with the National Institute of Standards and Technology (NIST), to develop "a plan, including precise timetables and budget estimates, for developing and adopting, in consultation with appropriate private sector organizations, design and construction standards for lifelines" and "recommendations of ways Federal regulatory authority could be used to expedite the implementation of such standards."

The Plan focuses on developing recommendations, encouraging and supporting the approval of these recommendations by the standards and professional organizations serving the lifeline community, and working with the lifeline community to achieve their effective implementation. The Plan is based on the technical input of experts from the private and public sectors who participated in a workshop held September 25-27, 1991, in Denver, Colorado. These experts determined that design guidelines and standards are needed to reduce the vulnerability of lifelines to earthquakes and that adequate knowledge bases exist or can be developed to produce them. The workshop produced a highly detailed approach for developing and implementing seismic standards and provided the technical detail upon which the current plan is based. The NEHRP Reauthorization Act also created the NEHRP Advisory Committee to advise the agencies on planning and implementing the Program (i.e., NEHRP). NIST and

FEMA have since worked closely with the NEHRP Advisory Committee to develop the final approach for this Plan.

Design guidelines lay out a set of principles, which for lifelines may include performance criteria, materials characteristics, and testing procedures for design, construction, maintenance, repair, and retro-fitting of both existing and proposed systems. Guidelines provide a basis for making judgments or determining a course of action; they may evolve into recommendations for standards. A standard, according to the National Standards Policy Advisory Committee, is "a prescribed set of rules, conditions, or requirements concerning definitions of terms; classification of components; specification of materials, performance, or operation; delineation of procedures; or measurement of quantity and quality in describing materials, products, systems, services, or practices."

Properly developed and effectively implemented lifeline seismic guidelines and standards will significantly reduce the vulnerability of both existing and proposed lifeline systems to future earthquakes. Guidelines and standards should (1) establish performance criteria for the construction, maintenance, and operation of existing and proposed lifeline systems, equipment, and materials for selected levels of seismic risk; (2) provide a basis for technical specifications for use by buyers and sellers of lifeline products and services to reduce the vulnerability of lifeline systems to earthquakes; and (3) provide a reliable basis for regulations to protect the public health, safety, and welfare.

THE NEED FOR LIFELINE SEISMIC DESIGN GUIDELINES AND STANDARDS

A large portion of the population of the United States lives in areas vulnerable to earthquake hazards. At least 39 of the 50 states are subject to major or moderate seismic risk.

Experiences in recent earthquakes show that lifeline systems not designed and constructed for earthquake resistance are subject to failure during earthquakes. Although loss of life and property damage are generally confined within the felt area of an earthquake, which can be quite large (as in the case of the Mexico City earthquake of 1985), economic losses caused by the failure of lifeline systems could be spread throughout the nation as a result of the close interdependency of its commercial activities.

Assessments of earthquake hazards indicate that one or more severe earthquakes can be expected to strike U.S. metropolitan areas in the next decade. Until actions are taken to improve the design and construction of lifelines, lifeline failures can be expected to result in substantial losses—estimated at billions of dollars and many lives for a single severe earthquake.

Although earthquakes are an inevitable hazard, they are not inevitable disasters. Experiences in recent years have shown consistently that lifelines properly designed to resist earthquakes perform well in spite of severe earthquake effects. For instance, San Francisco's Bay Area Rapid Transit system, which received special attention to seismic safety during its design, was functional immediately after the 1989 Loma Prieta earthquake. Yet currently, only in the case of highway bridges, nuclear power reactors, and dams do there exist nationally recognized guidelines and standards for the seismic design and construction of lifeline systems. The reason is that these are the areas where federal initiative has been undertaken to support design guidelines and standards development.

Federal initiative must be extended to all lifeline systems, not only because benefits extend broadly to private and public sector organizations but also because no single company, trade association, profession, or state can alone assume the costs of developing nationally applicable design guidelines and standards consistent among all the interdependent types of lifelines. Further, while voluntary private sector participation is essential to the success of the program, private organizations can justify their participation only if that participation is likely to produce timely results important to their respective businesses—that is, if when the developed guidelines and standards are properly implemented, the private sector organizations are benefited by the reduction of the seismic vulnerability of their existing and proposed lifeline systems, or by their ability to deliver better products and services for lifelines.

STRATEGY FOR DEVELOPMENT AND IMPLEMENTATION

There are diverse private and public sector responsibilities for the performance of lifeline systems. Seismic safety and functionality are two of many requirements for successful performance of lifelines. The Plan, therefore, calls for cooperation among existing organizations within the lifeline community in order to develop recommendations for seismic safety design guidelines and standards that are suitable for incorporation into the existing family of lifeline design guidelines and standards. These design guidelines and standards can be used voluntarily by lifeline organizations or referenced in regulations of local, state, or federal agencies.

Roles of Private and Public Sectors

A variety of private sector organizations must be directly involved in the development of recommendations for design guidelines and standards if they are to understand, have confidence in, and implement them effectively:

- The diverse owners—both private and public—of public works and utility systems are responsible for lifeline performance. Owning and operating organizations are vitally concerned with the efficiency and economy of lifeline design guidelines and standards.
- Manufacturers and suppliers of equipment and services for lifelines have high stakes in the development of recommendations for design guidelines and standards that will affect the market for their products and services.
- Design professionals have principal responsibilities for correctly interpreting and applying design guidelines and standards in the evaluation and retrofitting of existing lifelines and the design of new lifelines. These professionals and their research colleagues possess knowledge on the performance of lifelines in earthquakes.
- General and specialty contractors are responsible for correctly implementing design guidelines and standards in retrofitting and constructing lifelines. The constructability implications of recommendations for design guidelines and standards are critical to contractors and are best understood by them.

State, local, and federal government agencies have diverse responsibilities for lifeline performance as owners, regulators, guarantors of investments, and sources of information. It is in this last role that NEHRP will request funds to implement the Plan. The Plan provides mechanisms for the various governmental interests to be represented in the development and implementation of the recommendations for design guidelines and standards.

Cutting across both sectors are trade associations, technical societies, and professional societies, which aggregate the interests of owners, manufacturers, and suppliers and provide an efficient means of representing their interests in the development and implementation of recommendations for guidelines and standards. The Plan provides for such participation and uses as its principal implementation mechanism the existing standardization organizations.

The Recommended Approach to Guidelines and Standards Development

A cost-effective approach that will result in near-term implementation activities to reduce the current vulnerability of existing lifelines and simultaneously minimize the limitations that may exist in financial and human resources is being recommended. Such an approach takes into consideration limitations on resources; acknowledges particular features of lifelines that may have greater impact on loss of life, property damage, and economic consequences; and establishes a system of prioritization. It supports the timely and cost-effective development of guidelines and standards by focusing initially on the highest-priority types of lifeline systems, especially the performance of existing ones, for early realization of benefits to the public through demonstration projects. This approach has built-in flexibility resulting from the use of guidelines and standards prepared from current knowledge, their trial application in demonstration projects, and their successive improvement with experience.

A policy statement/strategy has been developed for the overall effort, and one will be developed for each lifeline system. The work will begin with an in-depth assessment of available research results, the state of system practices, and the vulnerability of lifeline systems to seismic effects. Work will begin on assessing and retrofitting existing lifelines by means of a generalized risk-based vulnerability assessment approach developed from the existing knowledge base. Lessons learned from the retrofitting of existing lifelines will be applied to the development of guidelines and standards for new lifeline systems. Participation by users and policy makers at the outset of the development process, especially in areas of demonstration projects, can provide vital support for the work of the technical community. Attention should be given to implementation strategies, education, and training during the development of guidelines and standards; the appropriate private sector standards development and professional organizations should be used as resources.

Management and Coordination

The approach calls for strong leadership; such a diverse and complex project will require very careful and skillful management and coordination. Such leadership will involve the NEHRP Lead Agency, NIST, and a group of private and public sector experts for lifeline seismic design guidelines and prestandards studies.

Close liaison will be maintained with the fundamental research programs of the National Science Foundation (NSF) and the U.S. Geological Survey (USGS) that are conducted under NEHRP. Research needs will be identified for NSF and USGS, and results of their research will be applied in the development of lifeline design guidelines and standards. Federal agencies outside NEHRP will also be involved in support of the project through the Interagency Committee on Seismic Safety in Construction (ICSSC).

The development and adoption of lifeline seismic design guidelines and standards will be carried out in two stages. The work in the first stage will be accomplished through a body called the Lifeline Seismic Safety Executive Board (hereafter referred to as the Board). The second stage will require sustained private sector standardization activities that must be carried out by the existing national standards groups and professional organizations, with assistance from the Board.

The Board will be made up of three components: the Board of Directors, the Lifeline Directorates, and the Executive Directorate.

The Board of Directors will consist of a chair, from the private sector, a representative of ICSSC and 12 to 15 technical experts recommended by major lifeline organizations. The membership of the Board of Directors must provide a balance between researchers and practitioners. The Board of Directors will define and address the needs and issues of all five lifeline systems to develop a prioritized overall program plan including the selection of demonstration projects.

The activities commissioned by the Board of Directors will be carried out by one of the Lifeline Directorates (hereafter referred to as the Directorates). A separate Directorate will be established for each of the five lifeline systems. The Directorates will address the specific issues and concerns in each lifeline category as well as conduct specific technical studies of relevance to the various lifelines. Each Directorate may have six to ten experts, selected by the Board of Directors.

The Executive Directorate will include a full-time director and staff selected by the *ad hoc* working group created by the NEHRP Lead Agency and NIST to form the LSSEB. This Directorate, supported by NIST, is to provide management and administrative support to the Board of Directors and the Lifeline Directorates.

The Board of Directors will establish a cooperative agreement with the ICSSC that, as a minimum, defines areas of common interest, establishes a subcommittee responsible for guiding joint activities, and appoints an ICSSC member to serve on each of the Lifeline Directorates.

Over the long term, the Lifeline Seismic Safety Executive Board's major functions and responsibilities will be as follows:

- To support the development and adoption of national voluntary consensus guidelines and standards

- To serve as an independent and technical authoritative focal point, working with the existing standards groups and professional organizations to ensure the development and application of private design guidelines and standards for lifelines

- To encourage lifeline industries and associated manufacturers, associations, and professionals to consider earthquakes and their impacts in the planning, design, construction, and operation of lifeline systems

- To develop recommendations, including priorities, for lifeline seismic safety guidelines and standards development, research, and implementation activities, including demonstration projects

- To conduct annual workshops to present progress reports and raise project-related issues and to encourage and obtain input from the industries and associated manufacturers' associations, standards groups, NEHRP, ICSSC, and professional organizations

- To submit an annual written report to the NEHRP Lead Agency, through NIST, on the progress and status of the project.

ICSSC can be a vital link in the implementation of these guidelines and standards through its member federal agencies. It will be represented on the Board of Directors and on each Lifeline Directorate, in accordance with the cooperative agreement discussed above. ICSSC also can play an important role in developing nationally applicable earthquake hazard reduction measures through its cooperative efforts with state and local governments and the private sector.

Work Plan

The process of developing and adopting seismic design guidelines and standards for lifelines begins with the establishment of the Board of Directors and the Executive Directorate. The Board of Directors will select the Lifeline Directorates' members and demonstration projects.

Demonstration projects are a key element in the process. They provide opportunities to show early success of the program. They also allow a concentrated effort, early on, on the performance of existing lifeline systems. Thus, priorities in the development of guidelines will be guided by the potential for demonstration projects.

The strategy is to learn from demonstration projects. It begins by categorizing lifelines both by nature and by size in order to select some for inclusion as early demonstration projects. From a comprehensive list, the Board will choose three to four instances, depending on the availability of resources. The selection should consider priorities for reducing earthquake hazards and for federal, state, and local government and industry collaboration.

These demonstration projects should be undertaken by full-time experts drawn from the Directorates, in collaboration with engineering organizations experienced in such projects and with consultants as appropriate. Collaboration in each demonstration project will be obtained from the affected industries and/or organizations before the projects proceed. Each project should include establishing the seismic hazard for several levels of probability; estimating the fragility of the various links and components; analyzing the implications of failure of the weakest links and components; developing a prioritized list for replacement and upgrading, including schedule and costs; and interacting with regulatory bodies and perhaps the public.

Draft guidelines should be prepared at the beginning of each of the demonstration projects. The result of each project will be an updated version, which should at that stage already be of potential practical use and which would become the starting point for subsequent projects and the prestandard—the starting point for standardization.

It is anticipated that in the early years of the project, the Board will be focusing on the development of prestandards and demonstration projects; in the latter years, it will be focusing on working with standards groups and professional organizations on the development and adoption of guidelines and standards. It is anticipated that at the end of the project, the Board will cease to exist unless it is deemed necessary by the NEHRP Lead Agency and NIST that the Board or an element of the Board be maintained for continued updates and consensus building.

Implementation

Education and implementation efforts should begin immediately when some lifeline prestandards are developed and ready for adoption by standards organizations through a consensus process. After the development of voluntary consensus lifeline seismic standards, NEHRP will assist the Board in promoting the implementation of such standards "by Federal, state, and local governments, national standards and model building codes organizations, architects and engineers, and others with a role in planning and constructing buildings and lifelines." Federal use of the standards will follow Office of Management and Budget (OMB) Circular A-119. To expedite the process, it is recommended that an executive order be drafted for the implementation of seismic standards for federal lifelines. However, it should be noted that a broadly applicable executive order will be infeasible before guidelines or standards are available for all types of federal lifelines. ICSSC also would have responsibility for recommending procedures for implementing the executive order pertaining to lifelines.

Funding and Scheduling

Funding to implement the Plan will be requested through separate budget requests by federal agencies with missions for support of research and development for lifeline guidelines and standards. Funds are needed to support NIST's role in managing the activities to be carried out by the Board and providing technical support to the implementation of the Plan. The majority of the funds will be used for private sector work to conduct the engineering studies of the Lifeline Directorates and demonstration projects.

The level of funding will depend on the stage of the project. Programmatic needs will be carefully reviewed annually, along with factors such as the support of full-time experts for each of the Directorates and the cost of conducting the demonstration projects, so that funding requests can be adjusted to develop lifeline seismic safety guidelines and standards expeditiously and efficiently.

The work by the Board and its Directorates is expected to take six to eight years to complete. However, for the more vulnerable lifeline systems identified and chosen as demonstration projects, only four years should be required to complete the work. It is estimated that standards for all five lifeline types will be completed and adopted for use in eight to ten years, through a well-coordinated effort including a comprehensive and aggressive education and training program.

CHAPTER 1: INTRODUCTION

1.1 OVERVIEW

This document has been prepared in response to the congressional mandate embodied in Public Law 101-614. The objective was to develop "a plan, including precise timetables and budget estimates, for developing and adopting, in consultation with appropriate private sector organizations, design and construction standards for lifelines" and "recommendations of ways Federal regulatory authority could be used to expedite the implementation of such standards." Such guidelines and standards would (1) establish performance criteria for the construction, maintenance, and operation of existing and new lifeline systems, equipment, and materials for selected levels of seismic risk; (2) provide a basis for technical specifications for use by buyers and sellers of lifeline products and services to reduce the vulnerability of lifeline systems to earthquakes; and (3) provide a reliable basis for regulations to protect the public health, safety, and welfare. The plan for developing and adopting these guidelines and standards will hereafter be referred to as the Plan.

Guidelines and standards development activities related to the five types of lifeline systems are presented. These systems are electric power, gas and liquid fuel, telecommunications, transportation, and water supply and sewers. Nuclear power facilities and dams are not included because seismic design requirements for these structures are covered under other federal programs.

This document has four chapters. Chapter 1 describes the consequences of earthquakes and specifically the vulnerability of lifelines to earthquake damage. It also provides a brief background discussion of the efforts, since the 1971 San Fernando earthquake, by both the private sector and the federal government in research and development for lifeline design guidelines and standards. The process of developing the Plan is described.

Chapter 2 elaborates on the lifeline systems' vulnerability to earthquake damage, with emphasis on the state of current practices for various types of lifelines. The critical roles played by the private and public sectors are discussed in Chapter 3.

The Plan is presented in detail in Chapter 4. Numerous issues critical to the success of such an approach are dealt with, including the emphasis on existing lifeline systems; risk-based system vulnerability concepts; the policy statement/strategy; the importance of strong leadership in management and coordination; guidelines and prestandards activities to begin the process; the creation of an organizational framework to guide the work; the development of demonstration projects; early implementation, including education and training; and the necessity of problem-focused research.

1.2 THE VULNERABILITY OF LIFELINES TO EARTHQUAKE DAMAGE

Among natural hazards, earthquakes can be the most devastating. The sudden release, without warning, of strains accumulated in a fault system causes a tremendous amount of energy to be dissipated in all directions through the propagation of seismic waves. As a result, several phenomena can be observed: A major earthquake may cause changes in elevation and surface ruptures over a large geographic area. Strong ground shaking may precipitate landslides and the liquefaction of loosely compacted and saturated sandy deposits. This temporary loss of soil bearing strength causes tilting, excessive settlement, or lateral spread of structures' foundations.

Seismic waves also affect structures. Structures resting on the ground are excited into vibration as a function of their frequency response to seismic waves. Low buildings and short and stiff bridges, which have higher response frequencies, will respond first to the incoming seismic waves, followed by tall buildings and long lifeline systems that have lower response frequencies. When the ground and the structure vibrate at or close to the same frequency, this resonance can cause local amplification of ground shaking and lead to severe damage or total collapse of inadequately designed and constructed structures.

A large portion of the population of the United States lives in areas vulnerable to earthquake threat. At least 39 of the 50 states are subject to major or moderate seismic risk. Experiences in recent earthquakes show that lifeline systems not designed and constructed for earthquake resistance are subject to failure when exposed to earthquakes. Although loss of life and property damage are generally confined within an earthquake's felt area, which can be quite large (as in the case of the Mexico City earthquake of 1985), economic losses caused by the failure of lifeline systems could be spread throughout the nation as a result of the close interdependency of its commercial activities.

Assessments of earthquake hazards indicate that one or more severe earthquakes can be expected to strike the nation's metropolitan areas in the next decade. Until actions are taken to improve the design and construction of lifelines, lifeline failures can be expected to result in substantial losses—estimated at billions of dollars and many lives for a single severe earthquake. Although earthquakes are an inevitable hazard, they are not inevitable disasters. Experiences in recent years have shown consistently that lifelines properly designed to resist earthquakes perform well in spite of severe earthquake effects. For instance, San Francisco's Bay Area Rapid Transit system, which received special attention to seismic safety during its design, was functional immediately after the 1989 Loma Prieta earthquake. Yet currently, only in the case of highway bridges, nuclear power reactors, and dams do there exist nationally recognized guidelines and standards for the seismic design and construction of lifeline systems. The reason is that these are the areas where federal initiative has been undertaken to support design guidelines and standards development.

1.3 THE NEED FOR LIFELINE SEISMIC DESIGN GUIDELINES AND STANDARDS

Federal initiative must be extended to all lifeline systems, not only because benefits extend broadly to private and public sector organizations but also because no single company, trade association, profession, or state can alone assume the costs of developing nationally applicable design guidelines and standards consistent among all the interdependent types of lifelines. Further, while voluntary private sector participation is essential to the success of the program, private organizations can justify their participation only if that participation is likely to produce timely results important to their respective businesses—that is, if when the developed guidelines and standards are properly implemented, the private sector organizations are benefited by the reduction of the seismic vulnerability of their existing and proposed lifeline systems, or by their ability to deliver better products and services for lifelines.

1.4 LIFELINES IN THE NATIONAL EARTHQUAKE HAZARDS REDUCTION PROGRAM

On November 16, 1990, the President signed into law Public Law 101-614, the National Earthquake Hazards Reduction Program Reauthorization Act. It amended the 1977 Earthquake Hazards Reduction Act, which had established the National Earthquake Hazards Reduction Program (NEHRP). The purpose of the act is to reduce the risks to life and property in the United States from future earthquakes through the establishment and maintenance of an effective earthquake hazards reduction program. NEHRP's objectives are:

- The education of the public, including state and local officials, as to earthquake phenomena; the identification of locations and structures that are especially susceptible to earthquake damage; the pinpointing of ways to reduce the adverse consequences of an earthquake; and related matters

- The development of technologically and economically feasible design and construction methods and procedures to make new and existing structures in areas of seismic risk earthquake resistant, giving priority to the development of such methods and procedures for power-generating plants, dams, hospitals, schools, public utilities and other lifelines, public safety structures, high-occupancy buildings, and other structures that are especially needed in time of disaster

- The implementation, to the greatest extent practicable, in all areas of high or moderate seismic risk, of a system (including personnel, technology, and procedures) for predicting damaging earthquakes and for identifying, evaluating, and accurately characterizing seismic hazards

- The development, publication, and promotion, in conjunction with state and local officials and professional organizations, of model building codes and other means to encourage consideration of information about seismic risk in making decisions about land-use policy and construction activity

- The development, in areas of seismic risk, of improved understanding of, and capability with respect to, earthquake-related issues—including methods of mitigating the risks from earthquakes, planning to prevent such risks, disseminating warnings of earthquakes, organizing emergency services, and planning for reconstruction and redevelopment after an earthquake

- The development of means of increasing the use of existing scientific and engineering knowledge to mitigate earthquake hazards

- The development of strategies that will ensure the availability of affordable earthquake insurance.

A major accomplishment of NEHRP is the development of the *NEHRP Recommended Provisions for Development of Seismic Regulations for New Buildings* [1]. The recommended provisions have led to the incorporation of up-to-date seismic design and construction provisions in nationally recognized voluntary consensus standards for new buildings and the three model building codes that provide the bases for the building regulations of most state and local governments. These provisions have also provided an effective means of implementing research results in building practices. Meanwhile, the research community—through fundamental research programs of the National Science Foundation (NSF) and the U.S. Geological Survey (USGS)—has responded to the need for knowledge that was revealed in the development of the NEHRP provisions.

This Plan for seismic design guidelines and standards for lifelines is based on this successful experience in cooperative private and public sector activities for building standards in NEHRP.

Specifically, Section 8(b) of Public Law 101-614 states:

> LIFELINES—The Director of the Agency [Federal Emergency Management Agency], in consultation with the Director of the National Institute of Standards and Technology, shall submit to the Congress . . . a plan, including precise timetable and budget estimates, for developing and adopting, in consultation with appropriate private sector organizations, design and construction standards for lifelines. The plan shall include recommendations of ways Federal authority could be used to expedite the implementation of such standards.

In response to this mandate, the Federal Emergency Management Agency (FEMA), in consultation with the National Institute of Standards and Technology (NIST), representatives of the federal and private sector and NEHRP's Advisory Committee, developed the Plan.

1.5 BACKGROUND FOR THE DEVELOPMENT OF LIFELINE SEISMIC DESIGN GUIDELINES AND STANDARDS

The 1971 San Fernando, California, earthquake demonstrated the vulnerability of lifelines. Modern highway bridges collapsed, and water supply and electricity were lost in the affected areas. In 1974, the American Society of Civil Engineers (ASCE) established its Technical Council on Lifeline Earthquake Engineering (TCLEE) to elevate the state of the art of lifeline earthquake engineering. Under NEHRP, NSF has sponsored substantial research efforts on lifelines. Since NSF's establishment of the National Center for Earthquake Engineering Research (NCEER) in 1986, NCEER has devoted a major segment of its program to lifeline research.

NEHRP has focused on buildings in its initial efforts to develop seismic safety practices. Seismic standards for lifelines have received limited and fragmentary attention. The Federal Highway Administration (FHWA) has supported the development of seismic design standards for highway bridges, which have been incorporated in the national standards of the American Association of State Highway and Transportation Officials (AASHTO), and the Interagency Committee on Dam Safety has recommended practices for the seismic safety of dams. TCLEE has produced *Advisory Notes on Lifeline Earthquake Engineering* [2] and *Guidelines for the Seismic Design of Oil and Gas Pipeline Systems* [3], but these are not definitive design and construction standards.

In 1985, FEMA asked the National Institute of Building Sciences (NIBS), the parent organization of the Building Seismic Safety Council (BSSC), to prepare a plan to reduce seismic hazards to new and existing lifelines [4]. Under the direction of a BSSC action plan committee, specialists in all lifeline categories and in legal/regulatory, political, social, economic, and seismic risk aspects of lifeline hazard mitigation were invited to prepare issue papers. Forty-two issue papers were circulated among peers and were the basis of discussions by the 65 participants at a workshop held November 5-7, 1986, in Denver. The major product of the workshop was a plan titled *Abatement of Seismic Hazards to Lifelines: An Action Plan* [5].

The BSSC plan recommended actions in four areas: (1) public policy and legal and financial strategies; (2) information transfer and dissemination; (3) emergency planning; and (4) scientific and engineering knowledge. Most of the recommended activities concerned the enhancement of scientific and engineering knowledge (e.g., improvement of geotechnical knowledge; increase in knowledge of performance of specific components; development of improved equipment and materials for use in seismic-resistant construction; development of design criteria, codes, and standards of practice for design, construction, and retrofitting of seismic-resistant lifeline facilities). However, the action plan did not focus on the systematic development and adoption of seismic design guidelines and standards for all types of lifelines, existing and new.

In 1989, the NIBS Ad Hoc Panel on Lifelines recommended that FEMA undertake a national coordinated program to mitigate the effects of earthquakes and other natural hazards on lifelines [6]. Recommended activities included awareness and education, vulnerability assessment, design criteria and standards, regulatory policy, and continuing guidance.

As indicated by the NIBS ad hoc panel, "design criteria and standards for lifeline hazard mitigation provide consistent minimum recommended levels of facility engineering design and construction practice. They identify natural hazard abatement techniques and practices for those responsible for all phases of lifeline design, construction, and operation and serve as the basis for model code provisions, which can be considered by local, state, and federal regulatory bodies for adoption into ordinances and regulations."

1.6 PLANNING FOR THE DEVELOPMENT OF LIFELINE SEISMIC DESIGN GUIDELINES AND STANDARDS

The Plan was prepared by FEMA, in consultation with NIST. Technical input, guidance, and resources were provided by ASCE's TCLEE, NCEER, other private sector organizations, several agencies of the Interagency Committee on Seismic Safety in Construction (ICSSC), and the NEHRP Advisory Committee. Individual contributors to the Plan are listed in the appendix.

1.7 REFERENCES

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CHAPTER 2: VULNERABILITY AND CURRENT PRACTICES

2.1 VULNERABILITY STUDIES

How much loss might a city or region experience from future earthquakes? 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 effects will be on a wide variety of buildings and structures of different ages and conditions. However, it is possible to make estimates that will indicate the nature and magnitude of the problem faced by a city or region. These estimates are referred to as vulnerability studies.

Lifeline experts propose conceptual breakdowns of lifeline systems as a basis for developing design, construction, and retrofit standards. Each system is broken down into elements (which may also be considered major subsystems) and possibly into components (individual items of equipment or closely integrated equipment) to determine its vulnerability to earthquakes.

2.1.1 The Conterminous United States

In September 1988, the Applied Technology Council (ATC), with support from the Federal Emergency Management Agency, initiated an assessment of the seismic vulnerability of lifeline systems nationwide. The purpose of the project was to develop a better understanding of the impact of lifeline disruption caused by earthquakes and to assist in the identification and prioritization of hazard mitigation measures and policies [1].

Four basic steps were followed to estimate lifeline damage and subsequent economic disruption for given earthquake scenarios: development of a national lifeline inventory database; development of seismic vulnerability functions for each lifeline system or system component; characterization and quantification of the seismic hazard nationwide; and development of estimates of direct damage and of indirect economic loss for each scenario earthquake.

Several problems were encountered that could not be resolved because of technical difficulties and lack of available data. For example, telecommunication systems, nuclear and fossil fuel power plants, dams, and certain water, electric, and transportation facility types at the regional transmission level were excluded from consideration because of the unavailability of inventory data or the need for more in-depth studies.

Interaction effects between lifelines, secondary economic effects (the impact of a reduced capacity of one economic sector on a dependent sector), and damage resulting from landslides also could not be considered because of a lack of inventory data nationwide. These and other limitations tend to underestimate the losses. Other factors in the study tend to overestimate the losses. Lack of capacity information for most lifelines was also a definite limitation. In the aggregate, the estimates of losses presented are considered to be quite conservative. Some of the study findings for eight scenario earthquakes are summarized below.

Direct-damage losses to regional networks and local distribution systems would range from \$1.2 billion for a Wasatch Front scenario to nearly \$10 billion for a New Madrid (surface wave magnitude [M_s] = 8.0) scenario. Under the other six scenarios, direct-damage losses would range from \$2.8 billion to over \$3.7 billion. (These figures are obtained by summing the values in Tables 2.1 and 2.2.) Indirect economic losses would range from \$3.9 billion for a Wasatch Front scenario to \$14.6 billion for a New Madrid (M_s = 8.0) scenario (Table 2.3).

Human death and injury due to the functional curtailment of lifelines generally can be expected to be very low. However, casualties could result from direct damage, especially catastrophic collapse of lifeline components. Lifeline failures that could cause substantial loss of life and injuries include bridge failure, railroad derailment, and pipeline failure. Unfortunately, data for estimating death and injury associated with these component failures are not available.

2.1.2 The Regional Level

Regional vulnerability studies, sponsored by FEMA, USGS, and NSF, that have estimated all losses in a region resulting from an earthquake have been performed in various parts of the country. Studies that have included some type of lifeline vulnerability estimate have been done for the following regions, ranked in order of their comprehensiveness in addressing lifelines [2]:

1. Southern California
2. Northern California
3. The New Madrid seismic zone
4. The Wasatch Front area in Utah
5. The Pacific Northwest, including Seattle, Washington, and Portland, Oregon
6. The Charleston, South Carolina, area
7. The Northeast, including Boston, Massachusetts.

Since the early 1970s, at least 20 published reports have focused on earthquake losses or reliability assessment of lifelines. Of these, at least one-third have focused on California. In addition, probably an equal number of studies have been performed for private sector entities, such as utility companies, and have not reached the general research community. Only a handful of studies, however, provide quantitative estimates of losses or vulnerability. Fewer consider the secondary, or indirect, effects of lifeline failures.

The findings of the studies [3-6] that provide quantitative estimates of regional vulnerability can be summarized as follows: for the city of Everett, Washington, direct lifeline losses ranging from \$100 million to \$304 million and indirect lifeline losses ranging from \$32 million to over \$136 million for a range of earthquake scenarios (M_s = 6.5 to 8.25); for St. Louis city and county, Missouri, direct lifeline losses of \$690 million for an M_s = 7.6 earthquake and \$1.062 billion for an M_s = 8.6; for the metropolitan Boston area, direct lifeline losses of \$156 million (plus 53% loss of functionality for oil) in an M_s = 6.25 earthquake; and for six cities in the central United States in the New Madrid seismic zone, direct lifeline losses of \$5.5 billion for an M_s = 7.6 earthquake and over \$8.1 billion for an M_s = 8.6.

Some studies have estimated numbers of breaks or service leaks or the percentage of disruption, and others have provided qualitative statements of lifeline vulnerability. In almost all cases where quantitative losses have been estimated, the largest direct losses are attributed to either transportation or electric power systems.

To a large extent, the data collected from the 1971 San Fernando and 1989 Loma Prieta earthquakes substantiate these relative vulnerabilities. In the 1971 San Fernando earthquake, direct damages to the electric power and transportation systems were among the highest. For electric power systems, direct losses exceeded \$33 million. In comparison, direct losses to natural gas systems were approximately $2 million. In the 1989 Loma Prieta earthquake, as well, the more significant direct losses were associated with electric power and transportation system failures.

2.2 LIFELINE SYSTEM VULNERABILITY

2.2.1 Electric Power Systems

The dependence of modern society on electric power becomes clear if power is lost for any reason; it is obvious to any individual from personal experience. But there are more subtle effects on community services and industry. In many respects, power systems are the lifelines to other lifelines. Because of the reliability of power systems in the United States, emergency power is typically provided only to those functions that would cause an immediate life-safety threat should there be a loss of power. Typically, emergency power is provided only for the control of systems so that they can be safely managed, rather than for their continued operation.

Many water systems are dependent on pumps to maintain pressure, so that a loss of power will quickly cause a drop in water pressure and flow. This can be critical for fire control and suppression after an earthquake. Even in the case of gravity-feed water systems, water treatment facilities require electric power for their control and operation; there can be a loss of water quality and safety with a loss of power.

Transportation systems would be severely affected by the loss of power. Mass transit in many large cities is directly powered by electricity. With the loss of power, traffic signals do not operate, so that urban transportation is severely disrupted. Liquid fuels that are used to power most motor vehicles would be useless without power to pump fuel from storage tanks to the vehicles.

While telephone systems are designed with emergency power backup, the introduction of optical fibers in user loops poses a new problem. These systems are often powered by batteries that are not provided with emergency recharging facilities. As a result, the impact of power disruption on telephone communications may be much more severe than it was in past earthquakes.

The impact of the loss of power on communities can also be severe. The loss of light would disrupt most business operation. The impact on computers, which permeate modern commerce, would be extreme. While most large data processing centers have emergency power so that the system can be safely shut off, terminals, such as those used by the banking system, would not operate. Within the home there would be a loss of refrigeration. Power losses longer than a day would cause severe health problems. Most heating systems will not operate without electricity, even if the primary energy source is gas. Under severe winter conditions this would result in extensive freezing of water pipes and severe exposure of persons in unheated buildings.

Electric power system seismic performance in the United States, as measured by power disruption, has been very good for the small and moderate earthquakes experienced to date. Network redundancy has been adequate to overcome the extensive damage to isolated high-voltage substations. In the case of the Loma Prieta earthquake, where several substations were damaged, the character of the damage and the use of emergency procedures made it possible to restore most service in less than one day.

Damage to power distribution systems has also occurred, but this has caused only localized disruption. Its occurrence is not well documented.

The major cause of power system damage to date has been the effect of induced vibration. Liquefaction has the potential to cause power system damage, but in the few cases where power facilities have been directly affected by liquefaction, its consequences have been minor. The effects of landslides, subsidence, ground faulting, and tsunamis on power systems have been minor. However, many power-generating stations are on shorelines, so tsunamis may have a potential damaging effect.

Since most damage observations in the United States have been limited to California earthquakes, extrapolation of power-system performance to large and great earthquakes must take several factors into consideration:

- There are no data from a great or major earthquake centered in a modern metropolitan area.

- Seismic design practices in California have been evolving since the 1920s; since the 1933 Long Beach earthquake, an impetus has been given to the seismic design of California power facilities.

- An earthquake occurring in most any region outside California will affect a larger area than an earthquake of the same magnitude occurring within California.

- Liquefaction may cause more damage to power-generating facilities than has been observed in California.

- California and many other seismically active regions of the world do not have coal-fired generating stations, so the seismic performance of these facilities is untested.

- Some power systems outside California have higher operating voltages. The seismic vulnerability of substation equipment (especially porcelain members) increases with its operating voltage.

2.2.2 Gas and Liquid Fuel Systems

Gas and liquid fuel systems provide energy for transportation as well as for electric power generation and the production of necessary goods and services, including heating in cold environments. In areas directly affected by a destructive earthquake, the general public could be adversely affected by the shutdown of oil and gas transmission lines, damage to gas distribution systems, or interruption of electric power generation due to loss of fuel supply. The lack of a fuel source can also pose a serious problem for many industrial facilities. Curtailed operation of such facilities affects not only the companies involved but the public served by or dependent upon the company's product or service. The monetary losses and social disturbance attributable to a shutdown can be substantial, especially if the disruption in service is for a significant period of time.

Earthquake damage to oil and gas transmission lines also may have an adverse effect on the populace hundreds of miles from the stricken area. For example, a number of pipelines transporting crude oil, crude oil products, and natural gas pass through the central United States within and adjacent to the New Madrid seismic zone in southeastern Missouri and northeastern Arkansas. The amount of crude oil transported by three pipelines that pass near or within the New Madrid seismic zone is estimated to be 1.4 million barrels per day, or about one-half the total amount delivered to refineries in the Midwest. In the case of natural gas, there are about 18.5 million residential customers in the Midwest and Northeast (8.8 and 9.7 million customers, respectively). About 70% of the Midwest gas and 60% of the Northeast gas is transported by pipelines that pass through or near the New Madrid region. Consequently, a major earthquake in the New Madrid area could cause shortages to as many as 18.5 million customers, with the relative impact depending to a large degree on time of year and weather conditions.

The effect on the national energy supply of earthquake damage to transmission pipelines in the New Madrid seismic zone is difficult to assess. Interruptions in crude oil delivery would not be immediate because some inventory would be held downstream in refineries. Normally, inventories on the order of two to three weeks should be available. However, the recurrence of a great earthquake in the New Madrid area that resulted in widespread liquefaction or catastrophic slides could leave a number of pipelines out of service for a longer period of time.

The earthquake consequences for gas transmission lines are similar to those for liquids lines, except that the potential impact on customers is more immediate, especially if the seismic event occurs in the winter. Only limited storage facilities are available to accommodate peak period usage.

The consequences of pipeline rupture differ for gas and liquid fuel pipelines. The principal concerns for natural gas transmission and distribution pipelines are explosion and fire, which could be a threat to public safety and could mean loss of service to customers. Environmental concerns are virtually nonexistent, because the release of natural gas to the atmosphere is generally inconsequential.

For crude oil or liquid oil product pipelines, the explosion and fire hazard is diminished considerably, but the potential release of crude oil or liquid products into watersheds and groundwater and the potential contamination of water supplies are serious environmental and health issues. The loss of service to customers is also an important concern but is secondary to the environmental threat.

Gas and liquid fuel transmission and distribution systems traverse large geographic areas and thus may encounter a wide variety of seismic hazards and soil conditions. The major seismic hazards that can significantly affect gas and liquid fuel systems are:

- Fault movement
- Liquefaction (lateral spreading, flow slides, loss of support, buoyancy)
- Landslides
- Ground shaking
- Tsunamis or seiches

The various components of gas and liquid fuel systems are affected by seismic hazards in different ways. For example, ground shaking and subsidence are major concerns for above-ground components, such as buildings and storage tanks, but are of little concern for buried pipelines. Faulting, liquefaction, and landslide hazards, on the other hand, can often be avoided for above-ground structures by careful siting but cannot always be avoided for buried pipelines. In coastal areas, tsunamis or seiches are potential hazards for marine terminal facilities.

Other potential seismic hazards, which are less likely to damage welded steel pipelines, include seismic wave propagation and subsidence.

2.2.3 Telecommunication Systems

There have been two major telecommunication system failures in recent years. While neither of them was earthquake-related, both demonstrated the potential impact of telecommunication disruption. The impact was widespread—six states, three airports, transatlantic long distance. One of these failures was caused by software, while the other was caused by power failure. The impact lasted only a few hours, since there was no physical damage to the equipment. The consequences of earthquake-related disruption with resultant damage to components in the telecommunication system would be many times more severe than the two incidents described above. The cost associated with the damage, both direct and indirect, would be huge. Emergency services and reconstruction efforts would be impaired. A damaged node in the network could cripple other states that are not considered seismically active. National security would be affected if communication was lost.

The earthquake performance of telecommunication systems has been satisfactory on the West Coast. However, the same cannot be said for potential performance on the East Coast and in the Midwest. Advances in technology have added more concentration and less dispersion to the system, thereby making it more vulnerable. The so-called redundant system in most cases is not truly redundant, since the cables—copper and fiber-optic—share the same route or the same conduit. Computers deployed in the network to facilitate network management are not protected against earthquake load. Failure of this equipment could impair the function of the network. In some cases, communications would be lost.

Little is known about the overall vulnerability of the telecommunication system. Several activities have been recommended to begin to remedy this situation.

A common occurrence in the telecommunication system during an earthquake is focused overload. A system is not designed to handle calls above its capacity, which is set according to the traffic patterns of each central and toll office. It is not cost-effective to provide full-capacity connectivity to all subscribers when the highest demand at peak periods is only a small percentage of full-capacity connectivity. Overload can be minimized by educating the public. They should be aware that indiscriminate use of the phone during and after earthquakes may cause hardship for people who need assistance and that the phone should be used for emergencies only; and they should know to place receivers back on the hook when they are knocked off by an earthquake. This information can be disseminated by the telecommunication industry.

Telecommunication operators can use network management features to direct or manage traffic to avoid overload. However, since the trend is toward unmanned offices, activating a special function for overload control may require human intervention. An alert mechanism should be in place to prompt key individuals to monitor and execute special functions (e.g., for essential services) in an emergency.

As signaling and circuit connection path functions are being performed less and less by switching equipment and more commonly by newer technology, the redundancy inherent in the existing system is greatly reduced. This will increase potential vulnerability unless compensated by sufficient redundant routes.

2.2.4 Transportation Systems

The consequences of failure in a transportation lifeline due to an earthquake or other natural disaster can involve:

- Direct loss of life due to collapse or structural failure of the lifeline
- Indirect loss of life due to an inability to respond to secondary catastrophes, such as fires, and/or provide emergency medical aid
- Delayed recovery operations
- Release of hazardous products (e.g., losses from tank cars derailed by track failure, gas leaks from ruptured utility lines)

- Direct loss of property and utility service (e.g., the collapse of a bridge carrying utilities)

- Losses due to interruption of access (e.g., export losses due to port damage)

- Disruption of economic activity across the nation as well as in the community directly affected.

Although transportation lifeline disruption or failure is not considered a major risk to life safety, the socioeconomic consequences can be particularly devastating to the general public. These include the primary impacts that flow directly from impeded access to hospitals, evacuation areas, emergency relief centers, and fire departments, and the secondary impacts due to closed mass-transit facilities and the inability to get to or from work for an extended period of time.

With the exception of systems in California, few transportation lifelines in the United States have been designed for earthquakes. As a consequence, their vulnerability to seismic loads is high and, in some cases, critically so. It is recognized that if a moderate earthquake of the past were to recur on the East Coast today, major if not crippling losses would be sustained.

Outside California, the probability of occurrence of a damaging earthquake is low, but the consequences of such an event would be very great, far greater than the consequences of such an event within California. Such a situation is the direct result of an absence of nationally applicable seismic design standards for transportation lifelines. However, the situation is further aggravated by the deteriorating state of the nation's infrastructure, which includes most of the transportation lifelines. Furthermore, many of these lifelines fall under multiple jurisdictions, both public and private, and many are dependent on each other or located in parallel arteries. Should one fail, others might fail as a consequence—the domino effect.

Historically, bridges have proved to be vulnerable to earthquakes, sustaining damage to substructures and foundations and in some cases being totally destroyed as substructures fail or superstructures are unseated from their supporting elements. In 1964 nearly every bridge along the partially completed Cooper River Highway in Alaska was seriously damaged or destroyed. Seven years later, the San Fernando earthquake damaged more than 60 bridges on the Golden State Freeway in California. It is estimated that it cost the state approximately $100 million to repair and replace these bridges, including the indirect costs due to bridge closures. In 1989, the Loma Prieta earthquake in Northern California damaged more than 80 bridges in a five-county region and caused the deaths of more than 40 people in bridge-related collapses alone. The cost of the earthquake to the transportation system was $1.8 billion, of which the damage to state-owned viaducts was about $200 million and the damage to other state-owned bridges was about $100 million.

Pavements are also vulnerable to earthquake damage, due principally to ground failure such as liquefaction. Recent examples include the failure of the approaches to the San Francisco-Oakland Bay Bridge in October 1989 and the closure of the highway between Limón and San José in Costa Rica due to the Valle de la Estrella earthquake of April 1991. Pavements can also be damaged as a result of fault rupturing, as observed during the Hebgen Lake earthquake in Montana in 1959.

Landslides are another common reason for highway closure, especially in mountainous regions. Slides occurred in Montana (1959), on Highway 17 in California during the Loma Prieta earthquake (October 1989), and also in the Philippines (Baguio, 1990).

Although railroad systems suffer damage similar to that suffered by highways, their operation is much more sensitive to permanent ground deformation than highway operation is. A survey of damage to railroad components during past earthquakes in the United States and Japan shows damage to bridges, embankment failures, vertical and horizontal track misalignments, tunnel misalignments, failure of tunnel linings, structural damage to railroad buildings, and overturned rail cars and locomotives.

Mass-transit systems have generally behaved well during large earthquakes (Mexico City, 1985, and San Francisco, 1989). This is most probably because they are essentially buried structures, and few lines actually cross active faults. However, loss of electric power can disrupt service, as it did in San Francisco during the Loma Prieta earthquake of 1989.

Ports and waterways are, by their nature, constructed on soft, saturated sites that are susceptible to site amplification effects and/or soil failure. Historically, damage due to earthquakes has included flooding due to tsunamis (Anchorage, 1964), massive flows and flooding due to liquefaction (Seward, Prince William Sound, 1964), and structural damage to wharves and container cranes (Oakland, 1989). Even relatively minor damage can close a port for an extended period of time, and loss of export revenue can have a crippling effect on some economies (e.g., Chile, 1985).

Failures of airport runway pavements have occurred in the past because of ground deformation and/or liquefaction effects. In 1989, 3000 feet of the north end of the 10,000-foot runway at Oakland Airport was damaged as a result of liquefaction, causing the closure of that section of the runway. Flight operations were not severely affected, because an adequate length of runway remained undamaged. At San Francisco Airport, however, damage to the windows and contents of the control tower caused temporary closure of the facility, followed by restricted operations for a period of 36 hours. The airport terminal building also experienced widespread secondary damage to nonstructural components. The potential for severe structural damage appears to be lower for airports than for other transportation systems, principally because the basic components are pavements and buildings. However, even minor structural damage can cause closure of a facility and severely impede recovery efforts. Current building codes are life-safety oriented and do not protect against damage to secondary, or nonstructural, components. Control centers at airports or at en route centers are particularly vulnerable to contents damage and consequential loss of operation. Similarly, loss of electric power, telecommunication, or radar equipment due to relatively minor structural damage can have a major impact on both local and regional air traffic operations.

2.2.5 Water and Sewer Systems

The disruption of water and sewer lifelines could seriously affect emergency facilities, fire suppression systems, telecommunication systems, water supplies, sewers, and sewage treatment plants.

- Emergency facilities: Water could be unavailable to serve emergency facilities. Hospitals in Santa Cruz, California, lost their water supplies in the 1989 Loma Prieta earthquake.

- Fire suppression systems: The loss of water systems would greatly increase the risk of conflagration, which is potentially more destructive than the earthquake itself. Following moderate earthquakes, water systems for fire suppression have not been functional in critical areas (San Francisco, 1906, 1989; Olympia, Washington, 1949; Seattle, Washington, 1965; and Santa Cruz, California, 1989).

- Telecommunication systems: The cutoff of water supplies with the resulting shutdown of cooling systems could render computer-dependent telecommunication systems inoperable.

- Water supplies: If distribution systems were damaged, drinking water would have to be trucked in until the water system could be restored. Businesses would have to remain closed until water service was restored because of health and fire hazards.