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Earthquake-Resilient Lifelines: NEHRP Research, Development and Implementation Roadmap

NEHRP Consultants Joint Venture
A partnership of the Applied Technology Council and the Consortium of Universities for Research in Earthquake Engineering

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National Institute of Standards and Technology
U.S. Department of Commerce

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Cover image – Balboa Blvd. after the 1994 Northridge earthquake. This is an example of collocation of lifelines. Lateral spreading damaged water and gas distribution mains and wastewater pipelines, and affected a 600-mm gas trunk line, two 750-mm gas transmission lines, 400-mm petroleum transmission pipeline, 1240-mm water trunk line, and 1730-mm water trunk line. Gas escaping from the ruptured 600-mm gas pipeline ignited, burning several homes. The water trunk lines failed, flooding parts of the neighborhood, and cutting off a substantial part of the water supply to San Fernando Valley. The fire in the photo is from a 150-mm gas distribution line. The fire from the 600-mm gas trunk line was over 50 m high, destroying overhead electric distribution lines. (Photo credit: MCEER, State University of New York at Buffalo)

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By
NEHRP Consultants Joint Venture
A partnership of the Applied Technology Council and the
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Preface

In September 2012 the NEHRP Consultants Joint Venture, a partnership of the Applied Technology Council (ATC) and the Consortium of Universities for Research in Earthquake Engineering (CUREE), commenced a task order project under National Institute of Standards and Technology (NIST) Contract SB1341-07-CQ-0019 to develop a National Earthquake Hazards Reduction Program (NEHRP) Research and Implementation Earthquake-Resilient Lifelines Roadmap. The primary objective of this task order was to develop a 10-year research, development, and implementation roadmap for generating new model earthquake-resilient design and construction standards for key lifeline systems and components.

The starting point for the roadmap development process was an initial effort to identify and summarize needed research, development, and implementation activities for lifelines in the areas of electric power, gas and liquid fuels, water, wastewater, telecommunications, transportation networks, lifeline interdependencies, and social, economic and institutional issues. This task was shared by members of the Project Technical Committee and Project Review Panel, who were asked specifically to focus on earthquakes, but also to consider multi-hazard exposure and resilience. The initial list of proposed research, development, and implementation activities then went through several rounds of review and refinement, including a joint meeting of members of the Project Technical Committee and Project Review Panel in December 2013.

A working draft of the roadmap was then prepared and distributed to a larger group of specialists from lifeline companies, lifeline industry organizations, local government officials, leading practitioners and academics, and representatives from insurance, finance, and key government agencies for review and discussion at a two-day workshop convened in May 2014.

The NEHRP Consultants Joint Venture is indebted to the leadership of Thomas D. O'Rourke, who served as Project Technical Director, and to the members of the Project Technical Committee, consisting of Laurie Johnson (Lead Editor), Craig A. Davis, Leonard Duenas-Osorio, Anne S. Kiremidjian, Alexis Kwasinski, Michael Mahoney (ex-officio), Stuart Nishenko, Douglas J. Nyman, Chris D. Poland, and Alex K. Tang, for their contributions in developing this report and the resulting recommendations. The members of the Project Review Panel, who were charged with reviewing the roadmap during the various stages of development and ensuring that technical results were accurate, are also gratefully acknowledged. These individuals consisted of Donald Ballantyne, Lloyd S. Cluff, C. B. Crouse, Andre Filiatrault, Douglas G. Honegger, Stephen A. Mahin, Michael J. O'Rourke, Charles Scawthorn, Kathleen Tierney, and Yumei Wang. Appreciation is also extended to the many individuals who participated in the roadmap review workshop in Oakland, California, in May 2014 and to Yousef Bozorgnia and the other individuals who provided material for the roadmap. The names and affiliations of all who contributed to this report are provided in the list of Project Participants and the list of Workshop Participants.

The NEHRP Consultants Joint Venture is also pleased to acknowledge John (Jack) R. Hayes, Jr., and Steven L. McCabe of NIST for their input and guidance in the preparation of this report, and Amber Houchen for ATC report production services.

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Executive Summary

Across the United States, natural and man-made disasters cause an estimated $57 billion in average annual costs, with single events like Hurricanes Katrina and Sandy causing losses in excess of $100 billion and $70 billion, respectively (NIST, 2014a; Aon Benfield, 2013). While damaging earthquakes happen with less frequency than other perils such as floods, tornadoes and hurricanes, the earthquake threat is quite real. According to recent updates of the National Seismic Hazard Maps (USGS, 2014), portions of 42 states and territories are at risk of experiencing strong ground shaking in the typical life of a building or infrastructure system. Sixteen of those states, including California, Oregon, Washington, Alaska, Hawaii, Tennessee, Missouri, and others are at very high risk. Also, over 150 million people, and thus almost half the U.S. population is exposed to earthquakes, reflecting the effects of increasing urbanization, especially along the West Coast.

A single earthquake is capable of causing $100 to $250 billion in direct damage and other economic losses as well as tens of thousands of casualties (FEMA, 2001). Such severe losses are possible if a major earthquake strikes Los Angeles, San Francisco Bay Area, Pacific Northwest or Central United States (Field et al., 2005; Kircher et al., 2006; Elnashai et al., 2008; Jones et al., 2008; RMS, 2008; CREW, 2013). Substantial loss of life as well as the destruction of buildings and lifelines will accompany a major U.S. earthquake. Lifeline-related damage will affect local business and commerce, and may have widespread economic effects for the rest of the country.

The extensive damage to modern, engineered transportation, electric power, water, and other lifeline systems and components caused by the relatively moderate magnitude-6.6 earthquake that occurred in the San Fernando Valley of Southern California on February 9, 1971, gave rise to the field of lifeline earthquake engineering and inspired engineering professionals to set a 30-year goal to raise the standards of lifeline performance in earthquakes across the United States.

Since then, progress on improving the seismic resilience of the nation's lifelines has been intermittent. In the 1990s, Federal agencies held workshops and developed a framework, titled *Plan for Developing and Adopting Seismic Design Guidelines and Standards for Lifelines* (FEMA, 1995), for improving lifeline performance in response to earthquakes and related disasters. The plan development effort was part of the National Earthquake Hazard Reduction Program (NEHRP), and numerous projects identified in this plan were carried out with NEHRP funding, including those conducted by the American Lifelines Alliance (ALA). This organization was established by the Federal Emergency Management Agency (FEMA) in 1999 to facilitate the creation, adoption, and implementation of design and retrofit guidelines and other national consensus documents that, when implemented by lifeline owners and operators, would systematically improve the performance of utility and transportation systems to acceptable levels in natural hazard events. From 1999 to 2005, the ALA carried out 27 projects, including 17 projects specifically directed at guideline-related tasks; six of these had results incorporated into new or modified American National Standards Institute (ANSI)-accredited consensus standards. Financial support for ALA, which ranged from $400,000 to $700,000 per year, was terminated in 2005 when NEHRP budget reductions were imposed by FEMA.

Subsequently, the *NEHRP Strategic Plan, Fiscal Years 2009–2013*, established a strategic priority to develop guidelines for earthquake-resilient lifeline components and systems (NEHRP, 2008). Following this, the 2011 National Research Council report, *National Earthquake Resilience: Research, Implementation, and Outreach* (NRC, 2011), endorsed the NEHRP strategic priority for lifelines, and provided a broad overview of recommended research and implementation activities in the lifelines area. The next year in its report, *Disaster Resilience: A National Imperative,* the National Academies (2012) called for more focused research into new materials and new processes to construct resilient infrastructure as well as more effective strategies for addressing infrastructure interdependencies. Since its inception in 2006, the NEHRP Advisory Committee on Earthquake Hazards Reduction (ACEHR) has also strongly endorsed the need for lifelines research and implementation work within NEHRP.

Responding to the need for earthquake-resilient lifelines and the calls for strategic action, the National Institute of Standards and Technology (NIST) sponsored this research, development and implementation roadmap. The roadmap focuses on six key lifeline systems: electric power, gas and liquid fuel, water, wastewater, telecommunications, and transportation networks. It also addresses lifeline interdependencies and socioeconomic and institutional research and implementation priorities that are needed to support resilient lifeline practices and improved performance during extreme events. High priority needs for industry practice and adoption as well as guidelines and consensus standards are included in the roadmap.

The roadmap is intended to guide the investments made by NIST and other NEHRP agencies in generating national performance and restoration goals in concert with the development of guidelines, manuals, and standards for key lifeline systems and components. These efforts are accompanied by a coherent and well-coordinated plan to promote their voluntary adoption by communities and lifeline providers. Key socioeconomic factors, institutional issues, and lifeline interdependencies, as well as research, development, and implementation needs are addressed for both individual and collective lifeline systems. While the roadmap focuses primarily on lifeline earthquake resilience issues, it also considers the multi-hazard aspects of lifeline performance as well as the integration of NEHRP-supported technology into an all-hazards framework for lifelines. Many of the priority topics identified in the earthquake-resilient lifelines roadmap have a direct bearing on national priorities to promote resilience and improve interdependent lifeline performance under multi-hazard conditions. Thus, they are a critical part of an overall strategy and plan to support hazard-resilient communities.

1. Roadmap Program Elements and Topics for Research, Development, and Implementation

The framework for this roadmap consists of four key program elements that define the range of proposed priority topics for research, development and implementation to be pursued over the next decade, as well as a consensus-based prioritization scheme for completing the work. The program elements are as follows:

- Program Element I. Establish national lifeline system performance and restoration goals.
- Program Element II. Develop lifeline system specific performance manuals, guidelines, standards, and codes.
- Program Element III. Conduct problem focused research for various lifeline systems.
- Program Element IV. Enable the adoption and implementation of lifeline system performance goals and standards.

A total of 28 recommended research, development and implementation priority topics are embedded within these four program elements. A consensus-based priority ranking of all the topics was developed during a workshop in May 2014 that was conducted as part of the roadmap development process.

The roadmap is not a static arrangement of priorities. It is a framework that includes dynamic interactions. It is intended for research topics in Program Element III to emerge from work undertaken in Program Elements I, II, and IV. As work is accomplished to establish national lifeline performance and restoration goals in conjunction with the development of guidelines and standards, gaps in knowledge and fundamental uncertainties will emerge that require research. These gaps cannot be fully anticipated at this stage in the roadmap development. They need time to crystalize as the initial investigations are undertaken and results are obtained.

Program Element I. Program Element I is the foundational element of this roadmap. Its objective is to establish a national framework of seismic performance and restoration goals for lifeline systems that reflects the evolving nature of communities, technology, business, and government. Its purpose is to help transition from current utility-specific crisis management practices to a more integrated and consistent approach to interdependent lifeline systems performance and integrated community resilience enhancement. Program Element I also provides input and guidance for the rest of the program elements.

Program Element I is defined by two complementary subgroups, a *Performance Framework* subgroup that is focused on existing practices and a modeling-based *Needs Assessment* subgroup.

The goal of the *Performance Framework* subgroup is to develop interdependent performance and restoration goals that are broadly applicable to all lifeline systems throughout earthquake-prone regions of the United States with consideration of current utility best practices. Such a framework must reflect realistic system evolution that is aligned with national and local community resilience priorities. The priority topics for research, development, and implementation in this subgroup are:

- Topic No. 1: Develop an overarching framework for national lifeline performance and restoration goals
- Topic No. 2: Assess current societal expectations of acceptable lifeline performance levels and restoration times informed by the phases of response and recovery
- Topic No. 3: Establish procedures to quantify hazards over spatially distributed lifeline systems

The goal of the *Needs Assessment* subgroup is to provide modeling methods to assess specific functionality levels and restoration times achievable with enhanced best practices. This subgroup also addresses current shortfalls in performance related to the absence of measures that account for lifeline interdependencies, and focuses on the need to align lifeline services with societal expectations. Priority topics for research, development, and implementation in this subgroup are:

- Topic No. 4: Develop modeling tools to support design approaches, planning, and restoration for interdependent lifeline systems
- Topic No. 5: Develop tools to quantify and rank the societal benefits and costs of different lifeline system performance levels and restoration times, as well as prioritize lifeline upgrades and investments

Program Element II. Program Element II of this roadmap focuses on the development of guidelines, manuals of best practice, and standards to improve system reliability. Since the 1971 San Fernando earthquake, many seismic guidelines and standards have been developed to cover gaps resulting from the paucity of codes and standards for lifelines in use prior to that earthquake. Existing best practice manuals and guidelines include those produced for different lifeline systems by the American Lifelines Alliance, the Technical Council on Lifeline Earthquake Engineering of the American Society of Civil Engineers, and other organizations.

Existing lifeline-specific guidelines and standards need to be expanded and updated to address advances in research, construction and operational experience. They need to reflect better recent technological advances , as well as address the national performance and restoration goals developed as part of this roadmap. They must include consideration of lifeline interdependencies. The priority topics for research, development, and implementation to address lifeline system reliability are:

- Topic No. 6: Develop guidelines for the analysis, design, and planning of electric power infrastructure in seismically vulnerable regions
- Topic No. 7: Develop guidelines for improving telecommunication system resilience under earthquake conditions
- Topic No. 8: Develop water system seismic guidelines and standards
- Topic No. 9: Develop wastewater system seismic guidelines and standards
- Topic No. 10: Develop a manual of best seismic practices for gas and liquid fuel transmission pipelines
- Topic No. 11: Develop a manual for improving the seismic performance of natural gas distribution systems
- Topic No. 12: Develop guidelines for mitigating damage to lifelines from tsunamis and other flood-related hazards
- Topic No. 13: Develop guidelines for post-earthquake lifeline assessment, response, and recovery
- Topic No. 14: Develop geohazard guidelines for owners and contractors for engineering, procurement, and construction of pipelines
- Topic No. 15: Develop seismic qualification standards for lifeline components and systems

Program Element III. Program Element III identifies priority topics that are organized in two main areas: (1) priorities related to research across lifelines, and (2) priorities related to research for specific lifeline systems.

The recommended topics for this program element attempt to fill gaps in knowledge and/or advance the state-of-the-art in lifeline risk and resiliency assessment and management. However, as noted earlier, these topics should be regarded as a starting point for an emerging dynamic and interactive process, with new topics being identified on the basis of work in other program elements.

New lifeline network paradigms are emerging in response to increased demands for energy, renewal of aging lifeline infrastructure, planning and operations for sustainability, and innovations in computational methods for complex networks. Lifeline risk and resiliency methods need to advance across lifelines to meet the challenges and opportunities created by these changes. The priority topics related to research across lifelines are:

- Topic No. 16: Evaluate the feasibility of new interdependent lifeline system configurations
- Topic No. 17: Develop methods for analysis and mitigation of damage from fire following earthquake and hazardous material releases
- Topic No. 18: Improve and extend methods for mitigating the effects of earthquake-induced ground displacement on underground pipelines, conduits, and cables

There are also issues that relate to only one or several lifelines but not all of them. To address these issues, the following priority topics for research related to specific lifeline systems have been identified.

- Topic No. 19: Evaluate distributed power generation and energy storage to reduce earthquake/natural hazard effects on electric power systems
- Topic No. 20: Develop a multi-hazard, multi-modal dynamic transportation network risk assessment model
- Topic No. 21: Develop water and wastewater system evaluation methods for earthquake impacts
- Topic No. 22: Develop tensile and compressive strain limits for welded steel pipelines in permanent ground displacement zones

Program Element IV. Program Element IV focuses on the research, development and implementation priorities necessary to advance the adoption and implementation of lifeline system performance goals and standards, and sustain lifeline system reliability and seismic resilience over time. It is organized into two subgroups: (1) priorities to enable adoption and implementation of lifeline system performance goals and standards, and (2) priorities for long-term earthquake resilience.

Following are the priority topics for research, development and implementation to enhance the capacity and willingness of lifeline owners and operators to adopt and implement system- and component-level performance goals and standards:

- Topic No. 23: Develop tools, guidance, incentives, and funding mechanisms for voluntary adoption and implementation of lifeline seismic resilience programs and earthquake-resilient design and construction standards

- Topic No. 24: Develop strategies and techniques for the public and key customers to engage lifeline system providers to define acceptable performance levels and restoration timeframes

To help sustain lifeline system reliability and seismic resilience, the following priority topics for research, development, and implementation are recommended:

- Topic No. 25: Assess the direct and indirect socioeconomic consequences and financial implications of different lifeline performance levels and restoration timeframes
- Topic No. 26: Implement post-earthquake information and response services for lifeline systems
- Topic No. 27: Develop and deploy intelligent lifeline monitoring, advanced sensors, and emergency response and restoration decision support systems
- Topic No. 28: Develop and deploy better tools, training, and guidance for emergency operation planning, response, and restoration of lifeline systems

2. Roadmap Cost Estimates

Roadmap Cost Estimates. Estimates of the cost to conduct the endeavors identified for all 28 topics range from $24.8 million to $55.0 million, which translates to approximately $2.5 to $5.5 million per year for 10 years, the anticipated length of the proposed roadmap program. Estimates of the total cost for each of the Program Elements are:

Program Element I:	$4.7 – $10.5 million
Program Element II:	$6.4 – $13.0 million
Program Element III:	$7.5 – $17.0 million
Program Element IV:	$6.2 – $14.5 million

3. Roadmap Management Plan

Lifelines lack a single umbrella organization to set performance goals and standards and advocate for system enhancements. This is a serious obstacle in ensuring cohesive and consistent management of this Lifelines Earthquake Resilience Roadmap. Thus, the roadmap recommends the creation of an umbrella organization to ensure stewardship for the necessary research, development, and implementation of earthquake and multi-hazard resilient lifelines. Such an organization is critically important for the development of best practices and guidelines, and essential for transforming guidelines and manuals of best practice into standards.

An agency well suited to support and supervise the development of a national lifelines resilience organization and program is NIST. Assistance can be provided from other NEHRP agencies. One agency that should be involved more actively is the Department of Homeland Security (DHS). DHS is responsible for the National Infrastructure Protection Plan (NIPP), which provides a framework to share threat information, reduce infrastructure vulnerabilities, minimize consequences, and facilitate response and recovery efforts for 16 critical infrastructure sectors. The NIPP includes virtually all lifeline systems, and therefore represents an overarching government program that influences lifeline policy and support.

Three organizational leadership models for an umbrella organization are considered in this report predicated on (1) the American Lifelines Alliance (ALA) model, which existed as a project within another organization and could be reinstated as an independent entity; (2) the Applied Technology Council (ATC) model, which exists as an independent non-profit corporation; and (3) a hybrid model that places the program within an established organization.

4. Roadmap Organization and Contents

The impetus for developing the roadmap and its scope and purpose are discussed in Chapter 1. Chapter 2 describes the vision for lifeline earthquake resilience and its relevance to achieving multi-hazard resilience and sustainable communities across the country. Chapter 3 describes the framework for the roadmap that is built around the four key program elements and 28 priority topics for research, development and implementation (described above) to be pursued over the next decade, as well as a consensus-based prioritization scheme for completing the work. Chapter 3 also discusses the management plan for implementing the roadmap. Finally, Chapter 4 contains detailed summaries of each of the recommended priority topics for research, development and implementation, along with a summary of the costs to carry out the endeavors identified for the various topics. The Appendices cover some of the major previous efforts in research, development, and implementation for different lifeline systems in the United States and other countries, and include a description of the National Infrastructure Protection Plan and Critical Infrastructure Partnership Advisory Council.

Chapter 1
Introduction

"As does a human body, a city has lifelines. In the city they provide for the supply and the flow of people, goods, information, energy, and water…The failure to function of one of the lifelines, or its severe impairment, brings… damage or disaster to the city. Knowledge of the risk of such failures is a stimulus for preventive measures. The acceptable level of risk is established by the individual for his body and by the citizenry for the city."
– C. Martin Duke (1972), "Founder of Lifeline Earthquake Engineering in the United States" (*Elliott and McDonough, 1999)*

Lifelines are synonymous with civil infrastructure and vital to our modern economy and quality of life. They are often grouped into six principal systems, which are the focus of this report:

- Electric power,
- Gas and liquid fuels,
- Telecommunications,
- Transportation,
- Water, and
- Wastewater systems.

Taken individually, or in aggregate, lifeline systems are intricately linked with the economic well-being, security, and social fabric of the communities they serve. In fact, lifelines may be regarded as the complex of delivery systems that define modern society and the communities within it. The effectiveness with which resources and services are delivered through lifeline systems influences, both locally and nationally, gross domestic product, jobs and household income, energy independence, and economic competitiveness (ASCE, 2013). When earthquakes or other hazards strike lifeline systems, they disrupt the flow of resources and provision of services that sustain communities. In the worst cases, these disruptions can lead to regional, national and even global social and economic impacts.

1.1 Impetus for this Roadmap

Alarmed by the extensive damage to modern, engineered transportation, electric power, water, and other lifeline systems and components caused by the relatively moderate magnitude-6.6 earthquake that occurred in the San Fernando Valley of Southern California on February 9, 1971, engineering professionals set a 30-year goal to raise the standards of lifeline performance in earthquakes across the United States. Their aim was to establish a comprehensive set of lifeline performance standards that would be confirmed in future earthquakes (Shinozuka, Rose, and Eguchi, 1998). For many, this point is seen as the time in which the field of lifeline earthquake engineering really began in the United States.

Over the next decades, our knowledge about both seismic risk and lifeline engineering advanced significantly as has the translation of that knowledge into lifeline seismic performance guidelines and industry practices. Many technological innovations in lifeline design, construction, operation and maintenance have also been achieved. During this time, there have also been several organizational efforts, both within the lifeline earthquake engineering community and among Federal agencies, to facilitate the creation, adoption and implementation of lifeline seismic performance guidelines and consensus standards.

In the 1990s, Federal agencies held workshops and developed a framework, titled *Plan for Developing and Adopting Seismic Design Guidelines and Standards for Lifelines* (FEMA, 1995), for improving lifeline performance in response to earthquakes and related disasters. The plan development effort was part of the National Earthquake Hazard Reduction Program (NEHRP), and numerous projects identified in this plan were subsequently funded and implemented with NEHRP funding.

In spite of all these efforts and progress made to date, there is still much more work that needs to be done. Technological advances and investigations of lifeline system performance and interdependencies following recent earthquakes and other disasters, in the United States and around the world, have underscored the need for a new generation of research, development, and implementation to improve the earthquake resilience of the nation’s lifelines before the next major earthquake strikes.

The *NEHRP Strategic Plan, Fiscal Years 2009–2013*, established a strategic priority to develop guidelines for earthquake-resilient lifeline components and systems (NEHRP, 2008). Following this, the 2011 National Research Council report, *National Earthquake Resilience: Research, Implementation, and Outreach* (NRC, 2011), endorsed the NEHRP strategic priority for lifelines, and provided a broad overview of recommended research and implementation activities in the lifelines area. The next year in its report, *Disaster Resilience: A National Imperative*, the National Academies (2012) called for more focused research into new materials and new processes to construct resilient infrastructure as well as more effective strategies for addressing infrastructure interdependencies. Furthermore, that report recognized that the process of enhancing infrastructure resilience is a shared responsibility and encouraged linking public and private infrastructure performance and interests to national and community resilience goals. Also, since its inception in 2006, the NEHRP Advisory Committee on Earthquake Hazards Reduction (ACEHR) has also strongly endorsed the need for lifelines research and implementation work within NEHRP.[1]

1.2 Roadmap Scope and Purpose

Responding to the urgent calls for strategic action and for priority to be given to improving the earthquake resilience of lifeline systems across the country, the National Institute of Standards and Technology (NIST) has undertaken the development of this research, development and implementation roadmap. NIST is designated as the Lead Agency for the National Earthquake Hazard Reduction Program (NEHRP)[2], and it supports coordination of the NEHRP research and implementation activities for the four NEHRP agencies—the Federal Emergency Management Agency (FEMA), NIST, the National Science Foundation (NSF), and the U.S. Geological Survey (USGS). NIST's NEHRP coordination team also supports management of the NIST Engineering Laboratory's Earthquake Risk Reduction in Buildings and Infrastructure Research and Development Program.

The roadmap focuses on six key lifeline systems: electric power, gas and liquid fuel, water, wastewater, telecommunications, and transportation networks. It also addresses lifeline interdependencies and socioeconomic and institutional research and implementation priorities that are needed to support the development of resilient lifeline practices and improved lifeline performance during extreme events. High priority needs for improved industry practice and adoption as well as guidelines and consensus standards are included in the roadmap.

The roadmap is intended to guide the investments made by NIST and other NEHRP agencies in generating national performance and restoration goals and accompanying guidelines, manuals, and standards for key lifeline systems and components. These efforts are accompanied by a coherent and well-coordinated plan to promote their voluntary adoption by communities and lifeline providers while also addressing the key socioeconomic and institutional issues, lifeline interdependencies, and other research, development, and implementation needs for both individual and collective lifeline systems. Community- and operator-level adoption is essential to reduce the risk of locally significant damage in the next major earthquake and to ensure that

[1] The ACEHR annual reports are available at http://www.nehrp.gov/committees/reports.htm.
[2] NIST was designated as the Lead Agency in the NEHRP Reauthorization Act of 2004 (Public Law PL 108-360).

lifeline damage and service disruptions do not result in serious regional, national and even possibly international social and economic disruptions.

1.3 Roadmap Relevance for Multi-Hazards

While the roadmap focuses primarily on lifeline earthquake resilience issues, it also considers the multi-hazard aspects of lifeline performance as well as the integration of NEHRP-supported technology into an all-hazards framework for lifelines.

NEHRP is the backbone of public policy to reduce the life-threatening and economically disruptive effects of earthquakes in the United States. It is an incubator for technology and programs through improvements in the perception, quantification, and communication of risk; advanced technologies for reinforcing and monitoring the built environment; loss assessment; emergency response procedures; and a process for achieving disaster preparedness (NRC, 2011; EERI, 2008). This roadmap builds on the existing multidisciplinary culture that exists for earthquake preparedness in NEHRP with goals and specific priorities that are readily adaptable to other natural hazards. It also draws upon the long history of NEHRP agencies in funding and studying the resilience of the built environment to earthquakes as well as other hazards and in developing and publishing key guidance documents for lifeline earthquake performance.

Lifelines are essential for emergency response, restoration of order, and recovery after earthquakes as well as other natural hazards and human threats. The same characteristics affecting lifeline performance under seismic conditions—including interdependencies, socioeconomic factors, and institutional constraints—affect lifeline operations and services when subjected to other hazards. By establishing an overarching performance framework for earthquake-resilient lifelines, this roadmap provides a pathway for the development of lifelines performance objectives under multi-hazard conditions as well. The network analysis procedures, metrics and tools developed to model system-wide lifeline response to earthquakes can be adapted to other hazards. Also, the lessons learned from disasters and system failures quite often are multi-hazard in nature. Similarly, the insights gained about lifeline system interdependencies and socioeconomic and organizational issues apply to multiple hazards. Intelligent monitoring and sensor technologies developed to improve lifeline system reliability to earthquakes also have multi-hazard applications.

In summary, many of the priority topics identified in the earthquake-resilient lifelines roadmap have a direct bearing on national priorities to promote resilience and improve interdependent lifeline performance under multi-hazard conditions. Thus, they are a critical part of an overall strategy and plan to support hazard-resilient communities.

1.4 Roadmap Framework and Organization

The roadmap is organized as follows. Chapter 2 describes the vision for lifeline earthquake resilience and its relevance to achieving multi-hazards resilience and building resilient and sustainable communities across the country. Chapter 3 describes the framework for the roadmap that is built around four key program elements and 28 priority topics for research, development and implementation to be pursued over the next decade, as well as a consensus-based prioritization scheme for completing the work. Chapter 3 also proposes a management plan for implementing the roadmap, which involves the creation of an umbrella organization to ensure stewardship for the necessary research, development, and implementation of earthquake and multi-hazard resilient lifelines. Such an organization is critically important for the development of best practices and guidelines, and essential for transforming guidelines and manuals of best practice into standards. Finally, Chapter 4 contains detailed summaries of each of the recommended priority topics for research, development and implementation, along with a summary of the costs to carry out the endeavors identified for the various topics. The Appendices cover some of the major previous efforts in research, development, and implementation for different lifeline systems in the United States and other countries, including a description of the National Infrastructure Protection Plan and Critical Infrastructure Partnership Advisory Council.

Chapter 2

Vision for Earthquake-Resilient Lifelines

This roadmap endeavors to help lifeline systems and their operations across the United States to become sufficiently resilient to withstand the seismic effects of the next major earthquake; restore safety, stability, and services quickly; and help the communities that they serve to resume work and other societal functioning within a reasonable period of time. This vision is accomplished through the development of national lifeline performance goals that help local communities and the operators of regional- and national-level lifeline infrastructure to secure the "last mile" of these complex delivery systems against disasters. This effort is accompanied by a coherent and well-coordinated plan to promote the voluntary adoption of these national goals by communities and lifeline providers while also addressing the key socioeconomic and institutional issues, lifeline interdependencies, and other research, development, and implementation needs for both individual and collective lifeline systems.

Resilience and lifelines converge in the communities that are exposed to hazards. Community recovery from disasters depends on the orderly and rapid restoration of lifeline services. Resilience in lifeline systems therefore needs to be extended to the community level to reduce the risk of locally significant damage, and prevent serious regional and nationwide economic repercussions. It is only when resilience is adopted by local communities that we can achieve a truly resilient nation.

The following sections of this chapter look at the earthquake risk in the United States, lifeline vulnerabilities to earthquakes and other hazards, and key characteristics of lifeline systems. The concept of lifeline resilience is explored, and the principal needs for resilience among lifeline systems are discussed as a prelude to presenting the earthquake-resilient lifeline roadmap in subsequent chapters.

2.1 Earthquakes and Disaster Risk in the United States

Across the United States, natural and man-made disasters cause an estimated $57 billion in average annual costs, with single events like Hurricanes Katrina and Sandy causing losses in excess of $100 billion and $70 billion, respectively (NIST, 2014a; Aon Benfield, 2013). While damaging earthquakes happen with less frequency than other perils such as floods, tornadoes and hurricanes, the earthquake threat is quite real. According to recent updates of the National Seismic Hazard Maps (USGS, 2014), 42 of the 50 states have a reasonable chance of experiencing damaging ground shaking from an earthquake in 50 years (the typical life of a building or infrastructure system); see Figure 2-1. Sixteen of those states, including California, Oregon, Washington, Alaska, Hawaii, Tennessee, Missouri, and others are at very high risk. Also, over 150 million people, and thus almost half the U.S. population is exposed to earthquakes, reflecting the effects of increasing urbanization, especially along the West Coast.

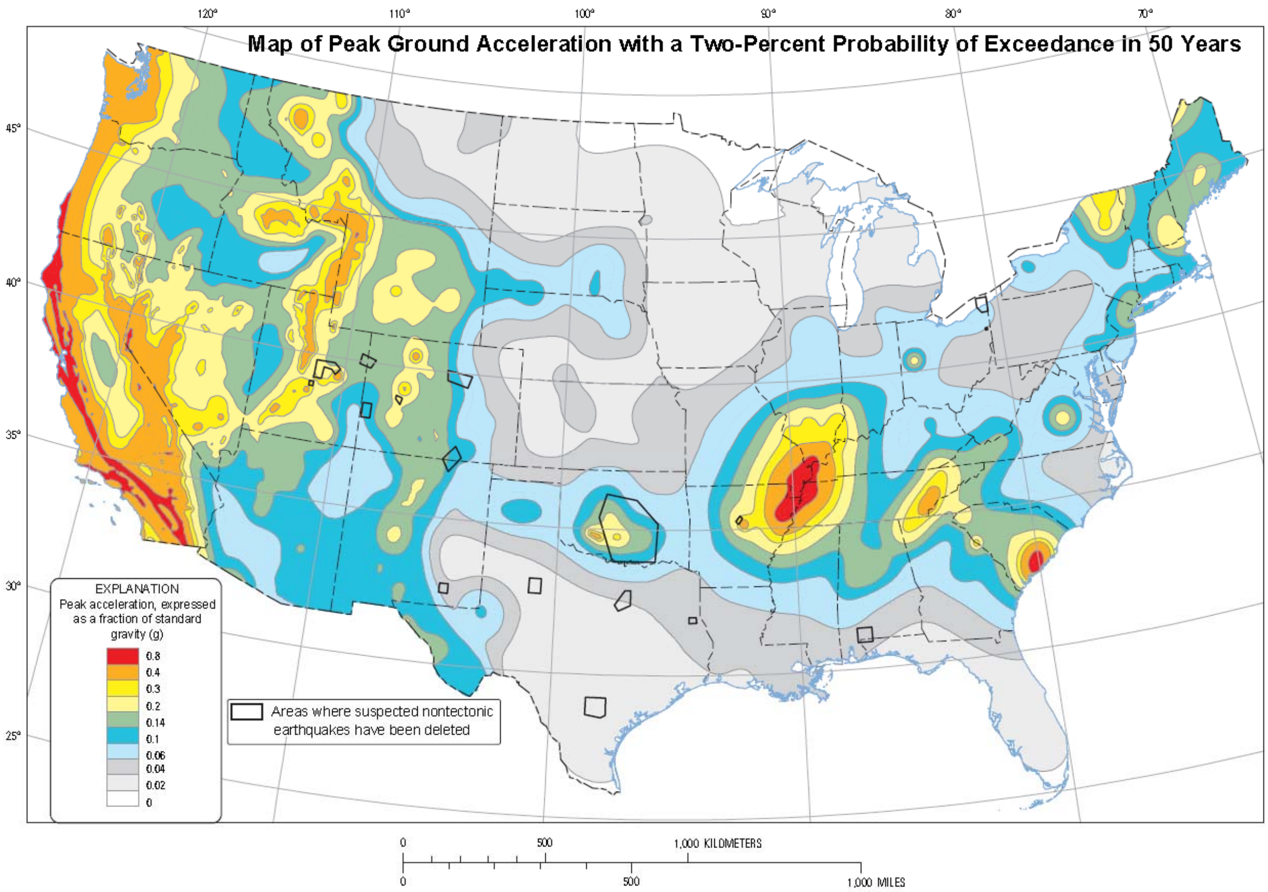


Figure 2-1 Map of conterminous United States showing earthquake ground motions that may be met or exceeded in the next 50 years (USGS, 2014).

A single earthquake is capable of causing $100 to $250 billion in direct damage and other economic losses as well as tens of thousands of casualties (FEMA, 2001). Such severe losses are possible if a major earthquake strikes Los Angeles, San Francisco Bay Area, Pacific Northwest or Central United States (Field et al., 2005; Kircher et al., 2006; Elnashai et al., 2008; Jones et al., 2008; RMS, 2008; CREW, 2013). With each of these events, there is expected to be disastrous loss of life as well as the destruction of buildings and lifelines, and it is the lifelines-related damages that are likely to cause widespread economic ripple effects for the rest of the country. For example, in a study of the likely impacts of a magnitude-7.8 earthquake occurring on the San Andreas Fault near the Los Angeles metropolitan area, it was found that $1.5 billion in direct damages to highways, gas pipelines, and water and wastewater systems could result in more than $55 billion in indirect economic losses due to the prolonged outage of water, and major interruptions of commerce and goods movement from the Ports of Los Angeles and Long Beach with nationwide implications (Jones et al., 2008).

The United States has not had a major damaging earthquake on this scale since the 1906 San Francisco earthquake. Our more recent earthquake experience has been with more moderate seismic events, many of which occurred near major metropolitan areas but with far less damage than with higher magnitude and more urban-centered events. Recent earthquakes include the magnitude-6.9 Loma Prieta earthquake that struck south of the San Francisco Bay Area in 1989, the magnitude-6.7 Northridge earthquake that was centered in the northern Los Angeles area in 1994, and the magnitude-6.8 Nisqually earthquake of 2001 that struck southwest of the Seattle-Tacoma area. The Northridge earthquake, for example, caused 57 deaths and $40 billion in direct damage and economic losses (Eguchi et al., 1998). This would be approximately $65 billion in 2014 dollars. However, estimates that a magnitude-7.2-to-7.5 earthquake centered on the Puente Hills Fault that runs underneath downtown Los Angeles could result in 3,000 to 18,000 fatalities, 142,000 to 735,000 displaced households, and between $82 and $252 billion in direct damage and economic losses (Field et al., 2005).

The current period of seismic quiescence contributes to a false sense of security. Furthermore, as time passes, the risk across the country for substantial damage due to earthquakes, and other natural hazard events and human threats, continues to increase because of the combined effects of urban development and population growth in vulnerable regions (NRC, 2011a). The country's annualized exposure to earthquake-related losses has been estimated as more than $6 billion (FEMA, 2001). With a risk exposure that continues to grow, the Earthquake Engineering Research Institute (EERI, 2003) estimates it will take well over 100 years to reduce the earthquake risk to an acceptable level at the recent rates of funding.

2.2 Vulnerability of Lifelines to Earthquakes and Other Natural Hazards

When earthquakes or other hazards strike lifeline systems, they disrupt the flow of resources and provision of services that sustain communities. In the worst cases, these disruptions can lead to regional, national and even global social and economic impacts, such as the devastating consequences of the 2011 Tohoku earthquake and tsunami's impacts at the Fukushima-Daiichi Nuclear Power Plant. The operation of all Japanese nuclear reactors was curtailed and none are back in service at the time of this report preparation. Not only did the loss of this essential lifeline system reduce Japan's electric power supply by 30%, it also led to a loss of confidence in many countries regarding the safety and reliability of nuclear power (NRC, 2014; Morton, 2012). In the United States, owners and operators of the country's 104 nuclear power plants are currently reassessing their exposure to seismic and flood hazards, at both the design- and beyond-design basis (NRC, 2014; NRC, 2011b).

Large segments of the nation's critical infrastructure are now more than 50 to 100 years old, with many portions built before the adoption of modern earthquake codes, standards, and guidelines. In 2013, the American Society of Civil Engineers (ASCE) graded the nation's infrastructure as a D+ across 16 categories, including all the lifeline systems addressed in this roadmap (ASCE, 2013). This marks the first time that the grades have improved in decades—up slightly higher from a D given with the 2009 Report Card[3]. The ASCE estimates that $3.6 trillion of investment is necessary by 2020 to bring each infrastructure category up to a state of good repair and a grade of B. Aging and repetitive use reduces the capacity of infrastructure to resist hazards, such as earthquakes.

Lifeline systems share three common characteristics that differentiate and distinguish their vulnerabilities to earthquakes and other hazards, from individual buildings and other local facilities. They are: geographical distribution and collocation, interdependency, and complexity (O'Rourke, 1998), and each is discussed further in the following sections.

2.2.1 Geographical Distribution and Collocation

Lifelines are constructed over broad geographical areas and thus, given the distance, can be subject to a wide range of seismic and other natural hazards, as well as a wide variety of responses to a particular hazard event. This characteristic has a profound influence on the planning and design of lifelines systems in comparison to an individual building or local facility. Given their dispersal, it is not practical to characterize and remediate hazards across entire networks with the same degree of detail as is possible for an individual building. Also, limitations in their location or direction within restrictive rights-of-way can result in significant exposure to hazards and lead to potentially complicated and troublesome interactions.

When different lifelines are collocated in the same area, all are vulnerable to disruption from a single cause. In 1989, a train derailment near Cajon Pass, just north of the metropolitan region of Los Angeles, California, set off a catastrophic fire when a damaged gasoline transmission pipeline exploded, destroying a number of homes and causing several deaths (FEMA, 1991). In response to the tragedy, Congress authorized FEMA to investigate lifeline interdependencies in Cajon Pass, where a large number of critical lifelines are collocated, and to consider the broader

[3] The ASCE notes that six infrastructure sectors benefited from either an increase in private investment, targeted efforts in cities and states to make upgrades or repairs, or from a one-time boost in Federal funding.

vulnerability issues of collocation for lifeline systems elsewhere in the United States (FEMA, 1991; FEMA, 1992a; FEMA, 1992b). Because Cajon Pass is intersected by the San Andreas Fault, lifeline vulnerability to earthquakes was an important part of the study.

2.2.2 Interdependency

Lifelines are interdependent. The disruption of one lifeline system may affect the performance of another. Electric power networks, for example, provide the energy for pumping stations, storage facilities and equipment control in liquid fuel and natural gas pipeline transmission and distribution systems. On the flipside, liquid fuel and natural gas pipelines provide fuel for electric power generation. Similar reciprocity exists among all lifelines systems.

The interdependent nature of lifelines and infrastructure during disasters was first recognized following the 1906 San Francisco earthquake when the conflagration of 490 blocks of buildings and associated facilities was related to water supply loss from liquefaction-induced ground deformation during the earthquake (O'Rourke et al., 2006; Scawthorn et al., 2006). After the 1994 Northridge earthquake, electric power was lost for nearly 24 hours in the Van Norman Complex, which receives and treats about 75% of the city's potable water and where the largest water pump station for the City of Los Angeles exists (O'Rourke, 2007).

The collapse of the Twin Towers in the 2001 World Trade Center disaster triggered water main breaks that flooded rail tunnels, a commuter station, and the vault containing all the cables for one of the largest telecommunication nodes in the world (Bonneau et al., 2009). As a result, there was a multi-day interruption of the Security Industry Data Network and the Security Industry Automation Corporation circuits used to execute and confirm block trades on the New York Stock Exchange. Also, after Hurricane Katrina, major supply routes for U.S. crude oil and refined petroleum products were disrupted due to electric power losses at the pump stations for three major transmission pipelines, which seriously reduced the supply of refined products to southern, midwestern, and eastern states (O'Rourke, 2010).

2.2.3 Complexity

The performance of lifelines also depends on the characteristics of many different constituent parts. Most lifeline systems have been built over many years and operate with components and facilities produced according to a myriad of construction and/or manufacturing techniques, standards, and design procedures. Moreover, system components have been exposed to repetitive loads, corrosion, fatigue, and the effects of adjacent construction, both in proportion to their age and proximity to sources that cause aging. Lifeline components are not only physically interconnected, but increasingly linked by intricate instrumentation, monitoring equipment, and wireless

Cascading Lifeline Damage: New York City Examples

The risks of natural hazards and human threats are especially severe in urban settings. The above photograph of the corner of Wall and Williams Streets in New York City during the 1920s illustrates the remarkable congestion of buried lifelines that often occurs an urban environment. Much of critical infrastructure is located underground, where it is removed from direct observation unless uncovered, and its state of repair and proximity to other structures is often unknown. Congestion increases risk due to proximity. Damage to one facility, such as a cast iron water main, can cascade rapidly and damage surrounding systems, such as electric and telecommunication cables and gas mains, with system-wide consequences.

Urban lifeline congestion has increased substantially since the 1920s, and there have been many instances of interdependent, cascading damage. For example, in August, 1983, a 12-inch-diameter cast iron water main ruptured near the intersection of 38th Street and 7th Avenue. Water from the burst main flooded an underground electric substation, shorting electric circuits and touching off an immense fire. Loss of the substation blacked out approximately one square mile of the city, including the Garment District and neighboring areas, and involving over 10,000 customers, including Macy's and Gimbel's department stores. The blackout also affected a telephone company central office, interrupting telecommunication service to tens of thousands of customers until emergency power was switched on. Phones using electric utility power were lost for a considerably longer time. The accident occurred during Market Week in the Garment District, when most out-of-town buyers come to New York to order next year's spring clothing lines. Direct and indirect business losses during this critical time have been estimated in the tens of millions of dollars (O'Rourke, et al., 2003).

controls. Lifeline performance in the future will be controlled to a greater degree by new “smart” technologies, which is a trend well demonstrated in the evolution of electric power and telecommunication lifelines.

Lifelines also reflect major differences in the institutional characteristics of their owners and operators. Public lifeline systems are operated with a different business culture than private lifeline systems. Public and private management practices involve different models of ownership, compensation, and reward structures. Public agencies can be quite diverse, and may develop different and even adversarial views within the same city or state administration. Private lifeline operators are often engaged in commercial competition with one another, and the relationship among all lifeline operators is influenced by the potential for service interruption due to adjacent construction, accidents, and neighboring lifeline failures in congested urban and suburban environments. All critical lifelines in the United States are also concerned about potential security threats, which has resulted in increased controls on information sharing and, in some cases, has hampered institutional cooperation among lifeline operators.

For all the above reasons, lifelines in the United States are *balkanized* with widely varying institutional imperatives, business agenda, and modes of operation. It is important to recognize the compartmentalized nature of lifeline operations and the diverse institutional characteristics that must be considered in developing an integrated approach to resilient lifeline systems.

2.3 Integrating Lifeline Facilities with System Performance Requirements

Lifelines are defined primarily as delivery systems. Most lifeline systems contain components or facilities that serve as sources of supply or as the processing facilities at the end of the delivery chain. Some of these facilities are not specifically addressed within lifeline earthquake engineering due to their special characteristics, which require unique engineering and operational skills. For example, lifeline systems for water include dams and large reservoirs as specific sources of supply, but the geotechnical and structural systems associated with dams and reservoirs are sufficiently complex and self-contained that they are engineered separately from the water transmission and distribution systems. Similarly for gas and liquid fuel lifelines, refineries and processing facilities are often engineered as separate complexes and thus treated as end nodes and not modeled as part of the gas and fuel delivery system. Similar reasoning applies to power plants for electric power systems, and gas and liquid fuel gathering fields. However, these specialty facilities are essential for assessing the overall performance capabilities of the entire system.

This roadmap recognizes these boundaries and therefore does not address some of these special facilities—namely dams, reservoirs, power plants, refinery and processing facilities, and gas and liquid fuel gathering fields—in the research, development, and implementation recommendations. However, these sources of supply and end point facilities must be considered in the development of system-wide performance goals.

For example, there is an important reciprocity between water reservoir response and the ability to pressurize downstream pipelines. Thus, the level of service (LOS) goals for water distribution systems needs to consider the potential ground deformation, leakage, and flooding expectations for dams and reservoirs. Furthermore, to ensure resilient water systems, the dams and reservoirs must be designed and maintained in a manner consistent with the overall water system performance goals, which may exceed the life-safety performance criteria commonly used for dam design. Similar considerations can be extended to power plants, gathering fields, and processing facilities, among others, to ensure that the system definition allows for a comprehensive assessment of performance consistent with community needs and expectations.

2.4 Defining Lifeline Earthquake Resilience

The resilience of an organization, community, or lifeline system is an overarching attribute that reflects its degree of preparedness and ability to respond to and recover from shocks. With regards to hazard events, resilience has been defined as "*the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events*" (The National Academies, 2012). The term resilience is applied to a range of topics that include physical security against terrorism, continuity in business operations, emergency planning and response for essential services, hazard mitigation, and the capability of the built environment (e.g., facilities, transportation systems, utilities) to physically resist and rapidly recover from disruptive events.

In an earthquake context, four key characteristics of resilience have been identified as: *Robustness, Redundancy, Rapidity*, and *Resourcefulness* (Bruneau et al., 2003). *Robustness* is the inherent strength or resistance in a system to withstand external demands without degradation or loss of functionality, which can be accomplished by strengthening of system components, redundancy and dispersion of key facilities, and improved standards. *Redundancy* involves system properties that allow for alternate options, choices, and substitutions under stress. *Rapidity* is the speed with which disruption can be overcome and safety, stability, and services restored. *Resourcefulness* is the capacity to mobilize needed resources and services in emergencies to restore safety, stability, and services. These four aspects of resilience place great emphasis on the human dimensions of communities served by lifelines as well as the organizations that are responsible for operating them.

The Hurricane Sandy Rebuilding Task Force (2013) recognized the importance of communities and organizations and their interconnectedness in stating that resilience involves enabling a region to respond effectively to a major hazard, recover quickly from it, and adapt to changing conditions, while also taking measures to reduce the risk of significant damage in the future. The national roadmap recently developed for windstorm and coastal inundation impact reduction indicates that "*characteristics of a resilient community include preparation for hazard events, continuity of operations during and after hazard events, and recovery plans that allow the population to resume work and activities within a reasonable period of time*" (NIST, 2014b, p.2-1).

In general, lifelines support three phases of community resilience to disasters: (1) emergency response and governance; (2) short-term restoration of basic functionality and the socio-economic fabric and workforce; and (3) long-term recovery of community and economic functions (SPUR, 2009). Lifelines are essential for regional and local industry, professional and commercial services, retail activities, and employee access to the workplace. The loss of electricity during Hurricane Sandy, for example, led to the disruption of credit card functionality and the consequent inability of motorists to refuel their vehicles at numerous service stations (Hurricane Sandy Rebuilding Task Force, 2013).

Currently, there are numerous barriers to achieving a consistent level of seismic performance and resilience across interdependent lifeline systems. Guidelines and standards for the seismic performance of individual lifeline systems and their components vary widely, with little consideration of interdependencies and little consistency in performance objectives or restoration goals. While some lifeline system owners nationwide have performed individual system seismic risk assessments to enhance their own preparedness and reduce service disruptions to their customers, few have considered system interdependencies, such as collocation and inter-operability, as well as the full array of social and economic costs of their disruptions both locally and beyond. Moreover, methods of analysis and models for lifeline system performance assessment that involve stakeholders are still at their infancy. Stakeholder engagement is necessary to develop consistent performance and restoration goals to achieve community resilience and support recovery of all lifeline systems. Lifeline system operators must develop these goals in concert with many different regulating bodies and funding sources that complicate efforts to manage, mitigate and restore multiple lifeline systems effectively.

This roadmap works to address these barriers by identifying the key overarching issues and national needs for lifelines, and then establishing a framework for addressing improvements in their collective and individual seismic performance. Lifeline resilience is essential for rapid and effective community recovery following disasters. Moreover, the improved resilience of both new and existing lifeline systems has long-term social and economic benefits for the public good, supports local and regional economic stability, and contributes to national security.

Chapter 3

Framework for Roadmap and Recommended Topics

The framework for this roadmap consists of four key program elements that define the range of proposed priority topics for research, development and implementation to be pursued over the next decade, as well as a consensus-based prioritization scheme for completing the work. The program elements are as follows:

- Program Element I. Establish national lifeline system performance and restoration goals.
- Program Element II. Develop lifeline system specific performance manuals, guidelines, standards, and codes.
- Program Element III. Conduct problem focused research for various lifeline systems.
- Program Element IV. Enable the adoption and implementation of lifeline system performance goals and standards.

A summary of the recommended research, development and implementation priorities, organized by program element, is provided in Table 3-1. It includes the consensus-based ranking of all the topics developed during a workshop in May 2014 that was conducted as part of the roadmap development process.

The four program elements are described in the next sections followed by a proposed management plan to ensure stewardship for research, development, and implementation of earthquake and multi-hazard resilient lifelines. Such a management plan is critically important for the development of best practices, guidelines, and standards.

The roadmap is not a static arrangement of priorities. It is a framework that includes dynamic interactions. It is intended for research topics in Program Element III to emerge from work undertaken in Program Elements I, II, and IV. As work is accomplished to establish national lifeline performance and restoration goals in conjunction with the development of guidelines and standards, gaps in knowledge and fundamental uncertainties will emerge that require research. These gaps cannot be fully anticipated at this stage in the roadmap development. They need time to crystalize as the initial investigations are undertaken and results are obtained.

Table 3-1 Summary of Lifeline System Research and Implementation Priorities

Topic	**ELEMENT I Establish National Lifeline System Performance and Restoration Goals**	*Priority Ranking**
	SUBGROUP I.1. Develop a Framework for the Establishment of Lifeline System Performance and Restoration Goals	
1	Develop an overarching framework for national lifeline performance and restoration goals	Highest
2	Assess current societal expectations of acceptable lifeline performance levels and restoration times informed by the phases of response and recovery	High
3	Establish procedures to quantify hazards over spatially distributed lifeline systems	Highest
	SUBGROUP I.2. Develop Methods for Lifeline System Performance and Restoration Needs Assessment	
4	Develop modeling tools to support design approaches, planning, and restoration for interdependent lifeline systems	High
5	Develop tools to quantify and rank the societal benefits and costs of different lifeline system performance levels and restoration times, as well as prioritize lifeline upgrades and investments	Highest
	ELEMENT II Develop Lifeline System Specific Performance Manuals, Guidelines, Standards, and Codes	
6	Develop guidelines for the analysis, design, and planning of electric power infrastructure in seismically vulnerable regions	Highest
7	Develop guidelines for improving telecommunication system resilience under earthquake conditions	Medium
8	Develop water system seismic guidelines and standards	Highest
9	Develop wastewater system seismic guidelines and standards	Highest
10	Develop a manual of best seismic practices for gas and liquid fuel transmission pipelines	High
11	Develop a manual for improving the seismic performance of natural gas distribution systems	High
12	Develop guidelines for mitigating damage to lifelines from tsunamis and other flood-related hazards	High
13	Develop guidelines for post-earthquake lifeline assessment, response, and recovery	Highest
14	Develop geohazard guidelines for owners and contractors for engineering, procurement, and construction of pipelines	High
15	Develop seismic qualification standards for lifeline components and systems	High

*Note: Priority rankings based on input received during the May 2014 Workshop

Table 3-1 Summary of Lifeline System Research and Implementation Priorities (continued)

Topic	ELEMENT III Conduct Problem Focused Research for Various Lifeline Systems	Priority Ranking*
	SUBGROUP III.1. Priorities Related to Research Across Lifelines	
16	Evaluate the feasibility of new interdependent lifeline system configurations	High
17	Develop methods for analysis and mitigation of damage from fire following earthquakes and hazardous material releases	High
18	Improve and extend methods for mitigating the effects of earthquake-induced ground displacement on underground pipelines, conduits, and cables	High
	SUBGROUP III.2. Priorities Related to Research for Specific Lifeline Systems	
19	Evaluate distributed power generation and energy storage to reduce earthquake/natural hazard effects on electric power systems	High
20	Develop a multi-hazard, multi-modal dynamic transportation network risk assessment model	High
21	Develop water and wastewater system evaluation methods for earthquake impacts	High
22	Develop tensile and compressive strain limits for welded steel pipelines in permanent ground displacement zones	Medium
	ELEMENT IV Enable the Adoption and Implementation of Lifeline System Performance Goals and Standards	
	SUBGROUP IV.1 Priorities to Enable Adoption and Implementation of Lifeline System Performance Goals and Standards	
23	Develop tools, guidance, incentives, and funding mechanisms for voluntary adoption and implementation of lifeline seismic resilience programs and earthquake-resilient design and construction standards	Highest
24	Develop strategies and techniques for the public and key customers to engage lifeline system providers to define acceptable performance levels and restoration timeframes	High
	SUBGROUP IV.2. Priorities for Long-Term Earthquake Resilience	
25	Assess the direct and indirect socioeconomic consequences and financial implications of different lifeline performance levels and restoration timeframes	Highest
26	Implement post-earthquake information and response services for lifeline systems	High
27	Develop and deploy intelligent lifeline monitoring, advanced sensors, and emergency response and restoration decision support systems	High
28	Develop and deploy better tools, training, and guidance for emergency operation planning, response, and restoration of lifeline systems	Highest

*Note: Priority rankings based on input received during the May 2014 Workshop

To start the process, research topics have been identified in Program Element III with the recognition that new topics will be identified as work progresses in the other program elements. Thus, the topics currently presented in Program Element III are to be regarded as a starting point for an emerging dynamic and interactive process in which these topics may be changed or replaced with new topics during implementation of the roadmap.

Program Element IV is focused on implementation and projects for achieving long term earthquake resilience. Priority topics identified here should be pursued concurrently with those in Program Elements I and II.

3.1 Program Element I. Establish National Lifeline System Performance and Restoration Goals

Program Element I is the foundational element of this roadmap. Its objective is to establish a national framework of seismic performance and restoration goals for lifeline systems that reflects the evolving nature of communities, technology, business, and government. Its purpose is to help transition from current utility-specific crisis management practices to a more integrated and consistent approach to interdependent lifeline systems performance and integrated community resilience enhancement.

3.1.1 Background

To develop a national framework for the seismic performance of lifelines, minimum lifeline performance requirements must first be established for each phase of seismic hazard mitigation, including emergency response, short-term socioeconomic restoration, and long-term community recovery and efforts to improve community resilience. The emergency response programs of each utility must be expanded to include short- to long-term planning for interdependent lifeline system operations, reliability and functionality. Suitable performance and restoration goals also need to be defined with appropriate timelines and phased geographical coverage that are informed by utility best practices today. The framework should be flexible for local adaptation in implementation and to reflect learning as research and technology progresses.

Stronger coordination and information sharing are also needed among government, industry, academics, and professional organizations (e.g., ASCE, American Society of Mechanical Engineers (ASME), American Water Works Association (AWWA), Earthquake Engineering Research Institute (EERI), and Institute of Electrical and Electronics Engineers (IEEE)), including government and other agencies not traditionally involved in hazard and risk reduction programs, such as the United States Departments of Energy, Transportation, and Defense. *A new umbrella organization that executes the research, development and implementation plans for* *resilient lifeline systems is needed to support the vision of Program Element I and its national-level focus.* The short- and long-term national performance and restoration goals should also inform the work of NEHRP agencies, the umbrella management organization proposed in this roadmap, and similar agencies dealing with other systems or hazards in order to achieve a resilient nation.

Program Element I is defined by two complementary subgroups, a *Performance Framework* subgroup that is focused on existing practices and a modeling-based *Needs Assessment* subgroup. The goal of the *Performance Framework* subgroup is to develop interdependent performance and restoration goals that are broadly applicable to all lifeline systems throughout earthquake-prone regions of the United States with consideration of current utility best practices. Such a framework must reflect realistic system evolution that is aligned with national and local community resilience priorities. This is followed by a *Needs Assessment* subgroup that provides modeling methods to assess specific functionality levels and restoration times achievable with enhanced best practices. This subgroup also addresses current shortfalls in performance related to the absence of measures that account for lifeline interdependencies, and focuses on the need to align lifeline services with societal expectations. Program Element I also provides input and guidance for the rest of the program elements.

Addressing the priority topics for research, development, and implementation specified in Program Element I should advance minimum design, operations, and mitigation practices, as well as a new culture of *resilience-based lifeline system objectives* that drives investment decisions and works to integrate national goals, community expectations, and multiple utility operator objectives. Topics within the subgroups are based on national needs, local community requirements, practical levels of service, utility best practices, current scientific literature, and outcomes from workshops and conferences on engineering, policy, and network science.

As discussed in Chapter 2, the supply sources and end-point processing facilities for some lifelines are sufficiently complex and self-contained that they have been regarded for practical purposes as separate systems. Examples include dams and large reservoirs for water supplies, power plants for electric power systems, and refineries and processing plants for gas and liquid fuel lifelines. Although it is pragmatically desirable to separate the engineering and planning for large reservoirs, power plants, and refineries from the delivery systems with which they are connected, the development of a national performance framework for lifelines should not be confined to these traditional boundaries. It is important in Program Element I to think comprehensively beyond traditional boundaries and consider all system components and facilities, including supply source and processing facilities, when developing a framework for lifeline performance goals.

3.1.2 Program Element I Subgroups

Subgroup I.1. Develop a framework for the establishment of lifeline system performance and restoration goals

This *Performance Framework* subgroup identifies priority topics essential to the establishment of national guidelines to achieve community resilience for all lifeline systems. It includes procedural steps for communities to follow to determine the performance and restoration goals of lifeline systems, including their interdependencies, as guided by broad national-level objectives as well as local practices, constraints and incentives. It calls for comparative studies of current performance goals and design documents used by different lifeline operators in light of individual and multi-system performance and restoration time objectives.

Past studies of public expectations of lifeline earthquake performance levels and restoration timeframes for different systems provide only general information from a limited number of communities. These past studies need updating to reflect modern societal perceptions and technological advancements (Tierney and Nigg, 1995; Tierney, 2000). It is also important to understand how public and commercial service expectations differ from projected seismic performance levels and restoration timeframes for different systems. For example, analyses performed as part of the State of Oregon's Resilience Plan found significant gaps between community expectations and service restoration time estimates for different lifeline systems (OSSPAC, 2013). In addition, these performance and restoration goals, along with public and commercial service expectation levels, will be updated to account for resource constraints and decision maker perspectives via modeling and simulations in Subgroup I.2.

The development of lifeline system performance and restoration goals also contributes to:

(a) A common design and operation vocabulary,

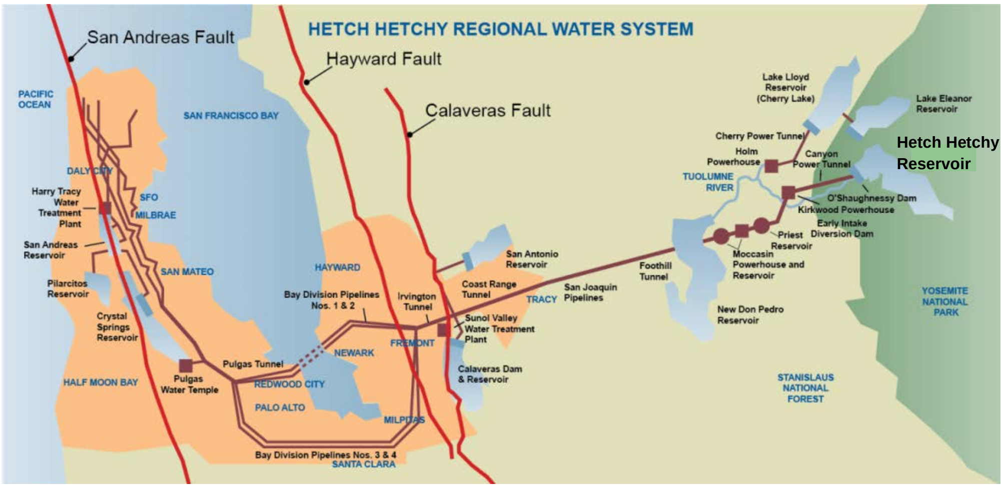
(b) Definitions and concepts applied across different lifeline sectors,

(c) Consistency in identifying the different geologic hazards threatening large spatially distributed systems, and

(d) Coordination among different lifelines through guidelines, levels of service goals, research, and adoption strategies.

The stewardship for developing performance and restoration goals and implementing best practices will be assigned to a new umbrella organization (see Section 3.5) that is proposed as part of this roadmap to oversee the lifeline systems resilience research and implementation plans.

Establishing Lifeline Performance Criteria: The San Francisco Regional Water System Example



The San Francisco Bay Area water supply extends 167 miles from the Hetch Hetchy Reservoir to San Francisco and crosses the Calaveras, Hayward, and San Andreas Faults. In November, 2002 San Francisco voters approved a $3.6 billion bond measure for a capital improvement program composed of 77 projects to upgrade, repair, and replace the aging water infrastructure supplying 2.4 million customers. A major part of this program was designing and building seismic resilient facilities that deliver water reliably in the event of a major earthquake. The capital improvement program, named the Water System Improvement Program, is now a water system upgrade that includes 81 projects at a total cost of $4.6 billion.

The San Francisco Public Utilities Commission (SFPUC, 2005) developed performance criteria for system-wide service after earthquakes. There are short- (24 hours) and long-term (30 days) levels of service goals for seismic reliability. Short-term service goals are based on delivering basic service (average winter month delivery) of 215 million gallons per day (MGD) within 24 hours after a major earthquake. A 90% confidence level is to be achieved in meeting this goal, which includes delivering basic service to at least 70% of turnouts within each customer group to improve uniformity of reliability across a customer group. It is assumed that no significant repairs are performed in the first 24 hours after a major earthquake. The long-term performance criteria are based on making temporary repairs to restore average day delivery of 300 MGD to customers. It is the intent that all water be disinfected.

The SFPUC performance criteria were critical for the implementation of hydraulic network modeling to assist system planning, and the integration of project designs and construction management to deliver specific water supply targets. These criteria are an example of the type of performance goals that support community resilience. Criteria like these can also provide the basis for developing a national framework for lifeline system performance goals.

The priority topics for research, development, and implementation in this subgroup include:

- Topic No. 1: Develop an overarching framework for national lifeline performance and restoration goals
- Topic No. 2: Assess current societal expectations of acceptable lifeline performance levels and restoration times informed by the phases of response and recovery
- Topic No. 3: Establish procedures to quantify hazards over spatially distributed lifeline systems

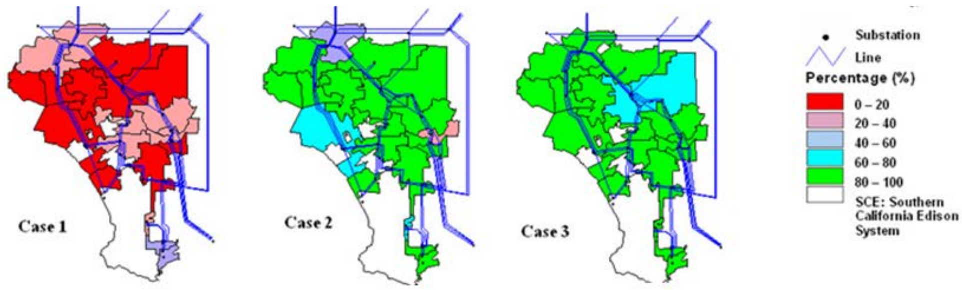
Subgroup I.2. Develop methods for lifeline system performance and restoration needs assessment

The *Needs Assessment* subgroup complements the work to develop lifeline system performance and restoration goals, defined under Subgroup I.1, by focusing on modeling tools. These tools help identify performance and restoration gaps, logistical needs, and investment strategies that become part of a national framework for the establishment of lifelines performance and restoration goals at the community level. The modeling should also address lifeline interdependencies. Until now, most modeling efforts have been focused on simplified systems and metrics, without full regard to system restoration or physical/institutional relationships among electric power, telecommunications, transportation, gas and liquid fuels, water and wastewater operations.

The modeling tools should help identify performance inconsistencies that result from the use of current manuals, guidelines, and standards. In addition, decision makers need better tools to determine the socioeconomic benefits, both direct and indirect, of different investments to upgrade lifeline systems and components to earthquake-resilient goals, with guidance on how to prioritize such investments over time. For example, the improved tools should help identify which components of aging water systems are most critical to upgrade to improve hospital sector reliability and which components of aging transportation systems are most critical to improve the reliability and economic vitality of a city or metropolitan region.

Informed by system-specific requirements and models, along with local constraints, interdependencies, and user expectation needs, this subgroup will identify effective strategies to reach national-level performance goals that ensure minimum community-level lifeline systems services. The identified performance gaps and operational needs, supported by modeling tools, will inform utilities about effective pre-event and post-disaster recovery interventions necessary to reach the nationally-consistent goals.

Lifeline System Simulation Modeling



Engineers and managers can use the current generation of lifeline network models to plan and design for complex performance under the highly variable and uncertain conditions, including earthquakes. For example, simulations of the post-earthquake performance of the Los Angeles Department of Water and Power electric power system were performed to show how improvements in key components affect system reliability after earthquakes (Shinozuka and Chang, 2004; Shinozuka et al., 2003). The Case 1 simulation results illustrated above show the ratio of mean power supply in the network damaged by a magnitude-7.3 Malibu Coast earthquake to electric power supply before the earthquake. The reductions in loss associated with retrofitting large electric power transformers are shown in Cases 2 and 3.

Such work provides an understanding of the vulnerability and potential for cascading losses in large regional electric power systems, such as the one operated by the Western States Coordinating Council (WSCC). This system covers approximately 1.8 million square miles and provides electric power for 71 million people in 14 states. Power flow simulations, initially undertaken for earthquake effects in Los Angeles, were expanded to investigate the loss of critical transmission facilities in the WSCC network (Shinozuka et al., 2003). The simulations showed that the entire Los Angeles area can be blacked out by the disruption of one transmission line at the border of Washington and Oregon.

Lifeline system simulations can be run for a suite of different scenarios that allow operations personnel to visualize a wide range of responses for an entire system or a specific part of a system. By running multiple scenarios, with and without system modifications, engineers and managers can identify recurrent patterns of response and develop an overview of potential performance, helping them plan for many eventualities and improving their ability to innovate during an extreme event. The plan that emerges from any particular suite of scenarios, however, is not as important as the planning process itself, because as soon as a disaster unfolds, the reality of the event will diverge from the features of the most meticulously designed scenario. With good planning, however, emergency managers and lifelines operators can improvise, and skilled improvisation enables emergency responders to adapt to rapidly changing field conditions. The ability to improvise is an important characteristic of resilience. Community resilience is enhanced markedly when improvisation is institutionalized in the cultures of lifeline operating companies.

Priority topics for research, development, and implementation in this subgroup include:

- Topic No. 4: Develop modeling tools to support design approaches, planning, and restoration for interdependent lifeline systems
- Topic No. 5: Develop tools to quantify and rank the societal benefits and costs of different lifeline system performance levels and restoration times, as well as prioritize lifeline upgrades and investments

3.2 Program Element II. Develop Lifeline System Specific Performance Manuals, Guidelines, Standards, and Codes

3.2.1 Background

The design and construction industry is governed by a variety of mandatory and non-mandatory documents most often referred to as Codes, Standards, Guidelines and Manuals. They are developed in a variety of ways and represent various levels of consensus. Each is important in the development and application of new technologies as well as setting minimum criteria when necessary. For the purpose of this report, the following definitions apply:

- *Codes*: Legally binding requirements that are adopted by entities having jurisdiction over the system or project, and that specifically state what must be done. They are written by code development organizations in mandatory language and should only reference standards that can be enforced.
- *Standards*: Voluntary design requirements that are most often written in mandatory language and specifically state what needs to be done to meet the requirements of the standards. They are written by standards development organizations following strict rules established by the American National Standards Institute (ANSI) that assure they represent a consensus of a balanced group of informed professionals and users.
- *Guidelines*: Design requirements that are written in non-mandatory language by a group of interested and informed individuals. They include various suggested design procedures related to a common topic that are subject to the interpretation of the user. Application of all or part of the guideline is at the discretion of the user, usually based on their experience and intuition. Guidelines often form the basis for pre-standard documents that are then taken through the consensus process to become standards.
- *Manuals*: Practical instructions to assist designers in the use of guidelines, standards, or codes. They often include suggestions related to techniques for applying the procedures, key assumption that need to be made, and usually include a variety of design examples.

The seismic design of buildings and infrastructure is directed by codes and standards. For example, in most localities the structural design of lifeline system buildings and facilities is governed by the *International Building Code* (IBC). The IBC defers to the *ASCE 7 Standard* for the prescription of minimum design loads and to material-specific codes such as the American Institute of Steel Construction (AISC) *Specification for Structural Steel Buildings,* the American Concrete Institute (ACI) *Building Code Requirements for Structural Concrete and Commentary,* and the American Wood Council (AWC) *National Design Specification for Wood Construction.*

In general, there are no seismic codes and standards covering entire lifeline systems. For example, seismic guidelines exist for specific system components, such as bridges, but they are not available for entire transportation networks. Also, while various installation, test, material, and emergency services standards exist for the purpose of assuring certain aspects of seismic performance, these standards do not address system-wide post-earthquake performance. Consequently, regulatory agencies, government entities, and lifeline organizations lack a comprehensive technical basis for establishing seismic safety requirements applied to lifeline systems.

Since the 1971 San Fernando earthquake, many seismic guidelines have been developed to cover gaps resulting from the paucity of codes and standards for lifelines. Guidelines are typically developed by groups of qualified practitioners, but their application and design is only voluntary. Technical manuals can be used to supplement codes and standards, but their use is not typical in the lifelines arena.

Guidelines, which define best practices, exist, but may need improvements to address performance objectives in accordance with the advances in research, construction and operations experience, and technology that have been realized in recent years. Standards, which prescribe minimum requirements for seismic resilience also exist, but may need improvement or extension to address seismic hazards more specifically and to guide adoption and implementation of national performance and restoration goals.

There is a natural evolution in system standards development that starts with an investigation of existing standards, guidelines, and best practices including elements that can be repaired within established restoration timeframes. In the initial stage, it is important to shorten development time by accessing and evaluating existing manuals of practice and guidelines. The next step is to identify gaps or deficiencies regarding seismic component performance and develop best practices, guidelines, and/or standards for them. Component behavior must then be integrated to arrive at a system level of functionality.

Functionality describes the system's state over time, during and following a disaster or other disruption, and the ability of the system to provide its intended services in a damaged state. It is an important measure of system resilience (i.e., its robustness). In the absence of functionality-damage quantification methods, it is nearly impossible to understand a system's degree of resiliency, much less compare resilience among different systems.

Each lifeline system also requires its own hierarchical set of system-level standards, guidelines, and manuals to assure continuous progress to improve seismic resilience. The system-level documents should contain linkage (reference) to underlying component level standards and manuals, many of which are currently established. Using a manual of best practices, guidelines, standards, and codes, the vulnerability of each component in the hierarchy of the system can be derived, and the probability of component failure (fragility) established. When all components of the system are accounted for, the highest risk components are identified as those with the potential to cause failure of the entire system or a critical portion of the system. The highest risk components represent the top priorities for upgrades.

Developing model standards for the seismic design of lifelines also requires collaboration with industry organizations. For example, the Pipeline Research Council International (PRCI) and the ASME have been responsible traditionally for the development and maintenance of design standards for gas and liquid fuel lifelines. Industry collaboration and consensus is paramount, and can most readily be achieved through cost-shared projects via joint funding from the Federal government (for example, the Pipeline Hazardous Materials and Safety Administration (PHMSA) of the U.S. Department of Transportation (DOT)) and PRCI. Priority topics under this program element have been developed to take advantage of this type of joint industry and government support.

3.2.2 Guidelines and Standards to Improve Lifeline System Resilience

Best practices and guidelines exist for many lifelines. For example, the American Lifelines Alliance (ALA), the Technical Council on Lifeline Earthquake Engineering (TCLEE) of the ASCE, and others have produced best practices and guidelines for different lifeline systems. The ALA summarized various guidelines and standards pertaining to lifeline performance in response to manmade hazards as of 2003, and developed a matrix of standards and guidelines for natural hazards as of 2004, which are presented as Tables A-1 and A-2, respectively, in Appendix A.

Many existing guidelines were developed a number of years ago, and are in need of updating. There are also guidelines and/or standards of practice that have been developed by the U.S. military, the Japan Society of Civil Engineers (JSCE), municipal utilities, and consultants that need to be collected and assessed. These documents are in varying levels of detail, incorporate an inconsistent list of considerations, and do not have consensus among a wide range of users in the United States. Also, funding for the ALA was terminated in 2005 and, thus, oversight for guidelines and standards development has been lacking for nearly a decade. Existing lifeline-specific guidelines and standards also need to be expanded to address the national performance and restoration goals developed as part of this roadmap and to include consideration of interdependencies with other lifelines.

By nature, standards and codes move through a balloting process to assure that there is national consensus related to the content. As described in Appendix A, ALA was able to encourage some of their guidelines to be taken through the standards process. Similarly, ASCE has developed and maintains a number of standards that were initiated through industry consensus-based processes led by the Applied Technology Council (ATC). In both cases, the process would be well served if there was a strong link between the development of guidelines and the standards process.

Program Element II of this roadmap focuses on the development of guidelines and manuals of best practice, which are then likely to serve in appropriate instances as the bases for actual standards and codes. The priority topics for research, development, and implementation to address lifeline system reliability are:

- Topic No. 6: Develop guidelines for the analysis, design, and planning of electric power infrastructure in seismically vulnerable regions
- Topic No. 7: Develop guidelines for improving telecommunication system resilience under earthquake conditions
- Topic No. 8: Develop water system seismic guidelines and standards
- Topic No. 9: Develop wastewater system seismic guidelines and standards
- Topic No. 10: Develop a manual of best seismic practices for gas and liquid fuel transmission pipelines
- Topic No. 11: Develop a manual for improving the seismic performance of natural gas distribution systems
- Topic No. 12: Develop guidelines for mitigating damage to lifelines from tsunamis and other flood-related hazards
- Topic No. 13: Develop guidelines for post-earthquake lifeline assessment, response, and recovery
- Topic No. 14: Develop geohazard guidelines for owners and contractors for engineering, procurement, and construction of pipelines
- Topic No. 15: Develop seismic qualification standards for lifeline components and systems

3.3 Program Element III. Conduct Problem Focused Research for Various Lifeline Systems

3.3.1 Background

In the past 40 years, considerable research has been conducted in lifeline earthquake engineering, with many research results transferred to practice. Significant research issues still remain, however, and need to be addressed in a systematic manner. The need arises because key lifeline performance problems have been addressed only to a limited extent or not at all. As lifelines, particularly electric power and telecommunications, shift towards decentralized operations, the system network structures and performance requirements are changing and cannot be addressed adequately with conventional methods. In addition, new materials, innovative designs, “smart” computer technology, and novel computational methods developed over the past two decades present opportunities for investigating efficient solutions to problems that previously could not be resolved.

The success of this program element hinges upon a dual focus on individual systems as well as the interdependencies among various systems. Understanding interdependencies is critical across all phases of the disaster cycle—mitigation, preparedness, response, and recovery. Such a “system of systems” approach provides the foundation for more resilient infrastructure, thus supporting regional and local communities, both of which are highly dependent on infrastructure performance. Within each lifeline system, multi-modal functions should be identified, and methods should be developed to assess their combined performance. Examples of transportation multi-modal functions present in most urban regions are car/truck transportation, heavy and light rail systems, and bus networks.

The combination of conventional electric power and telecommunications systems with new decentralized power grids and autonomous cell towers represents a distinct paradigm shift for combined lifeline operations. In addition, sustainability efforts are promoting combined water and sewer system designs, especially in urban areas. The implications during and after a major earthquake of new system network structures and combined system performance have not been investigated. The interdependencies of these new designs need to be studied, and methods for their evaluation need to be developed.

In the past several years, there have been significant innovations in the area of new, sustainable materials and novel designs for infrastructure components. It is important to investigate how these novel materials and component designs can help increase the resiliency of lifeline systems, including technologies that can be readily deployed and ones that require modification to fit specific needs. Researchers and practitioners also need to take advantage of modern computational methods, complex system analysis and optimization techniques, machine learning, and novel statistical analysis methods to advance the state-of-the-art in design and performance assessment of lifeline systems.

3.3.2 Program Element III Subgroups

Program Element III identifies priority topics that are organized in two main areas:

- Priorities related to research across lifelines
- Priorities related to research for specific lifeline systems

The topics attempt to fill gaps in knowledge and/or advance the state-of-the-art in lifeline risk and resiliency assessment and management. However, as noted earlier, these topics are to be regarded as a starting point for an emerging dynamic and interactive process, with new topics being identified on the basis of work in other program elements. Individual research topics in Program Element III may either be changed or replaced with new topics as the roadmap work progresses.

Subgroup III.1. Priorities related to research across lifelines

New lifeline network paradigms are emerging in response to increased demands for energy, renewal of aging lifeline infrastructure, planning and operations for sustainability, and innovations in computational methods for complex networks. Lifeline risk and resiliency methods need to advance to meet the challenges and opportunities created by these changes. The following priority topics have been identified to address this need.

- Topic No. 16: Evaluate the feasibility of new interdependent lifeline system configurations
- Topic No. 17: Develop methods for analysis and mitigation of damage from fire following earthquake and hazardous material releases
- Topic No. 18: Improve and extend methods for mitigating the effects of earthquake-induced ground displacement on underground pipelines, conduits, and cables

The majority of topics cut across all lifelines, but some focus mainly on specific subsets of lifelines. Many will require interdisciplinary teams to address the issues associated with complex, geographically distributed systems. Examples include the understanding of diverse failure modes within and across lifeline systems, temporal and geographical extents of failures, as well as assessment of the effects of crisis management response protocols, long-term planning projects, and utility resources on contingencies and future national-level resilience.

Subgroup III.2. Priorities related to research for specific lifeline systems

There are also issues that relate to only one or several lifelines but not all of them. To address these issues, the following priority topics for research related to specific lifeline systems have been identified.

- Topic No. 19: Evaluate distributed power generation and energy storage to reduce earthquake/natural hazard effects on electric power systems
- Topic No. 20: Develop a multi-hazard, multi-modal dynamic transportation network risk assessment model
- Topic No. 21: Develop water and wastewater system evaluation methods for earthquake impacts
- Topic No. 22: Develop tensile and compressive strain limits for welded steel pipelines in permanent ground displacement zones

3.4 Program Element IV. Enable the Adoption and Implementation of Lifeline System Performance Goals and Standards

3.4.1 Background

One of the last major studies to assess best practices in adoption and implementation of lifeline earthquake resilience was completed in 1998 (Taylor, Mittler, and Lund, 1998). It reflects U.S. case studies from the 1980s and 1990s in a timeframe characterized by recent, large and damaging earthquakes in the United States and strong public and government interest in addressing and overcoming lifeline system vulnerabilities. Since that time, deregulation and privatization of lifeline systems have also impacted the public and private ownership patterns, institutional arrangements, and collaboration among lifeline system providers across the United States.

Today, the nation's lifelines encompass thousands of individual systems and components that are owned, operated, and regulated in distinctly different ways. This pattern, in part, reflects the inherent diversity in providing various services vital to fulfilling societal needs. Also, in contrast to individual buildings, which occupy a specific site or location, lifeline systems are geographically distributed and interconnected, which adds to the complexity of ownership and regulatory issues. For example, many but not all water and wastewater systems are owned and operated by relatively small public entities with localized system coverage. On the other hand, most electric power, gas, liquid fuel, and telecommunications systems are owned and operated by larger, private entities with systems that typically cover many cities and states. The ownership and operation of transportation system networks are also quite diverse, with state and local authorities typically responsible for roads, highways, bridges and transit services; and ports, airports, and railroads commonly owned by quasi-public or private organizations.

Regulatory oversight spans Federal, state, and local jurisdictions, with some privately-owned lifeline systems subject to more regulations than the public ones (Taylor, Mittler, and Lund, 1998). Much of the regulatory oversight has been conferred from the Federal government to state and local control, and thus regulatory involvement can vary significantly from state to state and system to system. Privately-owned lifeline systems are often regulated by Federal interstate commerce authorities and state public utility commissions. Policies and regulations for many publicly-owned systems come from local jurisdictions that own and manage the systems. Some regulations apply to operational and performance standards, notably rates and consumer and environmental protections.

3.4.2 Program Element IV Subgroups

This program element focuses on the research, development and implementation priorities necessary to advance the adoption and implementation of lifeline system performance goals and standards, and sustain lifeline system reliability and seismic resilience over time. It is organized into two subgroups:

- Priorities to enable adoption and implementation of lifeline system performance goals and standards
- Priorities for long-term earthquake resilience

Subgroup IV.1. Priorities to enable adoption and implementation of lifeline system performance goals and standards

From the Federal perspective, the adoption and implementation of seismic mitigation measures is an essentially voluntary process (U.S. Congress, Office of Technology Assessment, 1995). Thus, owners and operators are the primary target audience for enhancing the adoption and implementation of consensus lifeline performance goals and standards. Additionally, it is important to target the public, especially at the community level, who are beneficiaries of lifeline services, as well as the policy makers and regulators, who influence how these services are provided.

Publicly-owned systems, in theory, should be continuously updated and protected because they are operated in the public interest; however, fiscal considerations can impede this process (FEMA, 1995). The motivations for privately-owned systems, in turn, may include protection of capital investment, avoidance of claims for damage or loss, and the maintenance of corporate values and competitive edge through safety and reliability (FEMA, 1995).

The Federal government does maintain some authority over lifelines through its construction funding programs. It can also facilitate action with its leadership and financial support for the translation of research results into guidance for improved performance, including model codes and standards when appropriate. Regulators and policymakers can also affect directly how consensus lifeline performance goals and standards are adopted and applied. For example, the San Francisco-based civic association, SPUR[4], developed a set of system performance and restoration times from an expected earthquake affecting the City of San Francisco (SPUR, 2009). One recommendation of the SPUR report was to form a Lifelines Council to help promote resiliency, response and restoration planning and collaboration among lifeline system providers. The City and County of San Francisco launched the Lifelines Council in 2009, and it serves as an intermediary body between lifeline system providers, policymakers and the public to consider local expectations and goals.[5]

Also, lifeline customers and the public-at-large can have an influential role in the adoption and implementation of consensus lifeline performance goals and standards. This comes most directly from customers of systems where there is market competitiveness. In more monopolistic service environments, the public can influence public policy and regulatory oversight of the system providers.

This roadmap recommends the following priority topics for research, development and implementation to enhance the capacity and willingness of lifeline owners and operators to adopt and implement system- and component-level performance goals and standards:

- Topic No. 23: Develop tools, guidance, incentives, and funding mechanisms for voluntary adoption and implementation of lifeline seismic resilience programs and earthquake-resilient design and construction standards
- Topic No. 24: Develop strategies and techniques for the public and key customers to engage lifeline system providers to define acceptable performance levels and restoration timeframes

Subgroup IV.2. Priorities for long-term earthquake resilience

Society-at-large benefits from the improvements in lifeline system reliability and long-term seismic resilience; however, costs for these improvements often fall to a narrower group of customers and can be susceptible to ownership changes and political and economic conditions. Investments made in lifeline system reliability and seismic resilience need to be protected, and can benefit significantly from improvements in system mitigation and monitoring as well as emergency response and restoration enhancements. This roadmap recommends the following priority

[4] See www.spur.org
[5] See http://sfgsa.org/lifelinescouncil

topics for research, development, and implementation to help sustain lifeline system reliability and seismic resilience:

- Topic No. 25: Assess the direct and indirect socioeconomic consequences and financial implications of different lifeline performance levels and restoration timeframes
- Topic No. 26: Implement post-earthquake information and response services for lifeline systems
- Topic No. 27: Develop and deploy intelligent lifeline monitoring, advanced sensors, and emergency response and restoration decision support systems
- Topic No. 28: Develop and deploy better tools, training, and guidance for emergency operation planning, response, and restoration of lifeline systems

3.5 Management Plan

Lifelines lack a single umbrella organization to set performance goals and standards and advocate for system enhancements. This is a serious obstacle in ensuring cohesive and consistent management of this Lifelines Earthquake Resilience Roadmap. Thus, the proposed management plan for this roadmap involves two steps. The first is to develop an organization or secure involvement with an existing organization that assures stewardship of a U.S. national lifelines resilience program and provides the basis over time to deal with evolving community needs and attendant lifeline performance goals and, where applicable, standards. The second step is to implement the identified lifeline roadmap priorities under the oversight of such an organization.

An agency well suited to support and supervise the development of a national lifelines resilience organization and program is NIST. Assistance can be provided from other NEHRP agencies. One agency that should be involved more actively is the Department of Homeland Security (DHS). DHS is responsible for the National Infrastructure Protection Plan (NIPP), which is described in Appendix D. The plan provides a framework to share threat information, reduce infrastructure vulnerabilities, minimize consequences, and facilitate response and recovery efforts for 16 critical infrastructure sectors. The NIPP includes virtually all lifeline systems, and therefore represents an overarching government program that influences lifeline policy and support. DHS should support FEMA’s involvement in a more substantial way or secure direct support from other departments and programs in DHS.

3.5.1 Organizational Leadership

Three organizational leadership models are considered in this report predicated on (1) the American Lifelines Alliance (ALA) model, which existed as a project within another organization and could be resurrected as an independent entity; (2) the

Applied Technology Council (ATC) model, which exists as an independent non-profit corporation; and (3) a hybrid model that places the program within an established organization.

3.5.1.1 The American Lifelines Alliance (ALA) Model

A description of ALA and its products is provided in Appendix A. The ALA was initiated by FEMA in 1999 through a cooperative agreement with the ASCE and initially ran as a project between FEMA and ASCE. After the first three-year contract and over $2 million in investment, support was continued with a year-to-year task order contract with the National Institute of Building Science (NIBS). The original plan for supporting ALA involved withdrawal of FEMA funding as ALA became self-sufficient.

The objective of ALA was to facilitate the creation, adoption, and implementation of design and retrofit guidelines for lifeline systems and to promote their development into American National Standards Institute (ANSI)-approved national consensus standards. When implemented by lifeline owners and operators, these guidelines and standards would systematically improve the performance of utility and transportation systems to acceptable levels in natural hazard events.

The organization of ALA relied upon an Advisory Working Group (AWG) of 10 to 12 members under a technical coordinator. An AWG member was assigned oversight responsibility for each project. Overall project direction and task approval was provided by FEMA, first through ASCE and then NIBS.

Initial funding was provided for several ALA guidelines projects in late 1999. Over eight years, ALA awarded 27 projects, including 17 projects specifically directed at guidelines-related tasks; six of these had results incorporated into new or modified ANSI-accredited standards. The annual ALA budget from 1999 to 2005 was between $400,000 and $700,000. Funding for ALA ended in 2005 when FEMA's NEHRP budget was significantly reduced. Project awards were completed at the end of 2007.

There are a number of lessons from the ALA experience. The organizational approach for technically managing ALA with a technical coordinator and an AWG was effective. All members of the AWG were compensated for their time at commercial rates. Fair compensation incentivized the AWG to give priority to the ALA work.

Several problems were also encountered. Projects addressing major topics typically required a multi-year effort, which was incompatible with the ALA’s year-to-year funding cycles. Working around a government fiscal year schedule often was an impediment. Projects would typically be defined early each year for submission into the Federal budget process, but then actual fiscal year funding, which determined which projects could be supported, was often not known until much later in the year. Requests for project proposals would typically occur late in the year with submissions due in early January. The selected teams would then have less than a year to complete the project before the Federal fiscal year ended on September 30th. The annual budgets for ALA were also modest given the national importance of lifelines and the need to improve community resilience against natural hazards.

ALA efforts were generally limited to transferring established good practices into documents that would provide a starting point for ANSI-accredited guidelines and standards activities. If additional research was required, ALA could be an advocate, but generally could not provide funding to conduct research. Near the end of ALA funding, identifying projects within this narrow scope became difficult, and ALA needed to expand its scope to include projects that were not strictly related to providing guidance. Moreover, it was difficult for ALA to take products to standards development organizations that were not initially involved in identifying the need for the project.

Many aspects of the ALA organization worked well and could be applied in the design of the management entity proposed as part of this roadmap. For example, the role of FEMA could be replaced by a Board of Directors. The Executive Director should be a paid full-time position with staff support. The Executive Director and the Board members should be well-recognized professionals within the lifeline community, and importance should be given to their ability to solicit funding from corporations and foundations. Membership, both individual and institutional, could be used to track shifts in user interests and, to a lesser extent, provide funding. Establishing the organization as a 501(c)(3) non-profit organization would allow the entity to accept funds from a variety of sources. An annual budget commensurate with the national importance of lifelines and community resilience should be allocated for the appropriate umbrella organization. It could then be supplemented through an industry-government partnership adding to the base of government support.

3.5.1.2 The Applied Technology Council (ATC) Model

Management and implementation of the Lifelines Earthquake Resilience Roadmap could be patterned after that of the Applied Technology Council (ATC), which is described in Appendix C. ATC is well suited to develop guidelines and pre-standards and ASCE/TCLEE and others are well positioned to develop manuals and consensus based standards.

There are several aspects of ATC that are noteworthy and potentially helpful in characterizing an appropriate organization for lifelines, including (1) a business model that enables the organization to expand and contract at will, depending on the availability of external funding; (2) a small permanent high-caliber professional staff who identify technical needs, write technical proposals for funding, manage projects, and execute product quality control, all in a consistent and reliable fashion; (3) a Board of Directors of nationally recognized leaders in structural, earthquake, wind, and fire engineering who set policy and assist in project identification and development; (4) a consistently applied consensus-based project/product development model that relies on highly qualified paid technical consultants to develop and overview project work; (5) a broad range of leading technical consultants who are willing to work on ATC projects, at compensation rates specified by ATC (often substantially less than prevailing commercial rates), because of the intellectual rewards and resulting professional contributions and recognition; and (6) government and private-sector agencies and organizations that are willing to fund ATC work, based on consistent implementation of an efficient non-profit business model and the ATC track record in product development.

The ATC model is that of an independent 501(c)(3) non-profit organization that functions under the guidance and oversight of a Board of Directors. It operates with a small full-time staff, led by an Executive Director, and as many as several hundred independently hired consultants at a given time. Office space for staff is rented, and meetings with consultants are conducted on a virtual basis (via phone and the internet) or in face-to-face meetings at rented or donated conference rooms. This model is similar to the proposed management structure based on the ALA model, as described at the end of Section 3.5.1.1. The success of the ATC-like model would also depend on many things, including Board membership, location of the office, the potential work force for the staffing selections, and the ability to find the right people for the operation, including the Executive Director.

3.5.1.3 Program within an Established Organization Model

Similar to the original arrangement for the ALA, a third option is to designate the responsibility for management and implementation of the Lifelines Earthquake Resilience Roadmap as a major program within an existing organization. The organization could be an association of lifeline or earthquake engineering professionals who already have, or desire to have, a research and development organizational component; a 501(c)(3) non-profit organization that already undertakes research and development activities in civil engineering, or preferably, earthquake engineering; or another entity that can demonstrate its ability and commitment to manage effectively and implement the Lifelines Earthquake Resilience Roadmap over the long term. The following governance and organizational structure would be desirable:

- A Governance Board consisting of balanced representation, with defined terms, from a broad range of lifeline organizations committed to the successful implementation of the Lifelines Earthquake Resilience Roadmap;
- A dedicated full-time Program Director and technical staff who have the experience, education, and skills necessary to implement the program with high potential for success;
- Dedicated support staff with demonstrated ability to provide the necessary technical, administrative, accounting, and contract coordination functions; and
- A business model already in place that defines how the necessary talent will be acquired to carry out the activities defined in the Lifelines Earthquake Resilience Roadmap. Reliance on volunteers to implement the program is not considered viable.

Chapter 4
Recommended Lifeline Research, Development, and Implementation Priority Topics

In this chapter, summaries for each of the 28 recommended priority topics for lifeline research, development, and implementation are provided in the order that they are presented in the framework: by Program Element, subgroup, and topic number. A summary of the estimated costs to execute the recommended topics is also provided at the end of the chapter.

4.1 Topic Summaries

Each priority topic is described in a one-page summary that consists of (1) the topic title; (2) topic description; (3) cost category; (4) duration; (5) type of endeavor needed to execute the recommended topic activities; (6) special personnel requirements (if specified); (7) potential funding sources; and (8) priority ranking.

1. **Topic Title.** The topic title concisely defines the topic and its scope.
2. **Topic Description**. Each topic description consists of an overview of the topic goal(s), background information, underlying purpose(s), and associated objectives and tasks. The intent is to provide basic context for the topic and identify the recommended approaches and activities to be undertaken and needed outcomes. Recommended activities include a broad range of research, development, and implementation functions, including fundamental research, technical guidance and standards development, and implementation strategies and activities. Outcomes include identified products and related impacts.
3. **Cost Category.** The estimated cost to conduct the needed work is indicated by a cost category defined in terms of an estimated cost range. Four cost ranges were defined by the roadmap development team: $200,000 to $500,000; $500,000 to $1,000,000; $1,000,000 to $2,000,000; and $2,000,000 to $5,000,000. The estimated costs and cost ranges evolved over the roadmap developmental period from ad hoc estimates provided by those who developed a particular topic, to consistently applied ranges based on group discussion and review and oversight provided by the roadmap development leaders. The resulting cost category for a given topic depends on the topic scope, duration, and number and specialties of the personnel involved in executing the topic activities.

4. **Duration.** The estimated time to conduct the activities described for each of the topics is indicated in one of three ranges: 2-3 years, 3-5 years, and 5-8 years. Some topics need to be completed before others can begin, so the time period required to complete all the topics is nominally 10 years. As in the case of the cost categories, the estimated duration to complete the work proposed for each topic evolved over the roadmap developmental period; initial estimates were provided by the individuals who developed the topic, and the final estimates were based on group discussion and review and oversight provided by the roadmap development leaders. Duration estimates considered the overall scope of the effort, anticipated difficulties, and personnel requirements.
5. **Type of Endeavor.** The type of endeavor to execute the recommended topic is defined in terms of a recommended personnel organizational structure. They are patterned after the organizational structures currently used in government and industry funded research and development projects in earthquake engineering and related sciences, where the goal is long-term viability and acceptance of the results. Such efforts typically involve technical committees composed of a small group of leading, respected practitioners (from private practice and industry) and researchers (from universities and industry) who are responsible for the practical direction and overall conduct of the endeavor. Their work is typically reviewed and guided by a blue-ribbon review panel composed of senior level specialists in the topic area(s) under consideration.
6. **Special Personnel Requirements.** Specialized personnel requirements are identified for some topics. Otherwise, it is presumed that knowledgeable research and practicing specialists would be required to complete the topic activities.
7. **Potential Funding Sources:** Potential funding sources for the recommended topic activities are provided in generalized terms (e.g., government, industry) or in specific terms, whereby a potential funding organization is identified.
8. **Priority Ranking.** The priority rankings are based on input received from participants in a project workshop in May 2014 that reviewed and evaluated the proposed topics for the roadmap. Participants included specialists from a variety of lifeline organizations, private engineering practitioners and researchers involved in lifeline earthquake engineering, regulators, and other lifeline professionals. Before the workshop, the list of recommended topics had been trimmed in several "whittle-down" rounds to include only those of greatest value. Priority options given to workshop participants were "Very High" (deemed "Highest" in this document), "High", and "Medium".

Following are the 28 recommended priority topics for lifeline research, development, and implementation.

ELEMENT I. Establish National Lifeline System Performance and Restoration Goals

SUBGROUP I.1. Develop a framework for the establishment of lifeline system performance and restoration goals

Topic No. 1	Develop an overarching framework for national lifeline performance and restoration goals.
Description	Goals: Develop a national framework to guide lifeline operators in setting minimum goals for system performance and restoration that are focused on achieving community resilience. These goals must be informed by past performance, system capabilities, best practices, costs, and existing performance gaps. Metrics and goals need to address pertinent hazards, different levels of service (LOS), and restoration times—all consistent with community needs and available funding mechanisms. The performance framework developed in this topic is intended to guide the identification of new topics, especially those related to Program Elements II and III. Objectives and tasks: - Clarify and standardize definitions and nomenclature pertaining to different lifelines. Summarize performance metrics used in previous and existing projects as well as those involved in guidelines and standards for specific lifelines, including the assumptions and limitations inherent in characterizing performance. - Document past thinking and debate on national best practices for performance and restoration goals, the metrics selected, and the resulting performance assessment frameworks. Evaluate how best practices, guidelines and standards were developed and applied in different lifeline systems. Evaluate the degree to which interdependencies among lifelines are reflected in the performance goals for individual systems. Summarize how system performance has been linked with community needs. - Develop a first generation of national performance and restoration guidelines that emerge from U.S. and international best practices, and address system capacities, service expectations, local hazards, and modeling capabilities. Note that the other topics in Program Element I are intended to be informed by and help expand on the performance framework established in this topic. Practical minimum requirements for lifeline performance and restoration need to be defined for different phases of operation, including emergency response, short-term socio-economic restoration, and long-term community recovery and resilience building. Resilience-based LOS should account for life safety, property protection, public health, environmental impact, business interruption, and the cost of repair.
Cost Category	$1,000,000 to $2,000,000
Duration	2-3 years
Type of Endeavor	Technical committee plus an expert advisory group, and a lifeline systems review panel.
Potential Funding Sources	Government, industry
Priority Ranking	Highest

ELEMENT I. Establish National Lifeline System Performance and Restoration Goals

SUBGROUP I.1. Develop a framework for the establishment of lifeline system performance and restoration goals

Topic No. 2	Assess current societal expectations of acceptable lifeline performance levels and restoration times informed by the phases of response and recovery.
Description	Goals: Given the differences in utility service expectations from lifeline system users, Topic No. 2 focuses on the societal expectations of system performance and restoration timeframes (e.g., by region, lifeline system, component, and social sectors, particularly public and commercial customers). An updated national assessment of performance and restoration expectations that is tempered by cost constraints is a necessary part of the development of earthquake-resilient design and construction goals for interdependent lifeline systems, components, and the communities they serve. Objectives and tasks: - Assess public expectations and the factors that influence those expectations. Pre- and post-earthquake expectations should be up-to-date and related to emergency response, short-term restoration of the socioeconomic fabric, and long-term recovery for resilience building. Societal expectations reveal gaps relative to minimum system capacity, levels of service (LOS), performance and restoration goals as established in Topic No. 1. - Understand why public expectations differ from projected seismic performance levels and restoration timeframes for different systems and for interdependent systems. Explore the effects of customer outreach and education in altering expectations and improving the perception of risk with respect to system operation during earthquakes. Investigate methods to engage public input for improving LOS and emergency operation plans. - Evaluate societal expectations and acceptable performance in context of the three phases of community response to earthquakes: (1) emergency operations and governance, (2) short-term restoration of basic functionality and workforce, and (3) long-term recovery of community and economy.
Cost Category	$200,000 to $500,000
Duration	2-3 years
Type of Endeavor	Technical committee plus an expert advisory group, and a lifeline systems review panel.
Potential Funding Sources	Government, industry
Priority Ranking	High

ELEMENT I. Establish National Lifeline System Performance and Restoration Goals

SUBGROUP I.1. Develop a framework for the establishment of lifeline system performance and restoration goals

Topic No. 3	**Establish procedures to quantify hazards over spatially distributed lifeline systems.**
Description	Goals: Given the uncertainties associated with selecting and applying ground motions for performance and restoration assessment across spatially distributed lifeline systems, as well as the difficulty in assessing local ground failure phenomena, Topic No. 3 focuses on developing procedures to quantify different earthquake hazards and their associated probabilities that affect large spatially distributed and interconnected lifeline networks. Objectives and tasks: - Develop tools, guidance documents, and standards for hazard quantification across geographically distributed systems, including network-specific hazard maps that account for sources and levels of transient and permanent ground deformation. - Develop quantitative ground failure assessment procedures (geotechnical and geological) that include: o Liquefaction mapping that can be applied throughout the United States for the estimation of differential settlements, lateral displacements, and associated disruption of underground pipelines and cables as well as damage to above-ground structures. o Identification and location of active faults and characterization of potential fault movements. o Landslides, including rock falls, debris flows, deep-seated slides, surficial slides, and expected movements. o Other forms of earthquake-induced differential settlement and lateral movements, such as settlement of loose unsaturated sands, lurching, and ground oscillation. o Spatially distributed transient ground motions. - Develop methods to estimate/quantify the amounts of movement for all of the above, and provide a framework to quantify transient and permanent ground deformation effects on components and system modeling.
Cost Category	$500,000 to $1,000,000
Duration	2-3 years
Type of Endeavor	Technical committee with specialized analysis plus review panel.
Potential Funding Sources	Government, industry
Priority Ranking	Highest

ELEMENT I. Establish National Lifeline System Performance and Restoration Goals

SUBGROUP I.2. Develop methods for lifeline system performance and restoration needs assessment

Topic No. 4	Develop modeling tools to support design approaches, planning, and restoration for interdependent lifeline systems.
Description	Goals: Given the lack of practical modeling tools for modern interdependent lifeline systems, Topic No. 4 focuses on the development of tools to model lifeline system performance. Examples need to be provided showing how modeling supports system operations, optimizes restoration and recovery, and accounts for the way in which interdependencies affect entire supply chains. The tools should be implementable in practice, and include simulation approaches, risk assessment, and optimization procedures that address both network characteristics and system operations to help quantify the capabilities of lifeline systems to withstand and recover from a diversity of failure modes. Objectives and tasks: - Develop open-source multi-system modeling applications that allow for network design, risk assessment, restoration processes, and emerging technologies, while building upon existing software such as HAZUS, MAEViz, and REDARS, among others. Optimization, statistical learning, complexity theory, network science, and reliability theory should be investigated and applied where appropriate. Game theory and agent-based formulations in the context of objective function modeling should also be examined, particularly for dynamic post-disaster environments with collocated systems. - Develop modeling tools that can cope with the computational complexity and have adequate input data sources as required for multi-dimensional lifeline system analyses. The models should replicate the way interdependent disruptions in operations cascade across systems, including adaptive operator behavior during restoration. - Perform sensitivity studies for ranking system components with respect to their performance and impact on restoration time in the host system and across interdependent lifeline systems. These models should assist life-cycle cost and benefit analyses that guide investment decisions (Topic No. 5). - Develop modeling applications that capture socio-technical factors, such as the role of operators on power and telecommunication systems, as well as the role of users in transportation networks with their intricate origin-destination patterns and trip incentives. The multi-modal characteristics of transportation, including rail, waterways, airways, and other transportation pathways, along with multiple sources of energy and water, should also be addressed in next generation modeling tools.
Cost Category	$2,000,000 to $5,000,000
Duration	3-5 years
Type of Endeavor	Multiple investigators plus industry collaborators, and a lifeline systems review panel
Potential Funding Sources	Government, industry
Priority Ranking	High

ELEMENT I. Establish National Lifeline System Performance and Restoration Goals

SUBGROUP I.2. Develop methods for lifeline system performance and restoration needs assessment

Topic No. 5	Develop tools to quantify and rank the societal benefits and costs of different lifeline system performance levels and restoration times, as well as prioritize lifeline upgrades and investments.
Description	Goals: In support of the role of utility managers who engage in the allocation of limited resources for lifeline systems resilience goals, while taking into account input from government agencies, engineers, and user stakeholders, Topic No. 5 focuses on providing guidance and tools for decision makers to determine the socioeconomic benefits, both direct and indirect, of different investments in upgrading lifeline systems and components to earthquake-resilient goals. Such goals and associated levels of service inform prioritization of investments over time. Decision analyses make use of tools from Topic No. 4 but enriched with multi-attribute utility or emerging outranking methodologies to assess how to close the gaps identified between the performance requirements from Topic No. 1 and expectations from Topic No. 2. Objectives and tasks: - Develop tools that address the growing complexity of interdependent lifeline systems within stakeholder-informed decision analysis frameworks with conflicting objectives. - Ensure that the developed tools capture decision maker preferences for achieving multi-system short- to long-term expected functionality, while including institutional culture and budgetary constraints, along with end user expectations and national performance and restoration time goals that best support overall recovery and resilience.
Cost Category	$1,000,000 to $2,000,000
Duration	3-5 years
Type of Endeavor	Technical committee plus an expert advisory group, and a lifeline systems review panel.
Special Personnel Requirements	Development team should include engineers, experts on decision theory and analysis, and other specialists, including industrial psychologists, behavioral economists, and business operations and business interruption experts.
Potential Funding Sources	Government, industry
Priority Ranking	Highest

ELEMENT II. Develop Lifeline System Specific Performance Manuals, Guidelines, Standards, and Codes

Topic No. 6	Develop guidelines for the analysis, design, and planning of electric power infrastructure in seismically vulnerable regions.
Description	Goals: Develop a practical approach to power infrastructure planning and technology development for areas at risk from seismic and other hazards with guidance for selecting the analytical tools and technological alternatives that balance investment and community resilience with the hazard probability. Objectives and tasks: - Develop guidelines to improve electric power performance under earthquake and other hazard effects, including analysis, design, and planning of electric power infrastructure. - Develop a check list for identifying system vulnerabilities, including system configuration, critical substations, components, monitoring, and community interfaces. - Ensure that guidelines consider community restoration priorities in the dynamic post-disaster environment as well as the investment required for infrastructure hardening versus post-disaster reconstruction direct and indirect costs. - Research effective ways for power infrastructure planning and technology development that incorporate the effects of human factors (such as public perception) in decision processes. Also consider the dynamic environment and changing human perceptions after an earthquake to identify analytical tools and technologies best suited for modeling pre- and post-disaster conditions. - Provide guidance to achieve both resistant and flexible system goals. Resistant power infrastructure can reduce outages during earthquakes. Flexible infrastructure can adapt to the post-earthquake environment in which a significant portion of the load, and thus the need for existing infrastructure, may have been lost. Incorporate risk assessment techniques and address regulatory limitations and human perceptions that can bias and constrain the quantification of risk.
Cost Category	$1,000,000 to $2,000,000
Duration	3-5 years
Type of Endeavor	Combined academic, industrial and engineering community endeavor.
Potential Funding Sources	Government, industry
Priority Ranking	Highest

Topic No. 7	Develop guidelines for improving telecommunication system resilience under earthquake conditions.
Description	Goals: Develop and implement a series of guidelines based on lessons learned from the past effects of earthquake hazards to enhance telecommunication systems resilience. Objectives and tasks: - Develop guidelines for reducing electric power consumption and backup power requirements for post-earthquake operations, including improved rechargeable technologies at cell sites, repeaters, digital carrier loops, and remotes. Establish minimum performance requirements for back-up power battery reserve times and capacities at critical lifeline facilities, including backup power management systems. Reduce post-disaster power consumption at cell sites and remotes. Reduce holding time of calls to allow more open circuits in communication networks as well as time to bring in backup generators. - Develop structural checklist and building inspection techniques for seismic preparedness of telecommunication cell sites and remotes. The goal is to reduce the probability of cell site loss due to damage or partial collapse of host buildings. - Develop procedures to increase circuits immediately after a disaster when call volume is extremely high, including telecommunication traffic control protocols to reduce the effects of abnormally high call volumes. For example, limiting call dwell time on non-priority lines will increase available circuits. - Develop guidelines for backup or reserve power for data communication equipment such as optical network terminal units and cable and DSL (Digital Subscriber Line) modems at customer premises. - Develop earthquake design criteria and retrofit options for data centers. The goal is to reduce the probability of losing critical data centers needed to maintain communication network operation during and after an earthquake. - Develop non-traditional methods and models for powering cell sites, e.g., by sharing backup generators used for elevators, roof solar power, wind or fuel cells. Options for providing power supply to cell sites in commercial buildings should be thoroughly explored. - Provide guidance for improved electric power to distributed network elements in modern communication networks, including wireless networks base stations and digital loop carrier (DLC) cabinets (also known as roadside cabinets for broadband services) in landline communication networks. The guidance should focus on reliable means to power equipment instead of feeding power from a nearby commercial power sources (e.g., aerial power line), such as using multi-pair copper cables to connect DLC cabinets to a central office, or powering from photovoltaic (PV) systems. Recent disaster experiences and best practices on power supply and distributed sources need to be summarized.
Cost Category	$1,000,000 to $2,000,000
Duration	3-5 years
Type of Endeavor	A joint industry (service providers and manufacturers) and government agency endeavor.
Potential Funding Sources	Joint government and industry
Priority Ranking	Medium

ELEMENT II. Develop Lifeline System Specific Performance Manuals, Guidelines, and Standards, and Codes

Topic No. 8	Develop water system seismic guidelines and standards.
Description	Goals: Develop consensus improvements and additions to existing guidelines and standards for water system seismic performance and resilience. Ensure the guidelines and standards are comprehensive and include seismic design criteria for all system and structural components. Also ensure that they reflect best practices embodied in guidelines and/or standards of practice promulgated by American Water Works Association (AWWA), ASCE, the Japan Society of Civil Engineers (JSCE), municipal utilities, and other institutions. *Objectives and tasks for the guidelines:* - Identify an appropriate organization to lead the development of water system seismic guidelines and standards such as the ASCE or the American Water Works Association (AWWA). - Develop an overarching/umbrella guideline to ensure consistency throughout each water system and among water and other interrelated systems for performance during events, emergency planning, response, and disaster recovery phases. - Formulate guidance for risk-based Level of Service (LOS) goals considering life safety, property protection, public health, environmental impact, business interruption, fire protection, and the cost of repair, including supporting research. - Improve the American Water Works Association (AWWA) J-100m system risk assessment standard to quantify performance and compare it to LOS goals (addressing systems with existing and new facilities). - Formulate guidance to assess treatment plant and pump station reliability (existing and new facilities) in support of the system risk assessment standard. - Formulate guidance on pipeline reliability assessments and seismic upgrades in support of the system risk assessment standard. *Objectives and tasks for the standards:* - Develop standards addressing the performance based evaluation of existing components and mitigation thereof. - Develop standards addressing the performance based design of new and replacement components. - Develop seismic performance provisions, standards, test methods, and specifications for equipment and materials. - Develop seismic provisions for inclusion in pipe support standards used in water systems. - Incorporate better methods for addressing sloshing effects in design standards for water treatment process tanks/reservoirs, baffles, and covers. - Develop standard seismic provisions for water wells, intakes, and other water supply components.
Cost Category	$1,000,000 to $2,000,000
Duration	3-5 years
Type of Endeavor	Joint industry and government study with technical committee and/or review panel.
Potential Funding Sources	Joint government and industry
Priority Ranking	Highest

ELEMENT II. Develop Lifeline System Specific Performance Manuals, Guidelines, Standards, and Codes

Topic No. 9	Develop wastewater system seismic guidelines and standards.
Description	Goals: Develop consensus improvements and additions to existing guidelines and standards for wastewater system seismic performance and resilience. Ensure the guidelines and standards are comprehensive and include seismic design criteria for all system and structural components. Also ensure that they reflect best practices embodied in guidelines and/or standards of practice for wastewater systems developed by the American Lifelines Alliance, the American Concrete Institute, the American Society of Civil Engineers, the military, the Japan Society of Civil Engineers (JSCE), municipal utilities, and other institutions. *Objectives and tasks for the guidelines:* - Identify an appropriate organization to lead the development of wastewater seismic guidelines and standards such as the ASCE or the Water Environment Federation. - Develop an overarching/umbrella guideline to ensure consistency throughout wastewater systems and among interrelated systems for emergency planning, response, and recovery disaster phases. - Formulate guidance for risk-based Level of Service (LOS) goals considering life safety, property protection, public health, environmental impact, business interruption, and the cost of repair, including supporting research. - Develop a standard for system risk assessment methodology incorporating the ability to quantify performance and compare it to LOS goals (addressing systems with existing and new facilities). - Formulate guidance to assess treatment plant and pump station reliability (existing and new facilities) in support of the system risk assessment standard. - Formulate guidance on pipeline reliability assessments and seismic upgrades in support of the system risk assessment standard. *Objectives and tasks for the standards:* - Develop standards addressing the performance based evaluation of existing components and mitigation thereof. - Develop standards addressing the performance based design of new and replacement components. - Develop seismic performance provisions, standards, test methods, and specifications for equipment and materials. - Incorporate better methods for addressing sloshing effects in design standards for wastewater process tanks, baffles, and covers.
Cost Category	$1,000,000 to $2,000,000
Duration	3-5 years
Project Type	Joint industry and government study with technical committee and/or review panel.
Potential Funding Sources	Joint government and industry
Priority Ranking	Highest

ELEMENT II. Develop Lifeline System Specific Performance Manuals, Guidelines, Standards, and Codes

Topic No. 10	Develop a manual of best seismic practices for gas and liquid fuel transmission pipelines.
Description	Goals: Develop a two-part manual of best seismic practices for gas and liquid fuel transmission lines with one devoted exclusively to new construction of transmission pipeline systems, and another devoted to existing transmission pipeline systems. Objectives and tasks: - Incorporate best practices on how seismic geotechnical hazards can be avoided or minimized with favorable routing and limited incremental cost to the project. - Develop options for improving seismic resistance that reflect the appreciable differences between existing transmission pipeline systems and new construction, such as the constraints of systems to an existing right-of-way, and the extensive right-of-way acquisition, permitting, and regulatory compliance required for new pipelines, especially interstate lines. Develop performance standards for pipeline monitoring and control systems and contingency measures for rapid assessment and repair of pipeline damage along rights-of-way.
Cost Category	$500,000 to $1,000,000
Duration	3-5 years
Type of Endeavor	Joint industry and government study conducted by a qualified contractor collaborating with a technical committee and/or review panel.
Special Personnel Requirements	Technical committee and/or review panel should include strong representation from pipeline transmission companies
Potential Funding Sources	Natural gas industry (Pipeline Research Council International) and U. S. Department of Transportation (DOT).
Priority Ranking	High

ELEMENT II. Develop Lifeline System Specific Performance Manuals, Guidelines, Standards, and Codes

Topic No. 11	Develop a manual for improving the seismic performance of natural gas distribution systems.
Description	Goals: Develop a manual for improving the seismic performance of natural gas distribution systems that helps to prioritize needs and costs, understanding that the costs to replace existing distribution piping in an urban environment are expensive and typically require funding through a separate rate case. New natural gas distribution piping systems are presently fabricated from welded steel pipe or polyethylene. Both of these construction options are resistant to damage from seismic wave propagation and can withstand modest amounts of permanent ground deformation (PGD). Objectives and tasks: - Provide guidance on new design. - Provide guidance on identifying vulnerable sections of existing distribution systems and setting priorities for replacement. Where a significant PGD hazard exists, options for improving the performance of distribution piping are often limited, given the virtual anchorage effects of multiple bends and tie-ins, rights-of-way that are dictated by street alignments, and the need to utilize high backfill compaction to assure integrity of overlying roads. - Ensure that the manual addresses the means to define post-earthquake damage scenarios, estimate service restoration requirements (e.g., contractor resources, materials, and equipment) and provide a timeline for service restoration.
Cost Category	$500,000 to $1,000,000
Duration	3-5 years
Type of Endeavor	Joint industry and government study conducted by a qualified contractor collaborating with a technical committee and/or review panel.
Special Personnel Requirements	Technical committee and/or review panel should include strong representation from pipeline transmission companies
Potential Funding Sources	Natural gas industry (Pipeline Research Council International) and U. S. Department of Transportation (DOT).
Priority Ranking	High

ELEMENT II. Develop Lifeline System Specific Performance Manuals, Guidelines, Standards, and Codes

Topic No. 12	Develop guidelines for mitigating damage to lifelines from tsunamis and other flood-related hazards.
Description	Goals: Develop guidelines to improve lifeline systems preparations and responses to tsunamis and tsunami-related damage. Traditionally, the focus on post-disaster lifeline performance has been on earthquake shaking, ground failure and related effects. Some of the most significant lifeline damage during recent earthquakes, such as the 2004 Indian Ocean, 2010 Maule, Chile and 2011 Tohoku, Japan events, was caused by tsunamis. Objectives and tasks: - Assess the effects of tsunamis on electric power grids, transportation networks, water supply systems, and wastewater conveyance and treatment systems to better understand best practices and lessons from recent tsunamis. - Develop design approaches to resist/accommodate tsunami generated hydro-dynamic forces, erosion, and other effects. - Provide an overview of the various priorities, procedures, and constraints associated with different systems to address the needs of multiple lifeline operators against tsunami-related damage. - Address lifeline interdependencies by identifying key links between each system and the other lifeline networks that interact with it in tsunami prone regions. - Develop design approaches and mitigation strategies that can also be applied to other flood-related hazards, such as hurricane-caused storm surges.
Cost Category	$200,000 to $500,000
Duration	2-3 years
Type of Endeavor	Combined academic and industrial research and development endeavor.
Potential Funding Sources	Joint government and industry
Priority Ranking	High

ELEMENT II. Develop Lifeline System Specific Performance Manuals, Guidelines, Standards, and Codes

Topic No. 13	Develop guidelines for post-earthquake lifeline assessment, response, and recovery.
Description	Goals: Develop a document to guide lifeline operators in preparing for and addressing post-earthquake response and recovery. Reference should be made to previous reconnaissance experience obtained by organizations like EERI and TCLEE. Objectives and tasks: - Provide an overview of the various priorities, procedures, interdependencies, and constraints associated with different systems to address the data and reconnaissance needs of individual lifeline operators. The lifeline systems to be addressed in this topic include electric power, gas and liquid fuels, telecommunications, transportation, water, and wastewater. - Provide guidance on vulnerability assessments for the purpose of estimating potential damage, options for rapid detection and assessment through monitoring (e.g., U.S. Geological Survey ShakeMap), post-earthquake inspection/assessment, priorities for labor, materials and equipment for repair and restoration, and emergency operations. - Provide guidance on the preparation and implementation of lifeline earthquake response plans, organizing and training staff for emergency response, and prearranging the logistics necessary to implement post-earthquake response together with long-term mitigation. - Provide guidance on the preparation and implementation of post-earthquake business recovery plans. - Address lifeline interdependencies by identifying key links between each system and the other lifeline networks that interact with it. Recommend measures to secure and recover interoperability and avoid damage related to collocation and loss of resources from other interdependent lifelines. - Address standards, protocols, and methods for collection, storage and curation of reconnaissance data.
Cost Category	$500,000 to $1,000,000
Duration	3-5 years
Type of Endeavor	Joint industry and government study conducted by a qualified contractor collaborating with a technical committee and/or review panel.
Potential Funding Sources	Government, industry
Priority Ranking	Highest

ELEMENT II. Develop Lifeline System Specific Performance Manuals, Guidelines, Standards, and Codes

Topic No. 14	Develop geohazard guidelines for owners and contractors for engineering, procurement, and construction of pipelines.
Description	Goals: Develop a guideline that promotes effective performance-based design and construction that involves the owner's project management team, the design professions, and the contractor during the execution of geohazard mitigation projects without bias to any party. The guidelines should also serve as a basis for regulators and lenders to evaluate geohazard mitigation for pipelines. Objectives and tasks: - Tailor the document for a broad audience consisting of pipeline owners, project managers, engineering staff, regulators and lenders. - Provide practical strategies for geohazard mitigation for owners, project management, and contractors. Address geohazard mitigation issues arising from inadequate and/or untimely scheduling and integration of field investigations with engineering design and construction. Emphasize the need for the owner to provide geohazard information in advance of engineering and construction and to identify further investigations to be undertaken by the contractor during project execution. For the contractor, emphasize the nature of geohazards affecting pipeline design and construction and implications of further investigation that could be required during detailed engineering and opening of the right-of-way. - Provide clear delineation of best international practice for pipeline geohazard mitigation, while avoiding unnecessary technical detail. - Provide guidance and recommendations for effective project execution, including model contract provisions that will be equitable for both owner and contractor, especially with regard to changes that become necessary as geohazard areas are encountered in construction and further characterized.
Cost Category	$200,000 to $500,000
Duration	2-3 years
Type of Endeavor	Joint industry and government study conducted by a qualified contractor collaborating with a technical committee and/or review panel.
Special Personnel Requirements	Technical committee and/or review panel should include strong representation from pipeline transmission companies.
Potential Funding Source	Natural gas industry (Pipeline Research Council International) and U. S. Department of Transportation (DOT).
Priority Ranking	High

ELEMENT II. Develop Lifeline System Specific Performance Manuals, Guidelines, Standards, and Codes

Topic No. 15	Develop seismic qualification standards for lifeline components and systems.
Description	Goals: Develop seismic qualification standards for various classes of lifeline components and systems to help ensure that facilities critical for reliable post-earthquake operations have met or exceeded minimum performance requirements for earthquake effects. Such standards will assist operators in confirming the desired levels of post-earthquake reliability can be achieved and the proper procedures have been followed in validating target performance. Objectives and tasks: - Incorporate best practices from seismic qualification standards for various classes of lifeline components and systems. For example, Bellcore (Communications Research), a part of Bell Laboratories, established a seismic qualification standard for equipment installation in central offices called NEBS (New Equipment Building System). That standard is now incorporated in GR-36-CORE, which deals with seismic anchoring and testing of equipment for Central Office application/installation. Other standards for electric power equipment and building facilities are incorporated in IEEE 693 and FEMA 460, respectively. - Recommend alternative methods for seismic qualification of new lifeline equipment to meet existing standards. For example, shake table testing can be performed on various components and equipment assemblages to verify that they satisfy required response design spectra. Special quasi-static testing can be performed on lifeline components to validate their ultimate strength and ductility. Moreover, seismic qualification may not always involve testing. For example, the Seismic Qualification User Group (SQUG) collects, evaluates, and facilitates the use of earthquake and testing experience data for the purpose of qualifying equipment in nuclear power plants without the need for testing.
Cost Category	$500,000 to $1,000,000
Duration	2-3 years
Type of Endeavor	Joint industry and government study conducted by a qualified contractor collaborating with a technical committee and/or review panel composed of representatives from lifeline companies.
Potential Funding Sources	Joint government and industry
Priority Ranking	High

ELEMENT III. Conduct Problem Focused Research for Various Lifeline Systems

SUBGROUP III.1. Priorities related to research across lifelines

Topic No. 16	Evaluate the feasibility of new interdependent lifeline system configurations.
Description	Goals: This topic focuses on guidance for interdependent network design and configurations that facilitate interoperability among different lifeline systems and improve earthquake and multi-hazard resilience. Examples include decentralized design, common hardware, and the ability to integrate new configurations and interdependent operations into existing legacy systems. Objectives and tasks: - Establish interdependent lifeline system benchmarks to enable assessment of future configurations, based on performance characteristics observed in past earthquakes, typical system topologies, functional settings, performance curves, restoration resources and prioritization schemes, usage patterns, and equipment preferences. - Perform a systematic evaluation of feasible future lifeline configurations informed by experience and simulation (using Topic No. 4 models). Quantify the performance of future decentralized lifeline systems, including the effects of the density of connections between different systems, optimal layout of facilities, and associated application of emerging technologies and practices. - Demonstrate how decentralized configurations can be used as mitigation strategies or system expansions to improve lifeline system resilience (in coordination with Topic No. 5). - Investigate adaptive weak coupling designs within and across systems to reveal intra- and interdependence for optimal operation of lifeline systems, while preventing failure propagations within and across them during abnormal events.
Cost Category	$500,000 to $1,000,000
Duration	2-3 years
Type of Endeavor	Several individual investigators plus a group of industry collaborators, and a lifeline systems review panel.
Potential Funding Sources	Government, industry
Priority Ranking	High

ELEMENT III. Conduct Problem Focused Research for Various Lifeline Systems

SUBGROUP III.1. Priorities related to research across lifelines

Topic No. 17	Develop methods for analysis and mitigation of damage from fire following earthquake and hazardous material releases.
Description	Goals: Develop guidelines to reduce the potential damage to lifeline systems in earthquakes from induced secondary phenomena, such as fires and hazardous materials. In addition, reduce the potential for secondary phenomena, such as fires following an earthquake or release of hazardous materials, due to failure of specific lifelines by increasing their resilience. Specific examples include the fires following the 1906 San Francisco and 1923 Tokyo earthquakes, and the radiation release at Fukushima following the 2011 Eastern Japan earthquake. Non-earthquake incidents, such as the Bhopal toxic gas release (1984), East Bay Hills fire (1991), San Bruno gas pipeline explosion (2010) and Lac-Mégantic (Québec) derailment (2013) demonstrate the on-going potential for such events, whose likelihood is greatly increased during an earthquake while, at the same time, emergency response capacity is exceeded. Objectives and tasks: - Review and catalog the range and severity of potential induced damage events. - Identify the risk related to such events. - Review and improve current methods for analyzing high priority induced damage phenomena (e.g., fire following earthquake or hazmat release). - Develop guidelines for mitigation of the risk due to the selected phenomena. - Identify a research program for analysis and mitigation of high priority induced damage phenomena.
Cost Category	$500,000 to $1,000,000
Duration	2-3 years
Type of Endeavor	Several individual investigators and utility collaborators, plus a lifeline systems and emergency responder review panel.
Potential Funding Sources	Government, industry
Priority Ranking	High

ELEMENT III. Conduct Problem Focused Research for Various Lifeline Systems

SUBGROUP III.1. Priorities related to research across lifelines

Topic No. 18	Improve and extend methods for mitigating the effects of earthquake-induced ground displacement on underground pipelines, conduits, and cables.
Description	Goals: Develop improved methodology for the engineering analysis, assessment and design of buried pipelines, conduits and cables for the effects of liquefaction-induced ground displacement, fault rupture and landslides. This research applies for both continuous pipelines (e.g., welded steel and thermally welded polyethylene) and segmented pipelines and conduits (typical of water and wastewater systems). Objectives and tasks: - Conduct geotechnical laboratory and field test programs to improve the current knowledge of pipe-soil interaction relevant to the assessment and design of pipelines crossing liquefaction hazard areas, tectonic faults and unstable slopes. The test programs should include consideration of horizontal, vertical and oblique displacement directions, a variety of backfill materials and grain-size distribution, and moisture content. - Conduct geotechnical test programs to determine various means of reducing or eliminating damage to buried cables (optical fiber, multipair copper cables, power conductors, signaling and control cables) due to liquefaction-induced ground settlement and lateral spread, landslides, ground oscillation, and surface faulting. - Develop methodology for direct use of mapped spectral response coefficients to estimate potential lateral spread displacements along the right-of-ways and alignments of distributed lifeline systems and at river and stream crossings. It is possible that the traditional mapped ground motion parameters could be expanded to include coefficients of the multilinear regression (MLR) characterization developed by Youd et al. (2002). - Develop improved methods to assess the potential for buoyant rise of buried pipelines in liquefiable deposits with emphasis on reducing the conservatism intrinsic to current calculation methods. Consideration should be given to both continuous and segmented pipelines, as their ability to bridge zones of liquefied soil varies.
Cost Category	$2,000,000 to $5,000,000
Duration	5-8 years
Type of Endeavor	University or industry research programs guided by a technical steering committee composed of qualified specialists and practitioners.
Potential Funding Sources	Potential supporting organizations include the Pipeline Research Council International (PRCI), the U.S. Department of Transportation (DOT), and the U.S. Geological Survey.
Priority Ranking	High

ELEMENT III. Conduct Problem Focused Research for Various Lifeline Systems

SUBGROUP III.2. Priorities related to research for specific lifeline systems

Topic No. 19	Evaluate distributed power generation and energy storage to reduce earthquake/natural hazard effects on electric power systems.
Description	Goals: Provide electric power during/after earthquakes that conventional power grids are not able to achieve because of centralized power generation and control architectures. Conventional grids provide power at least two orders of magnitude below what is required for critical facilities, such as data centers, communication central offices, and distributed network elements (Kwasinski, 2010). Microgrids (distributed power generation with independent control that can operate connected to a main grid or in islanded mode) represent a new paradigm whereby electric power distribution is shifted to electric power users instead of utilities. Microgrids integrate diverse power sources and local energy storage devices in a local system that can be independently controlled from the power grid. A microgrid in Sendai was successfully operated after the 2011 Tohoku earthquake and tsunami disaster (Kwasinski, 2011). The NYS2100 Commission (2013, p.15) indicates that "*The grid for the 21st century should seamlessly incorporate distributed generation, microgrids…*", and the Hurricane Sandy Rebuilding Task Force (2013, p.68) indicates that "*States should work …. to develop a new approach….[that]… would define policies and technical requirements for how to incorporate smart grid technology, microgrids, building controls, and distributed generation, including combined heat and power*". Objectives and tasks: - Conduct planning and development of modular and scalable microgrids resilient to earthquakes. The effort should involve system integration in an open architecture of local power generation sources, energy storage devices, and loads with a control and management platform that enables the microgrid to operate in islanding or grid connection mode. Mode transitions should occur seamlessly. Identify alternate approaches for power distribution, such as laddered or ring configurations with embedded power electronic circuits. - Evaluate planning, design guidelines and installation best practices for distributed generation components and systems, and also include local renewable energy sources, power generators (e.g., fuel cells or microturbines fueled by natural gas), local energy storage, power electronic interfaces, and associated control and management platforms. - Analyze generalized frameworks for microgrids stability assessments. - Explore installation and design approaches for energy storage applications at the distribution level, including grid-tied residential photovoltaic systems, and the development of associated standards and best practices to address safety concerns (e.g., fire risks and toxic materials).
Cost Category	$2,000,000 to $5,000,000
Duration	5-8 years
Type of Endeavor	A joint industry and university research and development endeavor.
Potential Funding Sources	Government, industry
Priority Ranking	High

ELEMENT III. Conduct Problem Focused Research for Various Lifeline Systems

SUBGROUP III.2. Priorities related to research for specific lifeline systems

Topic No. 20	Develop a multi-hazard, multi-modal dynamic transportation network risk assessment model.
Description	Goals: Develop a comprehensive transportation network analysis methodology that can be used by emergency response and recovery organizations and provides information on expected post-event losses from direct damage, single network functionality and multi-transportation mode functionality, and critical links in each system, and also enables resilience analysis capabilities. Objectives and tasks: - Consider system exposure to multi-hazard cascading events. For example, network systems that have been weakened by an earthquake may have limited evacuation capabilities when a tsunami follows. Similarly, bridge capacity to withstand an earthquake may be reduced because abutments or piers are weakened by scour in previous floods. - Consider multi-mode transportation systems, including highway, railway, light rail, bus, port, and ferry systems. Emergency response and long-term recovery depends not only on the availability of highway systems but other transportation modes that may be present in the affected region. Consideration of these systems requires multi-network functionality analysis. - Develop and implement dynamic network systems analysis methods for transportation networks that consider changes in pre- and post-event traffic demand. These methods should also include interdependencies among different transportation and lifeline systems. For example, post-event traffic demands can change depending on the availability of ferries, bus services or light rail. Similarly, the functionality of light rail will depend on the availability of electric power. - Include advanced computational methods for efficient analysis.
Cost Category	$1,000,000 to $2,000,000
Duration	3-5 years
Type of Endeavor	Technical committee with specialized analysis and testing expertise plus review panel.
Potential Funding Sources	Government, industry
Priority Ranking	High

ELEMENT III. Conduct Problem Focused Research for Various Lifeline Systems

SUBGROUP III.2. Priorities related to research for specific lifeline systems

Topic No. 21	Develop water and wastewater system evaluation methods for earthquake impacts.
Description	Goals: Improve water and wastewater system resilience with improved methods and tools for systems level analyses, quantifying functionality, and prioritizing system improvements. Objectives and tasks: - Develop methodologies and tools to perform systems level seismic evaluations, incorporating all applicable earthquake related hazards (e.g., liquefaction, landslide, faulting, ground shaking). The tools need to incorporate the water supply, treatment, transmission, and distribution subsystems and the wastewater collection, conveyance, treatment, and disposal subsystems. A large body of research on this topic already exists to inform development. The tools need to incorporate system performance requirements and operational expectations during and following an earthquake, as well as the ability to identify system deficiencies to be corrected. - Validate computerized and manual methodologies and their scalability. Larger and more complicated systems require more advanced computational methods. Simpler approaches may be used on smaller systems. Methods need to be reliable and easily accessible to smaller agencies. - Develop guidance documents to provide system operators with an understanding of the level of effort needed to perform an adequate evaluation and associated reliability assessment of their facilities. - Develop practical methods for quantifying water or wastewater system functionality for infrastructure owners, including how functionality improves when mitigation alternatives are implemented. The methods should help establish priorities for system improvements on the basis of loss of life and injury, public health, economic disruption, and environmental impacts. - Conduct research and develop processes and methods to effectively and efficiently deal with combined seismic and aging infrastructure risks.
Cost Category	$1,000,000 to $2,000,000
Duration	3-5 years
Type of Endeavor	Technical committee with specialized analysis capabilities plus review panel.
Potential Funding Sources	Government, industry
Priority Ranking	High

ELEMENT III. Conduct Problem Focused Research for Various Lifeline Systems

SUBGROUP III.2. Priorities related to research for specific lifeline systems

Topic No. 22	**Develop tensile and compressive strain limits for welded steel pipelines in permanent ground displacement zones.**
Description	Goals: Develop and implement a comprehensive program based partly upon laboratory testing and fracture mechanics principles to provide guidance for establishing reliable tensile and compressive strain limits for permanent ground displacement of buried pipelines. Objectives and tasks: - Review weld inspection records to characterize the probabilistic distribution of flaws for the purpose of establishing rational criteria for permanent ground displacement zones, such as fault rupture or landslides. - Develop a procedure/program for pipeline owners to donate pipe specimens for wide plate testing. Opportunities for collecting girth welds on existing pipelines occur when pipelines are replaced or rerouted. - Test existing girth welds to obtain information on the tension and compression strain capacity of existing pipelines. Conduct a statistically significant number of curved wide plate tensions tests and compression tests on girth weld specimens to develop performance data that relates allowable strain limits as a function of such parameters as fracture toughness, welding process, flaw size and inspection methods. - Maintain a database of the results from the pipe testing that includes information such as year of construction, pipe size, pipe wall thickness, specified pipe grade and actual pipe yield and ultimate strength, specified weld material and actual weld yield and ultimate strength, and strain at failure or maximum strain applied in the test.
Estimated Cost	$500,000 to $1,000,000
Duration	2-3 years
Type of Endeavor	Laboratory testing conducted at a university or commercial test laboratory under the guidance of a recognized industry technical committee.
Potential Funding Sources	Potential funding organizations include the Pipeline Research Council International (PRCI) and the U.S. Department of Transportation (DOT).
Priority Ranking	Medium

ELEMENT IV. Enable the Adoption and Implementation of Lifeline System Performance Goals and Standards

SUBGROUP IV.1. Priorities to enable adoption and implementation of lifeline system performance goals and standards

Topic No. 23	**Develop tools, guidance, incentives, and funding mechanisms for voluntary adoption and implementation of lifeline seismic resilience programs and earthquake-resilient design and construction standards.**
Description	Goals: Develop up-to-date tools and guidance to promote the voluntary adoption and implementation of community-focused seismic resilience programs and adequately fund and sustain such programs over time, particularly in light of current and future lifeline system ownership patterns, fiscal and regulatory environments and market conditions. Objectives and tasks: - Develop manuals with examples and options of resilience best practices based upon practical applications worldwide for different lifeline system types in all phases of resilience management: mitigation, preparedness, response and restoration. - Evaluate potential differences in the levels of sustained capital investment in system upgrades and hazard mitigation in different ownership scenarios and how different institutional cultures affect seismic resilience. Also study how outsourcing of lifeline system maintenance and services affects system reliability and resilience. - Identify options for funding seismic resilience over reasonable time-frames, including regional and multi-lifeline investments, infrastructure banks, public-private partnerships, and other mechanisms. - Develop a guidance document that updates understandings of institutional barriers to and facilitators of collaboration for earthquake loss reduction. Identify incentives (such as insurance), public interest and liability concerns, and market competitiveness and profitability issues, and discuss the role of public/private partnerships and regulators. - Develop better tools (both quantitative and qualitative approaches), education, and training for lifeline owners and operators to conduct vulnerability assessments and resilience gap analyses and identify and prioritize mitigation investments (in coordination with Topic No. 5), such as failure mode analyses and the use of risk management processes to prioritize and allocate limited resources. - Develop guidance on integrating lifeline mitigation into long-term plans (e.g., city master plans and utilities' capital investment plans). - Develop a better understanding of what customers are willing to pay for improved system reliability and develop guidance for building awareness among the public and key customers (e.g., businesses).
Cost Category	$1,000,000 to $2,000,000
Duration	3-5 years
Type of Endeavor	Technical committee including specialized analysis expertise plus review panel.
Potential Funding Sources	Government, industry
Priority Ranking	Highest

ELEMENT IV. Enable the Adoption and Implementation of Lifeline System Performance Goals and Standards

SUBGROUP IV.1. Priorities to enable adoption and implementation of lifeline system performance goals and standards

Topic No. 24	**Develop strategies and techniques for the public and key customers to engage lifeline system providers to define acceptable performance levels and restoration timeframes.**
Description	Goals: Provide models, strategies and techniques for public engagement in the adoption and implementation of lifeline system performance goals and standards. Public expectations of system performance and restoration timeframes can differ significantly from projected seismic performance levels and associated restoration timeframes. Developing locally acceptable performance levels and restoration timeframes requires the implementation of local lifeline community resilience programs as well as earthquake-resilient design and construction standards for key lifeline systems. Work on this topic should be informed by and coordinated with Topic Nos. 1 and 2. Objectives and tasks: - Evaluate the existing body of knowledge on public policy advocacy and identify relevant best practices based upon practical applications worldwide of utility-customer/public collaborations in defining lifeline performance levels and restoration timeframes. Examples include the Oregon Resilience Plan (Oregon Seismic Safety Policy Advisory Commission, 2013) and the work of the San Francisco Lifelines Council and the "Resilient City" community resilience framework for San Francisco (SPUR, 2009). - Develop better strategies and tools for the public and key customers to use in defining local expectations of lifeline system performance and restoration times. - Develop guidance on how to engage lifeline system providers to implement system performance goals and standards.
Cost Category	$200,000 to $500,000
Duration	2-3 years
Type of Endeavor	Technical committee including specialized analysis expertise plus review panel.
Potential Funding Sources	Government, industry
Priority Ranking	High

ELEMENT IV. Enable the Adoption and Implementation of Lifeline System Performance Goals and Standards

SUBGROUP IV.2. Priorities for long-term earthquake resilience

Topic No. 25	Assess the direct and indirect socioeconomic consequences and financial implications of different lifeline performance levels and restoration timeframes.
Description	Goals: Attain a better understanding of the socioeconomic consequences and financial implications of different lifeline performance levels and restoration time frames that can be used in the development of local lifeline seismic resilience programs and earthquake-resilient design and construction standards for lifeline components and systems. Objectives and tasks: - Evaluate lessons and best practices from recent earthquakes in the United States, New Zealand, Japan, Chile and elsewhere. Identify examples of socioeconomic disruptions, tolerances, and adaptations to various system outages and downtimes that include impacts to households, business, and government/institutional sectors. - Assess the impact and loss of revenue of lifeline system disruption on other lifeline systems as well as modern healthcare, education, business and community service sectors. Also consider changes over time influencing various lifeline systems, such as increases in societal dependence on electric power and telecommunications across the household, business, and government/institutional sectors. - Assess the effects of lifeline system outages on different social classes and groups. Outages may be more acute for vulnerable population groups and those residing in areas with older, more fragile systems. Such systems are often located in urban cores such that earthquake-related lifeline disruption may have a more significant impact on inner-city residents. - Study and characterize the economic and financial consequences of system performance and restoration timeframes (e.g., by region, by lifeline system and component, across multiple systems and by economic sectors). Focus on the economic consequences of disruption and inability to meet performance criteria for different lifeline systems in different regions of the United States. Lifeline interdependencies and their socioeconomic implications need to be incorporated in this work. - Develop guidance documents for lifeline operators/owners and customers on socioeconomic consequences and financial implications of different lifeline performance levels and restoration time frames.
Cost Category	$500,000 to $1,000,000
Duration	2-3 years
Type of Endeavor	Technical committee including specialized analysis expertise plus review panel.
Potential Funding Sources	Government, industry
Priority Ranking	Highest

Topic No. 26	Implement post-earthquake information and response services for lifeline systems.
Description	Goals: Improve the speed of emergency response and recovery and enhance system reliability through post-earthquake services that provide advanced situational intelligence about earthquake parameters and impacts. Existing post-earthquake services developed by the USGS and others include ShakeMap, ShakeCast, CISN Display, PAGER, and Earthquake Notification Service (ENS). ShakeAlert is a new tool that provides an earthquake early warning (EEW) so that real-time actions can be taken to protect lives and property while fault rupture is still occurring. Rapid response actions include moving personnel from unsafe locations and shutting down critical lifeline systems before the strong shaking starts. EEW has been implemented in Imperial County and Coachella Valley, California, for several years. California's Transportation Department (Caltrans) uses ShakeCast for bridge monitoring and rapid post-event deployment. Objectives and tasks: - Evaluate advanced situational intelligence services in terms of the metrics and performance standards established in Program Element 1. Identify specific opportunities and benefits of using each, develop case studies of their successful application, and identify technical implementation approaches to show how they can enhance intelligence and decision making capabilities. - For EEW, assess potential decisions and actions that may be taken, as well as their relative advantages and disadvantages for different lifeline systems. Identify potential impacts (good and bad) to system performance, public safety, and lifeline system liabilities. Develop tools and guidance documents for system operators and policy makers for risk informed decisions (risks of taking or not taking action). Identify opportunities for developing and adopting EEW systems beyond ShakeAlert. - Develop guidance and training for both lifeline system operators and customers on how to use advanced situational intelligence services to improve system operations and customer communications within seconds or minutes before shaking starts, to hours and days after the earthquake. The report prepared by ALA on ShakeMap and ShakeCast lifeline applications (see Appendix A) may provide a good starting place for portions of this work.
Cost Category	$2,000,000 to $5,000,000
Duration	5-8 years
Type of Endeavor	Joint government and industry endeavor with technical committee and/or review panel.
Potential Funding Sources	Joint government and industry
Priority Ranking	High

ELEMENT IV. Enable the Adoption and Implementation of Lifeline System Performance Goals and Standards

SUBGROUP IV.2. Priorities for long-term earthquake resilience

Topic No. 27	Develop and deploy intelligent lifeline monitoring, advanced sensors, and emergency response and restoration decision support systems.
Description	Goals: Provide critical information for lifeline system monitoring, emergency response, and restoration. Improve system reliability and seismic resilience decisions for combined use in earthquakes and other disasters, enhance the use of existing monitoring systems, and deploy new sensor technology. Objectives and tasks: - Research and document the decision making process for emergency operations and system restoration. Show how the decision process relates to size, complexity, and physical characteristics of different lifeline networks, and provide examples of how system performance is enhanced by smart sensor and monitoring technologies. - Develop and demonstrate advanced sensor systems, including energy scavenging technologies for remote, distributed sensors. - Catalogue how lifeline system providers liaise with each other (both upstream and downstream) and identify communication barriers and needs to enable the post-disaster flow of information and decisions. - Analyze the reliability and validity of existing decision support and real-time intelligent monitoring systems for mitigation, response, and restoration, including lifeline interdependencies tools (e.g., MUNICIPAL tool by Wallace (2013)) and active control systems (e.g., SCADA). - Define specific system capabilities and basic data requirements. Ensure systems can incorporate data from multiple sensors (e.g., earthquake early warning system, accelerometers, strain gages) placed directly on network components or links, as well as remote sensing data (e.g., satellite imagery and aerial photography). Incorporate wireless data networks, social media tools for post-disaster information gathering, and advanced data analysis algorithms into design. Research data processing needs, such as using multiple sensors and tracking of aggregate uncertainty. Develop methods for system inventory collection and archiving. - Develop and test representative pilot systems for different lifelines and geographical coverage, using actual earthquake data and realistic simulations. Account for interdependencies with other lifelines. Ensure pilot systems are scalable for a wide range of applications. Develop decision support capabilities for information delivery, data manipulation and communication. - Involve stakeholders in the initial design and pilot testing. Develop guidance/training for lifeline providers to use advanced monitoring.
Cost Category	$2,000,000 to $5,000,000
Duration	5-8 years
Type of Endeavor	Multiple investigators, physical data collection and survey/interview campaigns, and an interdisciplinary review panel that includes specialized experts, government and industry representatives.
Potential Funding Sources	Government, industry
Priority Ranking	High

ELEMENT IV. Enable the Adoption and Implementation of Lifeline System Performance Goals and Standards

SUBGROUP IV.2. Priorities for long-term earthquake resilience

Topic No. 28	Develop and deploy better tools, training, and guidance for emergency operation planning, response, and restoration of lifeline systems.
Description	Goals: Enhance emergency operations planning, response and restoration of different lifeline systems. Objectives and tasks: - Develop methodologies for estimating system restoration times based on expected damage, available resources (labor and materials), and earthquake size. Earthquake impacts to other lifelines as well as the greater community need to be included. - Develop guidance on how to provide services for prioritized areas/customers and balance load/services. For example, telecommunication network providers need guidance on when to use and deploy pre-recorded messages and terminate calls that are not emergency-oriented to provide access to more open circuits for improved emergency operations. - Provide consistent guidance on logistics planning for restoration and clarify who holds the responsibility for providing critical interim lifeline services, such as emergency water, electric power, telecommunications, and transportation when systems are disrupted. Preparations often lack pre-disaster coordination on the magnitude of lifeline system loss. There needs to be a level of accountability among lifeline system operators to provide critical services. - Provide better guidance for emergency organizations and lifeline system providers to prepare the public for the realistic duration of expected outages and to plan for and cover the likely incremental community impacts and needs as a result of the expected outages. - Develop training programs and procedures for conducting drills and educating lifeline system operations personnel on how to prepare emergency plans.
Cost Category	$500,000 to $1,000,000
Duration	3-5 years
Type of Endeavor	Joint industry and government study with technical committee and/or review panel.
Potential Funding Sources	Joint government and industry
Priority Ranking	Highest

4.2 Summary of Cost Estimates

Estimates of the cost to conduct the endeavors identified for all 28 topics are summarized in Table 4-1. The total estimated cost to complete work on all topics in the four Program Elements ranges from $24.8 million to $55.0 million, which translates to approximately $2.5 to $5.5 million per year for 10 years, the anticipated length of the proposed roadmap program. The total cost for each of the Program Elements is within approximately the same order of magnitude.

Table 4-1 Summary of Program Element and Topic Costs

Program Element	Topic No.	Topic Cost Range (x 10^6 dollars)	Program Element Cost Range (x 10^6 dollars)
I	1	$1.0 – $2.0	
	2	0.2 – 0.5	
	3	0.5 – 1.0	
	4	2.0 – 5.0	
	5	1.0 – 2.0	
			$4.7 – $10.5
II	6	1.0 – 2.0	
	7	1.0 – 2.0	
	8	1.0 – 2.0	
	9	1.0 – 2.0	
	10	0.5 – 1.0	
	11	0.5 – 1.0	
	12	0.2 – 0.5	
	13	0.5 – 1.0	
	14	0.2 – 0.5	
	15	0.5 – 1.0	
			$6.4 – $13.0
III	16	0.5 – 1.0	
	17	0.5 – 1.0	
	18	2.0 – 5.0	
	19	2.0 – 5.0	
	20	1.0 – 2.0	
	21	1.0 – 2.0	
	22	0.5 – 1.0	
			$7.5 – $17.0
IV	23	1.0 – 2.0	
	24	0.2 – 0.5	
	25	0.5 – 1.0	
	26	2.0 – 5.0	
	27	2.0 – 5.0	
	28	0.5 – 1.0	
			$6.2 – $14.5
Cost Range for all Topics and Program Elements:			$24.8 – $55.0

Appendix A
American Lifelines Alliance

A.1 Organization

In the 1990s FEMA, with technical support from NIST, held workshops and devised plans for developing a national program to assure that lifeline systems are more resilient to earthquakes and related disasters. These plans are embodied in FEMA 271, *Plan for Developing and Adopting Seismic Guidelines and Standards for Lifelines* (FEMA, 1995) and the sequel ICSSC TR-19/NISTIR 6085 Report, *Recommendations of the Lifeline Policymakers Workshop* (Mohraz and Chung, 1997). These plans envisioned an organization to stimulate a public-private partnership in reducing lifeline risks from earthquakes and related natural disasters.

FEMA took the recommendations and plans from these documents and put a cooperative agreement in place with the American Society of Civil Engineers (ASCE), for FY1999,[5] intended to create an independent [501(c)(3)], non-profit entity affiliated with a standards developing organization. The goal of such an entity, which was named the American Lifelines Alliance (ALA) during the project with ASCE, was to take research and lessons learned, and share them nationally. Late in 1998, concern developed within FEMA about the use of Federal funds for the establishment of a new organization. As a result, FEMA decided to run the organization as a project between FEMA and ASCE.

The objective of ALA was to facilitate the creation, adoption, and implementation of design and retrofit guidelines and other ANSI-approved national consensus documents that, when implemented by lifeline owners and operators, would systematically improve the performance of utility and transportation systems to acceptable levels in natural hazard events. The ALA initiated funding of the guidelines development projects in the fall 1999, focusing on all natural hazards, including earthquakes, floods, windstorms (taking into account both hurricanes and tornados), icing, and ground displacements (involving landslides, frost heave, and settlement). While the ALA's formation was closely tied to concerns about reducing earthquake hazards, by looking more broadly at multiple hazards, the ALA hoped its guidance could improve system reliability on a national scale, since the risk from various natural hazards across the country is highly variable.

[5] Initial funding included seed money of $200,000 from FEMA and $70,000 from NIST

Following the terrorist attacks of September 11, 2001, FEMA directed ALA to also address hazards posed by human threats, including chemical, biological, radiological, blast, and cyber threats. This change was consistent with the broader goals of FEMA and recognized that actions that minimize the effects of natural hazards also can improve resistance of structures and systems to man-made hazards. In late 2002, FEMA brought ALA under the Multihazard Mitigation Council through a partnership with the National Institute of Building Sciences (NIBS).

The ALA worked closely with the Lifelines Subcommittee of the Interagency Committee on Seismic Safety in Construction, which was charged with assisting Federal departments and agencies to develop and incorporate earthquake hazard reduction measures into their ongoing construction programs. The ALA efforts to develop national consensus guidance were aligned with many of the objectives of the Lifelines Subcommittee. The ALA products were intended to provide appropriately qualified seismic guidance that the Lifelines Subcommittee could use in the preparation and adoption of such guidance by Federal agencies.

From 1999 to 2005, the ALA carried out 27 projects, including 17 projects specifically directed at guideline-related tasks; six of these had results incorporated into new or modified ANSI-accredited standards. During this time period, the ALA's annual budget was between $400,000 and $700,000. Support for ALA was terminated in 2005 when NEHRP budget reductions were imposed by FEMA. Project awards were completed at the end of 2007.

A.2 ALA Existing Guidelines Matrices

As part of its work, the ALA developed matrices summarizing the status of natural and man-made hazards guidance available for lifeline systems as of 2003 and 2004, from standards development organizations, professional and industry organizations, and practitioners in the relevant fields in the United States (see Table A-1 and Table A-2 [page A-9], which have been re-formatted for this report to improve readability and augmented to define acronyms). The matrices identify the existing design and assessment guidelines or standards for different lifeline system components and specific natural and man-made hazards. The matrices help identify the need for guidance that does not yet exist or should be improved and modified.

A.3 ALA Guidelines and Report

During its tenure, the ALA also issued more than a dozen guidelines and reports that address earthquake and other natural hazard impacts on lifelines and infrastructure. These guidelines and reports are available at http://www.americanlifelinesalliance.org in the "New Guidelines" section of the website. Some of the key publications are briefly described below.

Table A-1 ALA Manmade Hazards Matrix Summary (Revised January 2003)

Electric Power		***Manmade Hazard Provisions***		
Component	***Guide/Standard***	***Loading***[1]	***Design***[2]	***Existing***[3]
System Reliability	$ Ø	Radiological, Blast, Cyber	Radiological, Blast, Cyber	
Transmission Towers	Ø	Blast	Blast	
Distribution Poles	Ø	Blast	Blast	
Buried Conduits	Ø	Radiological	Radiological	
Substations	IEEE (1)	Chemical		
	$		Radiological	
	Ø	Radiological		
Elect./Mechanical Equipment	Ø	Radiological, Cyber	Radiological, Cyber	

Natural Gas		***Manmade Hazard Provisions***		
Component	***Guide/Standard***	***Loading***	***Design***	***Existing***
System Reliability	NPC (2)	Radiological, Blast	Cyber	
	Ø		Radiological	
Buried Pipelines	DOT (3)			
	DOT (4)	Blast	Chemical	
	DOT (5)	Blast	Blast	
	DOT (6)	Blast		

Table notes (this page):

[1] Loading: Whether or not specific loads for various identified hazards are defined.
[2] Design: Existence of design and/or analysis that account for loads arising specified hazards.
[3] Existing: Analysis or design procedures (not loads) could be applied for existing components.
$ = Standards have been identified, but must be purchased for review.
Ø = Government standards exist, but are issued from a controlled or sensitive source.
= Empty box (cell) indicates guidelines and standards related to the specific hazards are not available.
IEEE (1): Institute for Electrical and Electronics Engineers, *Guide for Containment and Control of Oil Spills in Substations*.
NPC (2): National Petroleum Council, *Securing Oil and Natural Gas Infrastructures in the New Economy*.
DOT (3): Department of Transportation, *Code of Federal Regulations* (CFR) 49, 195.8, Transportation of Hazardous Liquids or CO_2 in Pipelines Constructed with other than Steel Pipes.
DOT (4): CFR 49, 192.755, Transportation of Natural Gas by Pipeline, Minimum Federal Safety Standards, Protecting Cast Iron Pipelines.
DOT (5): CFR 49, 192.614, Damage Prevention Program.
DOT (6): CFR 49, 149.442, Damage Prevention Program.

Table A-1 ALA Manmade Hazards Matrix Summary (Revised January 2003) (continued)

Natural Gas (continued)		*Manmade Hazard Provisions*		
Component	***Guide/Standard***	***Loading***[1]	***Design***[2]	***Existing***[3]
Aboveground Piping	DOT (7)			
	DOT (8)	Blast	Chemical	
	DOT (9)	Blast	Blast	
	DOT (10)	Blast		
Compressor Station Piping				
Well Facilities				
Offshore Production Installations	ISO (11) $	Chemical, Blast		
Elect./Mechanical Equipment	$ Ø	Radiological	Radiological	

Oil Products		*Manmade Hazard Provisions*		
Component	***Guide/Standard***	***Loading***	***Design***	***Existing***
System Reliability	NPC (12)	Cyber	Cyber	
	$			
	Ø	Radiological, Blast	Radiological, Blast	
Buried Pipelines	Ø	Blast	Blast	
Aboveground Piping	Ø	Blast	Blast	
Pumping Station Piping	Ø	Blast	Blast	
Well Facilities	Ø	Blast	Blast	

Table notes (this page):
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[2] Design: Existence of design and/or analysis that account for loads arising specified hazards.
[3] Existing: Analysis or design procedures (not loads) could be applied for existing components.
$ = Standards have been identified, but must be purchased for review.
Ø = Government standards exist, but are issued from a controlled or sensitive source.
= Empty box (cell) indicates guidelines and standards related to the specific hazards are not available.
DOT (7): CFR 49, 195.8, Transportation of Hazardous Liquids or CO_2 in Pipelines Constructed with other than Steel Pipe.
DOT (8): CFR, 49, 195.55 Protecting Cast Iron Pipelines.
DOT (9): CFR, 49, 192.614, Damage Prevention Program.
DOT (10): CFR, 49, 149.442, Damage Prevention Program.
ISO (11): International Organization for Standards, *Petroleum and Gas industries- Control and Mitigation of Fires and Explosions on Offshore Production Installations*.
NPC (12): National Petroleum Council, *Securing Oil & Natural Gas Infrastructures in the New Economy*.

Table A-1 ALA Manmade Hazards Matrix Summary (Revised January 2003) (continued)

Oil Products (continued)		***Manmade Hazard Provisions***		
Component	***Guide/Standard***	***Loading***[1]	***Design***[2]	***Existing***[3]
Refineries	Ø	Blast	Blast	
Storage Tanks	$ Ø	Blast		
Elect./Mechanical Equipment	Ø	Radiological, Blast, Cyber		

Liquefied Natural Gas Systems		***Manmade Hazard Provisions***		
Component	***Guide/Standard***	***Loading***	***Design***	***Existing***
System Reliability	$ Ø	Radiological, Blast, Cyber	Radiological, Blast, Cyber	
Piping	Ø	Blast	Blast	
Storage Tanks	Ø	Blast	Blast	
Elect./Mechanical Equipment	Ø	Radiological, Blast, Cyber	Radiological, Blast, Cyber	

Water Systems (Potable & Raw)		***Manmade Hazard Provisions***		
Component	***Guide/Standard***	***Loading***	***Design***	***Existing***
Treatment Units	US Congress (13)		Chemical, Biological	
	USACHPPM (14)	Radiological, Blast	Biological	
System Reliability	US Congress (15)		Chemical, Biological, Radiological, Cyber	
	US Congress (16)		Chemical, Biological	
Buried Pipelines				
Aboveground Pipelines				

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$ = Standards have been identified, but must be purchased for review.
Ø = Government standards exist, but are issued from a controlled or sensitive source.
 = Empty box (cell) indicates guidelines and standards related to the specific hazards are not available.
US Congress (13): Safe Drinking Water Act.
USACHPPM (14): U.S. Army Center for Health Promotion & Preventive Medicine, *Biological Warfare Agents as Threats to Potable Water, Environ Health Perspectives* 107:975-984.
US Congress (15): Water Infrastructure Security and Research Development Act.
US Congress (16): HR 3178 and the Development of Anti-Terrorism Tools for Water Infrastructure.

Table A-1 ALA Manmade Hazards Matrix Summary (Revised January 2003) (continued)

Water Systems (Potable & Raw) (continued)		***Manmade Hazard Provisions***		
Component	***Guide/Standard***	***Loading***[1]	***Design***[2]	***Existing***[3]
Pumping Plants	$			
Storage Tanks	$			
Well Facilities				

Waste Water Systems		***Manmade Hazard Provisions***		
Component	***Guide/Standard***	***Loading***	***Design***	***Existing***
System Reliability				
Buried Pipelines				
Aboveground Pipelines				
Pumping Plants	NFPA (17) $	Chemical, Blast		
Storage Tanks	$			

Telecommunications Systems		***Manmade Hazard Provisions***		
Component	***Guide/Standard***	***Loading***	***Design***	***Existing***
System Reliability	NFPA (17)	Cyber	Cyber	
	$			
	Ø	Radiological, Blast	Radiological, Blast	
Towers, Masts and Poles	Ø	Biological	Biological	
Buried Cables				
Underwater Cables				
Aboveground Cables				
Switching Equipment	Ø	Radiological, Cyber	Radiological, Cyber	
Cable Trays				

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$ = Standards have been identified, but must be purchased for review.
Ø = Government standards exist, but are issued from a controlled or sensitive source.
= Empty box (cell) indicates guidelines and standards related to the specific hazards are not available.
NFPA (17): National Fire Protection Association, *Standard for Fire Protection in Wastewater Treatment and Collection Facilities*.

Table A-1 ALA Manmade Hazards Matrix Summary (Revised January 2003) (continued)

Telecommunications Systems		***Manmade Hazard Provisions***		
Component	***Guide/Standard***	***Loading***[1]	***Design***[2]	***Existing***[3]
System Reliability	NFPA (17) $ Ø	Cyber Radiological, Blast	Cyber Radiological, Blast	
Towers, Masts and Poles	Ø	Biological	Biological	
Buried Cables				
Underwater Cables				
Aboveground Cables				
Switching Equipment	Ø	Radiological, Cyber	Radiological, Cyber	
Cable Trays				

Ports and Inland Waterways		***Manmade Hazard Provisions***		
Component	***Guide/Standard***	***Loading***	***Design***	***Existing***
System Reliability	$ Ø		Blast	
Piers/Wharves	$ Ø		Blast	
Breakwaters/Jetties			Blast	
Sea Walls			Blast	
Container Handling				
Cargo Movement				
Marine Oil Terminals	$ Ø		Blast	

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Ø = Government standards exist, but are issued from a controlled or sensitive source.
= Empty box (cell) indicates guidelines and standards related to the specific hazards are not available.
NFPA (17): National Fire Protection Association, *Standard for Fire Protection in Wastewater Treatment and Collection Facilities*.

Table A-1 ALA Manmade Hazards Matrix Summary (Revised January 2003) (continued)

Highways and Roads		*Manmade Hazard Provisions*		
Component	***Guide/Standard***	***Loading***[1]	***Design***[2]	***Existing***[3]
System Reliability				
Bridges	$			
Embankments				
Road Beds				
Culverts				
Tunnels				
Retaining Walls				
Signs				

Railroad		*Manmade Hazard Provisions*		
Component	***Guide/Standard***	***Loading***	***Design***	***Existing***
System Reliability				
Bridges	$			
Embankments				
Rails, Ties, and Ballast	$			
Culverts				
Tunnels				
Signs				

Infrastructure Interdependencies		*Manmade Hazard Provisions*		
Component	***Guide/Standard***	***Loading***	***Design***	***Existing***
Signs	Ø	Chemical, Biological, Radiological, Blast, Cyber	Chemical, Biological, Radiological, Blast, Cyber	

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[3] Existing: Analysis or design procedures (not loads) could be applied for existing components.
$ = Standards have been identified, but must be purchased for review. .
Ø = Government standards exist, but are issued from a controlled or sensitive source.
= Empty box indicates guidelines and standards related to the specific hazards are not available.

Table A-2 ALA Matrix of Standards and Guidelines for Natural Hazards (Revised May 2004)

Oil Products Systems		*Natural Hazard Provisions*[8]		
Component	***Guide/Standard***[1]	***Loading***	***Design***	***Existing***[7]
System Reliability[6]				
Buried Pipelines	ASME/ANSI B31.4	none[2]	none	
	ASCE TCLEE 1984	earthquake	earthquake	•
Aboveground Piping	ASME/ANSI B31.4	none[2]	none	
	ASME/ANSI B31.3	none[2]	earthquake, wind, ice	
	API 2510			
	API 2508			
	ASCE TCLEE 1984	earthquake	none	•
Pumping Station Piping	ASME/ANSI B31.4	none[2]	earthquake, wind, ice	
	ASME/ANSI B31.3	none[2]	none	
	API 2510			
	ASCE TCLEE 1984	earthquake	none	•
Well Facilities	ASME/ANSI B31.4	none[2]	none	
	ASME/ANSI B31.3	none[2]	earthquake, wind, ice	
	API RP 14E			
Refineries	API 2508			
	ASCE Petrochem.	earthquake, wind	earthquake, wind	•
	ASME/ANSI B31.3	none[2]	earthquake, wind, ice	
	ASME BPV[3]	none[2]	earthquake, wind, ice	
Storage Tanks	API 620	earthquake, wind	earthquake, wind	•
	API 650	earthquake, wind	earthquake, wind	•
	NFPA 59			
	API 2508			
	ASCE TCLEE 1984	earthquake	earthquake	•

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[2] "none" applies if a guideline or standard does not specifically identify how loads are to be obtained; if a group of standards is referenced, the natural hazard listed may be only covered in one document.

[3] ASME BPV refers to the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code that typically governs the design of all pressurized containers.

[6] "System Reliability" is a component of design referring to practices that are specifically developed to provide reasonable assurance that consequences of a natural hazard on system service will meet the goals established by stakeholders (owners, operators, regulators, insurers, customers, and users). Consequences are defined by multiple performance requirements but typically include impact on public safety, duration of service interruption, and costs to repair damage.

[7] "Existing" indicates that analysis or design procedures (NOT LOADS) could be applied for existing components.

[8] "Loading" refers to whether or not specific loads for various natural hazards are defined; "Design" refers to the existence of design and/or analysis procedures that account for loads arising from natural hazards.

All acronyms are defined at the end of the table.

Table A-2 ALA Matrix of Standards and Guidelines for Natural Hazards (Revised May 2004) (cont'd)

Natural Gas Systems		***Natural Hazard Provisions***[8]		
Component	***Guide/Standard***[1]	***Loading***	***Design***	***Existing***[7]
System Reliability[6]				
Buried Pipelines	ASME/ANSI B31.8	none[2]	none	
	PRCI (2000)	earthquake	earthquake	•
	ASCE TCLEE 1984	earthquake	earthquake	•
Aboveground Piping	ASME/ANSI B31.3	none[2]	earthquake, wind, ice	
	ASME/ANSI B31.8	none[2]	none	
	ANSI Z223.1	none[2]		
	NFPA 54, SGC, IFGC	none[2]		
	ASCE TCLEE 1984	earthquake	none	•
Compressor Station Piping	ASME/ANSI B31.3	none[2]	earthquake, wind, ice	
	ASME/ANSI B31.8	none[2]	none	
	ASCE TCLEE 1984	earthquake	none	•
Well Facilities	ASME/ANSI B31.4	none[2]	none	
	API RP 14E			
Liquefied Natural Gas (LNG) Facilities				
System Reliability[6]	NFPA 59A	earthquake	earthquake	
Piping	NFPA 59A	earthquake	earthquake	
Storage Tanks	*API 620*	earthquake, wind	earthquake, wind	
	API 650	earthquake, wind	earthquake, wind	
	ASME BPV[3]	none[2]	earthquake, wind, ice	
	NFPA 59A	earthquake, ref. ANSI A58.1 for wind and snow	earthquake, ref. ANSI A58.1 for wind and snow	
	ASCE 1984	earthquake	earthquake	

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[6] "System Reliability" is a component of design referring to practices that are specifically developed to provide reasonable assurance that consequences of a natural hazard on system service will meet the goals established by stakeholders (owners, operators, regulators, insurers, customers, and users). Consequences are defined by multiple performance requirements but typically include impact on public safety, duration of service interruption, and costs to repair damage.

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Table A-2 ALA Matrix of Standards and Guidelines for Natural Hazards (Revised May 2004) (cont'd)

Water Systems (Potable & Raw)		***Natural Hazard Provisions***[8]		
Component	***Guide/Standard***[1]	***Loading***	***Design***	***Existing***[7]
System Reliability[6]				
Buried Pipelines	AWWA M11	none[2]	none	
	ASCE TCLEE 15	earthquake	earthquake	•
Aboveground Pipelines	ASME/ANSI B31.3	none[2]	earthquake, wind, ice	
Pumping Plants	ASME B31.3	none[2]	earthquake, wind, ice	
Storage Tanks	ACI 350	earthquake	earthquake	•
	AWWA D[5]	earthquake, wind, snow	earthquake, wind, snow	•
	ASCE 1984	earthquake	earthquake	•
Well Facilities				
Canals				

Waste Water Systems		***Natural Hazard Provisions***[8]		
Component	***Guide/Standard***[1]	***Loading***	***Design***	***Existing***[7]
System Reliability[6]				
Buried Pipelines	AWWA M11	none[2]	none	
	ASCE TCLEE 15	earthquake	earthquake	•
Aboveground Pipelines	ASME/ANSI B31.3	none[2]	earthquake, wind, ice	
Treatment Plants	ASME B31.3	none[2]	earthquake, wind, ice	•
	WEF	earthquake, flood		•
Storage Tanks	ACI 350	earthquake	earthquake	•
	AWWA D[5]	earthquake, wind, snow	earthquake, wind, snow	•
	ASCE 1984	earthquake	earthquake	•

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[5] AWWA D refers to various American Water Works Association (AWWA) standards governing water storage tanks.

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[8] "Loading" refers to whether or not specific loads for various natural hazards are defined; "Design" refers to the existence of design and/or analysis procedures that account for loads arising from natural hazards.

All acronyms are defined at the end of the table.

Table A-2 ALA Matrix of Standards and Guidelines for Natural Hazards (Revised May 2004) (cont'd)

Electric Power Systems		***Natural Hazard Provisions***[8]		
Component	***Guide/Standard***[1]	***Loading***	***Design***	***Existing***[7]
System Reliability[6]				
Substations	IEEE-693	earthquake	earthquake	•
	RUS 1724e*	wind, ice, earthquake	wind, ice, earthquake	•
	ASCE TCLEE 1984	earthquake	earthquake	•
Transmission Towers & Poles	*ASCE-10**	wind, ice, earthquake	wind, ice, earthquake	•
	*ASCE Manual 72**	wind, ice, earthquake	wind, ice	•
	*ASCE Manual 74**	wind, ice, earthquake[2]	wind, ice	•
	*ASCE Manual 91**	wind, ice, earthquake	wind, ice, earthquake	•
	*ASCE Concrete Poles**	wind, ice, earthquake	wind, ice, earthquake	•
	PCI Prest. Conc. Poles*	wind, ice, earthquake	wind, ice, earthquake	•
	RUS 1724e*	wind, ice, earthquake	wind, ice, earthquake	•
	IEEE 605*	wind, ice, earthquake	wind, ice, earthquake	•
	IEEE 691*	none	none	•
	IEEE 693	earthquake	earthquake	•
	NESC	wind, ice, earthquake	wind, ice	•
Distribution Poles	NESC	wind, ice, earthquake	wind, ice	•
	RUS 160-2*	wind, ice, earthquake	wind, ice, earthquake	•
Buried Conduits				

Telecommunication Systems		***Natural Hazard Provisions***[8]		
Component	***Guide/Standard***[1]	***Loading***	***Design***	***Existing***[7]
System Reliability[6]				
Towers, Masts and Poles	TIA/EIA 222G (2003)	earthquake, wind, ice	earthquake, wind, ice	•
	TIA/EIA 222F	wind, ice	wind, ice	•

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[7] "Existing" indicates that analysis or design procedures (NOT LOADS) could be applied for existing components.

[8] "Loading" refers to whether or not specific loads for various natural hazards are defined; "Design" refers to the existence of design and/or analysis procedures that account for loads arising from natural hazards.

* This document refers to NESC and ASCE Manual 74.

All acronyms are defined at the end of the table.

Table A-2 ALA Matrix of Standards and Guidelines for Natural Hazards (Revised May 2004) (cont'd)

Telecommunication Systems (continued)		***Natural Hazard Provisions***[8]		
Component	***Guide/Standard***[1]	***Loading***	***Design***	***Existing***[7]
Buried Cables	*Bell Core*	earthquake, flood	earthquake, flood	
Underwater Cables				
Aboveground Cables	*Bell Core*	earthquake, wind, ice, snow	earthquake, wind, ice, snow	
Switching Equipment	*Bell Core*	earthquake, fire	earthquake, fire	
Cable Trays	*SMACNA*	none	earthquake	
	BSP (Bell System Practice)	none	earthquake	
	ASCE 7	earthquake, wind, ice, snow	earthquake, wind, ice, snow	

Ports and Inland Waterways		***Natural Hazard Provisions***[8]		
Component	***Guide/Standard***[1]	***Loading***	***Design***	***Existing***[7]
System Reliability[6]	*ASCE TCLEE 12*	earthquake		•
Piers/Wharves	*NCEL R-939*	earthquake	earthquake	
	NAVFAC DM-25.1			
	ASCE TCLEE 12	earthquake	earthquake	•
	NFESC TR-2069SHR	earthquake	earthquake	
Breakwaters/Jetties	*NCEL R-939*	earthquake	earthquake	
	ASCE TCLEE 12	earthquake	earthquake	•
Sea Walls	*NCEL R-939*	earthquake	earthquake	
	ASCE TCLEE 12	earthquake	earthquake	•
Container Handling	ASCE-7	earthquake, wind, snow, ice	earthquake, wind, snow, ice	
	IBC, SBC, UBC	earthquake, wind, snow, ice	earthquake, wind, snow, ice	
	ASCE TCLEE 12	earthquake	earthquake	•
	AISC	none[2]	earthquake, wind, snow, ice	

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[6] "System Reliability" is a component of design referring to practices that are specifically developed to provide reasonable assurance that consequences of a natural hazard on system service will meet the goals established by stakeholders (owners, operators, regulators, insurers, customers, and users). Consequences are defined by multiple performance requirements but typically include impact on public safety, duration of service interruption, and costs to repair damage.

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[8] "Loading" refers to whether or not specific loads for various natural hazards are defined; "Design" refers to the existence of design and/or analysis procedures that account for loads arising from natural hazards.

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Table A-2 ALA Matrix of Standards and Guidelines for Natural Hazards (Revised May 2004) (cont'd)

Ports and Inland Waterways (continued)		***Natural Hazard Provisions[8]***		
Component	***Guide/Standard[1]***	***Loading***	***Design***	***Existing[7]***
Cargo Movement	ASCE-7	earthquake, wind, snow, ice	earthquake, wind, snow, ice	
	IBC, SBC, UBC	earthquake, wind, snow, ice	earthquake, wind, snow, ice	
	ASCE-ASCE TCLEE 12	earthquake	earthquake	•
Marine Oil Terminals	*CSLC*	earthquake	earthquake	
	NFESC TR-2103-SHR	earthquake	earthquake	
	ASCE-7	earthquake, wind, snow, ice	earthquake, wind, snow, ice	
	NFPA[4]	earthquake	earthquake	

Highways and Roads		***Natural Hazard Provisions[8]***		
Component	***Guide/Standard[1]***	***Loading***	***Design***	***Existing[7]***
System Reliability[6]	*FHWA 106*	earthquake	earthquake	
Bridges	*AASHTO*	earthquake, wind, snow, ice, flood	earthquake, wind, snow, ice, flood	•
	CALTRANS	earthquake, wind, snow, ice, flood	earthquake, wind, snow, ice, flood	•
	FHWA-RD-94-052	earthquake	earthquake	•
	FHWA 106	earthquake	earthquake	•
Embankments	*CALTRANS*	earthquake	earthquake	•
Road Beds				
Culverts	*AASHTO*	none[2]	none	
	CALTRANS	none[2]	none	
Tunnels	*AASHTO*	none[2]	none	
	CALTRANS	none[2]	none	
Retaining Walls	*FHWA 106*	earthquake	earthquake	

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[6] "System Reliability" is a component of design referring to practices that are specifically developed to provide reasonable assurance that consequences of a natural hazard on system service will meet the goals established by stakeholders (owners, operators, regulators, insurers, customers, and users). Consequences are defined by multiple performance requirements but typically include impact on public safety, duration of service interruption, and costs to repair damage.

[7] "Existing" indicates that analysis or design procedures (NOT LOADS) could be applied for existing components.

[8] "Loading" refers to whether or not specific loads for various natural hazards are defined; "Design" refers to the existence of design and/or analysis procedures that account for loads arising from natural hazards.

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Table A-2 ALA Matrix of Standards and Guidelines for Natural Hazards (Revised May 2004) (cont'd)

Highways and Roads (continued)		***Natural Hazard Provisions[8]***		
Component	***Guide/Standard[1]***	***Loading***	***Design***	***Existing[7]***
Signs	ASCE-7	earthquake, wind, snow, ice	earthquake, wind, snow, ice	
	IBC, SBC, UBC	earthquake, wind, snow, ice	earthquake, wind, snow, ice	

Railroad		***Natural Hazard Provisions[8]***		
Component	***Guide/Standard[1]***	***Loading***	***Design***	***Existing[7]***
System Reliability[6]	AREMA Ch. 9			
Bridges	AREMA Ch. 7	wind	wind	
	AREMA Ch. 8	wind, ice	wind, ice	•
	AREMA Ch. 9	earthquake	earthquake	•
	AREMA Ch. 15	wind	wind	•
Embankments	AREMA Ch. 9	earthquake	earthquake	earthquake
Rails, Ties, and Ballast	AREMA Ch. 9	earthquake	earthquake	earthquake
Culverts	AREMA Ch. 9	earthquake	earthquake	earthquake
Tunnels	AREMA Ch. 9	earthquake	earthquake	earthquake
Signs	ASCE-7	earthquake, wind, snow, ice	earthquake, wind, snow, ice	
	IBC, SBC, UBC	earthquake, wind, snow, ice	earthquake, wind, snow, ice	

Electrical, Mechanical, and Architectural Components		***Natural Hazard Provisions[8]***		
Component	***Guide/Standard[1]***	***Loading***	***Design***	***Existing[7]***
Elect./Mech. Equip	ASCE-7	earthquake, wind, ice	earthquake, wind, ice	
	ASCE TCLEE 1984	earthquake	earthquake	•
	ASME BPV[3]	none[2]	earthquake, wind	
	NFPA[4]	earthquake	earthquake	

Table notes (this page):

[1] Documents in ***bold italics*** indicate that the guidelines were not produced by a consensus process as defined for Standards Developing Organizations (SDOs) approved by the American National Standards Institute (ANSI).

[2] "none" applies if a guideline or standard does not specifically identify how loads are to be obtained; if a group of standards is referenced, the natural hazard listed may be only covered in one document.

[6] "System Reliability" is a component of design referring to practices that are specifically developed to provide reasonable assurance that consequences of a natural hazard on system service will meet the goals established by stakeholders (owners, operators, regulators, insurers, customers, and users). Consequences are defined by multiple performance requirements but typically include impact on public safety, duration of service interruption, and costs to repair damage.

[7] "Existing" indicates that analysis or design procedures (NOT LOADS) could be applied for existing components.

[8] "Loading" refers to whether or not specific loads for various natural hazards are defined; "Design" refers to the existence of design and/or analysis procedures that account for loads arising from natural hazards.

All acronyms are defined at the end of the table.

Table A-2 ALA Matrix of Standards and Guidelines for Natural Hazards (Revised May 2004) (cont'd)

Electrical, Mechanical, and Architectural Components (continued)		*Natural Hazard Provisions*[8]		
Component	***Guide/Standard***[1]	***Loading***	***Design***	***Existing***[7]
Elect./Mech. Equip (continued)	*IBC, SBC, UBC*	earthquake, wind	earthquake, wind	
	SMACNA	earthquake	earthquake	•
Suspended Ceilings	*IBC, SBC, UBC*	earthquake	earthquake	
Elevated Floors				

Table notes (this page):

[1] Documents in ***bold italics*** indicate that the guidelines were not produced by a consensus process as defined for Standards Developing Organizations (SDOs) approved by the American National Standards Institute (ANSI).

[6] "System Reliability" is a component of design referring to practices that are specifically developed to provide reasonable assurance that consequences of a natural hazard on system service will meet the goals established by stakeholders (owners, operators, regulators, insurers, customers, and users). Consequences are defined by multiple performance requirements but typically include impact on public safety, duration of service interruption, and costs to repair damage.

[7] "Existing" indicates that analysis or design procedures (NOT LOADS) could be applied for existing components.

[8] "Loading" refers to whether or not specific loads for various natural hazards are defined; "Design" refers to the existence of design and/or analysis procedures that account for loads arising from natural hazards.

Acronyms:

AASHTO: American Association of State Highway and Transportation Officials
ANSI: American National Standards Institute
AASHTO: ACI: American Concrete Institute
API: American Petroleum Institute
AREMA: American Railway Engineering and Maintenance-of-Way Association
ASCE: American Society of Civil Engineers
ASME: American Society of Mechanical Engineers
AWWA: American Water Works Association
CAL TRANS: California Department of Transportation
FHWA: Federal Highway Administration
IBC: *International Building Code*
IEEE: Institute of Electronic and Electrical Engineers
IFGC: *International Fuel Gas Code*
NCEL: Naval Civil Engineering Laboratory
NAVFAC: Naval Facilities Engineering Command
NFESC: Naval Facilities Engineering Service Center
NESC: *National Electric Safety Code*
NFPA: National Fire Protection Association
PCI: Precast/Prestressed Concrete Institute
PRCI: Pipeline Research Council International
RUS: Rural Utilities Service
SMACNA: Sheet Metal and Air Conditioning Contractors' National Association
SBC: *Southern Building Code*; *Uniform Building Code*
TCLEE: ASCE Technical Council on Lifeline Earthquake Engineering
TIA/EIA: Telecommunications Industry Association (TIA), an offshoot of the Electronic Industries Alliance
UBC*: Uniform Building Code*
WEF: Water Environment Federation

The ALA developed four new comprehensive guidelines for lifeline system owners and operators on defining the scope of actions necessary to assess system performance during and after hazard events and make risk management decisions. They address electric power, oil and natural gas pipeline, water, and wastewater systems, covering both natural hazards and man-made hazards. Each guideline consists of a two-volume report with concise guidance provided in one volume and commentary and references provided in a separate volume. The documents are:

- *Guideline for Assessing the Performance of Electric Power Systems in Natural Hazard and Human Threat Events* (April 2005) and *Part 2 – Commentary* (April 2005)
- *Guideline for Assessing the Performance of Oil and Natural Gas Pipeline Systems in Natural Hazard and Human Threat Events* (April 2005) and *Part 2 – Commentary* (April 2005)
- *Guidelines for Implementing Performance Assessments of Water Systems, Volume I* (November 2005) and *Volume II: Commentary* (November 2005)
- *Wastewater System Performance Assessment Guideline, Part 1* (June 2004) and *Part 2 – Commentary* (June 2004).

Other more specific guidelines for different systems and for specific hazards were also developed. Often times, the ALA partnered with other professional organizations to complete the work. These guidelines are:

- *American Lifelines Alliance Post-Earthquake Information Systems (PIMS) Scoping Study* (September 2008). The ALA teamed with the University of Illinois at Urbana-Champaign (UIUC) to perform a scoping study to assess both the infrastructure requirements and the implementation requirements for establishing a national post-earthquake information management system (PIMS), called for in the Strategic Plan for the National Earthquake Hazards Reduction Program.
- *Flood-Resistant Local Road Systems: A Report Based on Case Studies* (January 2005). Developed for the ALA by the Association of State Floodplain Managers (ASFPM), in conjunction with the American Public Works Association (APWA), this report documents decision-making processes pertaining to flood-preparedness, planning, and post-flood repair/upgrade for local road transportation systems.
- *Seismic Guidelines for Water Pipelines* (March 2005) and *Commentary* (March 2005). These guidelines provide water utility personnel, pipe designers, and manufacturers with cost-effective approaches to design water pipelines with improved resistance to damage from earthquakes.

- *Guide for Seismic Evaluation of Active Mechanical Equipment* (October 2004). This guide provides seismic performance data for six classes of mechanical components: valves, valve operators, pumps, compressors, fans, and packaged air handling units.
- *U.S. Geological Survey's ShakeMap and ShakeCast: Improving Utilization within the American Lifelines Alliance (ALA) Community* (September 2004). ALA partnered with the U. S. Geological Survey (USGS) to provide guidance to utility operators on using ShakeMap—a tool that displays the extent of potentially damaging shaking based on data that are automatically generated following an earthquake—and ShakeCast—a tool that allows utilities to automatically determine the ground shaking values for an earthquake at their facilities, set thresholds for notification of damage states for each facility, and then automatically notify specified operators, inspectors, and others within their organizations responsible for those particular facilities.
- *Extreme Ice Thicknesses from Freezing Rain* (September 2004). This document was developed with the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) to create consistent national hazard maps of atmospheric ice thickness and concurrent wind speeds (in both English and metric units) for multiple return periods.
- *AREMA Handbook for Railway Storm Scour* (2004). ALA partnered with the American Railway Engineering and Maintenance of Way Association (AREMA) to update its Handbook for Streambed Erosion Hazard Recognition and Countermeasures for Railroad Embankments and Bridges.
- *Seismic Design Standards for Above-Ground Steel Storage Tanks* (2004). ALA partnered with the American Water Works Association (AWWA) and the American Petroleum Institute (API) to revise above-ground steel storage tank seismic design requirements contained in API and AWWA standards.
- *Seismic Design and Retrofit of Piping Systems* (July 2002). This guideline is for the seismic design of piping systems in essential facilities such as power plants, chemical process facilities, oil and gas pipelines and terminals, and post-earthquake critical institutions, such as hospitals; the guideline addresses new and existing above-ground piping systems that comply with the non-seismic provisions of the ASME B31 pressure piping codes for materials, design, fabrication, examination, and testing.
- *Guidelines for the Design of Buried Steel Pipe* (July 2001 with addenda through February 2005). This guideline presents design provisions for use in evaluating the integrity of both new and existing welded buried pipe of carbon or alloy steel fabricated for a range of applied loads.

- *Seismic Fragility Formulations for Water Systems, Part 1 – Guidelines* (April 2001) and *Part 2 – Appendices* (April 2001). This guideline presents procedures that can be used to evaluate the probability of earthquake damage to water transmission systems.

Appendix B
ASCE Technical Council on Lifeline Earthquake Engineering

The Technical Council on Lifeline Earthquake Engineering (TCLEE)[6] is part of the American Society of Civil Engineers (ASCE).

B.1 TCLEE Organization

TCLEE was first initiated in 1974 by a group of academics and practitioners, under the leadership of Professor C. Martin Duke of the University of California, Los Angeles (UCLA). They noted that the extensive damage to utilities such as telecommunications, water, power, and transportations following the 1971 San Fernando earthquake, which was not traditional building damage, had wide ranging and significant impacts on the communities affected by the earthquake. Professor Duke served as the first Chair of TCLEE, and was instrumental in creating four technical sub-committees (electric power and communications, water and sewage, gas and liquid fuels, and transportation) and an Executive Committee to address general issues regarding the state-of-the art and practice of lifeline earthquake engineering.

The group was officially announced as a Technical Council of the American Society of Civil Engineers (ASCE) in 1975. Its first Executive Committee (ExCom) Chair was Michael Yachnis, who served one year followed by Robert V. Whitman. The ExCom positions were officially established in the late 1980s with a process of five year rotations from being an ExCom member progressing to Past Chair.

TCLEE currently consists of nine technical committees: Electric Power and Telecommunication, Earthquake Investigation, Ports (harbor and airport), Gas and Liquid Fuel, Transportation (e.g., highways, bridges, and railway), Water and Wastewater, Seismic Risk, Programs and Publications, and Lifeline System Interdependency (recently added in 2009).

The purpose of TCLEE is to advance the state-of-the-art and practice of lifeline engineering for earthquakes, hurricanes, and other extreme events through the following endeavors:

[6] The TCLEE website is http://www.asce.org/TCLEE/.

1. Investigate performance and participate in the development of guidelines, pre-standards, and standards for the extreme event design and construction of lifelines;
2. Encourage lifeline organizations, industries, and associated manufacturers, associations, and professionals to consider extreme events and their impacts in the planning, design, emergency planning, and operation of lifelines;
3. Serve as a primary resource for establishing broad consensus on lifeline issues;
4. Identify and prioritize research needs related to lifeline planning, design, construction, and operation; and
5. Support and/or conduct programs for education and technology transfer on lifeline earthquake and other extreme event issues.

Although the main goal of TCLEE relating to earthquake effects has not changed, the organization has incorporated multi-hazard effects into its mission and projects. The last TCLEE conference theme of "Lifeline Earthquake Engineering in a Multihazard Environment" reflects this involvement. Multihazard integration started in 2005 with an investigation of transportation system performance after Hurricane Katrina.

TCLEE members are volunteers who contribute their time and knowledge to advance TCLEE objectives and goals. TCLEE members do not have to be ASCE members but non-ASCE members cannot request reimbursements from ASCE. The majority of members provide their own financial support for attending committee meetings. The current membership is a mix of practitioners (government and private consulting) and academic research professionals. For the past 10 years, the TCLEE ExCom has consisted of an equal mix of practitioners and academia. The total number of members is between 160 and 180.

TCLEE continues to produce state-of-the-practice monographs on specific topics of interest in lifeline earthquake engineering through each of its committees. Post-earthquake investigations and resulting monographs are currently a very active topic. The committees hold annual meetings and encourage new membership. TCLEE holds regional, national, and international workshops and participates in workshops of interest held by others. The most recent workshop was held in Chengdu, China, where TCLEE helped sponsor the 6th China-Japan-US Trilateral Symposium on Lifeline Earthquake Engineering in May 2013. The next conference will be in a few years from now and will be held jointly with the Council on Critical Infrastructure. Future workshops are being considered in collaboration with EERI annual meetings and other ASCE conferences.

ASCE is developing a new Infrastructure Resilience Division (IRD) into which TCLEE will be incorporated. The IRD will become effective in October 2014. The activities of TCLEE are intended to continue and meet the IRD vision and mission. The IRD mission is to *continuously improve the resilience of civil infrastructure and lifeline systems*. The IRD mission will be to *reduce service loss and the resulting impacts to our nation's communities from all-hazards events by improving the resilience of our civil infrastructure and lifeline systems*. TCLEE's mission fits within the IRD, but will be expanded to ensure better coordination among lifeline systems across all hazards of importance throughout the nation.

B.2 TCLEE Publications

Over the years, TCLEE has produced a monograph series, other TCLEE publications, an ASCE manual, and TCLEE post-earthquake investigation reports, which are listed in the following sections. Most of these publications may be purchased from ASCE, telephone 1-800-548-ASCE (2723), or online at www.asce.org. Of these, the most widely distributed publications are:

- Eidinger, J. M., and Avila, E. A., Editors, 1999, *Guidelines for the Seismic Evaluation and Upgrade of Water Transmission Facilities*, TCLEE Monograph No. 15.
- Nyman, D., Editor, 1984, *Guidelines for the Seismic Design of Oil and Gas Pipeline Systems*, TCLEE Committee on Gas and Liquid Fuel Lifelines.
- Scawthorn, C., Eidinger, J. M., and Schiff, A. J., Editors, 2005, *Fire Following Earthquake*, TCLEE Monograph No. 26.
- Schiff, A. J., Editor, year, *Guide to Improved Earthquake Performance of Electric Power Systems*, ASCE Manual 96.
- Schiff, A. J., Editor, 1997, *Guide to Post-Earthquake Investigation of Lifelines*, TCLEE Monograph No. 11.
- Tang, A. K., and Schiff, A. J., Editors, 1996, *Methods of Achieving Improved Seismic Performance of Communications Systems*, TCLEE Monograph No. 10.
- Werner, S. D., Editor, 1998, *Seismic Guidelines for Ports*, TCLEE Monograph No. 12.

B.2.1 TCLEE Monograph Series

No. 1, *Recent Lifeline Seismic Risk Studies*, Kiremidjian, A. S., Editor, 1990.

No. 2, *Seismic Lost Estimates for a Hypothetical Water System, A Demonstration Project*, Taylor, C. E., Editor, August 1991.

No. 3, *Guide to Post-Earthquake Investigations of Lifelines,* Schiff, A. J., Editor, August 1991.

No. 4, *Lifeline Earthquake Engineering, Proceedings of the 3rd U.S. Conference on Lifeline Earthquake Engineering*, August 22-23, 1991, Los Angeles, California, Cassaro, M., Editor, August 1991.

No. 5, *Lifeline Earthquake Engineering in the Central and Eastern U.S.*, Ballantyne, D., Editor, September 1992.

No. 6, *Lifeline Earthquake Engineering, Proceeding of the 4th U.S. Conference on Lifeline Earthquake Engineering*, August 10-12, 1995, San Francisco, California, O'Rourke, M. J., Editor, August 1995.

No. 7, *Critical Issues and State of the Art on Lifeline Earthquake Engineering*, Schiff, A. J. and Buckle, I., Editors, October 1995.

No. 8, *Northridge Earthquake: Lifeline Performance and Post- Earthquake Response*, Schiff, A. J., Editor, August 1995.

No. 9, *Seismic Design for Natural Gas Distributors*, McDonough, P. W., August 1995.

No. 10, *Methods of Achieving Improved Seismic Performance of Communications Systems*, Tang, A. K., and Schiff, A. J., Editors, September 1996.

No. 11, *Guide to Post-Earthquake Investigation of Lifelines*, Schiff, A. J., Editor, July 1997.

No. 12, *Seismic Guidelines for Ports*, Werner, S. D., Editor, March 1998.

No. 13, *Overcoming Barriers: Lifeline Seismic Improvement Programs*, Taylor, C. E., Mittler, E., and Lund, Le Val, September 1998.

No. 14, *Hyogo-Ken Nambu Earthquake of January 17, 1995-Lifeline Performance*, Schiff, A. J. Editor, 1998.

No. 15, *Guidelines for the Seismic Evaluation and Upgrade of Water Transmission Facilities*, Eidinger, J. M., and Avila, E. A., Editors, January 1999.

No. 16, "Optimizing Post-Earthquake Lifeline System Reliability," *Proceedings of the 5th U.S. Conference on Lifeline Earthquake Engineering*, Seattle, Washington, Elliott, W. M., and McDonough, P. W., Editors, August 1999.

No. 17, *Ismit (Kocaeli), Turkey Earthquake of August 16, 1999, Including Duzce Earthquake of November 12, 1999—Lifeline Performance*, Tang, A. K., Editor, September 2000.

No. 18, *Chi-Chi, Taiwan, Earthquake of September 21, 1999—Lifeline Performance*, Schiff, A. J., and Tang, A. K., Editors, October 2000.

No. 19, *Gujarat (Kutch) India, M7.7 Earthquake of January 26, 2001 and NAPA M5.2 Earthquake of September 3, 2000*, Eidinger, J. M., Editor, June 2001.

No. 20, *The Nisqually, Washington, Earthquake of February 2001—Lifeline Performance*, McDonough, P. W., Editor, February 2002.

No. 21, *Acceptable Risk Process— Lifelines and Natural Hazards*, Taylor, C. E., and VanMarcke, E. H., Editors, March 2002.

No. 22, *Seismic Screening Checklists for Water and Wastewater Facilities*, Heubach, W. F., Editor, September 2002.

No. 23, *Atico, Peru Mw 8.4 Earthquake of June 23, 2001*, Edwards, C. L., Editor, October 2002.

No. 24, *Lifeline Performance of El Salvador Earthquakes of January 13 and February 13, 2001*, Lund, L. V., and Sepponen, C., Editors, September 2002.

No. 25, *Advancing Mitigation Technologies and Disaster Response for Lifeline System: Proceedings of the Sixth U.S. Conference and Workshop on Lifeline Earthquake Engineering*, Beavers, J. E., Editor, August 2003.

No. 26, *Fire Following Earthquake*, Scawthorn, C., Eidinger, J. M., and Schiff, A. J., Editors, 2005.

No. 27, *Zemmouri, Algeria, Mw 6.8 Earthquake of May 31, 2003*, Edwards, C. L., Editor, 2004.

No. 28, *San Simeon Earthquake of December 22, 2003 and Denali, Alaska, Earthquake of November 3, 2002*, Yashinsky, M., and Lund, L. V., Editors, 2004.

No. 29, *Hurricane Katrina: Performance of Transportation Systems*, DesRoches, R., Editor, 2006.

No. 30, *Sumatra-Andaman Islands Earthquake and Tsunami of December 26, 2004 Lifeline Performance*, Strand, C., and Masek, J., Editors, 2008.

No. 31, *Kashiwazaki, Japan Earthquake of July 16, 2007 Lifeline Performance*, Tang, A. K., and Schiff, A. J., Editors, 2008.

No. 32, *Pisco, Peru Earthquake of August 15, 2007 Lifeline Performance*, Tang, A. K., and Johansson, J., Editors, 2008.

No. 33, *Pacific Northwest Storm of December 15, 2007 Lifeline Performance*, Elliott, T., and Tang, A. K., Editors, 2009.

No. 34, *Seismic Resilience of Natural Gas Systems Improving Performance*, McDonough, P. W., Editor, 2012.

No. 35, *Haiti M_w 7.0 Earthquake of January 12, 2010 Lifeline Performance,* Edwards, C. L., Editor. 2012.

No. 36, *Chile Earthquake of 2010 Lifeline Performance*, Tang, A. K., and Eidinger, J. M., Editors, 2013.

No. 37, *Padang, West Sumatra, Indonesia, Earthquake of 2009 Lifeline Performance*, Tang, A. K., Editor, 2013.

No. 38, *International Efforts in Lifeline Earthquake Engineering*, Davis, C., Du, X., Miyajima, M., and Yan, L., Editors, 2014.

Pending Publications (The monograph number is not yet assigned):

Wenchuan, (Sichuan) China Earthquake of May 12, 2008 Lifeline Performance, Tang, A. K., Editor.

Lushan, (Sichuan) China, Earthquake of April 20, 2013 Lifeline Performance, Eidinger, J. M., Tang, A. K., and Davis, C. A., Editors.

Christchurch, New Zealand Earthquake Sequence of September 04, 2010, February 22, 2011, June 13, 2011, and December 23, 2011 Lifeline Performance, Eidinger, J. M., and Tang, A. K., Editors.

Tohoku, Japan Earthquake and Tsunami of March 11, 2011 Lifeline Performance, Edwards, C. L., and Tang, A. K., Editors.

B.2.2 Other TCLEE Publications

Duke, C. M., Editor, *The Current State of Knowledge of Lifeline Earthquake Engineering*, 1977.

Dowd, M., Editor, *Annotated Bibliography on Lifeline Earthquake Engineering*, 1980.

Smith, D. J. Jr., Editor, *Lifeline Earthquake Engineering: The Current State of Knowledge*, 1981.

Hall, W., J., Editor, *Advisory Notes on Lifeline Earthquake Engineering*, 1983.

Nyman, D., Editor, *Guidelines for the Seismic Design of Oil and Gas Pipeline Systems*, TCLEE Committee on Gas and Liquid Fuel Lifelines, 1984.

Cooper, J., Editor, *Lifeline Earthquake Engineering: Performance, Design and Construction*, 1984.

Eguchi, R. T., and Crouse, C. B., *Lifeline Seismic Risk Analysis—Case Studies*, 1986.

Cassaro, M., and Martinez-Romero, E., Editors, *The Mexico Earthquakes—1985 Factors Involved and Lessons Learned*, 1986.

Wang, L. R. L., and Whitman, R. V., *Seismic Evaluation of Lifeline Systems— Case Studies*, 1986.

Cassaro, M. and Cooper, J., Editors, *Seismic Design and Construction of Complex Civil Engineering Systems*, 1988.

Werner, S. D. and Dickenson, S. E., Editors, Hyogoken-Nanbu (Kobe) Earthquake of January 17, 1995: *A Post-Earthquake Reconnaissance of Port Facilities*, TCLEE Committee on Ports and Harbors Lifelines, 1996.

B.2.3 ASCE Manual

Schiff, A. J., Editor, 1999, *Guide to Improved Earthquake Performance of Electric Power Systems*, ASCE Manual 96.

B.2.4 TCLEE Earthquake Investigation Reports

TCLEE has also prepared numerous earthquake reports that have appeared in other publications. References to these reports associated with TCLEE monographs can be viewed on the ASCE/TCLEE web site at http://www.asce.org/BookstoreSeries.aspx?id=2147486137&series=TCLEE&title=TCLEE%20Monographs. The short reports are each about five to 15 pages long, contain a summary of main observations and some pictures, and can be downloaded.

Appendix C

U.S. and International Research and Implementation Activities and Organizations

This appendix highlights some of the major lifelines-related work of the following U.S. and international research and implementation activities and organizations:

1. Multidisciplinary Center for Earthquake Engineering Research (MCEER)
2. Pacific Earthquake Engineering Research Center (PEER)
3. Mid-America Earthquake (MAE) Center
4. George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES)
5. Applied Technology Council (ATC)
6. Japanese Guidelines, Standards and Codes in Lifeline Earthquake Engineering
7. New Zealand Lifeline Earthquake Engineering

C.1 MCEER

Originally established by the National Science Foundation, MCEER was the first National Center for Earthquake Engineering Research. During its first ten years of operation, from 1986 to 1997, the center was known by the acronym, NCEER. In 1998 it became known as the Multidisciplinary Center for Earthquake Engineering Research (MCEER) from which the current name, MCEER, evolved. Since its inception it has been headquartered at the University at Buffalo, State University of New York. Lifeline earthquake engineering has always played a major role in the MCEER research program, as was a key part of the initial successful competitive proposal to become a national earthquake engineering research center.

During its tenure, MCEER has published about 80 major reports focused on lifelines, in combination with many hundreds of technical journal, conference, and workshop papers. Most MCEER lifeline (except highways) publications are available for download at its web site: http://mceer.buffalo.edu/publications/catalog/categories/topics/Lifelines.html.

Selected major lifelines programs supported by MCEER are described below under the following headings:

- U.S.-Japan Lifelines and Liquefaction Research and Development
- Improved Seismic Performance of Water Supply Systems
- Improved Seismic Performance of Electric Power Systems
- Improved Seismic Performance of Transportation Systems, and
- Monographs

C.1.1 U.S.-Japan Lifelines and Liquefaction Research and Development

Led by researchers at Cornell and Waseda Universities, MCEER supported collaborative research on the earthquake resistant design of lifeline facilities and countermeasures against liquefaction for 20 years (1986-2006). This collaborative program involved researchers from dozens of U.S. and Japanese universities as well as practicing engineers and managers of lifeline systems. The overall goal of the collaborative effort was to develop planning, design, and construction procedures to mitigate the effects of earthquake-induced ground deformation, including transient and permanent movements, on lifeline components and systems. The collaboration resulted in eight major workshops with published proceedings containing over 400 papers; two volumes of case histories (Hamada and O'Rourke, 1992; O'Rourke and Hamada. 1992); and many new modeling procedures and experimental findings that have improved the earthquake resistant design of lifeline systems worldwide.

C.1.2 Improved Seismic Performance of Water Supply Systems

In 1986, a research team supported by MCEER developed the first hydraulic network model of water supply responses to earthquakes, and applied it to the San Francisco Auxiliary Water Supply System (AWSS). Simulations performed with the hydraulic network model were combined with a fire spreading model and results showed that the AWSS would not be reliable in suppressing fire in a future severe earthquake. The results of coupled water supply and fire simulations were presented to the San Francisco mayor and other city officials, and a $46 million bond measure was developed and passed with 89% voter approval, to provide funding for rehabilitation of the AWSS and other fire-related infrastructure (Scawthorn, et al., 2006).

Furthermore, combined water supply and fire spreading simulations were used to build additional water distribution resources that actually suppressed a major fire in the Marina District during the 1989 Loma Prieta earthquake, thereby saving lives and substantial property losses (O'Rourke, 2010). The MCEER work, which involved characterization of liquefaction hazards for underground infrastructure, has been used extensively in the engineering supported by recent 2010 and 2014 bond measures in San Francisco for seismic retrofitting of the AWSS.

Based on the experience gained in San Francisco, an MCEER research team developed a hydraulic network model that accounts for all 11,700 kilometers of water trunk and distribution pipelines and related facilities (e.g., tanks, reservoirs, pressure regulation stations) in the Los Angeles Department of Water and Power (LADWP) system (O'Rourke, 2010). The model accounts for the aggregated seismic hazard in Los Angeles through an ensemble of 59 scenario earthquakes, providing a library from which engineers can select specific scenarios or combinations of scenarios to assess system performance. The decision support system works with risk and reliability assessment tools to provide metrics of system performance. The computer simulations account for the interaction of water and electric power supplies, and model output can be used to evaluate the regional economic and community impacts of water losses. All system input and output can be visualized through GIS with advanced query logic and web-based features. The simulations are dynamic in time, and account for loss of service as tanks and local reservoirs lose water over time through leaks and breaks in pipelines. Simulations performed for the Los Angeles water supply response to a magnitude-7.8 earthquake on the southern San Andreas fault show that opening reservoirs, which have been disconnected because of water quality regulations, improves serviceability significantly in the locations of highest population, and thus is an effective emergency response measure. The results of these simulations have been used to establish emergency response plans and policy for post-earthquake water supply restoration.

C.1.3 Improved Seismic Performance of Electric Power Systems

A research team supported by MCEER developed a model for integrated electric power supply systems. Methodologies for evaluating the post-earthquake performance of electric transmission systems were applied to the Los Angeles area to show how improvements in transformer resilience affect system reliability during earthquakes (e.g., Shinozuka and Chang, 2004). Such work provides an understanding of the vulnerability and potential for cascading losses in large regional electric power systems, such as the one operated by the Western States Coordinating Council (WSCC). This system covers approximately 1.8 million square miles and provides electric power for 71 million people in 14 states. Power flow simulations, initially undertaken for earthquake effects in Los Angeles, were expanded to investigate the loss of critical transmission facilities in the WSCC network (Shinozuka, et al., 2003). The simulations showed that the entire Los Angeles area can be blacked out by the disruption of one transmission line at the border of Washington and Oregon. MCEER researchers used shake table tests to characterize electric power transformer functional resilience and identify key vulnerabilities. The research team showed that the seismic base isolation of transformers reduces internal demand on components, nearly eliminates sliding of key spacers, and enhances transformer life following earthquakes.

C.1.4 Improved Seismic Performance of Transportation Systems

MCEER research on transportation systems has focused on highways and highway bridges. The primary emphasis has been on earthquakes, but a number of studies have been completed on highway and highway bridge response to hurricanes. MCEER highway publications are available for downloading at its web site: http://mceer.buffalo.edu/publications/Bridge_and_Highway_Reports/default.asp.

A major accomplishment of the MCEER transportation network research has been the development and validation of the public domain software REDARS (Risks from Earthquake Damage to Roadway Systems). REDARS is a software program for deterministic and probabilistic seismic risk analysis (SRA) of highway systems. The main modules of the REDARS SRA methodology cover hazards, lifeline components and overall system and economics issues. The northern Los Angeles highway system was used as a demonstration application of the SRA methodology. The software incorporates data and methodologies pertaining to engineering issues, repair and reconstruction, system network risk analysis, and socioeconomic considerations for impacts resulting from system damage. The products outlined also provide a mechanism to estimate system-wide direct losses and indirect losses due to reduced traffic flows and/or increased travel times.

MCEER researchers have developed statistical and analytical methods to assess the seismic performance of highway transportation networks. The seismic vulnerability of bridges is expressed in the form of fragility curves associated with the states of minor, moderate, major and collapse damage, and mechanistically defined in terms of the extent of ductility rotation of bridge columns. On the basis of statistical and analytical tools developed, a design acceptance criterion is suggested that can verify the target performance level of a newly designed bridge under a prescribed level of seismic hazard.

MCEER developed a course of action that can be used by the New York State Department of Transportation to respond to assess the safety and functionality of highway bridges in an orderly and expeditious manner following an earthquake. The proposed Earthquake Response Plan consists of four response levels, delineated by ranges of earthquake magnitude.

C.1.5 Monographs

MCEER has published a series of monographs that provide state-of-the-art studies and summaries for earthquake resilience applications. Of particular interest for lifelines is the monograph, *Engineering and Socioeconomic Impacts of Earthquakes:*

An Analysis of Electricity Lifeline Disruptions in the New Madrid Area (Shinozuka, et al., 1998). This pioneering work focused on Memphis, Tennessee, to develop a multidisciplinary study of the socioeconomic impacts of the electric power system disruption due to a repeat of the 1811-12 New Madrid earthquakes. The work was the first of its kind to apply a multi-disciplinary methodology to trace earthquake effects through a critical lifeline system to the host regional economy. The study includes modeling of the Memphis economy, seismic performance of the electrical power system, estimation of the direct and indirect regional economic impacts and social impacts, and recommendations for lifeline risk reduction policy formulation and implementation.

Of additional interest is the MCEER monograph, *Seismic Design of Buried and Offshore Pipelines* (O'Rourke and Liu, 2012). This work is an update of a previous monograph, *Response of Buried Pipelines to Earthquake Effects* (O'Rourke and Liu, 1999), to include offshore pipelines used most frequently in the oil and gas industry. The work provides an overview of earthquake effects on underground pipelines, pipeline failure modes, soil-pipeline interaction, analytical models, and countermeasures to reduce earthquake damage.

C.2 Pacific Earthquake Engineering Research (PEER) Center

In 1996, the Pacific Earthquake Engineering Research Center (PEER) Lifelines Program was initiated with a contract between the University of California, Berkeley, and the Pacific Gas & Electric Company (PG&E). The contract entitled "Directed Studies for Reducing Seismic Vulnerability of Gas and Electrical Distribution & Transmission Systems," was used as a matching fund to secure a funding from the National Science Foundation to formalize PEER as a national earthquake engineering research center. Following the establishment of PEER, the scope of the PEER Lifelines Program was expanded with the addition of other partners including the California Energy Commission (CEC) and California Department of Transportation (Caltrans).

The goal of the PEER Lifelines Program is to improve the seismic safety and reliability of lifeline systems. The projects in this program are primarily user-driven research projects, with strong collaboration among sponsoring lifelines organizations and PEER researchers. This interaction results in products that are both scientifically sound and able to solve real problems affecting lifeline system operations. The multiple-lifelines-agencies approach of the PEER Lifelines Program allows it to address large multidisciplinary earthquake engineering problems.

C.2.1 Scope of the PEER Lifelines Program

The research projects in the PEER Lifelines Program range from engineering characterization of ground motions, local soil response, the response of bridge structures, and the performance of electric substation equipment. The lifelines research projects are organized into eight topics as shown in Figure C-1.

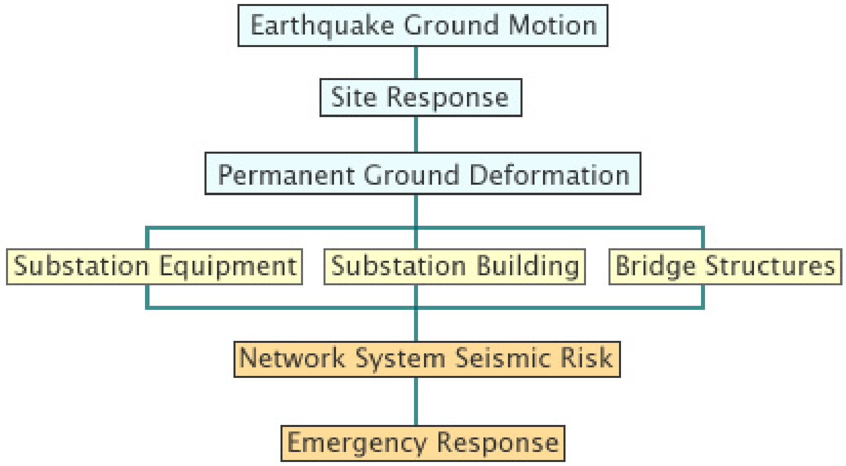

Figure C-1 Organization of PEER Lifelines Program research projects.

The PEER Lifelines Program has successfully organized multidisciplinary teams of practicing engineers (geotechnical, structural); scientists (geologists, seismologists, and social scientists); funding agencies (Federal, State of California, private industry); academics, and end-users. An example of such successful multidisciplinary collaboration is the “Next Generation of Ground-Motion Attenuation Models" for the western United States (NGA-West) research program that has resulted in major advances in the characterization of seismic hazard, especially in the western United States. The NGA database is the largest uniformly processed digital recordings of earthquake ground motions in the world and is used by researchers and practitioners worldwide. Under the NGA program, multiple ground motion models were also developed. These ground motion models were adopted by the USGS for the development of the U.S. National Seismic Hazard Maps, which are the fundamental input data for building codes nationwide. Thus, the products of this project have affected seismic design, analysis and evaluation of an entire spectrum of facilities, including power plants, dams, buildings, bridges and other civil engineering facilities.

Since its inception the PEER Lifelines Program has awarded over 140 research projects on a wide range of multidisciplinary research tasks. The Program has resulted in the publication of numerous PEER reports that are available free of charge to the public at the PEER web site: http://peer.berkeley.edu/publications/peer_reports.html.

C.2.2 PEER Transportation Systems Research Program

During the initial efforts to establish PEER, the State of California enacted Senate Bill (SB)-1864 with annual funding of PEER to carry out research on the seismic performance of a wide range of transportation systems. The PEER Transportation Systems Research Program is a very active program that coordinates research projects on the seismic performance of bridges, highway systems, high-speed rail, and ports, among others. Since its inception, the Program has funded and coordinated numerous experimental and analytical research projects. The results have been published as PEER reports, which can be found at the PEER website (link provided above).

At PEER, the Transportation Systems Research Program is in continuous interaction with the PEER Lifelines Program to harmonize the activities of these two large research programs and avoid any duplication of efforts. The Transportation Systems Research Program (TSRP) is managed by the TSRP research committee, which includes two members of the PEER Lifelines Program management committee as the liaison members.

C.3 Mid-America Earthquake (MAE) Center

The Mid-America Earthquake (MAE) Center was founded in 1997 by the National Science Foundation (NSF) as one of the three national earthquake engineering research centers. The MAE Center emerged from the years of NSF support as a research center offering a mix of expertise, resources and experience, graduating from the NSF Engineering Research Center Program in 2009. In 2013, the center expanded its focus to consider multiple natural hazards and human-made threats. Previously geared toward earthquake engineering research, the center now derives its acronym, MAE, from its new focus on developing a Multi-hazard Approach to Engineering. The headquarters of the MAE Center resides within the Department of Civil and Environmental Engineering at the University of Illinois at Urbana-Champaign.

A significant portion of the research conducted at the MAE Center is in the area of lifeline earthquake engineering. As a result, many reports, technical journals, and conference/workshop papers focused on lifelines have been published by the MAE Center, most of which are available at the center website: http://mae.cee.illinois.edu/publications/publications.html.

The following selected highlights are representative of the range of lifeline earthquake engineering research supported by the MAE Center.

C.3.1 The MAEViz Cyberenvironment: From Source to Society

MAEViz is an extensible, open-source platform designed to support hazard risk management and analysis. MAEViz is a network aware application and cyber-environment model that connects researchers and decision makers in modeling earthquake events, developing risk reduction strategies and implementing mitigation plans to minimize the impact of earthquake disasters. MAEViz provides a pathway for researchers to add new data and algorithms quickly to assure the latest scientific models and understandings are available and comparable so decisions are based on state-of-the-art engineering understanding. MAEViz is capable of interacting with remote data and computational sources as well as running analyses locally so research scientists and decision makers can generate information when a catastrophic event occurs and provide first-responders with results information. MAEViz is built upon the Eclipse Rich Client Platform (RCP), and uses a number of open-source standards compliant libraries to enable middleware, geographic information system (GIS) components and visualization libraries. MAEViz's data management and workflow-oriented execution model is designed to incorporate new data types and new analysis modules to provide the scientific community with a powerful tool to model, compare and validate the latest findings with currently accepted concepts and models.

The following are the types of reports available from the MAEViz Application: Bridge Damage Summary; Bridge Damage; Bridge Functionality; Bridge Repair Costs; Bridge Cost/Benefit Ratio Report; Building Damage Detail; Building Damage Summary; Building Economic Damage Summary; Building Non-Structural Damage; and Building Benefit/Cost Ratio Report.

MAEViz supports all of the following analysis for lifelines: Buried Pipeline Damage, Electric Power Facility Damage, Electric Power Plant Loss, Electric Substation Damage, Potable Water Facility Damage, Utility Network Builder, and Water Tank Damage.

The MAEViz cyber-environment continues to integrate cutting edge science and technology to provide geographically distributed researchers, engineers, scientists, social scientists, and decision makers with a new generation of impact assessment software. To date, MAEViz has supported about 40 different analyses for buildings, bridges, hazards, lifelines, and socioeconomic models driven by the MAE Center community. MAEViz made significant strides in improving usability and providing an intuitive interface to its many analyses. Moreover, the center integrated the efforts of engineers, social scientists, and economists so that MAEViz could support capabilities such as social vulnerability, fiscal impact, household and population dislocation, shelter requirements, short-term shelter needs, business content loss, business interruption loss, and business inventory loss. Combining the information from the social vulnerability and the structural damage analysis enables the computation of expected household and population dislocation. The expected dislocation can then be used to determine shelter needs and shelter requirements (e.g., food, water). Local and regional planners can also feed the residential damage into the fiscal impact analysis to determine the anticipated property tax loss of a region based on decreased value of the structure. These capabilities can provide local and regional planners the tools necessary for effective seismic hazard planning and mitigation.

C.3.2 Transportation Network Test Bed Project

The functionality of a transportation network following an earthquake is critical for post-earthquake response and long-term recovery. The Transportation Test Bed Project of the MAE Center integrated the various tools developed by the Center into a comprehensive evaluation of the performance of the transportation network in Charleston, South Carolina. Using state-of-the-art tools, such as enhanced fragility models for bridges, damage-functionality relationships, and a detailed inventory analysis, the distribution of potential bridge damage and functionality were evaluated for several scenario events in order to aid in the identification of emergency routes and assess areas for investment in retrofit. Unlike previous seismic risk assessments performed in the central and southeastern United States, this project used fragility models that were specific to the characteristic of bridges in the region.

C.3.3 Memphis Test Bed Project

This test bed project investigated the impact of a large-magnitude earthquake originating in the New Madrid Seismic Zone near Memphis, Tennessee, and the surrounding area in Shelby County. The project synthesized diverse research thrusts within the MAE Center on ground shaking and failure hazard prediction, inventory collection, damage state and functionality prediction, and socioeconomic effects. The research from each of these thrusts was developed within a general framework for regional loss assessment that focused on the specific effects of an earthquake event in Mid-America. Building, bridge, and roadway inventories in Memphis allowed for detailed assessment of damage to the urban environment and transportation network.

The outcome of the analyses provided a broad perspective of the risk to the study region, ranging from direct economic impact of repair and replacement costs, to response and recovery considerations such as transportation and utility lifeline functionality, displaced households, and temporary shelter requirements. Social and economic vulnerability were evaluated at a high resolution and aggregated for visualization in localized zones of interest. The results of this study were helpful in developing strategies for mitigation, response, and recovery in the Memphis region, and serve as a model for similar investigations in other regions.

C.3.4 Laclede Gas and CenterPoint Energy Project

This project used the MAE Center's MAEViz seismic loss estimation and visualization software to estimate the seismic impact from a New Madrid earthquake to Laclede Gas's pipeline network in the greater St. Louis, Missouri area.

Laclede Gas is the primary supplier of gas to businesses and homes in the metropolitan area and much of its gas network is composed of cast-iron pipelines. Damage and repair estimates were calculated and visualized using MAEViz. The software was used to determine the performance of the utility network following a significant earthquake. Interdependencies between the gas utility network and other lifelines, such as the power network, were also examined.

CenterPoint Energy is the main supplier of gas to Laclede. CenterPoint, which is headquartered in Shreveport, Louisiana, is a natural gas producer and supply company. It provides Laclede with gas via its interstate pipeline system that stretches from Northeast Louisiana north through Arkansas and Missouri to St. Louis. Much of CenterPoint's pipeline network crosses through the New Madrid Seismic Zone so it is at significant risk from a New Madrid earthquake. The loss assessment objectives described above for Laclede were also conducted for CenterPoint. CenterPoint co-funded this project with Laclede with the intent of sharing assessment results.

C.3.5 Liquefaction-Dependent Fragilities for Bridges

Bridges and buildings are vulnerable to soil liquefaction, which is especially true for the Mississippi embayment, where there are abundant liquefiable soils. Available fragility relationships often ignore liquefaction effects, or model them by applying an empirical factor to magnify the damage.

The MAE Center derived analytically-based fragility relationships that account for soil-structure interaction and liquefaction. Use was made of the state-of-the-art soil models in OpenSees (from the PEER Center) and the structural models and capabilities of ZEUS-NL (from the MAE Center), in combination with the simulation coordination platform UI-SimCor (from MAE and NEES@UIUC). Use of such analytically-robust models in estimating damage and failure probabilities provides more reliable predictions of damage to assist emergency response planning.

C.4 Network for Earthquake Engineering Simulation (NEES)

The George E. Brown, Jr. Network for Earthquake Engineering Research (NEES) operated as a multi-university consortium of equipment sites focused on advanced laboratory and computational simulation of earthquake and tsunami effects on the built environment. The sites shared high performance internet connectivity, specialized software, and common standards for archiving data collected during experiments and tests at the equipment sites.

The National Science Foundation funded construction of NEES during 2000-2004, with NEES operations starting in 2004 and ending in 2014. The NEES Equipment Sites included Cornell University, Lehigh University, Oregon State University, Rensselaer Polytechnic Institute, State University of New York at Buffalo, University of California at Berkeley, University of California at Davis, University of California at Los Angeles, University of California at San Diego, University of California at Santa Barbara, University of Illinois at Urbana-Champaign, University of Minnesota, University of Nevada at Reno, and University of Texas at Austin. The University of Colorado-Boulder and the San Diego Supercomputer Center (SDSC) were also NEES Equipment Sites until 2009.

Management of the network was provided initially by NEESinc, a non-profit, tax-exempt corporation, headquartered in Davis, California that was legally dissolved in 2010. In 2009, NEES management and the cyber-infrastructure operations were moved to Purdue University. The NEES equipment sites included two geotechnical centrifuges, three field experimental and monitoring facilities, seven large-scale laboratory experimentation facilities, three shake tables, and one tsunami wave basin.

Approximately 243 research projects and 1,626 research experiments were undertaken through NEES: http://nees.org/about/overview/researchfacts. Twenty of these projects were associated with lifelines or sensors that can be used to monitor lifeline systems. Projects associated with underground lifelines were undertaken primarily at the Large Scale Lifeline Testing Facility at Cornell University. Projects associated with highway bridges were undertaken primarily at the University of Nevada at Reno.

Research summaries of key NEES projects are provided in the report entitled *NEES 2004-2014 A Decade of Earthquake Engineering Research* available at https://nees.org/retrospective

C.5 Applied Technology Council (ATC)

The Applied Technology Council (ATC) is a non-profit, tax-exempt corporation established in 1973 through the efforts of the Structural Engineers Association of California. ATC's mission is to develop state-of-the-art, user-friendly engineering resources and applications for use in mitigating the effects of natural and other hazards on the built environment. ATC also identifies and encourages needed research and develops consensus opinions on structural engineering issues in a non-proprietary format. ATC thereby fulfills a unique role in funded information transfer.

ATC is guided by a Board of Directors consisting of representatives appointed by the Structural Engineering Institute of the ASCE, the National Council of Structural Engineers Associations, the Structural Engineers Association of California, the Structural Engineers Association of New York, the Western Council of Structural Engineers Associations, and four at-large representatives concerned with the practice of structural engineering. Each director serves a three-year term.

Project management and administration are carried out by a full-time Executive Director and support staff. Project work is conducted by a wide range of highly qualified consulting professionals, thus incorporating the experience of many individuals from academia, research, and professional practice who would not be available from any single organization. Funding for ATC projects is obtained from government agencies and from the private sector in the form of tax-deductible contributions.

Early projects (in the 1970s) focused on the development of new methods of seismic design for buildings and highway bridges, with funding provided by the National Science Foundation, the National Bureau of Standards (now NIST), the Department of Housing and Urban Development, and the Federal Highway Administration. In the 1980s, ATC proposed and received funding from the then newly-established Federal Emergency Management Agency (FEMA), whose mission of earthquake hazard mitigation, response and recovery, aligned well with the mission of ATC. Soon thereafter, ATC's client list expanded to include California state agencies, the U. S. Geological Survey, and other agencies, including the Civil Protection Agency of Italy. As a result, the suite of ATC projects expanded from a focus on seismic design of new structures to areas of pre-event earthquake damage estimation, seismic hazard mapping, seismic evaluation and retrofit of structures, and post-earthquake building safety evaluation. In the 1990s the organization expanded its scope to include other natural hazards, such as windstorms and coastal inundation. In recent years, annual funding for ATC projects has been in the $4 to $6 million range, with the cumulative historical total approaching $150 million. Funding agencies now include FEMA, NIST, the California Earthquake Authority, the Charles Pankow Foundation, and the City and County of San Francisco.

ATC reports that address the earthquake performance of lifelines include:

1. ATC-13: The report, *Earthquake Damage Evaluation Data for California*, was developed under a contract with the Federal Emergency Management Agency (FEMA). It presents expert-opinion earthquake damage and loss estimates for industrial, commercial, residential, utility and transportation facilities in California. Included are damage probability matrices for 78 classes of structures and estimates of time required to restore damaged facilities to pre-earthquake usability. Available through ATC. (Published 1985, 492 pages)
2. ATC-25: The report, *Seismic Vulnerability and Impact of Disruption of Lifelines in the Conterminous State*s, was developed under a contract with FEMA. Available through ATC. (Published 1991, 440 pages)
3. ATC-25-1: The report, *A Model Methodology for Assessment of Seismic Vulnerability and Impact of Disruption of Water Supply Systems*, was developed

under a contract with FEMA. Available through ATC. (Published 1992, 147 pages)

4. ATC-52-1, *Here Today—Here Tomorrow: The Road to Earthquake Resilience in San Francisco: Potential Earthquake Impacts*. The report addresses fire following earthquakes, and thereby indirectly addresses water systems. Available through ATC. (Published 2010, 78 pages)
5. ATC-52-1A, *Here Today—Here Tomorrow: The Road to Earthquake Resilience in San Francisco: Potential Earthquake Impacts Technical Documentation*. Report addresses fire following earthquakes, and thereby indirectly addresses water systems. Available through ATC. (Published 2010, 160 pages)

ATC has also produced reports in the transportation lifelines area—several key reports on bridge seismic design, including ATC-6, *Seismic Design Guidelines for Highway Bridges*, which were later adopted by the American Association of Highway and Transportation Officials as a standard specification (for the design of federally funded bridges); ATC-32, *Improved Seismic Design Criteria for California Bridges: Provisional Recommendations*, an effort mandated by the State of California following significant bridge damage during the 1989 Loma Prieta earthquake; and the ATC-49 series, *Recommended LRFD*[7] *Guidelines for the Seismic Design of Highway Bridges.*

Overall, the organization has been successful in (a) obtaining grants and contracts to advance the technology and practice of structural engineering, and (b) producing resource documents that have been widely used and accepted by design professionals nationwide. The reasons for this success include:

1. A business model that enables the organization to expand and contract at will, depending on the availability of external funding;
2. A small permanent high-caliber professional staff who identify technical needs, write technical proposals for funding, manage projects, and execute product quality control, all in a consistent reliable fashion;
3. A Board of Directors of nationally recognized leaders in structural, earthquake, wind, coastal, and fire engineering who set policy and assist in project identification and development;
4. A consistently applied consensus-based project/product development model that relies on highly qualified technical consultants under contract to develop and overview project work;

[7] LRFD: Load and resistance factor design

5. A broad range of leading technical consultants who are willing to work on ATC projects, at compensation rates specified by ATC (often substantially less than prevailing commercial rates), because of the intellectual rewards and resulting professional contributions and recognition; and government and private-sector agencies and organizations that are willing to fund ATC work, based on consistent implementation of an efficient non-profit business model and the ATC track record in product development.

C.6 Japanese Guidelines, Standards and Codes in Lifeline Earthquake Engineering

In the last two decades, Japan has experienced a number of earthquakes that have significantly damaged lifelines, and subsequently undertaken review and revision of seismic design practices for virtually all lifelines. Major Japanese earthquakes and their impact on lifeline practices are listed in Table C-1. The revisions to Japanese lifeline guidelines, standards, and codes have been major multi-year, well-funded efforts, with the latest revisions in progress after the 2011 Great East Japan Earthquake and Tsunami (Tohoku earthquake).

Table C-1 Recent Japanese Earthquakes Affecting Lifelines and Their Design

Earthquake Name and Date	Magnitude	Lifeline Impacts
Hyogo-ken Nanbu Earthquake (Jan. 1995)	7.2	Major failure of highways, rail, port, water/wastewater, power, gas and other lifelines
Tottori-ken Seibu Earthquake (Oct. 2000)	7.3	
Geiyo Earthquake (Mar. 2001)	6.7	
Tokachi Offshore Earthquake (Sept. 2003)	8.0	Major damage to tanks, oil refineries
Niigata-ken Chuetsu Earthquake (Oct. 2004)	6.8	Damage, fire and radioactive leak at Kariwa Kashiwazaki Nuclear Power Station (world's largest); major landslides and damage to road network
Fukuoka-ken Western Offshore Earthquake (Mar. 2005)	7.0	
Niigata-ken Chuetsu Offshore Earthquake (July 2007)	6.8	
Miyagi/Iwate Inland Earthquake (June 2008)	7.2	
Great Eastern Japan Earthquake and Tsunami (March 2011)	9.0	Catastrophic damage to Fukushima I Nuclear Power Station (NPS), shutdown of all NPSs, coastal lifelines heavily damaged, major port damage, Sendai airport heavily damaged

Oversight of lifeline earthquake design in Japan is similar to that in the United States, with basic structural design prescribed by a particular code for each type of lifeline.

Lifeline standards and codes are developed by each lifeline industry with little or no cross-industry coordination. Probably the greatest degree of government involvement in the development of best practices is for roads and bridges, with the Japanese Ministry of Land, Industry, Transport and Tourism (MLIT) being significantly involved in design standards.

The Japan Society of Civil Engineers (JSCE) plays a significant role in Japan with regard to earthquake engineering in general, and particularly with regard to lifelines. The JSCE Earthquake Engineering Committee is large and active, with numerous subcommittees addressing many aspects of infrastructure seismic structural design. Table C-2 presents a select and limited list of design documents published by the JSCE. Attention is drawn to JSCE (2003) "code PLATFORM", which is a unifying document, and JSCE (2008), which is a detailed glossary of terms for performance based design.

Table C-2 Selected Codes and Guidelines Published by Japanese Society of Civil Engineers (JSCE)

JSCE (2003)	Principles, guidelines and terminologies for structural design code drafting founded on the performance based design concept, *ver.1.0 code PLATFORM*, Committee for basic study for drafting the principles, guidelines and terminologies for structural design code
JSCE (2007a)	*Standard Specifications for Concrete Structures*, JGC15
JSCE (2007b)	*Standard Specifications for Steel and Composite Structures*
JSCE (2008)	*Glossary of Key Terms for Structural Design Codes founded on Performance based Design Concept*

The JSCE Earthquake Engineering Committee pays less attention to operational considerations, which are typically covered by other organizations, such as the Japan Electric Association, Japan Gas Association, and Japan Water Works Association (see Table C-3). Performance-based design concepts are ubiquitous among the codes, and some codes also have provisions for reliability-based design. All codes focus on component (e.g., tank, bridge) seismic design, and no code focuses significantly on system performance. This is a major gap in both Japan and the U.S. standards and codes.

The Japanese Society of Civil Engineers Earthquake Resistant Design Codes in Japan (JSCE, 2000) is the most recent authoritative overview of Japanese design codes. This publication treats selected lifelines, and is available in English. A much larger Handbook of Urban Lifelines (JSCE, 2010), treating not just seismic but all urban lifeline issues, was published by JSCE in 2010 and is currently in press in English (JSCE, in press).

Although a comparison of U.S. and Japanese lifeline earthquake design practices is beyond the scope of this report, some observations regarding Japanese practices are worth noting. For example, Japan has fostered new technologies that are largely

Table C-3 Selected Japanese Lifeline Earthquake-Related Design Documents*

Lifeline	Standards	Publisher	Date
Electric power	Earthquake Disaster Countermeasure Guidelines for Electronic System at Transformer Substation	Japan Electric Assn.	2009
	Seismic Design Guidelines for Thermal Power Station	Japan Electric Assn.	1999
Gas	Earthquake Disaster Prevention Guidelines	Japan Gas Assn.	2007
	Design Guidelines for Main and Sub Pipes	Japan Gas Assn.	2013
	Seismic Design Guidelines for High Pressure Gas Pipeline	Japan Gas Assn.	2013
Telecom	Seismic Design Guidelines for Underground Pipeline Facilities (Draft)	Access Network Service Systems Laboratories, NTT	1999
Water	Seismic Planning Guidelines for Water Supply System (Draft)	Ministry of Health and Welfare	2012
	Guidelines and Instructions for Earthquake-Resistant Construction Methods for Waterworks Facilities	Japan Water Works Assn.	2009
Sewage	Guidelines and Instructions for Earthquake-Resistant Countermeasures for Sewage Facilities	Japan Sewage Works Assn.	2006
	Earthquake Disaster Countermeasure Manual for Sewage System	Japan Sewage Works Assn.	1997
Common utility duct	Seismic Design for Common Utility Duct	Japan Road Assn.	2007
Roads and Highways	Design Spec. for Highway Bridges, Part V Seismic Design	Japan Road Assn.	2012
	Handbook for Countermeasures for Disaster to Road	Japan Road Assn.	2012
Rail	The Design Standards for Railway Structures and Commentary (Seismic Design) (supplemented by many calculation examples)	Railway Technical Research Institute	2012
Ports and Harbors	Technical Standards and Commentaries for Port and Harbour Facilities in Japan	Port and Airport Research Institute	2009
Oil and Liquid Fuels	Design Recommendation for Storage Tanks and Their Supports with Emphasis on Seismic Design	Architectural Inst. Japan, Sub-Committee for Design of Storage Tanks	2010
	Seismic Standard for Oil Tank	Fire and Disaster Management Agency, Ministry of Internal Affairs and Communications	n/a
	Earthquake and Tsunami Countermeasures for Combinat Port (Outline)	Ministry of Land, Infrastructure, Transport and Tourism	2012
Airports	Seismic Design and Design Example for Airport Facilities	Service Center of Port Engineering (SCOPE)	2008

* Documents dated prior to 2000 may have more recent editions but these could not be identified.

absent in U.S. practice. Natural gas distribution systems in Japan are generally equipped with "smart" gas meters that include a seismic shutoff for each service line. These devices were installed nationwide following the 1995 Hyogo-ken Nanbu earthquake (Kobe earthquake). The "smart" meters installed in U.S. gas service areas allow for automatic meter reading, but do not provide for seismic shutoff.

Tokyo Gas, Ltd. performed extensive studies on reducing the risk of fire following earthquake and implemented a finely-grained distribution block system for the efficient control of gas flow. California gas utilities have some "block-level" control capability, but generally are much weaker with respect to seismic distribution controls.

In Japan, earthquake early warning (EEW) systems have been deployed for seismic detection, leading to the automatic depowering and braking of Shinkansen trains. Comparable systems are currently being implemented for the San Francisco Bay Area Rapid Transit (BART) system, and are generally not available for other California rail systems. Moreover, EEW broadcasts are available for the general public over mobile phones in Japan, whereas a mobile telephone-based system for early warning is not available in the United States.

C.7 New Zealand Lifeline Earthquake Engineering

New Zealand has a long record of productive activity in lifeline earthquake engineering. In the 1990s, the Centre of Advanced Engineering in Christchurch undertook two pioneering studies related to lifelines. The first was completed in 1991, and was focused on both the individual performance and interdependencies among lifelines subjected to seismic hazards in Wellington (Centre for Advanced Engineering, 1991). The study and resulting report address seismic hazards and geology, and their influence on the performance of key lifeline systems. The lifelines covered in the study include water, wastewater, gas and liquid fuels, electric power, telecommunications, transportation, and building services. This work was one of the first to address interdependencies of lifelines with explicit examples of interdependencies affecting Wellington. The work involved collaboration among academics, lifeline operators, and engineering designers and consultants.

A second pioneering study undertaken by the Centre for Advanced Engineering (1997) was focused on the multi-hazard performance of lifelines in Christchurch. This work was a multidisciplinary effort that included earthquake, tsunami, flood, wind and snow storm, and landslide hazards. The lifelines and associated services covered include water, wastewater, gas and liquid fuels, electric power, telecommunications, transportation, and building and fire services. The work involved consideration of interdependent lifeline performance across all hazards. It was helpful in guiding a regional lifelines working group in Christchurch to implement measures to reduce seismic vulnerabilities before the damaging Canterbury Earthquake Sequence of 2010-2011.

Since the Canterbury Earthquake Sequence, lifeline earthquake engineering activities have intensified, with extensive investigations of the impact of earthquakes on the lifeline performance in Christchurch and the Canterbury area. As an example, the 2010-2011 Canterbury Earthquake Sequence Special Issue of *Earthquake Spectra* (Elwood, et al. 2014) provides a detailed summary of the performance of water, wastewater, and natural gas pipeline networks, electric power, and telecommunication systems.

Regional vulnerability projects have been organized by the New Zealand Lifelines committee, see: http://www.civildefence.govt.nz/memwebsite.nsf/wpg_URL/For-the-CDEM-Sector-Lifeline-Utilities-New-Zealand-Lifelines-Committee?OpenDocument. For example, recent work on transportation lifeline vulnerabilities in Wellington can be found at http://www.gw.govt.nz/assets/Emergencies--Hazards/Lifelines/13-03-23-Transport-Access-full-project-report-FINAL-corrected.pdf.

The Natural Hazards Research Platform http://www.naturalhazards.org.nz/ coordinates much government funded research on hazards. Current earthquake related infrastructure research covered by the Platform includes projects on *Bridge Performance* (Universities of Canterbury and Auckland), *Liquefaction Impacts on Pipe Networks* (University of Canterbury) and *Lifelines, Hospital Services and Housing* (a consortium including University of Canterbury and GNS Science).

The Ministry of Business, Innovation and Employment (MBIE) has funded infrastructure research, including studies on "Seismic Response of Underground Services" (Opus), and "Resilient Infrastructure through Effective Organisations" (Resilient Organisations Research Programme, University of Canterbury). MBIE has also funded a research program, "Economics of Resilient Infrastructure", which is a modelling initiative aimed to better understand economy-wide losses from infrastructure failure. A four-year program led by GNS Science aims to quantify the full range of societal costs. Additional information on lifelines programs supported through the Natural Hazards Research Platform may be found at http://www.naturalhazards.org.nz/NHRP/Hazard-themes/Societal-Resilience/Economics-of-Resilient-Infrastructure.

The National Infrastructure Unit of the New Zealand Treasury leads infrastructure resilience work across the national government. Resilience and earthquake issues are prominent in the work program and documents. Recent Treasury reports covering infrastructure resilience are at www.infrastructure.govt.nz. Sector resilience indicators are one focus area of the Unit.

The National Ministry of Civil Defence and Emergency Management (MCDEM) commissioned a formal government review of the overall MCDEM response to the February 2011 earthquake in the Canterbury Earthquake Sequence. The review team's report is available at http://www.civildefence.govt.nz/, and includes a 22-page chapter on lifelines.

The Stronger Christchurch Infrastructure Rebuild Team's (SCIRT's) program deals with the design, repair and reconstruction of horizontal infrastructure damaged in the Canterbury Earthquake Sequence, primarily roads, water and wastewater systems, see http://strongerchristchurch.govt.nz/. SCIRT's work has been informed by advice and reports from academic and research organizations including the University of Canterbury and personnel associated with the Technical Council on Lifeline Earthquake Engineering (TCLEE).

A recent report prepared by the Centre for Advanced Engineering, with support from the Canterbury Earthquake Recovery Authority (CERA) and cooperation of the Canterbury Lifeline Utilities Group, summarizes around 100 documents relating to lifelines performance in the earthquakes—see http://www.cae.co.nz/ and click on "lifelines".

Appendix D
National Infrastructure Protection Plan

D.1 Background

The National Infrastructure Protection Plan (NIPP) was first developed in 2006 (DHS, 2006) to provide a national plan for ensuring the security of 17 critical infrastructure sectors, including agriculture and food systems, the defense-industrial base, energy systems, public health and health care facilities, national monuments and icons, banking and finance systems, drinking water systems, chemical facilities, commercial facilities, dams, emergency services, nuclear power systems, information technology systems, telecommunications systems, postal and shipping services, transportation systems, and government facilities. In February, 2013, the President issued Presidential Policy Directive-21, *Critical Infrastructure Security and Resilience* http://www.whitehouse.gov/the-press-office/2013/02/12/presidential-policy-directive-critical-infrastructure-security-and-resil, which calls for the development of an updated plan that includes 16 critical infrastructure sectors, including chemical; commercial facilities; communications; critical manufacturing; dams (including locks and levees); defense industrial base; emergency services; energy; financial services; food and agriculture; government facilities; health care and public health; information technology; nuclear reactors, materials, and waste; transportation systems; and water and wastewater systems. The 2013 NIPP (DHS, 2013b) provides a framework to share threat information, reduce infrastructure vulnerabilities, minimize consequences, and facilitate response and recovery efforts. It is available at http://www.dhs.gov/publication/national-infrastructure-protection-plan-fact-sheet.

The 2013 NIPP is closely aligned with Executive Order 13636 *Improving Critical Infrastructure Cybersecurity* http://www.gpo.gov/fdsys/pkg/FR-2013-02-19/pdf/2013-03915.pdf, which was also issued in February 2013. The Executive Order calls for the Federal Government to coordinate closely with critical infrastructure owners and operators to improve information sharing about cybersecurity and cooperate on risk-based approaches to cybersecurity. Objectives are set for the Federal Government to reduce cyber risk to critical infrastructure, provide incentives for strong cybersecurity practices, improve information sharing relater to cyber threats, and provide for protection of privacy and civil liberties within the context of critical infrastructure security and resilience practices.

D.2 National Infrastructure Protection Plan (NIPP)

Although not explicitly aligned with or developed for lifelines or earthquakes, the NIPP does include virtually all lifeline systems, and therefore represents an overarching government program that influences lifelines policy and support. The principal threats to critical infrastructure that guide the NIPP include acts of terrorism, cyber threats, extreme weather, pandemics, and accidents and technical failures.

The 2013 NIPP provides an updated approach to critical infrastructure security and resilience with emphasis on the integration of cybersecurity and physical security efforts. It advocates information sharing about threats and interdependencies as a principal component of the risk management approach, and it promotes cross sector and cross jurisdictional coordination.

The NIPP promotes collaboration between private sector owners and operators and their government counterparts as the primary mechanism for collective action towards national critical infrastructure security and resilience. A Federal department or agency is designated as the lead agency, known as a Sector Specific Agency (SSA), for each of the 16 critical infrastructure sectors. The NIPP provides the sector and cross-sector partnership structure—consisting of Sector Coordinating Councils, Government Coordinating Councils, SSAs, and cross-sector councils—which brings together representatives from Federal and state, local, tribal, and territorial (SLTT) governments, regional entities, the private sector, and non-governmental organizations to collaborate on critical infrastructure security and resilience programs and approaches, and to achieve national goals and objectives. These councils provide primary organizational structures for coordinating critical infrastructure security and resilience efforts and activities within and across the 16 sectors.

The Critical Infrastructure Partnership Advisory Council (CIPAC) was chartered under the auspices of DHS to support implementation of the NIPP. It coordinates Federal infrastructure protection and resilience programs with similar activities of the private sector and of the SLTT governments. The CIPAC may develop policy advice and recommendations on critical infrastructure protection and resilience matters for DHS, the SSAs, and other Federal departments and agencies supporting critical infrastructure protection and resilience programs. The CIPAC and SSA organization and activities within each sector are summarized in CIPAC annual reports (e.g., DHS, 2013a) http://www.dhs.gov/sites/default/files/publications/CIPAC_2013_annual_report.pdf.

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