The Role of the *NEHRP Recommended Seismic Provisions* in the Development of Nationwide Seismic Building Code Regulations: A Thirty-Five-Year Retrospective

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Prepared for the Federal Emergency Management Agency of the U.S. Department of Homeland Security

By

The National Institute of Building Sciences
Building Seismic Safety Council

The National Institute of Building Sciences
Building Seismic Safety Council
Washington, DC
2020

The National Institute of Building Sciences (NIBS) brings together members of the building industry, labor and consumer interests, government representatives, and regulatory agencies to identify and resolve problems and potential problems around the construction of housing and commercial buildings. NIBS is a nonprofit, non-governmental organization established by Congress in 1974.

The Building Seismic Safety Council (BSSC) was established as a Council of NIBS in 1979 to contend with the complex technical, regulatory, social, and economic issues of developing and promulgating earthquake risk mitigation provisions for buildings on a national scope.

BSSC's fundamental purpose is to enhance public safety by providing a national forum to foster improved seismic planning, design, construction, and regulation. To fulfill its mission, the BSSC:

- Evaluates research findings, practices, and field investigations to develop seismic safety provisions
- Encourages and promotes the adoption of provisions by the national standards and model building codes
- Provides ongoing education for structural design professionals through training materials, webinars, workshops, and colloquia
- Offers educational outreach on seismic design and construction to the non-technical building community and the general public
- Advises government bodies on their programs of research, development, and implementation.

BSSC is an independent, voluntary membership body representing a wide variety of building community interests. Its activities are structured to provide all entities with the opportunity to participate. It brings together the needed expertise and relevant public and private interests to resolve issues related to the seismic safety of the built environment through authoritative guidance and assistance backed by a broad consensus.

This report was prepared under Contract HSFE60-15-D-0022 between the Federal Emergency Management Agency and the National Institute of Building Sciences.

For further information on Building Seismic Safety Council activities and products, see the council's website: https://www.nibs.org/page/bssc.

Foreword

As one of the National Earthquake Hazards Reduction Program (NEHRP) agencies, the Federal Emergency Management Agency (FEMA) is commissioned by the National Earthquake Hazards Reduction Act of 1977 (PL 95-124) and subsequent reauthorizations including the latest Reauthorization Act of 2018 (PL 115-307) to assist implementation of new scientific knowledge and research results for the NEHRP mission – to reduce the risks of life and property from future earthquakes in the United States. One effective way to protect the nation from future destructive earthquakes is to strengthen the national seismic-resistant building codes and to encourage their adoption and enforcement by the earthquake prone communities. The *NEHRP Recommended Seismic Provisions for New Buildings and Other Structures* plays a key role to introduce best available science and research results into the development and improvement of the building codes and design standards.

In retrospect, the *NEHRP Recommended Provisions* not only provided many critical steppingstones to form the foundation of modern U.S. seismic-resistant codes and standards, but also helped to explore new ways to advance earthquake science and risk reduction technologies. Over the past thirty-five years, many scientists, researchers, engineers, code and standard experts, material industry experts, and professionals from the NEHRP agencies contributed to the success of the *NEHRP Provisions*. This report captures the history of the *NEHRP Provisions* and many great benefits it has introduced.

Most people living in the high earthquake hazard regions may not have much knowledge about the seismic-resistant building codes; however, they rely on the codes for protection against earthquakes. This report will help communicate the concepts and values of the seismic-resistant building codes and the code support resource - the *NEHRP Provisions*. FEMA is thankful to the Provisions Update Committee members and experts who contributed or reviewed this report, and the Building Seismic Safety Council (BSSS) of National Institute of Building Sciences for developing the ten editions of the NEHRP Provisions and this informative report for the broad customers of NEHRP.

Federal Emergency Management Agency

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Preface and Acknowledgements

In the United States, about half the American population across more than 20 states has a moderate or high risk of experiencing damaging earthquakes. Earthquakes are a real threat. Our nation's seismic risk is largely mitigated through earthquake-resistant buildings, which are regulated by model building codes. Designing structures to be resistant to a major earthquake is a very complex process and developing seismic design provisions and codes that are applicable across the nation is even more daunting. Fortunately, the National Earthquake Hazards Reduction Program (NEHRP), through the development of the *NEHRP Recommended Seismic Provisions for New Buildings and other Structures* (the *Provisions*), provided an essential platform to advance our seismic design practices effectively and efficiently. Over the past forty years, the *NEHRP Recommended Seismic Provisions* has been the starting point of seismic code changes and the mechanism to transfer research into application. The *NEHRP Recommended Seismic Provisions* is the focal point of the efforts of research and practicing engineers, codes and standards officials, and earth science experts in a unified effort to reduce seismic risk through state-of-the-art building codes.

It is my great pleasure to introduce this Thirty-Five Year Retrospective to look at what we have learned, achieved, and more importantly, what we may expect in the future.

This document reflects very generous contributions of time and expertise on the part of many individuals who participated in the development of the *NEHRP Recommended Seismic Provisions* over the past thirty-five years. Several present or former members of the Provisions Update Committee of the Building Seismic Safety Council are acknowledged for their assistance in reviewing this document and writing content for it: David Bonneville, John Gillengerten, S. K. Ghosh, Jim Harris, Bill Holmes, Ron Hamburger, and Loring A. Wyllie, Jr. David Bonowitz and Keith Porter are also acknowledged for their contributions.

On behalf of the National Institute of Standards and Technology and U.S. Geological Survey, Steve McCabe and Nicolas Luco (respectively), provided significant reviews on this document.

Mai Tong of the Federal Emergency Management Agency (FEMA) led the effort creating this document. Robert D. Hanson, consultant to FEMA, also helped guide this project.

Finally, I wish to thank consultant Robert Reitherman and BSSC Executive Director Jiqiu Yuan, who served as the lead editors of this publication.

Charles Carter
Chair, BSSC Board of Direction
President, American Institute of Steel Construction

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Executive Summary

The National Earthquake Hazards Reduction Program (NEHRP) *Recommended Seismic Provisions for New Buildings and Other Structures* (*Provisions*) is a technical resource document for improving national seismic design standards and model building codes. The document is regularly updated and published by FEMA. The first edition was published in 1985, and the 10th edition was published in October 2020.

Figure 1. The Ten Editions of the *NEHRP Recommended Seismic Provisions*, 1985 to 2020. All are available for download from https://www.nibs.org/page/bssc_pubs.

Because earthquakes can cause significant losses, building damage, and disruption of operations, building codes that strengthen and improve building seismic performance are of great importance. The national model building codes in the United States, which regulate the design, construction, alternation, and maintenance of buildings and other structures, are adopted, and enforced by state, local, tribal, and territorial jurisdictions. This is one of the primary ways a community safeguards itself from potential earthquake losses. Forty years ago, state, local, tribal, and territorial governments did not adopt the same nationwide seismic regulations, causing inconsistencies in levels of protection.

Since its inception, the *NEHRP Recommended Seismic Provisions* has sought to provide nationwide consistency in seismic code regulations while accounting for varying seismicity and different approaches for new and existing buildings. The *NEHRP Recommended Seismic Provisions* offers the latest geoscience information about varying levels of seismicity and provides the benefit of making the architecture, engineering, construction, and construction materials industries operate more efficiently. Figure 2 presents the U.S. seismic regulations and seismic codes development and the role of the *NEHRP Recommended Seismic Provisions*.

Key Facts About the NEHRP Recommended Seismic Provisions

The *NEHRP Recommended Seismic Provisions*:

- provides state-of-the-art information on seismic design and construction, is the starting point of seismic code changes, and is essential to the development of nationally applicable building codes and standards;
- is updated regularly with careful evaluation of possible revisions, taking into account technical merit and practical aspects;

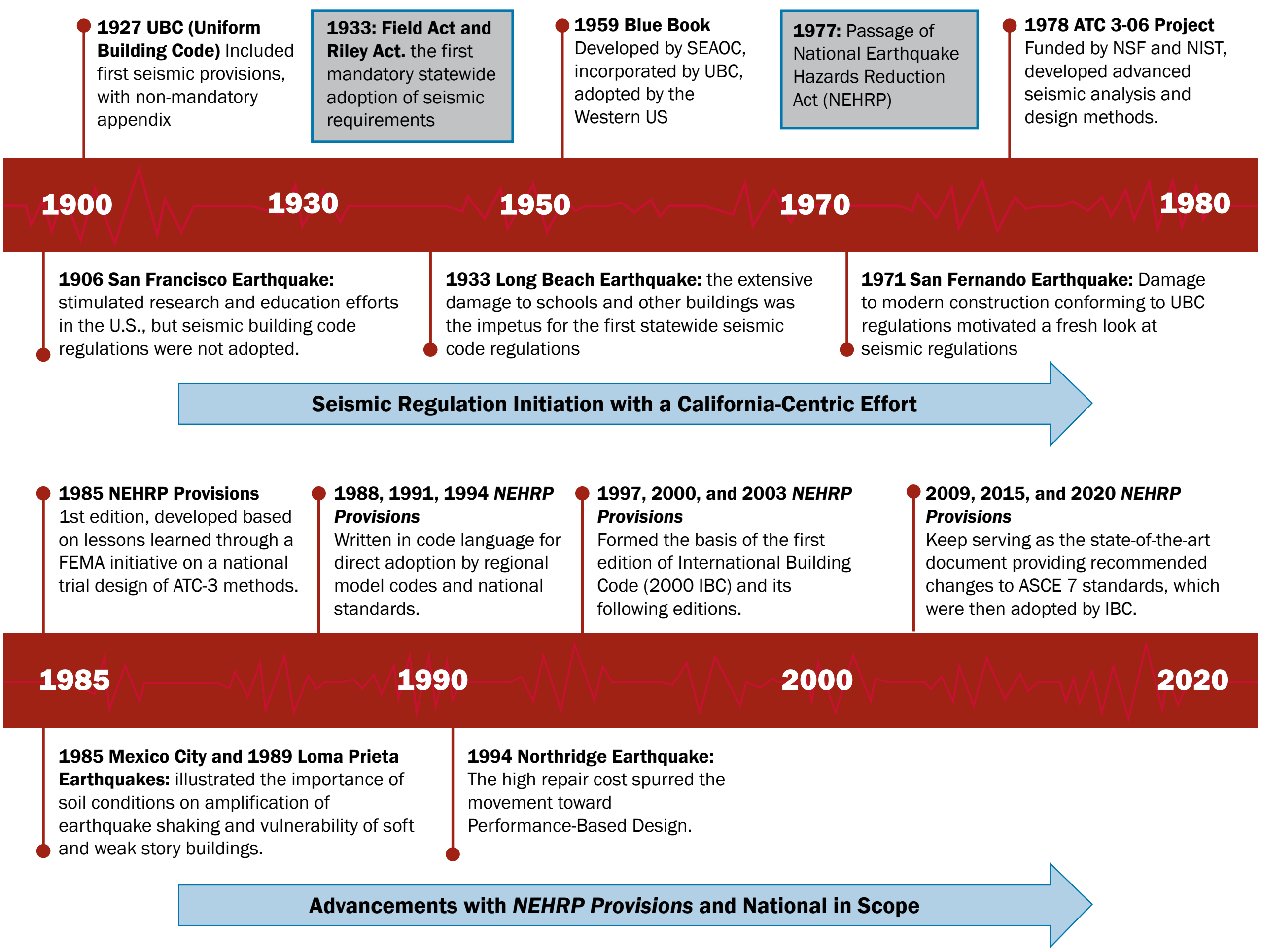


Figure 2. U.S. Seismic Regulations and Seismic Codes Development and the Role of *NEHRP Recommended Seismic Provisions*.

- is developed by the national experts on the Building Seismic Safety Council (BSSC) Provisions Update Committee and its subcommittees (Issue Teams) through a formal consensus process funded by FEMA;
- reduces the nation's seismic risk as new construction incorporates features of the *NEHRP Recommended Seismic Provisions*. The inclusive process of the *NEHRP Recommended Seismic Provisions* also prompts wide acceptance by the building industry and encourages state, local, tribal, and territorial jurisdictions to adopt the latest seismic codes and standards;
- is one of the most important NEHRP products and has become a well-known brand name in the United States and internationally; and
- is a convergence of the efforts among the four NEHRP agencies and private sector partners, and is a mechanism to transfer research into implementation, see Figure 3.

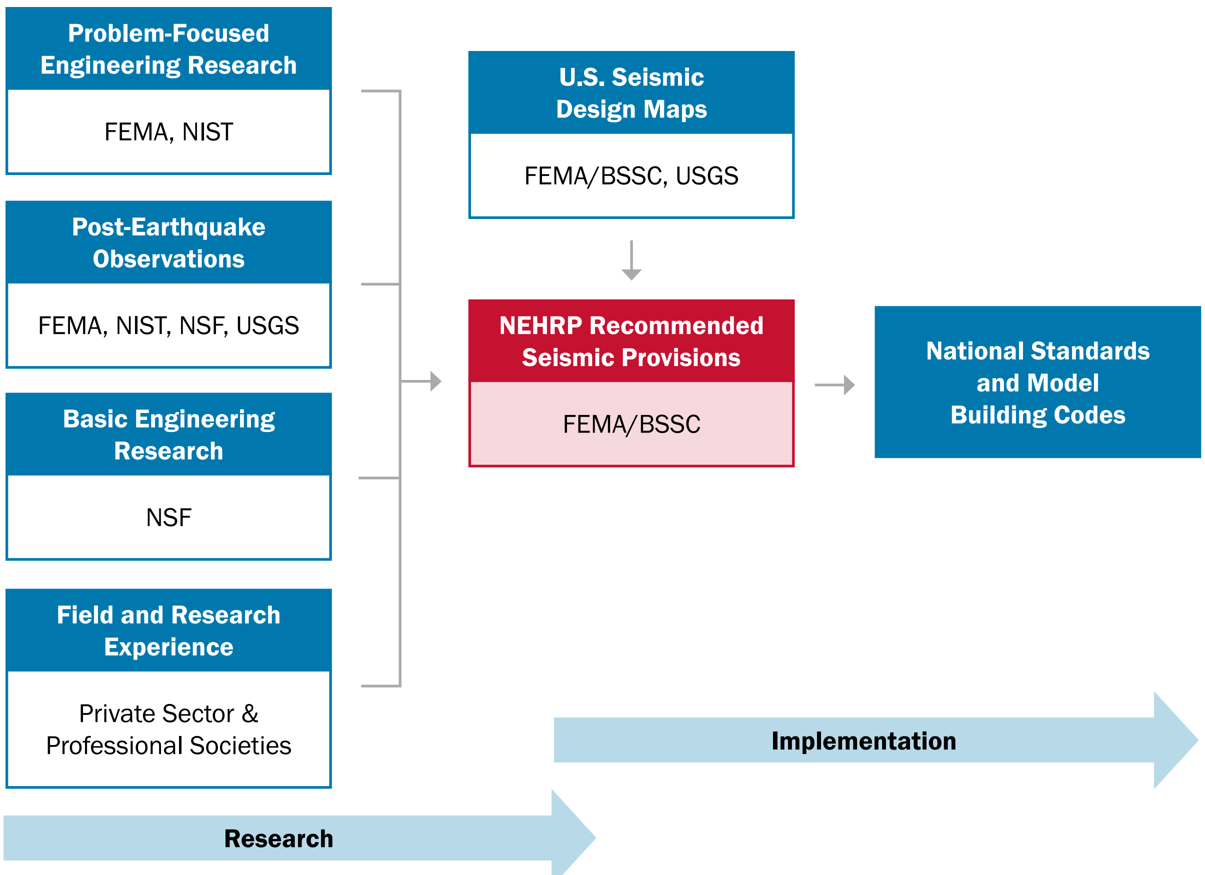


Figure 3. Roles of NEHRP Agencies and of the *NEHRP Recommended Seismic Provisions*.

Fundamentals of Seismic Design

There are three important and distinct seismic design steps:

- **Determine the risk of seismic ground shaking from the U.S. seismic design value maps** and translate the ground shaking into parameters engineers need to analyze a building's seismic capacity, particularly its strength and stiffness.
- **Design the required strength and stiffness of the structure**.
- **Provide effective detailing** to assure an effective design of both structural and nonstructural systems. Examples of nonstructural systems include windows, partitions, heating-ventilating-air-conditioning, electrical and communication components, and plumbing.

Figure 4 shows a graphic outline of the three-step seismic design process: determination of the hazard of ground shaking from design maps, determination of required building strength to resist the shaking, and detailing. An overview of the process is provided in FEMA P-749 (FEMA 2010).

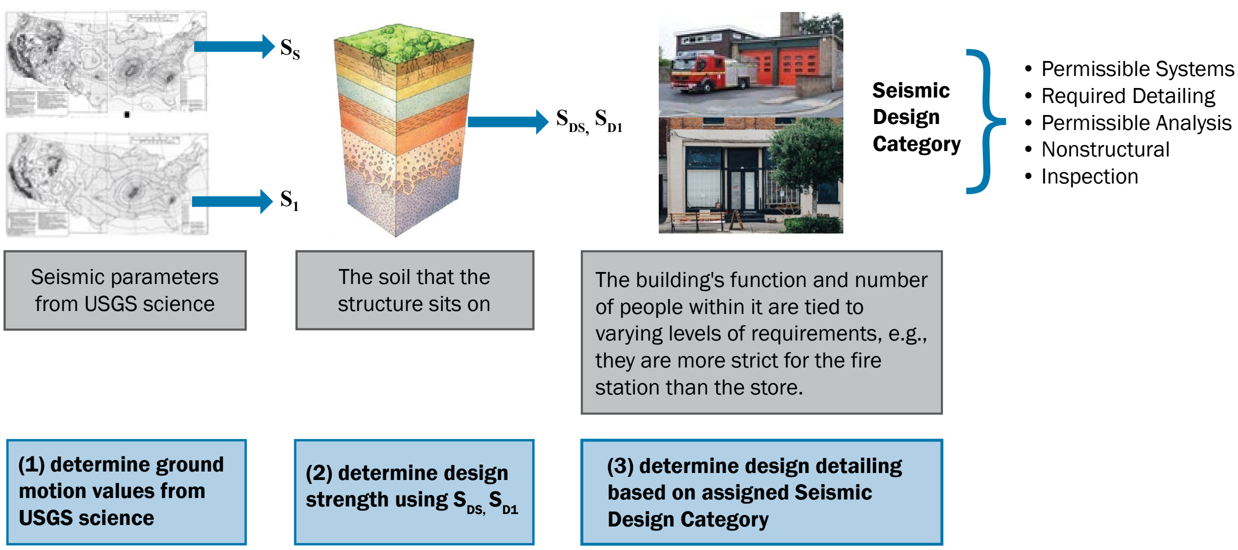


Figure 4. The process of incorporating the latest information on seismicity from U.S. Geological Survey into Seismic Design.

Seismic Mapping

The NEHRP *Recommended Seismic Provisions* was the first document that developed modern, nationally applicable seismic design maps that were derived directly from the USGS National Seismic Hazard Model, through collaboration among FEMA, BSSC, and USGS. In this context, seismic hazard refers to the probability of sites experiencing various levels of ground shaking. Figure 5 shows different maps of the United States from pre-*Provisions* days to now. The NEHRP *Recommended Seismic Provisions* process has sharpened the role of USGS over the years to become the central provider of ground motion mapping for design purposes. The USGS maps are produced at a detailed street map scale not shown here and can be accessed digitally by designers anywhere in the country.

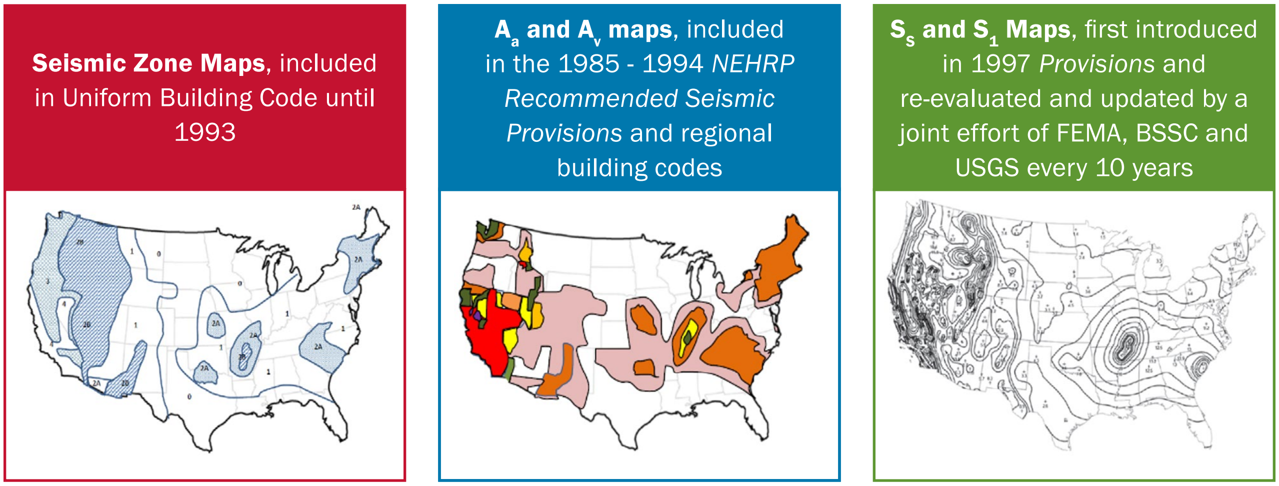
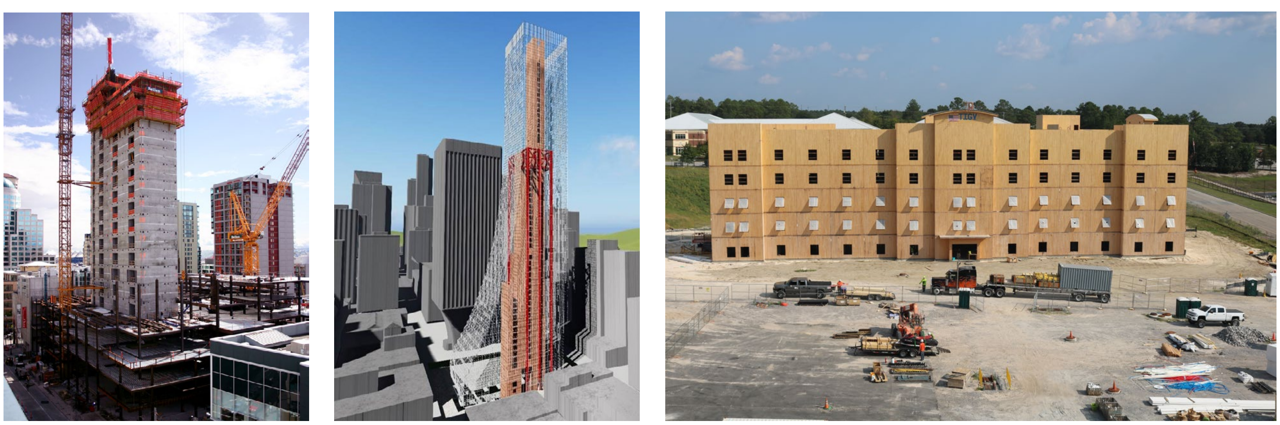


Figure 5. Improvements to Seismic Mapping

Keeping Up with Building Technology

As materials and methods of constructing buildings change and improve, updates to the *NEHRP Recommended Seismic Provisions* must consider new building innovations. BSSC provides a national and authoritative forum to evaluate and assess new technologies of all kinds with a focus on new seismic design methods and innovative new seismic structural and nonstructural systems. Figure 6 shows three newly developed seismic force resisting systems that were reviewed and approved in the 2020 *Provisions* (Building Seismic Safety Council 2017).

Another example is that the 2015 *Provisions* developed comprehensive guidelines and requirements for nonlinear response history analysis, a computer simulation of what would happen if the actual constructed building were subjected to earthquakes. It is the basis for seismic design of most tall new buildings in seismically active regions of the world, as well as buildings employing advanced protective technologies.



(a) (b) (c)

Figure 6. The three new seismic force-resisting systems that now have detailed requirements in the 2020 *NEHRP Recommended Seismic Provisions*: (a) reinforced concrete ductile coupled walls, (source: MKA); (b) steel and concrete coupled composite plate shear walls (Source: MKA); and (c) cross-laminated timber shear wall (Source: Lendlease).

Seismic Design Category

The *NEHRP Recommended Seismic Provisions* originated the Seismic Design Category that is directly based on the intensity of ground shaking anticipated at the building site, including the effects of soil conditions, and the building's intended use or occupancy, referred to as its risk category. The risk category is a basic building code factor for considerations like fire protection and exiting in addition to earthquake concerns. To simplify the contour maps of seismic ground shaking in the *NEHRP Recommended Seismic Provisions*, the International Residential Code (IRC) that applies to one- and two-unit housing up to three stories in height instead provides maps for the default soil type and risk category, as shown in Figure 7. FEMA uses these simplified maps to reflect the likelihood of an area experiencing earthquake shaking of various intensities that damage buildings.

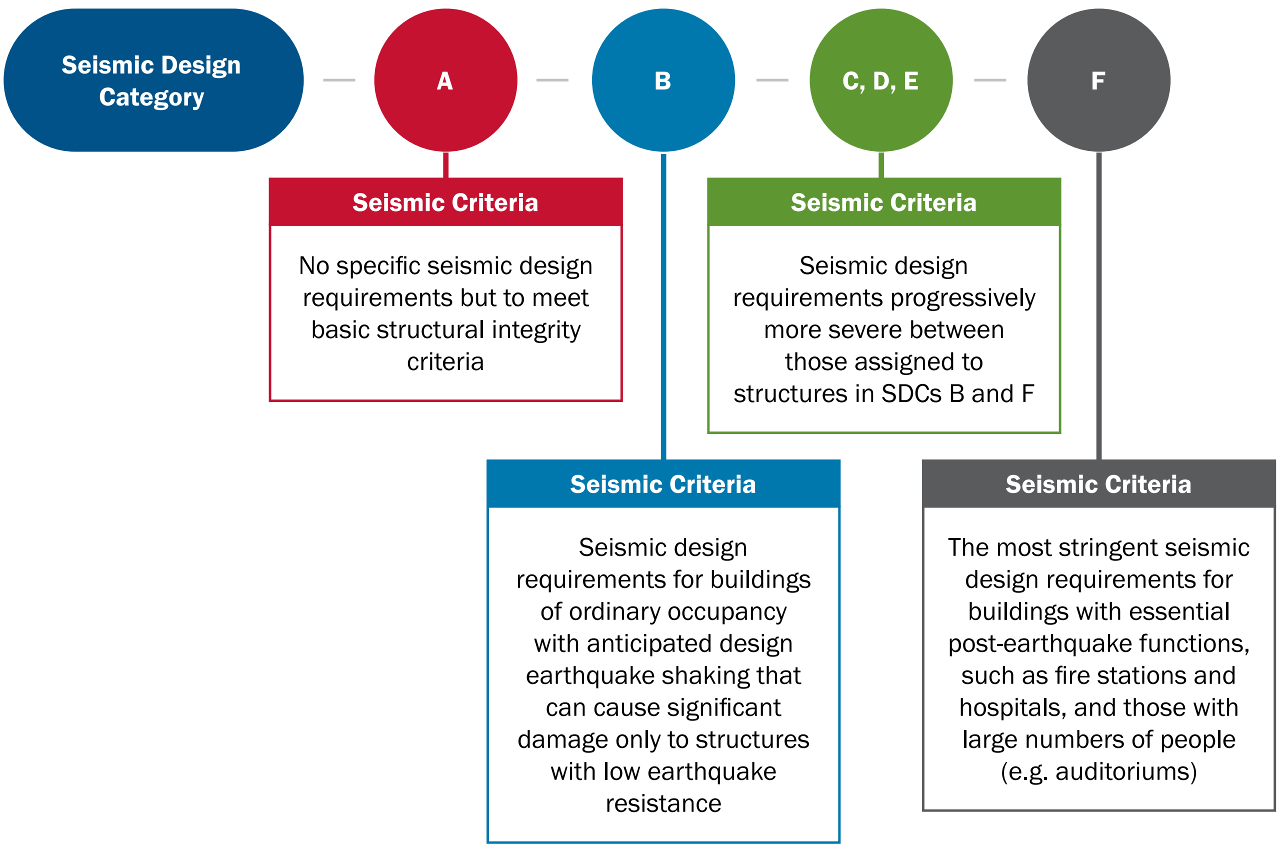


Figure 7. Seismic Design Categories

Detailed Nonstructural Protection Provisions

Nonstructural components include the architectural, mechanical, electrical, and plumbing systems of a building. These systems typically comprise at least three quarters of the original construction cost of an office or commercial building and a much higher percentage of the value of an institutional or health services building. Prior to the *NEHRP Recommended Seismic Provisions*, building code seismic regulations for nonstructural components were only generally stated. The *NEHRP Recommended Seismic Provisions* modernized this process by categorizing many specific types of components and their acceptable performance in terms of engineered capacities for anchorage, bracing, allowance for differential movement, and in the case of some equipment in essential occupancies, continued functionality after an earthquake.

(a) (b)

Figure 8. Examples of Nonstructural Damage: (a) The extreme drift experienced by Olive View Hospital in the 1971 San Fernando Earthquake also rendered nonstructural components damaged and non-functional; (b) In the 1994 Northridge Earthquake in the Los Angeles region, this heavy soffit or exterior ceiling collapsed over the entrance. Nonstructural protection involves secure attachments of the nonstructural components to the structure.

Future Improvements

The following improvements are being considered for future editions of the *NEHRP Recommended Seismic Provisions*.

Investment Returns (Benefit vs. Cost)

A study conducted by the National Institute of Building Sciences Multi-Hazard Mitigation Council (2020a) concluded that enhanced earthquake design requirements over the last 30 years could save $7 billion per year in future losses while only adding $600 million per year in construction cost, producing a national average benefit-cost ratio of 12:1. The Benefit-Cost Ratio is greatest where seismicity is greatest, but the net benefits are also evident in areas of only moderate seismicity. Designing up to the requirements of the *NEHRP Recommended Seismic Provisions* does not guarantee complete protection free of damage, but it does lead to greatly reduced damage. In a sense, the *NEHRP Recommended Seismic Provisions* acts as a type of lifelong immunization for the building, giving it earthquake resistance that can be mobilized any time an earthquake occurs.

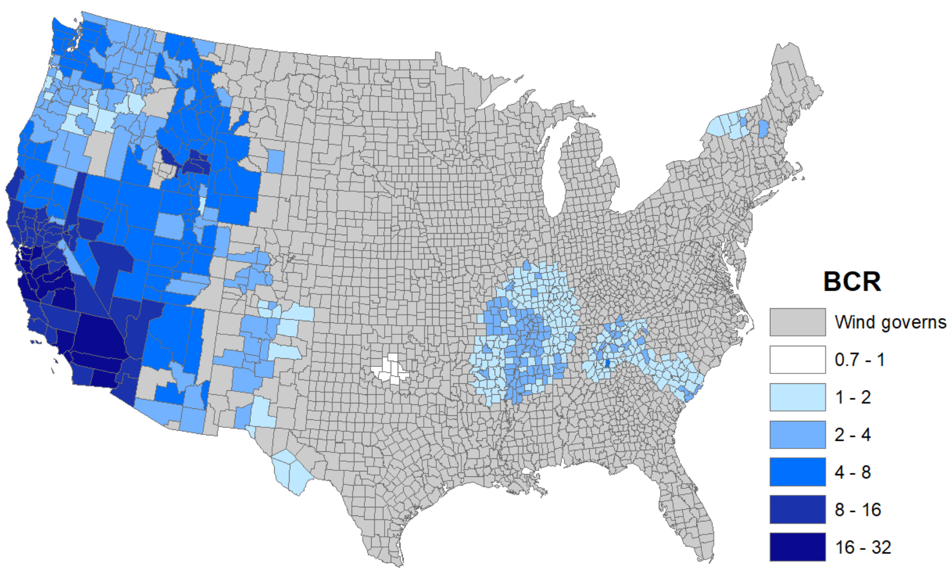


Figure 9. Benefit-cost ratios for new building design to comply with 2018 I-Code requirements for earthquake, relative to 1988. (Multi-Hazard Mitigation Council 2020 https://www.nibs.org/page/mitigationsaves)

Staying Up to Date

The *NEHRP Recommended Seismic Provisions* continues to be updated by FEMA and BSSC today through evaluation of the large volume of new seismic information produced every year from analytical studies, laboratory testing, earth science research, new construction products and methods, input on practical seismic design aspects from the building industry and design practitioners, and by the lessons learned from recent earthquakes.

Community-Based Design

Conceptual ideas are proposed to consider seismic protection of an entire community in addition to individual structures, especially considering the lifelines/utilities systems, such as electricity, water and wastewater, and transportation. The process by which the *NEHRP Seismic Provisions* is developed for buildings is instrumental for development of more robust standards and guidelines for lifelines/utilities. The *NEHRP Recommended Seismic Provisions* included white papers on post-earthquake functional recovery and economic performance criteria in its 2015 and 2020 editions, and a more comprehensive effort is recommended to address resilience-based seismic design through the consideration of functional recovery. The seismic design criteria in the future *Provisions* may help address both life safety and resilience, while today's building code is primarily concerned with safety only. However, the current code-minimum level of protection does afford considerable property damage protection and improves the ability to quickly recover.

Outreach, Education, Dissemination

The FEMA program in support of the *NEHRP Recommended Seismic Provisions* is not limited to the development and publication of each new edition. The *NEHRP Recommended Seismic Provisions* and companion documents are widely referenced throughout the United States and globally as a university-level earthquake engineering teaching resource. Supporting publications for education provide design examples to walk a practicing engineer through the process of using the *NEHRP Recommended Seismic Provisions*. Outreach, education, and dissemination activities to support the application of the *NEHRP Recommended Seismic Provisions* will continue to be an important objective along with the development process.

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Chapter 1

The NEHRP Recommended Seismic Provisions

1.1 About the NEHRP Program

Earthquakes are one of the most destructive disasters and a national problem in the United States. Almost half of the population—more than 143 million people—reside in portions of the conterminous 48 states that are at risk of experiencing a damaging earthquake (USGS, 2015). Annual earthquake losses are estimated to be $6.1 billion per year, and the majority of the losses (80%) are concentrated in 55 major metropolitan areas (FEMA, 2017). In the United States, the national model building codes regulate the design, construction, alteration, and maintenance of structures. Adopted and enforced by states and local jurisdictions, these codes are one of the primary ways a community protects itself and its individual citizens from potential earthquake disasters.

Now, nationally applicable seismic regulations for buildings are integrated into the U.S. national model building codes, but this was not the case four decades ago. Some areas of the western United States had already adopted and enforced seismic regulations, but following the observed damage from the San Fernando earthquake of 1971, it was clear that those building code provisions needed significant improvement. There were widely varying seismic provisions in building codes and standards used throughout the country, and in some cases no provisions were implemented. Today the situation is quite different, and essential to that development has been the National Earthquake Hazards Reduction Program (*NEHRP*) *Recommended Seismic Provisions for New Buildings and Other Structures*, called here the *NEHRP Recommended Seismic Provisions or Provisions* (FEMA 1985 and later).

The *NEHRP Recommended Seismic Provisions* made it possible to develop nationally applicable seismic regulations.

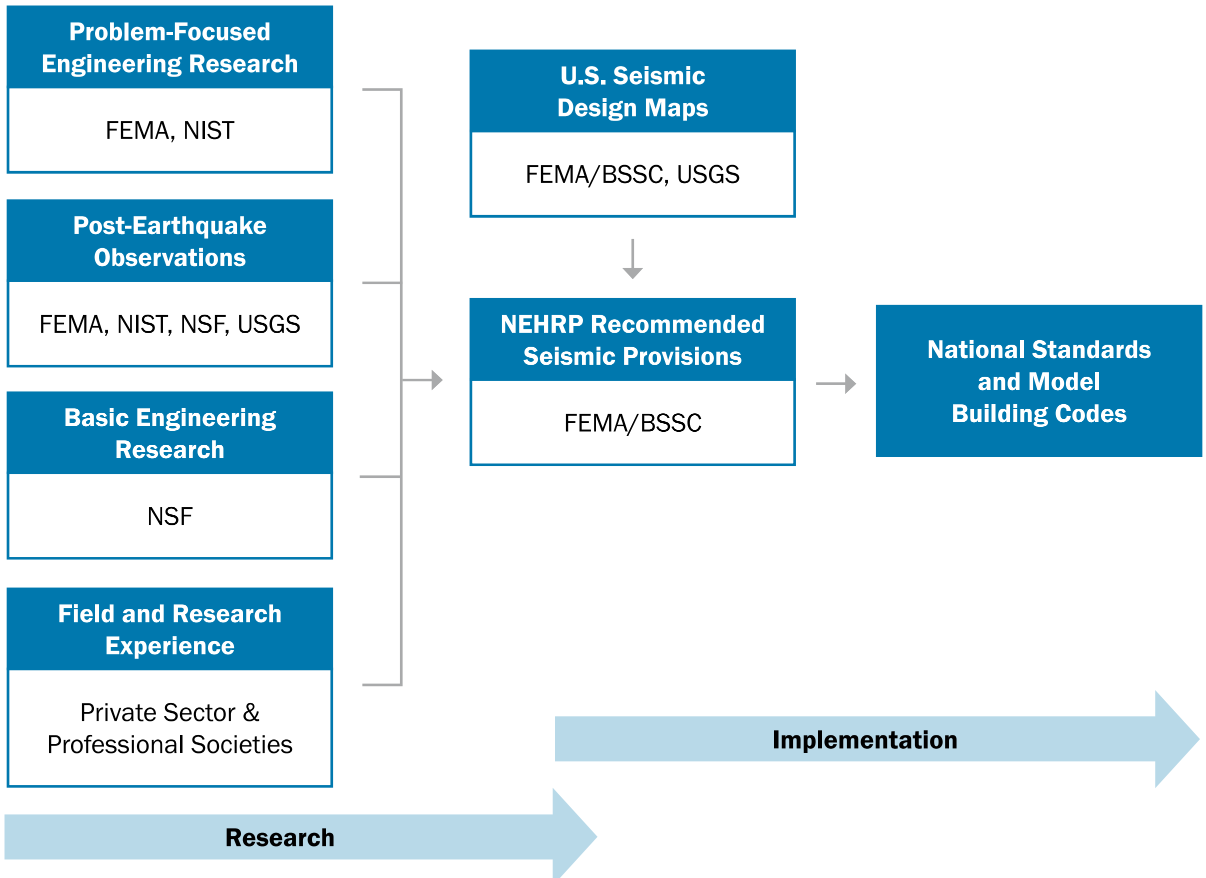
In 1977, the U.S. Congress passed the Earthquake Hazards Reduction Act, (Public Law 95-124), which established the National Earthquake Hazards Reduction Program (NEHRP) "to reduce the risks of life and property from future earthquakes in the United States through the establishment and maintenance of an effective earthquake hazards reduction program." It authorized NEHRP funding for the four designated federal agencies: Federal

Emergency Management Agency (FEMA), U.S. Geological Survey (USGS), National Science Foundation (NSF), and the National Institute of Standards and Technology (NIST). Over the four decades, the NEHRP Act has been reauthorized several times with the latest in 2018.

The responsibilities of the four NEHRP agencies are briefly summarized in Figure 1-1 and also stated in the report, NEHRP Issues in Brief, by the Congressional Research Service (2018):

- "NIST is the lead NEHRP agency, with primary responsibility for NEHRP planning and coordination. NIST supports the development of performance-based seismic engineering tools, working with FEMA and other groups to promote the commercial application of the tools through building codes, standards, and construction practices.
- "FEMA assists other federal, state, local, tribal, and territorial agencies and private-sector groups to prepare and disseminate building codes and best design practices structures and lifeline infrastructure. FEMA also aids development of performance-based codes for buildings and other structures.
- "USGS conducts research and other activities to characterize and assess earthquake risks. The agency
    - operates a forum, using the National Earthquake Information Center (NEIC), for the international exchange of earthquake information;
    - works with other NEHRP agencies to coordinate activities with earthquake-reduction efforts in other countries; and
    - develops and maintains seismic-hazard maps, in support of building codes for structures and lifelines, and other maps needed for performance-based design approaches.
- "NSF supports basic research in engineering and earth science to improve safety and performance of buildings, structures, and lifelines."

The *NEHRP Recommended Seismic Provisions* is one of the most important NEHRP products. It is a convergence of the efforts among the four NEHRP agencies and the private sector and is a mechanism to transfer research into implementation.



Notes: FEMA = Federal Emergency Management Agency; NIST = National Institute of Standards and Technology; USGS = U.S. Geological Survey; NSF = National Science Foundation; BSSC = Building Seismic Safety Council.

Figure 1-1. The *NEHRP Recommended Seismic Provisions* serves as a convergence of the efforts among the four NEHRP agencies and private sectors and a mechanism to transfer research results for improving seismic design practice.

This report focuses on the *NEHRP Recommended Seismic Provisions*, one of the most important NEHRP products, and is a convergence of the efforts among the four NEHRP agencies, as shown in Figure 1-1. The *NEHRP Recommended Seismic Provisions* has been essential to the development and acceptance of a nationwide building code for earthquake-resistant design. When adopted in the national design standards and building codes, the new, knowledge based *NEHRP Recommended Seismic Provisions* strengthens the nation's capability to mitigate seismic risk and improve earthquake resilience.

As new buildings incorporate the earthquake-resistant features of the *NEHRP Recommended Seismic Provisions*, the earthquake protection of the nation's building stock is increasingly improved, which is a critical step in improving the safety and resilience of the built environment. Since the incorporation of the *NEHRP Recommend*

Seismic Provisions into the model building codes and standards, there has not been a large earthquake in a major metropolitan area of the United States that has affected buildings designed according to those requirements. Buildings experiencing the 1989 Loma Prieta Earthquake or 1994 Northridge Earthquake were designed according to earlier provisions of the Uniform Building Code.

However, newer buildings in communities that have experienced locally strong shaking due to moderate seismic events have generally performed well, and this is one of the best validations of the effectiveness of the current seismic code approach. Shake-table and other testing of full-size buildings or structural components and testing of architectural and other nonstructural components of buildings indicate that the innovations represented by the *NEHRP Recommended Seismic Provisions* will contribute greatly to the resilience of our communities when a major earthquake strikes.

This report summarizes the development process and successful model of the *NEHRP Recommended Seismic Provisions*, important technical breakthroughs, improvements in earthquake-resistant design, contributions to resilience, and the role of the *NEHRP Recommended Seismic Provisions* in the future of the nation's earthquake hazard reduction effort.

Key Facts About the NEHRP Recommended Seismic Provisions

The *NEHRP Recommended Seismic Provisions*:

- provides state-of-the-art information on seismic design and construction, is the starting point of seismic code changes, and is essential to the development of nationally applicable building codes and standards;
- is updated regularly with careful evaluation of possible revisions, taking into account technical merit and practical aspects;
- is developed by the national experts on the BSSC Provisions Update Committee and its subcommittees (Issue Teams) through a formal consensus process funded by FEMA;
- is a convergence of the efforts among the four NEHRP agencies and private sectors, and is a mechanism to transfer research into implementation;

- reduces the nation's seismic risk as new construction incorporates features of the *NEHRP Recommended Seismic Provisions*; and
- is one of the most important NEHRP products and has become a well-known brand name in the United States and internationally.

1.2 NEHRP Recommended Seismic Provisions Development

The *NEHRP Recommended Seismic Provisions* is a technical resource document published by FEMA. The first edition was published in 1985 (FEMA 1985), with eight subsequent editions issued (FEMA 1988, 1991, 1994, 1997, 2000, 2003, 2009, and 2015). The latest 2020 edition will mark its 10th edition. The format of the *NEHRP Recommended Seismic Provisions* has evolved over time from a code language document adopted by regional building codes and by reference required for the design of federal buildings (Executive Order 12699, see Section 4.3 Protecting Federal Buildings from Earthquakes), to a resource document that scrutinizes the broadest extent of the seismic design process, without duplicating unchanged code language from previous editions. However, its key function and mission have never changed, which is to provide state-of-the-art information to improve the seismic design procedures in

> The nation's seismic risk mitigation is achieved through state-of-the-art seismic design provisions along with effective code enforcement.

Figure 1-2. The Ten Editions of the *NEHRP Recommended Seismic Provisions*.

The inclusive process of the *NEHRP Recommended Seismic Provisions* is a key innovation under the NEHRP Program. While it involves the effort of all four NEHRP agencies, it is also the bridge that provides input by private sector construction and design industries and by university researchers.

the national seismic design standards and model building codes.

The *NEHRP Recommended Seismic Provisions* is developed through a consensus process conducted by the Provisions Update Committee (PUC) formed by the BSSC through funding provided by FEMA under the NEHRP Program. See Figure 1-3. The BSSC is a council of the National Institute of Building Sciences, which was founded by the U.S. Congress in 1974 to provide a national platform to solve complicated building science issues. The BSSC became part of NIBS in 1979. Shortly afterward, FEMA (the lead NEHRP agency at the time) commissioned BSSC to conduct a nationwide trial use of the Applied Technology Council's report, ATC 3-06, (commonly called ATC-3) Tentative Provisions for Development of Seismic Regulations for Buildings (Applied Technology Council 1978).

Funded by NSF and NIST, the ATC 3 project was an initial effort to develop a comprehensive analysis and design standard for use in seismic design. A team of 60 experts was engaged in this seminal effort to develop that evolved into the first edition of the *NEHRP Recommended Seismic Provisions*. The ATC-3 effort came in

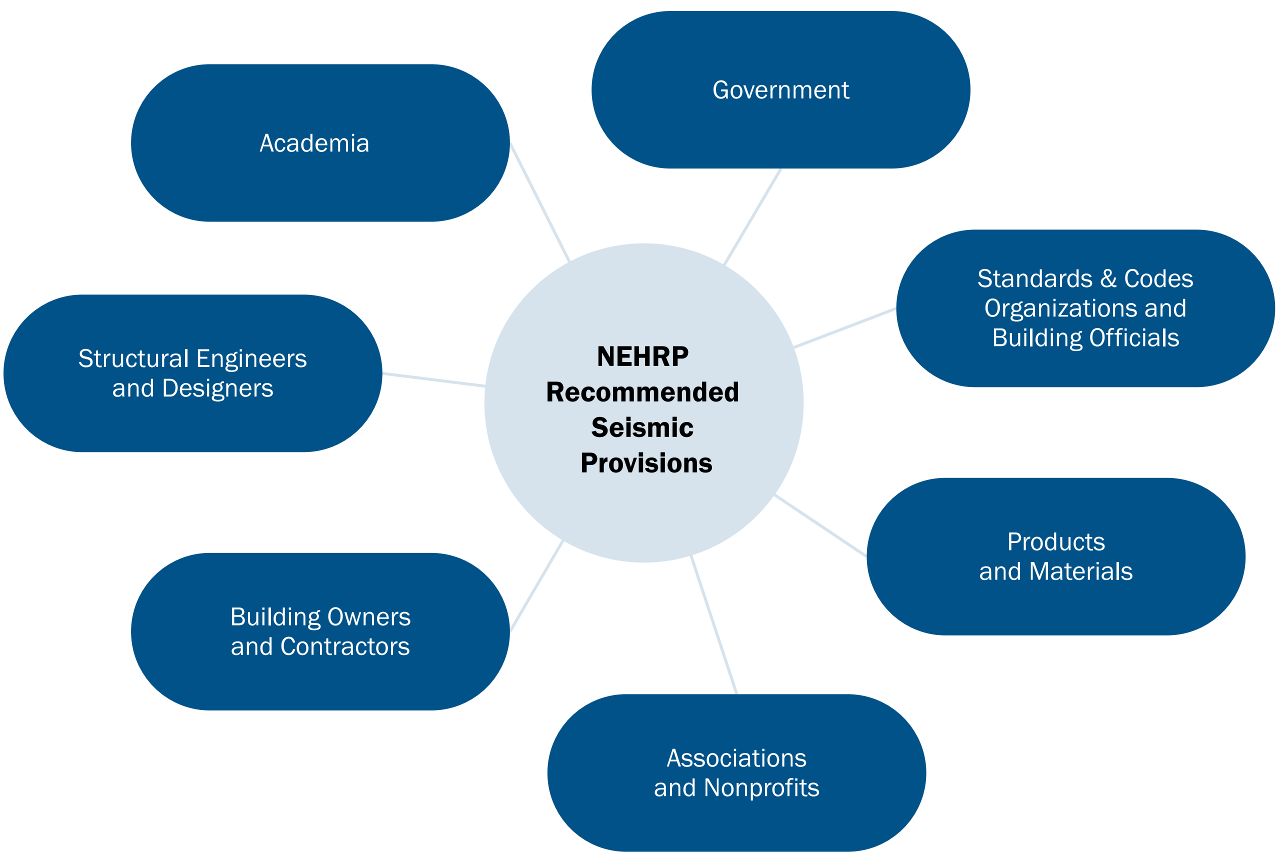


Figure 1-3. The inclusive process of the *NEHRP Recommended Seismic Provisions* development process.

the wake of the 1971 San Fernando Earthquake, which revealed significant deficiencies in seismic code provisions, resulting in unacceptable levels of damage in a moderate size (magnitude 6 1/2) earthquake, even to recently built engineered buildings.

The success of the *NEHRP Recommended Seismic Provisions* is due to its inclusive, rigorous process, a key innovation under NEHRP. While the development of the *NEHRP Recommended Seismic Provisions* involves the effort of all four NEHRP agencies, it also provides a bridge for input by the public and private sectors of building codes and standard organizations, construction and design industries, and by university researchers. Each *NEHRP Recommended Seismic Provisions* development cycle involves a large number of volunteer subject matter experts, thus providing cost savings to the federal government. This effort has involved over one hundred national experts, thousands of hours of volunteer time, and dedicated support from the NEHRP federal agencies, with expertise across structural engineering, seismology, geotechnical engineering, construction material associations, building industry associations, building officials, and others. FEMA support allows the process to continue on a stable course from update to update.

The steps through which a new edition of the *NEHRP Recommended Seismic Provisions* is produced and building codes and standards are updated are briefly described below and are summarized in Yuan (2016). Figure 1-4 portrays the relationships among the organizations involved in the development of an edition of the *NEHRP Recommended Seismic Provisions* in an organizational chart. Figure 1-5 is a flow chart showing how the *NEHRP Recommended Seismic Provisions* is developed and the following steps that result in adoption of seismic regulations in the building code.

The process by which the *NEHRP Recommended Seismic Provisions* is incorporated into the building codes that state, local, tribal, and territorial governments adopt is complicated and requires a set of orderly, transparent steps. Note that in the United States, the federal government does not promulgate private sector construction codes; rather, it regulates the construction of federal agencies and instrumentalities (see Section 4.3 Protecting Federal Buildings from Earthquakes), for which the *NEHRP Recommended Seismic Provisions* has been very useful.

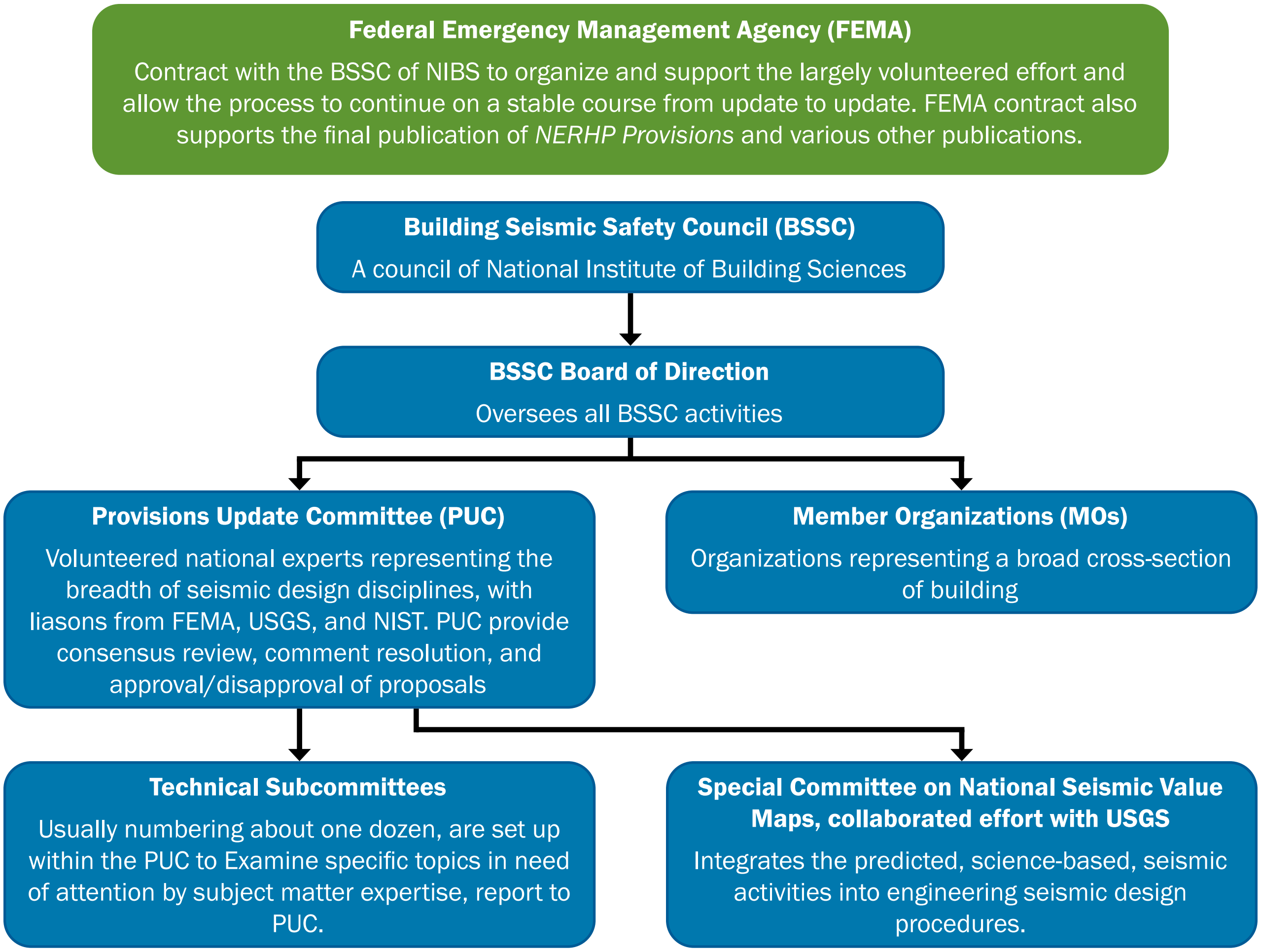


Figure 1-4. Chart of Relationships Among Organizations in the Development of the *NEHRP Recommended Seismic Provisions.*

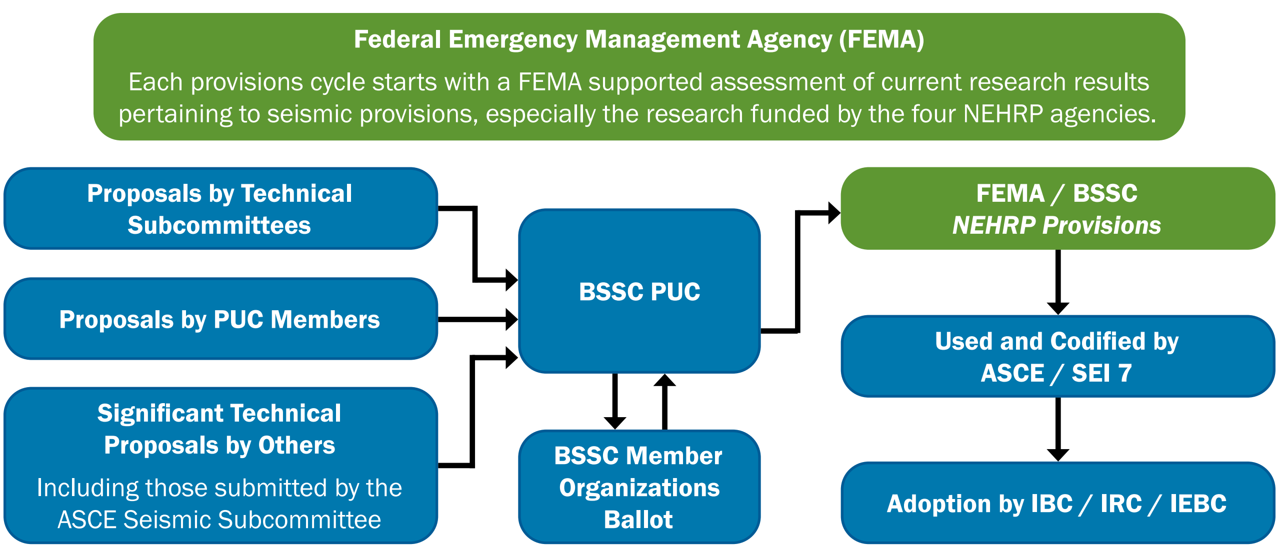


Figure 1-5. Flow Chart Illustrating How Seismic Building Code Regulations Are Developed.

1.3 The Process of Developing the NEHRP Recommended Seismic Provisions

1. **Prior to a new update cycle of the *NEHRP Recommended Seismic Provisions,* FEMA conducts assessments of current research results and the emergence of new technologies.**

In particular, this includes the research developed or funded by the four NEHRP agencies, the critical issues recommended for further study by the previous PUC, and input received from other stakeholders, such as earthquake engineers, building codes and standards organizations, design practitioners, and construction industries.

Based on this assessment, FEMA then identifies key areas of focus, conceives the scope of the new cycle of development and prepares a contract with NIBS/BSSC for the next update cycle. Based on the coordinated assessment and input, the PUC is assembled with volunteered national subject matter experts based on specialties and needs. The span of the expertise of these members over the years and the large amount of effort contributed by volunteers can be found on the BSSC website (https://www.nibs.org/page/bssc_puc). Their contribution and dedication have greatly multiplied the effect of the federal funding provided.

FEMA recognizes that the scope of the PUC's work is to consider recently developed and available research results rather than to conduct new research. New research and in-depth analysis studies to fill technical gaps are not expected from the PUC; rather, FEMA coordinates with other NEHRP agencies or private sectors to fund separate projects to carry out needed studies. FEMA, NIST, and USGS have representatives on the PUC serving as non-voting members to assist the PUC in conducting a fully independent, consensus-based evaluation of the available research results and new data, including the NEHRP-funded research results. While NSF does not have a representative on the PUC, many of its sponsored research projects contribute to the *NEHRP Recommended Seismic Provisions*. The research recommended by the PUC after each update cycle is also explored by NSF-funded researchers.

Each update cycle, a key effort is the adoption of new seismic hazard models developed by USGS, which forecast the likelihood of strong shaking in the United States. The new hazard models are reviewed and discussed before they are used to develop the national seismic design maps. Approximately every ten years, FEMA coordinates and funds a separate committee to investigate issues related to seismic design maps used by the *NEHRP Recommended Seismic Provisions* and national codes and standards. At the conclusion of each cycle of updates to the *NEHRP Recommended Seismic Provisions*, the PUC identifies important research needs in a forward-looking process that was not typically part of previous seismic code development efforts.

In addition, starting with 2009 *Provisions*, Resource Papers are published with each edition of the *NEHRP Recommended Seismic Provisions* to stimulate discussion on emerging design techniques and issues that are not yet sufficiently developed for inclusion into codes and standards.

The organized volunteer subject matter experts are a great cost savings to the federal government. It greatly multiplies the effect of the federal funding provided.

2. Development of the latest edition of the *NEHRP Recommended Seismic Provisions*.

The 2020 Provisions Issue Teams are covering the following topics:

- seismic design performance criteria and objectives
- seismic-force resisting systems and their design parameters
- seismic analysis procedures
- coupled shear walls
- nonstructural components
- non-building structures
- soil-structure interaction
- diaphragms
- multi-period response spectra
- site soil classes
- building irregularities
- seismic design maps

The technical proposals for changes developed by the Issue Teams are voted on by the PUC, and any negative ballots must be resolved. Originally, the *NEHRP Recommended Seismic Provisions* was a self-contained seismic regulatory resource with complete code language and provisions for seismic design, but since the 2009 edition, it has adopted the ASCE/SEI 7 standard by reference and only the recommended updates to the standard are included. Each proposal for change is accompanied by commentary as background information.

3. **Approval of a final version of the *NEHRP Recommended Seismic Provisions*.**

The BSSC member organizations formally vote on each recommendation, with a two-thirds majority needed for approval. Note the breadth of the organizations and interests represented in BSSC, including organizations representing building owners, construction materials industries, earthquake research institutes, architects, and government agencies, as well as engineering associations. See Figure 1-6 for the Member Organizations under the 2020 *Provisions* development cycle. While this inclusiveness has helped pave the way for widespread acceptance, especially in the early years, the process was contentious at times. The updated *NEHRP Recommended Seismic Provisions* is then published as a FEMA NEHRP document. Upon incorporating the final resolution to resolve the PUC ballot, the PUC-approved technical change proposals are submitted to the BSSC Board for acceptance and approval.

The PUC addresses any negative or yes-with-reservation votes by the BSSC Member Organizations before each proposal is ultimately included in the updated *NEHRP Recommended Seismic Provisions*.

> The inclusive process of the *NEHRP Recommended Seismic Provisions* prompts the wide acceptance by the building industry and encourages state, local, tribal, and territorial jurisdictions to adopt the latest seismic codes and standards.

Figure 1-6. The BSSC Member Organizations under the 2020 *NEHRP Recommended Seismic Provisions* Development Cycle

4. Incorporation of the *NEHRP Recommended Seismic Provisions* into the American Society of Civil Engineers (ASCE) ASCE/SEI 7 (ASCE 2017), noted as ASCE 7 here.

During *NEHRP Recommended Seismic Provisions* development process, the PUC will evaluate change proposals based on their technical significance and readiness for code implementation. Those that are ready for incorporation into ASCE 7 and International Building Code (IBC) will be included in Part 1 of the *NEHRP Recommended Seismic Provisions*; those that are not yet fully developed are placed in Part 3 of the *NEHRP Recommended Seismic Provisions*, which is a collection of resources for trial use or future improvements.

Major technical changes and innovations are first vetted by the updating process. The *NEHRP Recommended Seismic Provisions* serves as the starting point in the process of U.S. seismic standards development and update.

Once the updates are approved, they are forwarded to the Seismic Subcommittee (SSC) of ASCE 7 for consideration. The recommended changes in Part 1 of the *NEHRP Recommended Seismic Provisions* are often further revised to be in compatible code language at the ASCE 7 Seismic Subcommittee. This is a process that is closely coordinated by a joint committee with members from both PUC and ASCE 7 SSC. ASCE 7 (currently ASCE 7-16) is a complete set of requirements for determining design loads including not only earthquakes but also wind, flood, snow, and other loadings on buildings. The IBC incorporates that lengthy standard by reference rather than re-printing it in the code itself.

5. Adoption of ASCE 7 by the International Code Council (ICC).

ICC was formed in 1996 as a unification of the three model code development organizations then in existence in the United States: the Southern Building Code Congress International (SBCCI), publisher of the Standard Building Code (SBC); the International Conference of Building Code Officials (ICBO), publisher of the Uniform Building Code (UBC); and the Building Officials and Code Administrators International (BOCA), publisher of the National Building Code (NBC). The regions where these different codes were commonly adopted were, respectively, the South, the West, and the Midwest and East. The cooperative agreement among these three code bodies in 1996 paved the way for the issuance of the first edition of the IBC (International Code Council 2000). The current version was published in 2018 (International Code Council 2018). ICC also promulgates the IRC (International Code Council 2018) for small dwellings and other codes such as for existing buildings, electrical and plumbing systems, fire and life safety, and other building-related topics. These are the model code documents that are adopted into mandatory building regulations by state, local, tribal, and territorial governments.

The first edition of the ICC's national model building code, the IBC 2000, took the 1997 *Provisions* and with some reformatting made them the complete seismic requirements in the code. Rather than explicitly citing seismic loading criteria within the body of the IBC, the ICC started to directly reference ASCE 7 in its 2006 edition to avoid the potential for conflicts with this national standard that is maintained through a rigorous American National Standards Institute ANSI consensus process.

Because the *NEHRP Recommended Seismic Provisions* has been the state-of-the-art document on seismic provisions over the years and applicable nationwide, it was referenced to meet Presidential Executive Orders, as discussed in Section 4.3.

The essential process of updating the *NEHRP Recommended Seismic Provisions* by BSSC continues today. Focused study and deliberation are required to sift through the large volume of new seismic information produced every year by analytical and testing research, earth science research, development of new construction products and methods, input on practical aspects from building industry and design practitioners, and by the lessons learned from earthquakes. The following chapters of this document focus on some of the key accomplishments of aspects of the ongoing development of the *NEHRP Recommended Seismic Provisions*, in particular the lead technical role in that effort performed by the PUC.

The format of the *NEHRP Recommended Seismic Provisions* has evolved over time. However, its key function and mission to provide state-of-knowledge information to improve the seismic design procedures in the national seismic design standards and model building codes have never changed.

6. *NEHRP Recommended Seismic Provisions* Education and Outreach.

Building code seismic regulations are only useful when they are effectively implemented. Seismic design is one of the more complex engineering subjects, and changes in the code require that designers, building officials, and construction entities keep up with the revisions.

As each new edition of the *NEHRP Recommended Seismic Provisions* is being completed, work is underway to produce companion education and training resources. For example, for the 2015 *Provisions*, FEMA produced an extensively illustrated volume of design examples, FEMA P-1051 (FEMA 2016a), design flow charts, FEMA P-1051B (FEMA 2016c), as well as a training and education document with presentation slides, P-1052 (FEMA 2016b). FEMA also offers free webinars. These design examples and training materials are developed to guide the targeted audience of design practitioners in properly applying the new code changes in various situations and for different building designs.

In the past, FEMA conducted week-long courses on the *NEHRP*

Recommended Seismic Provisions for engineering faculty to facilitate incorporation of the *Provisions* into their courses. Several dozen U.S. universities now offer graduate level courses in earthquake engineering—one on structures and one on geotechnical engineering—and such courses are channels for the direct use of the *NEHRP Recommended Seismic Provisions* in higher education. Undergraduate civil engineering design classes also commonly include some content on seismic design, which often draws on the principles and procedures in the building code. Thus, the training and education strategy includes refresher training for engineers familiar with the previous edition of the *NEHRP Recommended Seismic Provisions* as well as educational resources for those new to the regulations in the building code.

1.4 An Example of the Updating of the NEHRP Recommended Seismic Provisions

The training and education strategy included in the *NEHRP Recommended Seismic Provisions* provides refresher training for engineers familiar with the previous edition of the *NEHRP Recommended Seismic Provisions* as well as educational resources for those new to the regulations in the building code.

How are the *NEHRP Recommended Seismic Provisions* updated to keep up with new research and the advancement of engineering practice? The following example highlights a technical development that made its way from the *NEHRP Recommended Seismic Provisions* into building code regulations such as ASCE 7 and the IBC.

Chapter 16 of the *NEHRP Recommended Seismic Provisions* deals with nonlinear response history analysis ("Nonlinear" is briefly explained later in this section) and was updated by Issue Team 4 of the 2015 PUC. Before the 2015 *Provisions*, ASCE 7 specified that nonlinear response history analyses be performed using ground motions scaled to the design earthquake level and that design acceptance checks be performed to ensure that mean element actions do not exceed two-thirds of the deformations at which loss of gravity-load-carrying capacity would occur. The PUC judged that these requirements lacked specificity in many areas, leading to inconsistencies in interpretation.

In the 2015 *NEHRP Recommended Seismic Provisions*, a complete reformulation of requirements was undertaken to require analysis at the Risk-Targeted Maximum Considered Earthquake. This analysis method is a sophisticated procedure in which the building design is subjected by computer analysis to a number of simulated earthquakes the building may experience. The earthquakes are represented by precise records of actual earthquake ground motions. It is necessary to first select which recorded ground motions to use out of the thousands available, varying by magnitude, distance, soil, and the specific type of faulting. It is essential to standardize how the "ingredients" of this "recipe" are selected and mixed. Then comes the process of "baking" the ingredients, or the process by which the selected ground motions will be run through the computer model of the building to guide the seismic design of all its structural members and connections.

The analysis looks at the response of a building over perhaps 30 seconds of strong shaking, motion by motion, split-second by split-second, "blow by blow," thus providing a history of the building's response. Each earthquake jolt causes the building to respond to forces throughout its structure. This determines how much it moves and distorts from its previous geometry. That time history is what is provided by this response history analytical method.

"Nonlinear" usually refers to the behavior of the structure after it has used up its elastic (linear) capacity to "bounce back" undamaged. After elastic (no-damage) capacity is used up, the structure needs to have sufficient ductility to experience some damage (e.g., cracking of concrete, bending of reinforcing bars) while remaining intact and carrying load. The reader can think of linear behavior as depicted on a graph with a linear or straight line: double the load, and the building's drift or sideways distortion doubles, reduce the load to zero, and building returns to its original geometry. Nonlinear behavior can be visualized as the portion of the deformation-force graph that departs from the linear portion to show increasing deformation even without significant extra load. Damage softens the structure causing it to deform more. Its inherent vibrational property called the period of vibration also changes, and that changes response, thus complicating the analysis. How to represent the building undergoing inelastic behavior as a mathematical model is a critical step, and one for which guidance is provided in the *NEHRP Recommended Seismic Provisions*.

FEMA 440, *Improvement of Nonlinear Static Seismic Analysis Procedures* (2013) discusses the latest advances in nonlinear static analysis and describes the process more in depth:

https://www. fema.gov/ media-library/ assets/ documents/855

The reader may wonder why engineers design buildings to behave inelastically, which means they are expected to incur damage in a large earthquake. Why contemplate designing the building to have any damage at all? Why not make the building stay perfectly elastic and damage-free? The answer is that in a severe earthquake, trying to achieve a no-damage performance level would be like designing an automobile to experience a high-speed collision without any dents. Thus, earthquake engineers use the term earthquake-resistant rather than earthquake-proof. It should be emphasized that designing to a level higher than the minimum safety standard expressed in the *NEHRP Recommended Seismic Provisions* is encouraged. See Section Chapter 5 for more information on resilience.

The 2015 *NEHRP Recommended Seismic Provisions* developed comprehensive guidelines and requirements for nonlinear response history analysis, which can be considered a simulation of what would happen if the actual constructed building were subjected to earthquakes. It is the basis for seismic design of most tall new buildings in seismically active regions of the world, as well as buildings employing advanced protective technologies.

Higher performance usually incurs an additional cost. Even with above-code-minimum design, some repairable damage caused by what the engineer would call nonlinear response is still usually a reasonable expectation. It is a fact of life that most buildings subjected to the most intense shaking contemplated in the building code, even those designed to the latest code, will have some nonlinear behavior, that is, some damage. The more positive aspect to the design basis of the building code is that while the *NEHRP Recommended Seismic Provisions* and the IBC are aimed at safety (not functionality or complete damage prevention) substantial property protection is provided by designs that meet the *NEHRP Recommended Seismic Provisions*.

The prescriptive seismic design regulations for houses are found in the International Residential Code (IRC) rather than the International Building Code. While the IRC does not directly involve the *NEHRP Provisions*, the IRC seismic maps are produced by USGS following the *NEHRP Provisions* updated seismic design value maps. Nonetheless, the current seismic design approaches developed in the *NEHRP Recommended Seismic Provisions* have influenced the less complex seismic regulations found in the IRC.

Nonlinear response history analysis can be considered a simulation of what would happen if the actual constructed building were subjected to several representative earthquakes. Weak spots are identified from this analysis or collection of computer analyses, so that the results envelop the worst results (stresses, amount of sideways deflection or drift, and other engineering parameters). A revised design is finalized to address weaknesses found in one or another of these computer analyses. The criteria used to accept a design are included in the *NEHRP Recommended Seismic Provisions* to ensure consistent application of the method.

The nonlinear response history analysis procedure is recognized as a more precise tool to analyze and design buildings than more simple procedures, but national design standards and codes did not have comprehensive guidelines and requirements for employing this method in design. Without guidance for the use of this sophisticated procedure, different engineers could conduct analyses of the same design and get significantly different results.

The issue team for this updating task involved 26 members, including practitioners, researchers, and experts from NEHRP agencies. Their update proposals took five years to pass the step of evaluation and approval by the full PUC and then were further modified before incorporation into ASCE 7. The new chapter now in ASCE 7-16 includes the needed guidance and requirements on ground motions, modeling, and acceptance criteria of analysis results, and today it is the basis for seismic design of most new tall buildings in seismically active regions of the world, as well as buildings employing advanced protective technologies including seismic isolation and energy dissipation.

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Chapter 2

Brief Historical Background of the *NEHRP Recommended Seismic Provisions*

This section summarizes the history of the *NEHRP Recommended Seismic Provisions*, beginning slightly before the first edition was published in 1985. A brief history of the development of seismic regulations in buildings codes in the United States extending further back is included in Appendix B. Figure 2-1 is a timeline to illustrate the evolution of the seismic regulations and *NEHRP Recommended Seismic Provisions.*

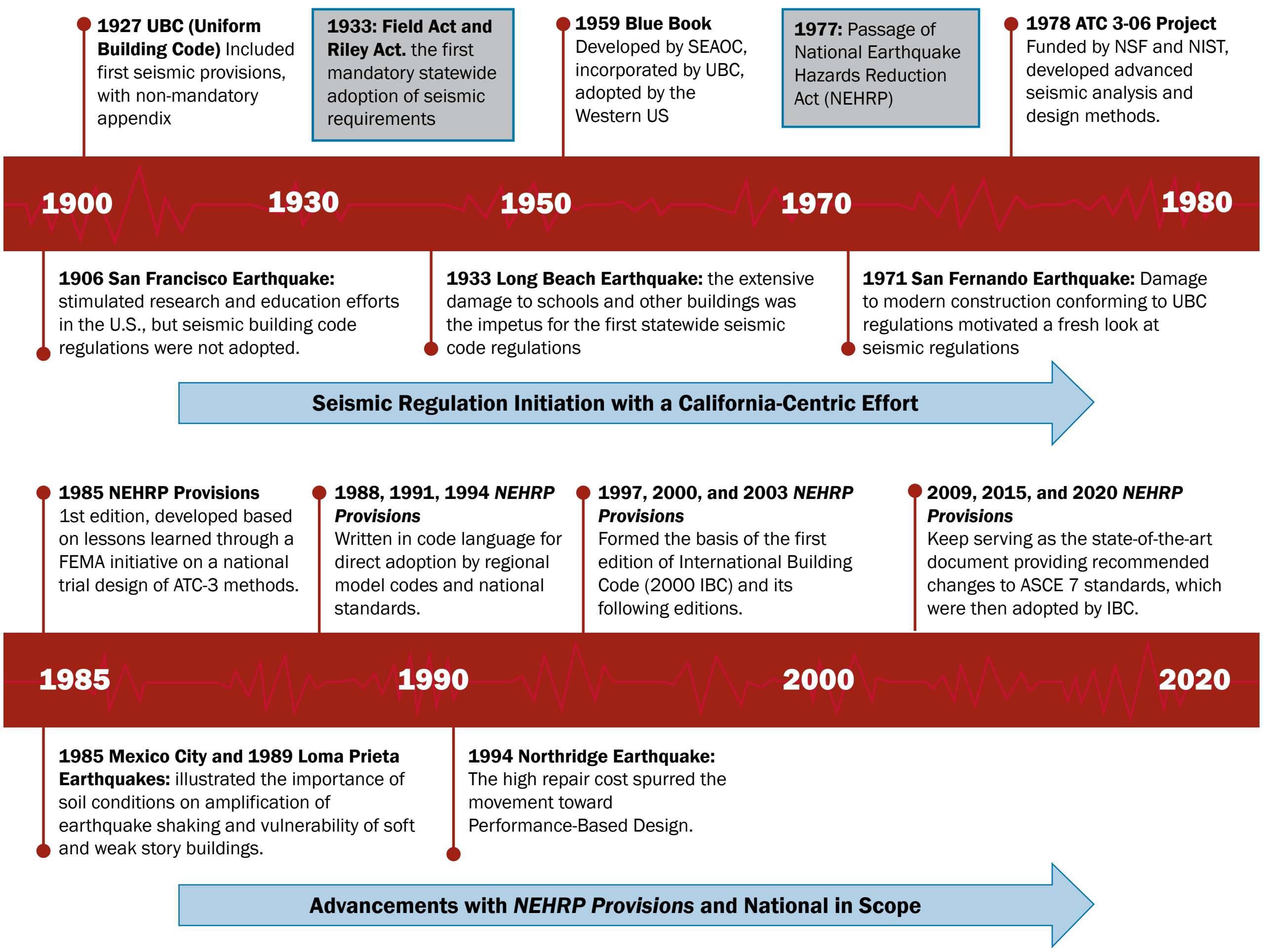


Figure 2-1. U.S. Seismic Regulations and Seismic Codes Development and the Role of *NEHRP Recommended Seismic Provisions.*

Before the *NEHRP Recommended Seismic Provisions*, the involvement of individuals and stakeholders was more regional than national, fewer experts and resources were employed, and the process was not fully documented. The leading effort for seismic code development was managed by the Structural Engineers Association of California (SEAOC). The Seismology Committee of SEAOC wrote the suggested earthquake regulations in a publication called the Blue Book, Recommended Lateral Force Requirements and Commentary, (SEAOC 1959 and subsequent editions). These provisions were essentially adopted verbatim in the Uniform Building Code (UBC) by the International Conference of Building Officials (ICBO), one of the three regional building code councils.

Before the *NEHRP Recommended Seismic Provisions*, the seismic code and standard development process was more regional than national.

This SEAOC product, updated periodically, was a major contribution to the development of seismic design and had worldwide influence. California had enacted seismic code regulations dating back to 1933, and other western states where the UBC was used also needed that input from SEAOC to obtain earthquake code provisions as they began to adopt such regulations. The 1971 San Fernando Earthquake highlighted the need for a major review and overhaul of seismic regulations, a process that was beyond the resources of a volunteer professional organization in one state to accomplish. Until the 1990s, the SEAOC Blue Book was the primary source for earthquake provisions in U.S. building codes. They were adapted into a standard by the American National Standards Institute (ANSI) into ANSI 58.1, which was eventually adopted into the other two regional model codes in the United States, the Standard Building Code and the National Building Code, with some time delays.

The period from the 1990s until the adoption of the 2006 IBC by the State of California marked a period of transition, with California using periodically issued editions of the UBC while much of the rest of the country began to rely on the 1997, 2000, or 2003 *Provisions*. As explained earlier, the *NEHRP Recommended Seismic Provisions* were implemented via their adoption in ASCE 7. This was accomplished through adoption of the 2000, 2003, and the 2006 editions of the IBC, as shown in Figure 2-2.

Beyond that point, the role and character of the *NEHRP Recommended Seismic Provisions* changed. The 2009 *Provisions* adopted ASCE 7-05 and proposed a number of modifications to it in Part 1, which were then considered for adoption in ASCE 7-10. The 2015 *Provisions* adopted ASCE 7-10 proposed a number of modifications to it in Part 1, which were then considered for adoption in ASCE 7-16. The 2020 *Provisions* has adopted ASCE 7-16 and proposed a number

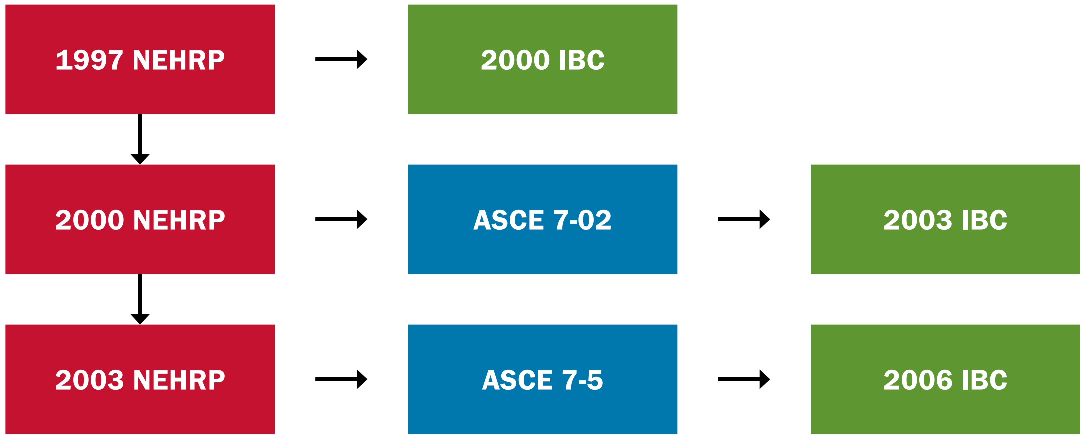


Figure 2-2. Adoption of the *NEHRP Recommended Seismic Provisions* into the IBC

of modifications to it in Part 1, which are being considered for adoption in ASCE 7-22.

As with many other aspects of the improvement in efforts to control earthquake risks in the United States, the passage of the 1977 National Earthquake Hazards Reduction Act was a key event in building code development. It directed funding for earthquake hazard reduction to four agencies—FEMA, NSF, NIST, and USGS—and also provided a goal of coordinating federal efforts. The fact that the acronym NEHRP is such a well-known "brand name" within the earthquake field and associated with hundreds of publications, conferences, committees, and so on, indicates its pervasive influence. However, one should not overlook efforts that preceded NEHRP, such as the National Bureau of Standards *Building Practices for Disaster Mitigation* (National Bureau of Standards 1972). The influential ATC-3 document was also in process prior to NEHRP, with funding from the National Science Foundation and the National Bureau of Standards (which became NIST in 1988).

The passage and reauthorizations of the National Earthquake Hazards Reduction Act are important in building code development. The *NEHRP Recommended Seismic Provisions* has become a well-known brand name in the earthquake field and has prevalent influence.

Damage in the 1971 San Fernando Earthquake to modern construction conforming to building code regulations made it evident to engineers that the regulations needed to be given a fresh look. Rule-of-thumb regulations after the 1933 Long Beach Earthquake had been updated sporadically and incrementally, often looking retrospectively at the damage from the last earthquake. The participants in the ATC-3 project were given a different charge; they needed to develop the provisions that would most rationally guide seismic design from essentially a blank slate. Concepts discussed below such as ductility, nonstructural damage, and improved mapping of the hazard of seismic shaking that are still important in the *NEHRP Recommended*

Seismic Provisions were first discussed and documented in the Commentary to the resulting ATC-3 provisions.

Given the completion of that ATC-3 project, the question then became what should be done with the document since it didn't have any power to enforce its recommendations. How should the advanced ideas and procedures it contained be implemented? The ATC project was completed in 1978, and the first edition of the *NEHRP Recommended Seismic Provisions* was issued in 1985. The key intermediary step was the funding of the Building Seismic Safety Council by FEMA to superintend that implementation process. Without that FEMA initiative, it is difficult to imagine how the advanced thinking in ATC-3 would have found its way into nationwide seismic provisions. BSSC concluded that the ATC-3 document needed additional vetting and review prior to implementation, and one of BSSC's first projects in 1983-1984 was to have engineering firms around the country do hypothetical but realistic designs known as trial designs of several different types of buildings using the ATC-3 provisions to compare the results and costs with then-present practice (Building Seismic Safety Council 1984). In five cities where no seismic provisions were then adopted, 29 building designs were conducted.

The first *NEHRP Recommended Seismic Provisions* edition was developed based on the ATC-3 document, with additional vetting and review process superintended by FEMA through BSSC. The advanced design requirements increased the construction cost by 1-2%.

In four cities where there were seismic regulations, the comparison was made on 23 building designs. Moving to the ATC-3 level of design was found to typically increase construction cost between 1% to 2%. (Building Seismic Safety Council 1984). A recent study focused on Memphis, Tennessee found similar results. (NEHRP Consultants Joint Venture, 2013). The ATC-3 provisions were revised based on findings from the trial designs, and those completed revisions became the first 1985 edition of the *NEHRP Recommended Seismic Provisions*. Since then, each edition has served as the basis for the development of the succeeding edition.

In the 1970s, as these developments in building codes were occurring, information concerning the risk posed by rare but damaging ground motions in the Midwest, East, and South in the United States was becoming well-known in the geological and seismological literature. This became another reason that more experts and interested parties began to get involved in seismic building code regulations across the country. The problem of dealing with rare but large earthquakes in some regions of the country remains an important topic today (see Section 3.1 Seismic Mapping). A comparison of the *NEHRP Recommended Seismic Provisions* with the treatment of the seismic hazard of ground shaking prior to their development, for example the treatment in the 1988 Uniform Building Code, shows how much additional attention this subject of the infrequent but large earthquake has warranted (Hamburger 2016).

Over the past few decades, more universities across the country have begun to introduce earthquake engineering courses into their civil engineering curricula. Graduate level courses, now typically one devoted to structural earthquake engineering and another devoted to geotechnical earthquake engineering, are common among a number of universities, while in the 1960s and 1970s such courses were common only in California universities. Students obtaining their PhDs from institutions that offered graduate level earthquake engineering programs(such as California Institute of Technology (Caltech), University of California at Berkeley, Stanford, University of Illinois at Urbana-Champaign, or the University of Michigan), became professors who taught earthquake courses and developed research programs at other universities. Engineers with earthquake engineering backgrounds began to graduate, becoming useful additions to engineering offices as building regulations also diffused. As the size of the knowledgebase and earthquake engineering community continued to rapidly increase, it became necessary to provide a national arena for the development of seismic regulations for buildings (see Chapter 1 for a description of this overall process). The process of developing the *NEHRP Recommended Seismic Provisions* provides inclusiveness, a way for input to be received from a variety of sources, and it is also an instrument for exploiting or mobilizing a wide variety of resources.

In 1996, the three regionally based model building code organizations merged to promulgate the International Building Code, first published in 2000. The *NEHRP Recommended Seismic Provisions* were already being updated and published by FEMA since 1985, thus providing a single source of advanced, consensus-based seismic provisions that could be adopted into ASCE 7 and thence into the IBC. Note that while the UBC was previously the most advanced code to be enacted and used in building design in areas of high seismicity, and even though it was used by many engineers abroad, the UBC was a California-centric rather than national document.

Without the *NEHRP Recommended Seismic Provisions*, there would have been inconsistent versions of seismic provisions in various codes and standards that would have made it difficult for the IBC to deal with that especially complex subject on seismic design. The knowledgeable and experienced experts of the PUC

The *NEHRP Recommended Seismic Provisions* has created a national arena in which code updates are debated and resolved nationally. It has a great benefit to both the design and construction because regulations do not suddenly change crossing a state line.

are a central resource and evaluate the technical merits of code changes. Standardization of seismic building code requirements benefits both the design and construction industries. While the mapped ground motion severities vary greatly across the country, a constructor or designer has recourse to a standard set of provisions that do not suddenly change crossing a state line.

One can consider the BSSC PUC and the *NEHRP Recommended Seismic Provisions* to be the funnel into which proposed seismic code changes are put to enter the stream of implementation into the building code. The *NEHRP Recommended Seismic Provisions* has created a national arena in which code updates are debated and resolved. The process by which the seismic regulations are developed to take form in the building code has been a model for how other hazards such as wind or flood can be consistently treated, and for how federal agencies can coordinate their risk reduction programs.

Chapter 3

Major Technical Changes

This chapter selects a few important topics to indicate the role of the *NEHRP Recommended Seismic Provisions* and to make comparisons with the pre-*Provisions* era.

In general, there are three important and distinct parts of seismic design:

- Determine the seismic hazard at a site. Translate the ground shaking into engineering parameters that are needed to analyze a building's seismic capacity, particularly its strength and stiffness.
- Determine design strength and stiffness of the structure. Design for sufficient capacity to withstand seismic forces and building movement.
- Provide effective detailing. Assure an effective design through detailing of the structural and nonstructural systems (such as glazing and partitions, heating-ventilating-air-conditioning, electrical and communication, and plumbing).

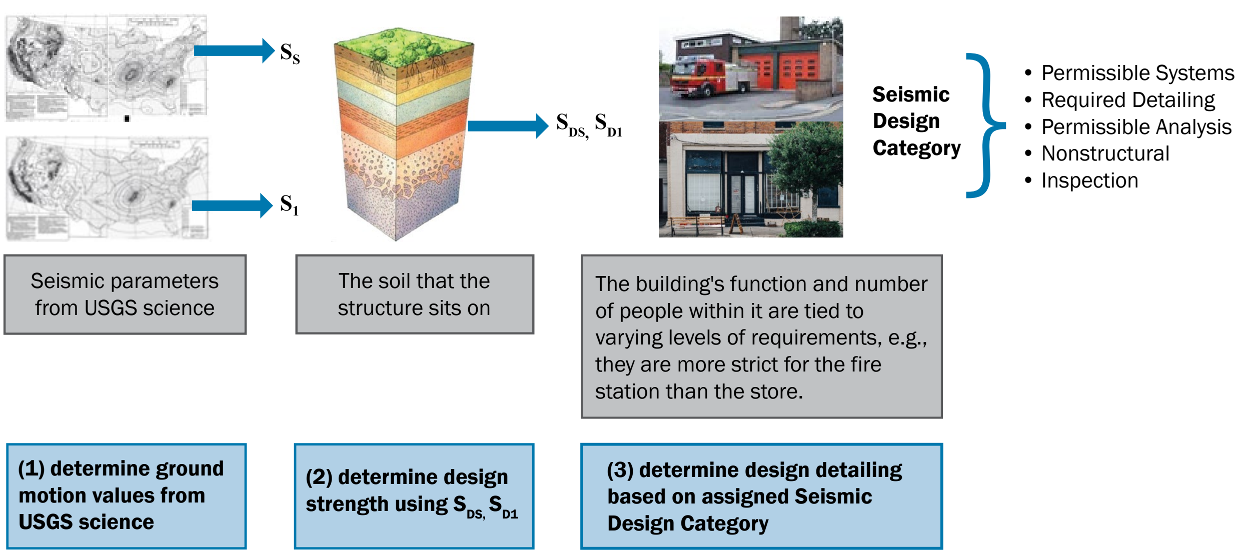


Figure 3-1. The process of incorporating the latest information on seismicity from U.S. Geological into Seismic Design.

Figure 3-1 shows a graphic outline of the three-step seismic design process, starting with the determination of seismic hazard from design maps, then the determination of required building strength to resist the earthquake shaking, to design structural system and detailing.

3.1 Seismic Mapping

The likelihood of strong ground shaking varies greatly across the United States, and the *NEHRP Recommended Seismic Provisions*, while not the first document to depict seismicity across the U.S, were the first to include seismic design maps derived directly from the U.S. Geological Survey National Seismic Hazard Model in a way that is calibrated with the associated structural and nonstructural design requirements.

The *NEHRP Recommended Seismic Provisions* was the first to include USGS seismic hazard modeling, which are now collaboratively developed and updated by USGS FEMA, and BSSC.

Before the *NEHRP Recommended Seismic Provisions*, the use of state-of-the-art mapping of ground motion severities and related probabilities was much less developed. Furthermore, many advances in earth science and geotechnical engineering have been made over the past 40 years. The role of the U.S. Geological Survey (USGS) within NEHRP has been sharpened over these years to make USGS the central provider of ground motion hazard mapping for design purposes. The evolution of the U.S. Seismic Value Maps is demonstrated in Figure 3-2.

Geologists find new faults and evidence as to the frequency and size of earthquakes those faults can produce; seismologists develop new research results on how earthquake ground motions propagate from a rupturing fault to a building site; geotechnical engineers have learned much about the ways the local soil

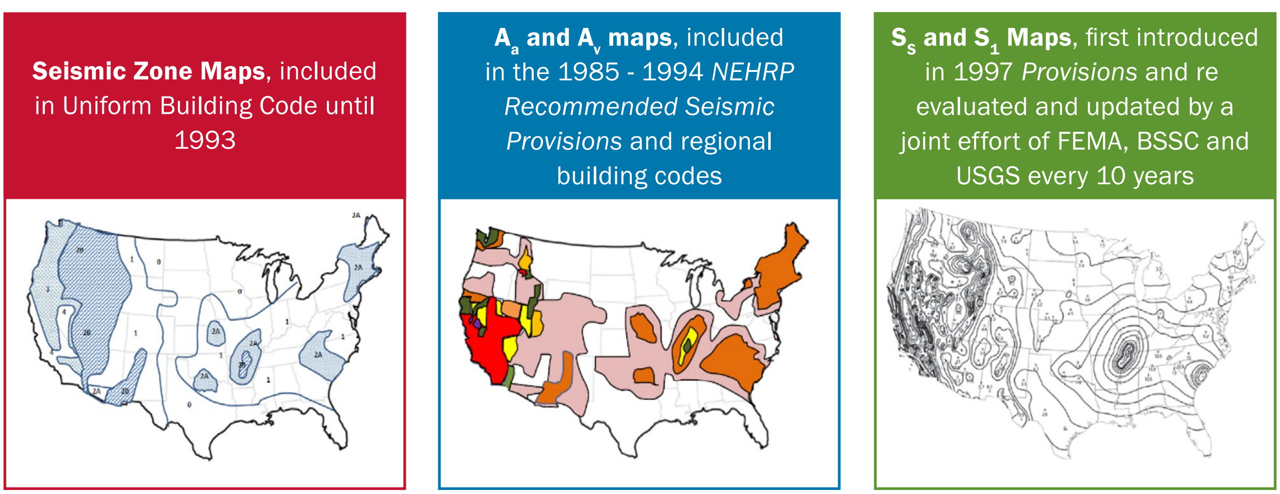


Figure 3-2. Evolution of the U.S. Seismic Value Maps

conditions affect those motions. Quantitatively connecting those elements together to forecast shaking severity and likelihood at a particular site is called probabilistic seismic hazard analysis. Today, that analysis goes beyond labeling large zones with a single seismicity value to providing detailed contours or computerized ground motion values at a street map scale. These refinements in the current body of knowledge have continually affected updates to the *NEHRP Recommended Seismic Provisions*.

Fewer parameters were provided by the seismic maps in the pre-*Provisions* era. This is akin to the difference between a weather station that only provided the daily maximum temperature in one era then later evolved to provide barometric pressure, wind speed and direction, humidity, and solar radiation as part of a data package to describe the weather. Pre-*Provisions* maps in building codes used qualitative representations of ground motions throughout broad regions that were not quantitively tied to probabilistic seismic hazard analysis. However, since the 1997 *Provisions*, the more complicated reality of ground motions is more fully reflected. Since the early days when ATC-3 and its seismic mapping approach were making their way into the first edition (1985) of the *NEHRP Recommended Seismic Provisions*, there have been advancements in probabilistic seismic hazard analysis. For example, the 2009 *Provisions* departed from the former criterion of a probabilistic Maximum Considered Earthquake. The most severe earthquakes considered by the *NEHRP Recommended Seismic Provisions* had a 10% chance of exceedance in an exposure period of 50 years, or an average return period of 475 years. The 2009 updating changed to a direct consideration of the implications for building collapse. This was accomplished by convolving the probability of collapse or severe damage for a given ground shaking level with the hazard of the ground shaking and thereby considering characteristics of the building as regulated by the various design requirements. This results in what is called a risk-targeted approach, explained in simple terms by Luco (2012, 2019).

When translating seismic risk into building design, it is not just the size of earthquakes that can occur in a region that is relevant; it is also the frequency or probability with which they occur.

In developing nationally applicable maps for design, there is an issue that is easy to describe but very difficult to solve. It is not just the size of earthquakes that can occur in a region that is relevant; it is also the frequency or probability with which they occur. One might quickly conclude that a large earthquake could strike the Central United States again, similar to the large 1811-1812 New Madrid Earthquakes, as seismologists looking over timespans of thousands of years tell us will probably occur, and that therefore the mapped values and associated building requirements would be the same as for a west coast site where the largest earthquake is similar in size. However, the probability of seeing that extreme ground motion at the western site is several times higher than the probability in the central part of the country. It confounds common sense to design buildings in the two regions for the same level of earthquake shaking when one region has frequent earthquakes and in the other, they are rare. Yet, buildings in the central United States must be designed with sufficient strength that there are not mass collapses in a large earthquake, even if one only occurs on average once every several hundred years. (Hamburger 2016, Nordenson and Bell 2000).

When the earth science community advances our understanding of the intensity and frequency of earthquakes, the engineers need to update its design basis by translating the science into engineering terms, one of the major tasks under Project 97, Project 07, and Project 17.

Thus, providing a uniform level of safety (or the inverse, protection from a uniform level of risk) was one of the thorniest problems the *NEHRP Recommended Seismic Provisions* had to solve. For decades, acceptable risk was often talked about in seismic design circles, but the *NEHRP Recommended Seismic Provisions* and ATC-3 explicitly discussed acceptable risk and quantified it. In the western United States, where there was a historical record of where earthquakes occurred, how large they were, and where most seismic sources, or causative faults, were known, a deterministic approach that took in this historical data was deemed appropriate near active sources. In most of the midwestern and eastern United States where this level of historic data didn't exist, probabilistic projections into the future made more sense. A subcommittee of the PUC for the *NEHRP Recommended Seismic Provisions* and the USGS developed a method to marry these two approaches, which has recently been revisited by a Project 17 subcommittee.

UBC	**Project 97** IBC 2000, 2003, 2006, 2009	**Project 07** IBC 2012, 2015, 2018, 2021	**Project 17** IBC 2024...
"475 year" 10%-50 year motion	"Uniform hazard" with 2,475 years return period Introduced "deterministic cap" where probablistic motion exceeded "practical" levels	"Uniform risk" 1%/50 year collapse probability Updated definition and calculation of "deterministic cap"	"Uniform risk" 1%/50 year collapse probability Updated definition and calculation of "deterministic cap"

Figure 3-3. Revolution through the *NERHP Recommended Seismic Provisions* Process in an effort to Provide a Uniform Level of Safety Across the Nation

Circa 1997, 2007, and 2017, respectively, Project 97, Project 07, and Project 17, instituted new processes for developing the seismic maps in the *NEHRP Recommended Seismic Provisions* from the USGS National Seismic Hazard Model. USGS tasked its scientists with collaborating with engineers to develop the latest and most appropriate earthquake ground motions analysis for design across the country.

Project 97, Project 07, Project 17 brought more resources into the arena where the *NEHRP Recommended Seismic Provisions* was being developed, including involving many experts around the nation. These ground motion mapping projects have occurred approximately ten years apart and are a collaborative effort of FEMA, BSSC, and USGS, which in itself emphasizes another of the key roles the *NEHRP Recommended Seismic Provisions* have provided: a central forum where the relevant information and opinion on earthquake motions for design can be shared. Spanning between earthquake science and engineering is a significant challenge. It has been said that scientists seek discoveries and engineers solve problems. Geoscience data and findings, when incorporated into the *NEHRP Recommended Seismic Provisions*, have major implications on building design. Engineers are always looking ahead to the next step in the calculation where the ground motions are combined with building characteristics to determine required strength and stiffness of the structure and estimated performance.

The *NEHRP Recommended Seismic Provisions* has provided a central forum where the relevant information and opinion on earthquake motions for design can be shared, a great model of marrying science and engineering into building science.

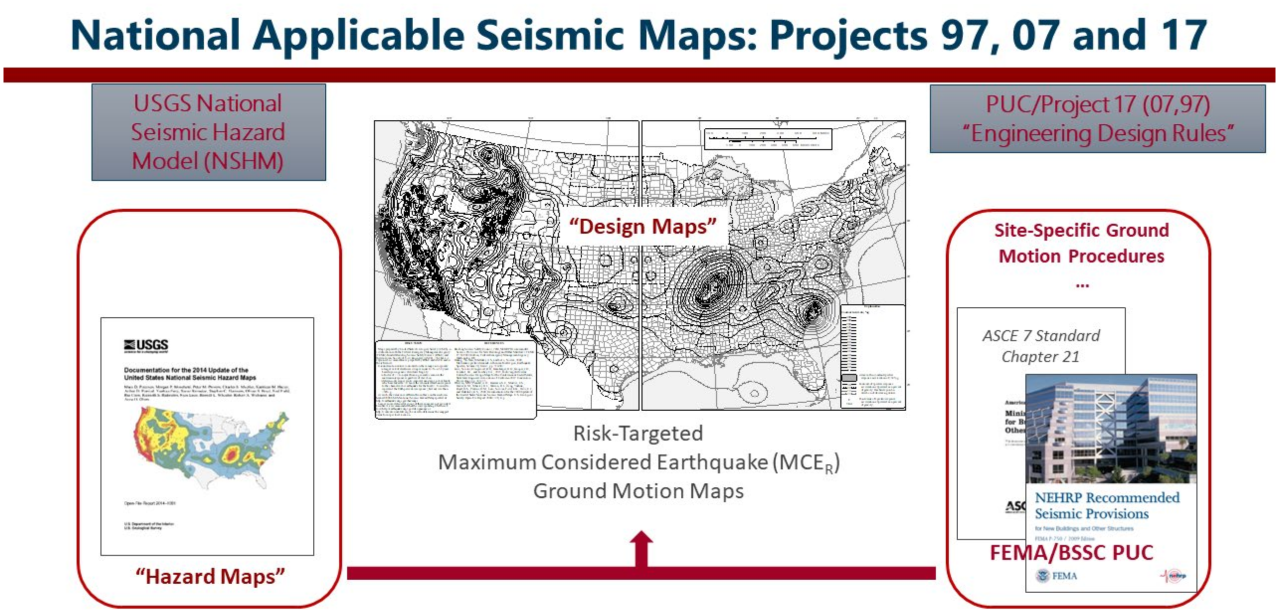


Figure 3-4. A Joint Effort Among USGS, FEMA, BSSC to Develop National Applicable Seismic Maps under NEHRP Program, a Model of Marrying Science and Engineering into Seismic Provisions

3.2 Ductility and Response Modification Factors

Structural materials deform when loaded, and these deformations can basically be characterized as elastic, when the material returns to its original shape when unloaded, or inelastic, when the material remains permanently deformed. In many cases, elastic is the same as linear, as explained before, and inelastic for practical purposes is nonlinear, but they are distinct concepts. There are some cases where the structure remains elastic but behaves nonlinearly, for example when one building pounds against another, and when you stretch a rubber band, it remains elastic and returns to its original shape and size, but as you pull on it, the resistance increases, so the force-deformation curve is not linear. Most structural elements are designed to perform within the elastic range, not only because permanent deformations are generally undesirable, but also because design calculations are much simpler for elastic behavior. Materials and structural elements that can be deformed into the inelastic range and not completely fail, such as by fracturing, are characterized as ductile; conversely, materials and structural elements that fail without much deformation in the inelastic range are non-ductile, or brittle. A classic teaching example: a paper clip can be bent and not break apart (it is ductile); a piece of chalk that is flexed breaks in a brittle manner (it is non-ductile).

The 1906 San Francisco Earthquake did not bring about a forward- looking approach to seismic design (see Appendix B). Earthquake forces experienced by structures are inertial forces, the product of the accelerations and the mass of the building, but that approach was not used in building codes in the United States until after the 1933 Long Beach Earthquake. The formula in the early editions of the Uniform Building Code applied a seismic coefficient or factor of approximately 5% or less, which was then multiplied by the mass or weight of the building to calculate the total lateral load. By the 1970s and 1980s, this lateral-force design factor had been increased to 10% to 20%. Aside from the level of design forces, engineers noted that such designs, particularly those with ductile materials such as steel, had improved performance in earthquakes. This was true even though an increasing supply of strong ground motion records showed that the peak accelerations of earthquakes could be much larger than 10 to 20% of gravity. It became obvious that structures of code-level lateral strength could not stay in the elastic range and that ductility was necessary. It was more practical and economical to provide ductility than to make the structures sufficiently strong to prevent inelastic response.

During the development of building codes, ductility of various materials and structural systems was measured in several ways. Then in 1978, the ATC-3 project developed the concept of Response Modification Factors, intended to transform an inelastic earthquake response to elastic levels for simplified design with overall required design levels roughly equivalent to previous methods. The Response Modification Factor, R, incorporated both the ductility expected from a given structural lateral-force resisting system and the expected overstrength, that is, elastic strength over and above what is estimated by simple calculations. For example, the strength of bearing walls in resisting lateral loads is calculated, but the contribution of nonstructural partitions is not, though they may contribute some strength as well. Safety factors also make the probable earthquake-resistance of the structure higher

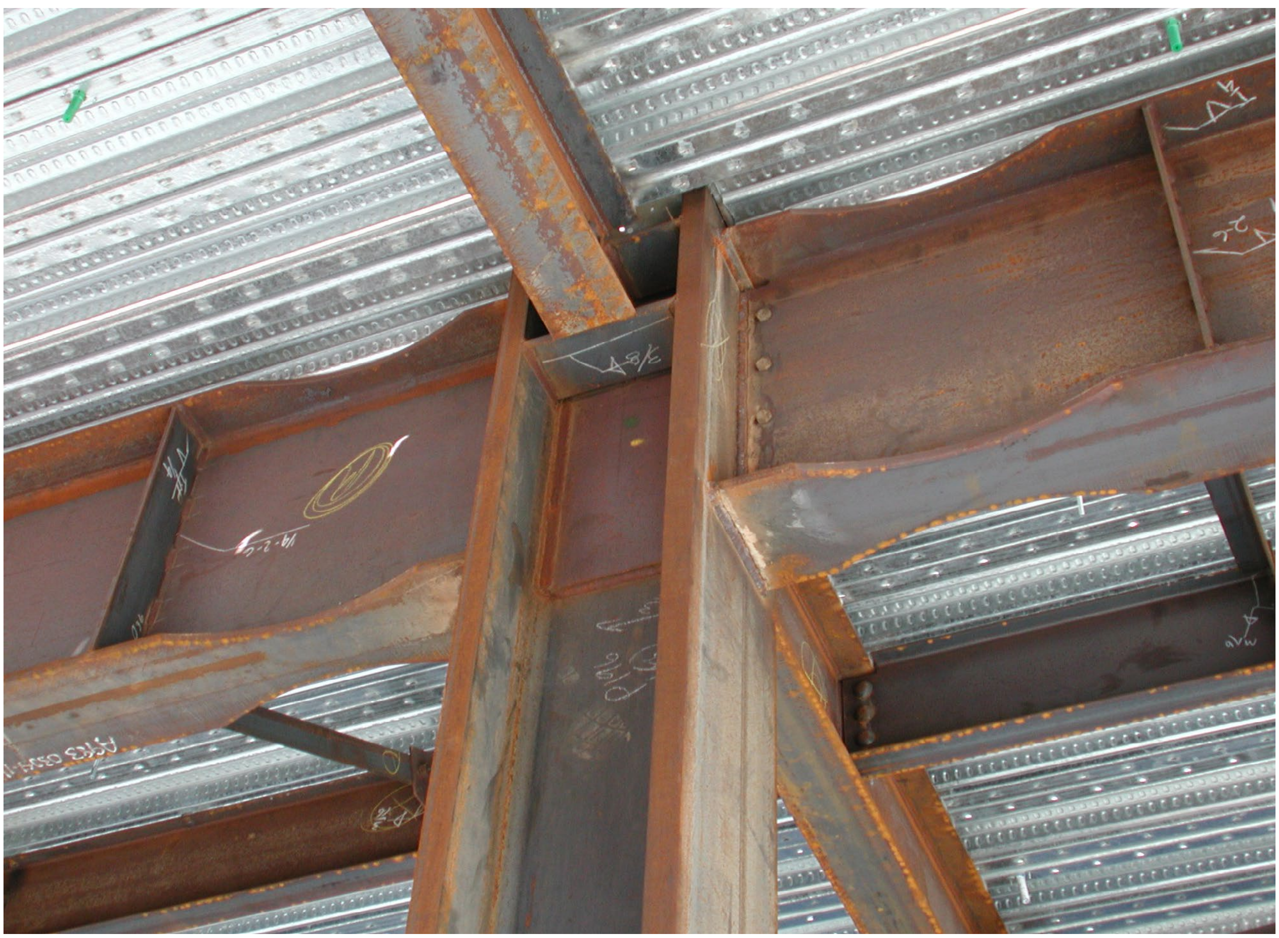


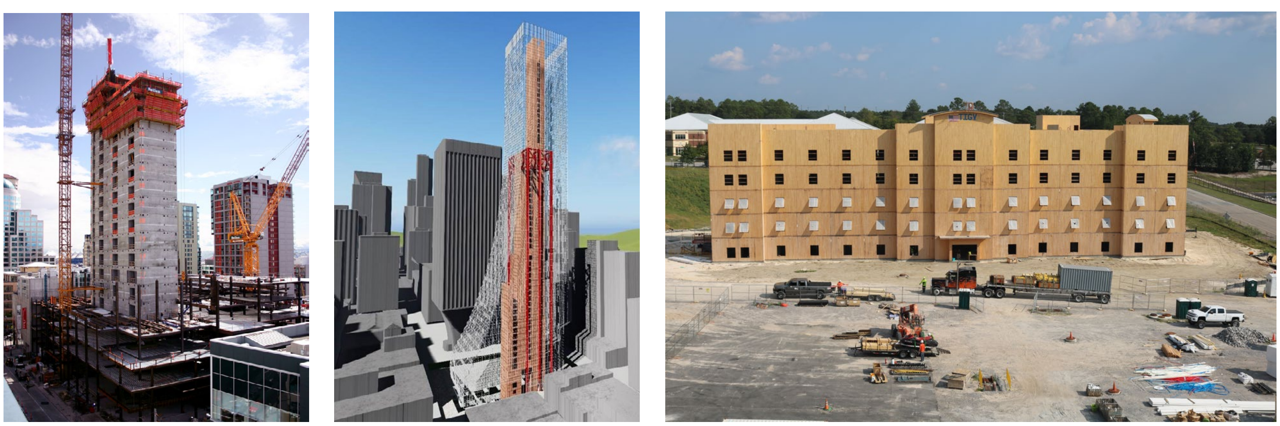
Figure 3-5. In this technique for allowing a steel frame to deform in a ductile manner, the beam is intentionally weakened with a "dogbone" cutout so that inelastic behavior will be concentrated in that segment of the frame, protecting the column from damage. (Source: *Chia-Ming Uang*)

than calculations indicate. R factors became one of the most important parameters in seismic design. They considered inelastic behavior by reducing the required strength of the structure. A given R factor was also associated with a number of proportioning and detailing requirements in addition to the influence of the R on the design lateral loads. Advocates of various systems (moment frames, braced frames, shear walls, etc.) and various materials (primarily steel, concrete, wood, masonry) had strong feelings about appropriate R factors for their systems, and there is some still adjustment occurring.

The *NEHRP Recommended Seismic Provisions* provide a national and authoritative forum to evaluate and assess new seismic design methods, new technology, and innovative seismic resisting systems.

Until the national platform of the *NEHRP Recommended Seismic Provisions* was developed, there was no fair and effective forum in which to set R factors, and there was no accepted method to calculate and validate them. The Provisions Update Committee provided such a forum and was purposely balanced among construction material interests, academia, practice, and geographical distribution. Recently, the PUC formally accepted the FEMA P-695 method to calculate acceptable seismic design factors, including the R factor, to be applied to all new systems introduced into the code (FEMA 2009). FEMA P-695 calibrated R factors for major lateral force-resisting systems and set the performance objective as 10% probability of collapse at the maximum considered earthquake (MCE_R) motions, a criterion now adopted by ASCE 7.

To answer the questions of how much elastic strength and ductility to provide in a structure and how much ductility to



(a) (b) (c)

Figure 3-6. The Three New Seismic Force-Resisting Systems that Are Introduced and Approved in the 2020 *NEHRP Recommended Seismic Provisions*: (1) reinforced concrete ductile coupled walls (Source: MKA), (2) steel and concrete coupled composite plate shear walls (Source: MKA), and (3) cross-laminated timber shear walls (Source: Lendlease).

give it to remain stable when forces exceed the elastic level, (how much "overdraft" protection is needed in the "checking account"), the ground shaking and induced seismic loading must be known. Through its 1985 edition, the UBC used a Z factor that was roughly indicative of the peak acceleration on rock expected to be exceeded approximately once every approximately every 475 years, on average (corresponding to a probability of 10% in fifty years). The upper-bound design base shear or the flat-top part of the design spectrum was soil-independent; the descending branch or the period-dependent part of the design spectrum varied with one divided by the square root of T (T being the period of vibration) and was modified by a site coefficient S; there was a lower-bound design base shear that was soil-independent. Because short buildings tend to be stiffer in resisting horizontal seismic loads, they have natural vibration periods that are shorter, that is, it takes less time for the structure to naturally tend to vibrate back and forth. The inverse is true for tall buildings, which tend to sway back and forth in a longer period of time, that is, they have

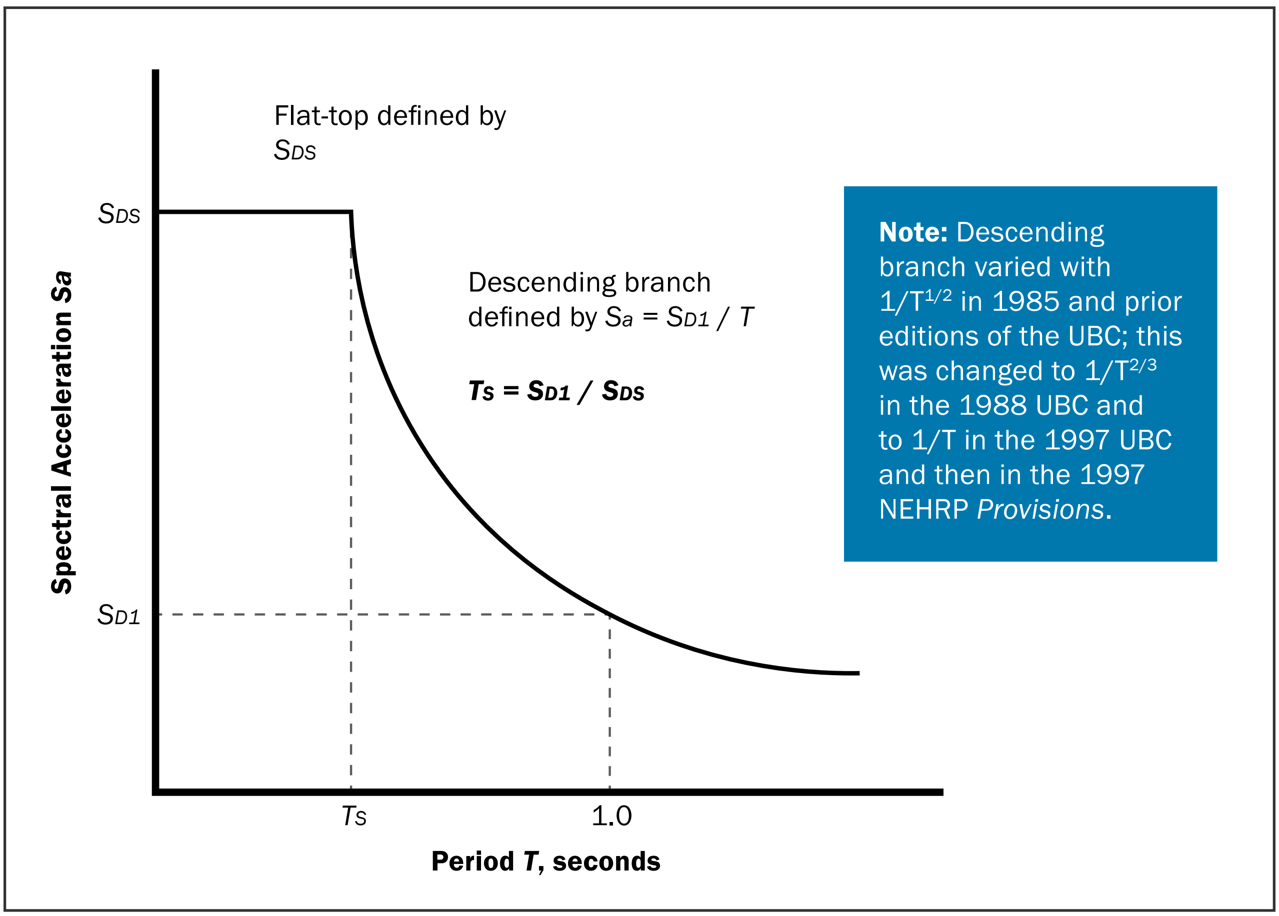


Figure 3-7. *NEHRP Seismic Provisions* Generic Design Spectrum.

a longer period of vibration. It is fortunate that the level of load as one proceeds to the right in the graph of Figure 3-7, the declining portion of the curve representing taller buildings, diminishes. A tall building may weigh many times that of a short building, but fortunately, it can be designed for a lesser lateral load per pound.

The design response spectrum shown generically in Figure 3-7 can be approximately interpreted as depicting the amount of seismic load a building must resist, proportional to its mass. In essence, this is the load per pound, or the percentage of the weight of the building that is calculated as the seismic design load. The tall building usually resonates or tunes in to the ground's vibrations less than the short building. The tall building has a natural tendency to sway; the short building is stiffer and tends to shiver. Additional factors such as the local soils characteristics, distance from the earthquake and type of faulting, and the transmission path of the seismic waves are now incorporated in the design spectrum. From the 1997 to 2003 editions of the *NEHRP Recommended Seismic Provisions*, the Maximum Considered Earthquake (MCE) ground motions underlying the design spectrum were, in most of the country, expected to be exceeded once every 2,500 years, on average, which is a long enough time window to capture the effects of large, infrequent earthquakes such as those that happened in the winter of 1811-1812 in the central United States (the New Madrid Earthquakes). The more recent uniform risk-targeted MCE (i.e., MCE_R) ground motions also capture such infrequent earthquakes. In both cases, the design forces are set at 2/3 MCE because the ductile detailing and other aspects of the design are intended to allow the building to perform safely at 1.5 times its design level.

For longer period structures on soft soil, ASCE/SEI 7-16 prohibits the general use of the three-parameter spectrum, instead requiring site-specific hazard determination. In the 2020 *Provisions* cycle, a Multiperiod Response Spectra (MPRS) Work Group under the BSSC Project 17 Committee on Seismic Design Value Maps was charged with evaluation and development of multi-period response spectra and related procedures as a replacement to the present three-domain response spectra. The committee also considered how the basic design procedures embedded in ASCE/SEI 7 should be modified for compatibility with the multi-period response spectra. This resulted in the development of a series of comprehensive multi-period response spectra proposals with changes to Chapter 11 and related changes to Chapter 20, Chapter 21, and Chapter 22 in the 2020 NEHRP Provisions, FEMA P2082.

(Kircher 2019, FEMA 2020). The MPRS procedures not only cover the conterminous US, but also are extended for all non-conterminous states and territories.

FEMA P-2078, *Procedures for Developing Multi-Period Response Spectra of Non-Conterminous United States Sites* (FEMA 2020) provides the technical basis and associated methods for the USGS to develop MPRS for sites in non-conterminous United States regions.

The changes collectively improve the accuracy of the design ground motions and enhance the reliability of the seismic design parameters derived from them by defining design ground motions in terms of site-specific MPRS. MPRS have also corrected an issue that caused underestimation of ground motion shaking intensity for tall buildings at soft soil sites near major faults. Such changes make better use of the available earth science, which has, in general, sufficiently advanced to accurately define spectral response for different site conditions over a broad range of periods. It also eliminates the need for site-specific hazard analysis required by ASCE/SEI 7-16 for certain soft soil sites. The changes to Chapter 11 incorporate values of S_{MS} and S_{M1} derived from multi-period site-specific MCE_R response spectra (provided online by the USGS, in lieu of mapped values of S_S and S_1, for user-specified site location e.g., latitude, longitude and site class) that include site amplification and other site (and source) dependent effects. The definition of design parameters S_{DS} and S_{D1} (two-thirds of S_{MS} and S_{M1}) and their use in Chapter 12 and other chapters to define seismic loads for equivalent lateral force (ELF) design, etc., remain the same as that of ASCE/SEI 7-16 (and prior editions ASCE/SEI 7). Traditional methods familiar to and commonly used by engineering practitioners for building design will not change.

Geotechnical engineers analyze data on soils and site-specific investigation, such as borings, to determine site characteristics. Structural engineers will then use the site characteristics to determine seismic loads. The site characteristics also have a great effect on the required level of ductility in the structure, along with limitations on building height and structural system, a significant change from the codes in earlier years.

In comparing overall building design requirements in the earlier *NEHRP Recommended Seismic Provisions* to the later ones, one might ask why the design levels have sometimes risen or fallen more for some buildings than others in a given region. A significant part of the answer is that increased knowledge of the seismological and geotechnical nature of ground motions has made some sites have higher or lower predicted effects on structural response than other sites in the same region that may have previously been mapped as being identical.

Since the *NEHRP Recommended Seismic Provisions* were developed, the advent and improvement of computers has made it more practical to directly consider inelastic behavior, particularly for design of large or important buildings. Guidance for such design was needed (see Section 1.4 An Example of the Updating of the NEHRP Recommended Seismic Provisions).

3.3 Combining Occupancy with Seismic Mapping

Seismic Zone

In the 1997 edition of the Uniform Building Code and the seismic codes, standards, and other documents based on the UBC, seismic detailing requirements and other restrictions such as height limits on certain structural systems depended upon the Seismic Zone in which a structure is located. Zones where large regions in which the intensity of seismic ground motion, corresponding to a certain probability of occurrence, was within certain ranges. The United States was divided into Seismic Zones 0 through 4, with 0 indicating the weakest earthquake ground motion and 4 indicating the strongest. The level of seismic detailing (ordinary, intermediate, or special), the height limits on structural systems, and the type of analysis that must, as a minimum, be carried out as the basis of design, were all determined solely or in part by the Seismic Zone.

Seismic Performance Categories

Given that public safety is a primary code objective and that not all buildings in a Seismic Zone are equally crucial to public safety, a new mechanism called the Seismic Performance Category (SPC) was developed in the ATC 3 document, and was used in all the *NEHRP Recommended Seismic Provisions* through 1994. In all these documents, the SPC, rather than the Seismic Zone, was the determinant of seismic detailing requirements and other restrictions. It was thus dictated that, in many cases, the seismic design requirements for a hospital be more restrictive than those for a small business structure constructed on the same site. The detailing requirements for Seismic Performance Categories A & B, C, and D & E were roughly equivalent to those for Seismic Zones 0 & 1, 2, and 3 & 4, respectively.

Seismic Design Categories

A subsequent development was the establishment of Seismic Design Categories as the determinant of seismic detailing requirements in the 1997 *NEHRP Recommended Seismic Provisions* and the 2000 IBC.

Building performance during a seismic event depends not only on the severity of the subsurface rock motion but also on the type of soil upon which a structure is founded. It is logical, however, to expect significantly different requirements for different uses of a building, as is done with fire protection and other hazard-related code requirements. The SDC is a function of location, building occupancy, and soil type. For a structure, the SDC needs to be determined twice—first as a function of the short-period seismic input parameter, S_{DS}, and a second time as a function of the long-period seismic input parameter, S_{D1}. The more severe category governs.

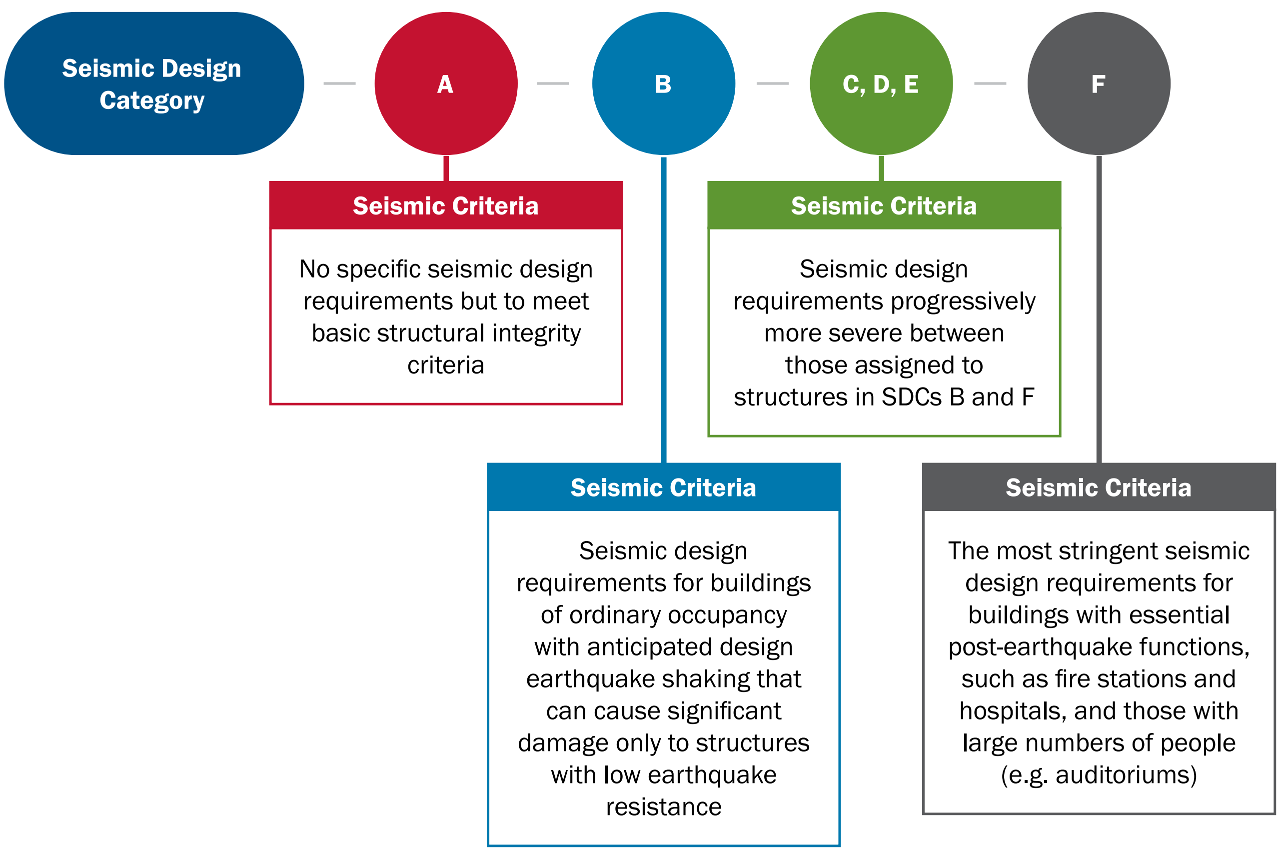


Figure 3-8. Seismic Design Categories

In 1978, ATC-3 made the level of detailing, as well as other restrictions concerning permissible structural systems, height, irregularity, and analysis procedure, a function of occupancy. This was a major departure from prior practice and was continued in all the *NEHRP Recommended Seismic Provisions* through the 1994 edition. Now, starting with the 1997 *Provisions* and the 2000 IBC, the level of detailing and the other restrictions have been made a function of the soil characteristics at the site of the structure in addition to occupancy. This is a further major departure from prior practice across the United States, a move that has had a profound impact on the economic and safety aspects of earthquake-resistant construction across the nation.

In most seismic regulations prior to the *NEHRP Recommended Seismic Provisions*, the occupancy or use of a building increased design forces and required some associated structural detailing, but the occupancy did not have a major impact on other aspects of the analysis and design. Beginning in the 1996 UBC, an Importance or I factor was introduced that increased design forces 50% for some critical occupancies. It is logical, however, to expect significantly different requirements for different uses of a building, as is done with fire protection and other hazard-related code requirements.

The N*EHRP Recommended Seismic Provisions* introduced the important concept of Seismic Design Category, which establishes the different post-earthquake performance expectations for different occupancies of buildings.

The SDC in the *NEHRP Recommended Seismic Provisions* added the sophistication of discriminating between two buildings with the same site characteristics where one has a higher occupancy or inherent risk, such as a facility storing hazardous materials. SDC is a tool to achieve the two purposes in the *NEHRP Recommended Seismic Provisions*:

- protect health, safety, and welfare by minimizing the earthquake- related risk to life, and
- improve the capability of essential facilities, facilities containing many people, and facilities housing large quantities of hazardous materials to remain functional after an earthquake.

As discussed later (see Chapter 5), current thinking about community resilience also has an impact on the *NEHRP Recommended Seismic Provisions*.

The SDC encourages inherently earthquake-resistant structural configurations by applying extra requirements for irregular layouts of the building or its framing. An example of a vertical irregular configuration is a soft-story building that has stiff shear walls in upper stories supported by columns at ground level. As the building deflects sideways, the columns tend to take the brunt of the loading. An example of an irregularity in plan is a building with high lateral resistance along one side of the building but little on the opposite side where extensive windows might be located, leading to torsion, or twisting of the building in plan. Building irregularities are discussed below.

The SDC assigned to a building applies more stringent requirements in some instances and loosens the requirements for other buildings. A cookie cutter approach across the United States for many different building uses is not logical; a hospital on poor soil in a highly seismic locale should not be designed to the same category as a small store on the other side of town on competent soil, for example. Those risk factors are covered by the SDC.

There is an approximate relationship among SDCs, observed intensity values as classified in the Modified Mercalli Intensity scale (MMI), and expected structure damage (FEMA 2015a p. 200):

MMI V	No real damage	SDC A
MMI VI	Light nonstructural damage	SDC B
MMI VII	Hazardous nonstructural damage	SDC C
MMI VIII	Hazardous damage to susceptible structures	SDC D
MMI IX	Hazardous damage to robust structures	SDC E

3.4 Building Deflections (Drift)

The *NEHRP Recommended Seismic Provisions* recognized, included, and standardized the way building deflection is consideration in seismic design practice.

Strong earthquake shaking will induce large lateral forces that tend to move structures horizontally and produce large horizontal displacements in the structure. These horizontal displacements have proven to be particularly damaging and can cause instability. Before the *NEHRP Recommended Seismic Provisions*, the amount that a building leaned over at its roof (total drift) and the amount by which one floor deflected sideways compared to adjacent ones (interstory drift) were not major seismic design considerations. Research and experience in actual earthquakes have proven that drift is in fact a major indicator of the amount of damage a building will incur. Methods for more accurately calculating drift began to develop in the 1960s and 1970s and were incorporated into early editions of the *NEHRP Recommended Seismic Provisions*.

Drift is important as a measure of the demand on the structure: different types of structures have their own tolerance for drift, and exceeding those limits leads to structural damage. Drift is also essential for considering nonstructural damage to vertically oriented components such as windows and partitions that can be damaged when they are forced to "go along for the ride" as the building distorts. Drift is such an important parameter that it is the primary factor predicting expected building performance, both for structural and nonstructural damage. Nonstructural damage to equipment is also closely related to acceleration.

3.5 Nonstructural Components

Nonstructural components include the architectural, mechanical, electrical, and plumbing systems of a structure. These systems typically comprise three quarters of the original construction cost of a building. In some buildings, such as hospitals and high-tech manufacturing plants, the value of the equipment in the building can cost more than the building itself. Prior to the *NEHRP Recommended Seismic Provisions*, U.S. building codes typically provided only brief, generic seismic design provisions for limited categories of nonstructural components.

Figure 3-9. The extreme drift and structural damage experienced by Olive View Hospital in the 1971 San Fernando Earthquake also rendered nonstructural components damaged and non-functional. (Source: *Robert Olson, NISEE-PEER*)

The *NEHRP Recommended Seismic Provisions* editions have provided key support for the development of comprehensive seismic design requirements for nonstructural components. The 1985 edition of the *NEHRP Recommended Seismic Provisions* adopted the nonstructural requirements of ATC-3 (ATC, 1978), which introduced a new, more rigorous approach to the design of nonstructural components. The 1985 *Provisions* provided design procedures based on the type of component and seismic hazard levels, as well as the performance objectives for the component. The design procedures considered the influence that the structure supporting the components had on the forces that the components experience during an earthquake. In the 1994 *Provisions*, the recommended design procedures for nonstructural components were substantially revised, with further refinements in the determination of the design properties of nonstructural components. The 1994 *Provisions* was adopted with modifications by the 1997 UBC introducing these innovations into design practice. The nonstructural requirements in the 1997 *Provisions* adopted the format for the design formulas incorporated into the 1997 UBC and included updates to the lateral force equation based on information collected in the 1994 Northridge Earthquake.

The *NEHRP Recommended Seismic Provisions* provide a framework for determining design lateral forces and displacements for nonstructural components that has been refined over several decades. The framework includes analysis methods used for critical and essential nonstructural components that must function following the earthquake. The building industry has partnered with code enforcement organizations to develop testing and analysis procedures, allowing certification that specific criteria of the *NEHRP Recommended Seismic Provisions* has been met. Over time, the *NEHRP Recommended Seismic Provisions* has been enhanced with the enhanced design requirements, such as for:

- glass curtain wall and storefront systems;
- quality assurance requirements for nonstructural components;
- inspection requirements for component anchorage;
- ceiling systems;
- mechanical and electrical components; and
- inspection of the installation of cladding.

Revisions focus on reducing hazards to life safety and enhancing the performance of critical systems such as those providing

The *NEHRP Recommended Seismic Provisions* provides key support for the development of seismic design of nonstructural components, like architectural, mechanical, electrical, and plumbing systems, which are key elements in developing functional recovery practice and resilience-based design.

emergency power or containing hazardous materials. Special seismic certifications were required for mechanical and electrical components that must operate following an earthquake, through shake table testing.

In the 2020 *Provisions* FEMA P-2082 (FEMA 2020), new procedures for determining the seismic design force for nonstructural equations were introduced. The new design procedures are based on equations and underlying research produced by the Applied Technology Council and published by NIST (2017 and 2018). The goal of the effort was to develop equations that have a more rigorous scientific basis and capture the key parameters that influence nonstructural component response while remaining appropriate for practical use in design by engineers. Many factors were identified that contribute to the magnitude of seismic forces that nonstructural components experience in strong earthquake shaking. A set of equations combining the selected parameters of interest was tested using an extensive set of nonlinear response history analyses of archetype buildings and components as well as analysis of ground and floor motion records from instrumented buildings. Today's deployment of strong motion accelerographs includes many such instruments installed in various levels of major buildings as well as on the ground.

The proposed revisions to the design equations address the influence of supporting structure on nonstructural component demands. This information, along with the type of component, height of the structure, and the height of the point of attachment of the component to the structure (which are all currently required), allow the designer to obtain a significantly more accurate design lateral force.

3.6 Building Irregularities

A structure is termed regular if the distribution of its mass, strength, and stiffness is such that it will sway in a uniform manner when subjected to ground shaking. Regular structures tend to dissipate the earthquake's energy more uniformly throughout the structure and generally have better performance. In an irregular structure, however, the damage can be concentrated in one or a few locations, resulting in extreme local damage and a loss of the structure's ability to survive the earthquake. The aforementioned soft story is one example (see Figure 3-11). Before the *NEHRP Recommended Seismic Provisions*, building codes in the

Figure 3-10. In the 1994 Northridge Earthquake in the Los Angeles region, this heavy soffit or exterior ceiling collapsed over the entrance. Nonstructural protection involves secure attachments of the nonstructural components to the structure. (Source: *Robert Reitherman*)

FEMA P-2012, *Assessing Seismic Performance of Buildings with Configuration Irregularities* (FEMA 2018) quantitively evaluated triggers and related design requirements for structural irregularities.

https://www.fema.gov/sites/default/files/2020-08/fema_assessing-seismic-performance-irregularities_p-2012.pdf

United States often dealt with irregularities in the configuration of a building in only a general way, although the 1988 UBC had already begun that process. Engineers need to know with quantitative specificity when an irregularity is significant and if so how to take that into account In some cases, the straightforward solution is simply to revise the architectural layout to remove the structural irregularity, but due to competing factors in the overall design process, this rarely happens. In other cases, more earthquake-resistant structural members are required.

An example of a nonsymmetrical plan is a building approximately the shape of a shoe box with a stiff concrete core at one end of the building for elevators and services and only more flexible frames at the other end. When the building is loaded sideways by the ground motion, the end with the stiff core does not deflect much while the other end does.

When looking down on the building (looking at it in plan), it

Figure 3-11. The extreme drift or sideways distortion of the Olive View Hospital in the 1971 San Fernando was caused by a soft-story condition: strong and stiff walls were discontinued at the ground story level, and all of the deformation was imposed on the columns. (Source: *William Godden, NISEE-PEER*)

would be seen to twist or experience torsion, which can be a significant cause of damage. An example of a lack of redundancy would be a building held up by only four columns at the corners. If any single column is badly damaged, there is no backup to take up the load. FEMA P-2012, Assessing Seismic Performance of Buildings with Configuration Irregularities, (FEMA 2018), reported a systematic evaluation of the building irregularities through a rigorous analysis process. The 2020 *Provisions* incorporated the findings of the report by removing the restriction on mass irregularity and enhanced requirements and analysis procedures for torsional irregularities.

3.7 Simplification of Seismic Design Procedures and Provisions

A great deal of thought and effort has gone into making the *NEHRP Recommended Seismic Provisions* as easy to understand and efficient to apply as possible.

For example, FEMA funded BSSC for a program to simplify seismic design and provisions in 2009, which developed the new chapter 24, Seismic Design Requirements for Seismic Design Category B Buildings in the 2015 *Provisions*. In this Seismic Design Category, the risk is relatively low because of low seismicity, which pertains to large areas of the United States. The 2015 Provisions contain a new chapter, Chapter 24, which has a simplified, alternate seismic design procedure for structures in Seismic Design Category (SDC) B. A structure in SDC B designed using 2015 *Provisions* Chapter 24 is essentially equivalent to a design using ASCE 7-10, Chapter 12, but the engineer has the convenience of a much simpler, more transparent, and easy to follow design requirement document to work with.

FEMA P-1091, *Recommended Simplified Provisions for Seismic Design Category B Buildings* (FEMA 2017) included specific seismic design requirements for Seismic Design Category B (SDC B) buildings:

https://www.fema.gov/media-library-data/1516221536008-f3c43a06fe9f039bd72e98d228f6494e/FEMA_P-1091_508.pdf

An alternate design procedure for rigid walls-flexible diaphragm (RWFD) buildings was also introduced by the same BSSC program. For the RWFD building type, this procedure demonstrated that design provisions targeted for a single building type can be simpler and more consistently meet expected performance objectives. The procedure formed the basis for improved RWFD design recommendations published in FEMA P-1026 (FEMA 2015), which was updated and adopted in the 2020 *NEHRP Provisions* (FEMA 2020).

These are examples of how input from practitioners has affected the *NEHRP Recommended Seismic Provisions*, with the aim to achieve equivalent quality in seismically resistant construction with less design and/or construction cost.

Chapter 4

Continual Efforts to Reduce Earthquake Risks

As more construction inventory is added each year that incorporates the earthquake-resistant features of the *NEHRP Recommended Seismic Provisions*, the nation's building stock is becoming increasingly improved. This is a critical step in improving the safety and resilience of the built environment. This chapter looks at the economic impact of the implementation of the *NEHRP Recommended Seismic Provisions* over the past decades and the increase in the protection of essential function and federal buildings.

4.1 Economic Impacts

The National Institute of Building Science Natural Hazard Mitigation Saves study (Multi-Hazard Mitigation Council 2020a) estimates that the enhanced earthquake design requirement over the last 30 years saves $7 billion per year of new construction while only adding $600 million per year in construction cost, producing a Benefit-Cost Ratio of 12:1.

> The *NEHRP Recommended Seismic Provisions* substantially and highly cost effectively reduce the nation's disaster liability. Enhanced earthquake design requirement over the last 30 years save $7 billion per year of new construction while only adding $600 million per year in construction cost, producing a benefit-cost ratio of 12:1.

Before the *NEHRP Recommended Seismic Provisions*, the ever-increasing construction of new buildings that were not adequately designed to resist earthquakes produced an ever-increasing inventory of earthquake risks. Many buildings constructed prior to the advent of the *NEHRP Recommended Seismic Provisions* constitute an unfortunate legacy of vulnerability.

The average building on the west coast of the United States constructed to the building code 30 years ago is two-thirds as strong or stiff as the same design built to the 2018 IBC (Multi-Hazard Mitigation Council 2020). This is a product of both the continuing sophistication in ground motion mapping and the increasing structural requirements.

The increased cost of incorporating the *NEHRP Recommended Seismic Provisions* into a building, as compared no provisions or minimal provisions, has been estimated to be only 1.6% based on a study of 52 hypothetical buildings in seven U.S. cities (Multi-Hazard Mitigation Council 2020b). A NIST study comparing the cost of redesigning six particular buildings in Memphis, Tennessee to comply with the 2012 IBC, rather than the 1999 Southern Building Code, estimated this would add no more than 1% to the resulting construction cost, while increasing strength and stiffness on average by 60% (NEHRP Consultants Joint Venture 2013). The modest cost increase estimated by these two studies agrees with construction cost manuals, which show that the structural materials associated with the lateral force resisting system account for about 2% of the total construction cost of a common new low-rise office building. Increasing these materials by 50% can produce a similar increase in strength and stiffness, at a cost of 50% x 2% = 1% (Multi-Hazard Mitigation Council 2020a, summarized in Multi-Hazard Mitigation Council 2020b). The added construction cost as a fraction of total value (land plus building) gets lower as land value increases.

In one of the most recent Benefit-Cost Analysis of seismic design provisions, Natural Hazard Mitigation Saves by NIBS estimates the costs and the benefits of designing next year's buildings to 2018 seismic requirements rather than those of 1988. On average, buildings built to current standards are about 50% stronger and stiffer (and better detailed) than those of 30 years earlier. Greater strength tends to reduce the potential for structural damage, red tagging (posting of the building as unsafe to occupy), collapse, and loss of life, while greater stiffness tends to reduce costly damage to drift-sensitive nonstructural components. Better detailing tends to reduce damage to acceleration-sensitive nonstructural components.

Natural Hazard Mitigation Saves estimated the Benefit-Cost Ratio of the difference in strength and stiffness requirements on a geographic basis, varying the mix of structural materials, lateral force resisting system, height, and use to match local practice. Natural disaster losses in the United States are approaching $100 billion per year, which suggests that development of the *NEHRP Recommended Seismic Provisions* has substantially and highly cost effectively reduced the nation's disaster liability (Insurance Information Institute 2020).

Figure 4-1 shows the sources of these benefits. 2018 I-Codes reduce property repair costs by $3 billion on average per year of new construction relative to 1988 *Provisions*, which by itself saves the property owners the added construction cost five times over in the long run. Reduction in additional living expenses and direct business interruption (losses associated with not being able to use the building during repairs) saves $2 billion, meaning that these savings alone, which accrue to tenants, also pay for the added

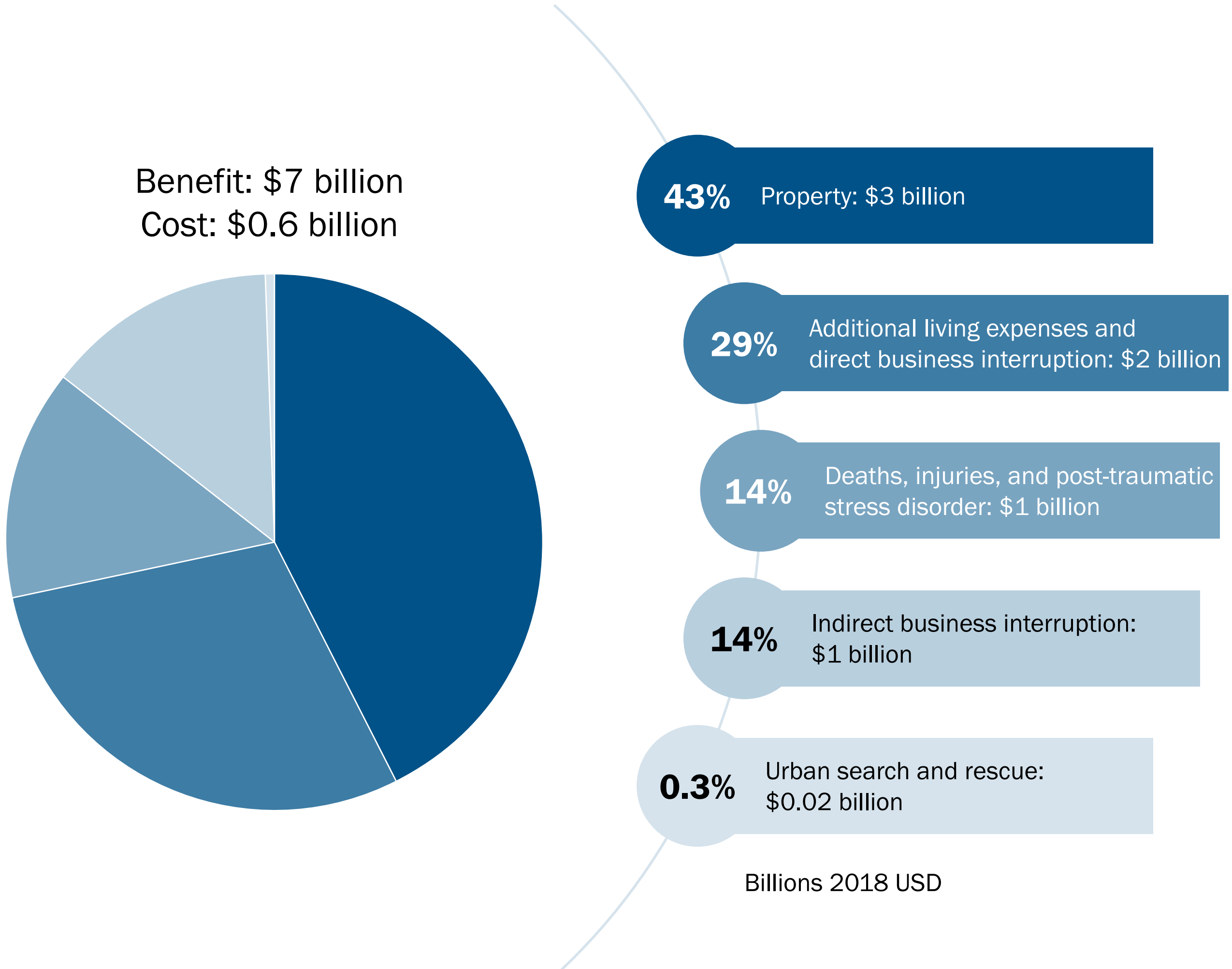


Figure 4-1. Total costs and benefits of new design to comply with 2018 I-Code requirements for earthquake, relative to 1988. (Source: Multi-Hazard Mitigation Council 2020a)

construction cost three times over. At federally acceptable costs to avoid future statistical deaths and injuries, the avoidance of deaths, injuries, and post-traumatic stress disorder saves $1 billion. The reduction in indirect business interruption, which accrues to the rest of the economy by reducing losses to everybody who buys or sells to the building occupants, also saves $1 billion, again more than paying for the added construction costs. Substantial savings also accrue to governments in the form of lower urban search and rescue costs (shown in the figure), as well as from more stable tax revenues and lower recovery costs (not shown to avoid double-counting). Virtually everybody wins on average in the long run.

Figure 4-2 shows that virtually every location in the 48 states subject to seismic design criteria wins as well, with local benefit-cost ratios as high as 30:1, that is, $30 saved per additional $1 of construction cost. The figure shows that benefit-cost ratios

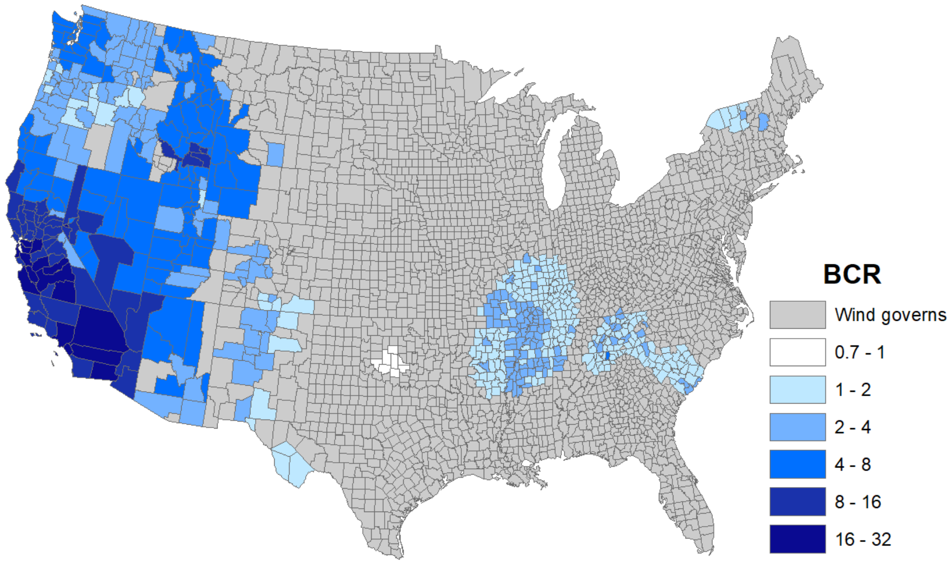


Figure 4-2. Benefit-cost ratios for seismic code compliance are highest in high-seismicity areas. (Source: Multi-Hazard Mitigation Council 2020)

are higher where seismicity is higher. Note that in much of the country, wind design forces exceed those for earthquake, so these areas are shown in gray, along with a small portion of Oklahoma where design forces have been raised to better protect people from seismicity associated with deep well injection (fracking).

Development of stricter seismic design provisions also produces intangible benefits that were acknowledged but could not be calculated in Natural Hazard Mitigation Saves. Among these benefits are peace of mind, continuity of life, savings of mementos, pets, environmental benefits, and protection of society's most vulnerable populations, to the extent that they live or work in newer buildings. If the authors had been able to quantify these benefits, they would have increased the numerator in the benefit-cost ratio, producing a higher overall value and higher locally varying values in Figure 4-2.

4.2 Essential Function Buildings

The preceding sections primarily discussed the role of the *NEHRP Recommended Seismic Provisions* in providing the building code provisions for the design of buildings of ordinary occupancies, as compared to facilities that have critical emergency response functions. A recent report from FEMA and NIST (2020) emphasizes two different aspects of protecting essential functions after an earthquake: reoccupancy and functional recovery. Achieving the goal of reoccupancy means being able to re-enter a building that has been determined to be safe. However, a building that is safe to occupy that has damaged equipment might not be function. Functional recovery refers to being able to not only occupy a building but to be able to use its usual functions. These goals can be broadly applied to the building stock in general to further the goal of resilience.

In addition, some buildings have critical functions whose disruption would cause serious effects, even if the building can be re-occupied and used a few days after an earthquake. The *NEHRP Recommended Seismic Provisions* have evolved to include increasingly detailed and comprehensive requirements for such buildings.

NEHRP Recommended Seismic Provisions Influence on Hospital Design

Prior to the 1971 San Fernando Earthquake, there were few differences between the structural design of essential facilities such as hospitals as compared to other commercial and institutional structures. One of the lessons learned in this earthquake was the importance of being able to provide essential services such as healthcare following an earthquake. As a result, a new category of building performance was needed: buildings that could undergo design level earthquake shaking and still perform essential functions. In response to the 1971 San Fernando Earthquake, criteria were added to building codes that were in use in areas of high seismic risk, such as California, that increased the design loads for essential buildings and put limits on some design features. These changes were intended to reduce earthquake-induced damage. However, the focus was primarily on improving structural performance by specifying higher design forces, and less emphasis was placed on improving the performance of nonstructural components.

At the same time that improvements in seismic performance were being implemented, advances in medical care were transforming hospitals. Less emphasis was being placed on providing beds for patients while greater emphasis was placed on providing advanced diagnostic and treatment services. This transformation spurred rapid increases in the complexity of the architectural components, mechanical and electrical systems, and medical equipment. Today, nonstructural components and contents account for over 90% of the cost to build and equip a hospital. The *NEHRP Recommended Seismic Provisions* has continuously played a critical role in helping to achieve the goal of hospitals being able to provide services in the aftermath of strong earthquake shaking.

The *NEHRP Recommended Seismic Provisions* has introduced a number of innovations that improve the expected performance of essential facilities, such as hospitals. An important step towards maintaining functionality was the provision of special certification for mechanical and electrical components that were required to operate following an earthquake. This certification requires shake table testing of the components to show that they will function following the design earthquake. Components in essential facilities are designed for higher earthquake loads to reduce the possibility of damage that could inhibit post-earthquake operation. Special consideration is given to nonstructural components that must accommodate the displacements of the structure that occur during an earthquake. Exterior cladding and glazing, mechanical and electrical systems, and other nonstructural components sensitive to lateral displacements are designed to avoid damage that inhibits essential functions. In addition, inspection during construction is important. Incorporation of these and other and other innovations introduced in the *NEHRP Recommended Seismic Provisions* has substantially improved the ability of hospitals to continue to provide services following an earthquake.

Figure 4-3. The 1994 Northridge Earthquake seemingly only cosmetically damaged this hospital's sign, but the cause was lunging of inadequately restrained air conditioning equipment that disabled the functioning of the facility. (Source: Robert Reitherman)

Other Essential Function Buildings

One can understand what a critical function is by imagining what would happen if a particular building's operation were to cease because of earthquake damage. Some functions must operate continuously, and any downtime could have serious consequences. Facilities such as hospitals, air traffic control facilities, control centers for utilities, and fire and police facilities require protection of their functionality.

One of the ways the *NEHRP Recommended Seismic Provisions* provides extra protection for essential function buildings is via the importance factor, I. This concept goes back to the response to the 1971 San Fernando Earthquake and the implementation of California's Hospital Act, discussed above, along with the Veteran Administration's similar but more comprehensive requirements for hospitals (including on-site water and other utility self-sufficiency), and changes implemented in the 1976 UBC.

Because some amount of electrical system outage must be anticipated in an earthquake, back-up power systems are of critical importance. As discussed earlier, both drift and acceleration can cause nonstructural damage. A large emergency power generator is composed of a high-horsepower engine, fuel, battery power, exhaust flue, cooling, and electrical connection to the building. The direct effect of shaking on batteries can make them topple (they are needed to start the motor, just as in an automobile) and the heavy (therefore high inertial load) motor-generator set can shift off its bearings. An exhaust flue that extends through a wall or roof can be sheared by the deflection of those parts of the buildings. Uninterruptible power systems are often heavy, and tall pieces of equipment that have to be restrained to keep from toppling. Examples from earthquakes of such failures are provided in Holmes and Reitherman (2014) and in *Reducing the Risks of Nonstructural Earthquake Damage - A Practical Guide* (FEMA 2012).

4.3 Protecting Federal Buildings from Earthquakes

The existence of a standardized national set of earthquake provisions has been essential to the success of the federal government's improvement of the seismic performance of its inventory of buildings, and in recent years, the *NEHRP Recommended Seismic Provisions* has provided that resource. The seismic code to which a building is designed is perhaps the most important determinant of how a building will fare when strong shaking occurs. The majority of losses from earthquakes has been due to building damage. Both the initial impact in terms of property damage and casualties and the ensuing recovery demands are largely due to the way a community's buildings have performed in the earthquake, although the importance of lifelines, beyond the scope of the *NEHRP Recommended Seismic Provisions*, should also be mentioned. Lifelines include water, wastewater, communications and energy generation and distribution systems and transportation systems.

As stated earlier, federal buildings are not under the jurisdiction of state, local, tribal, and territorial governments, thus the process of adopting seismic regulations, with the *NEHRP Recommended Seismic Provisions* leading to the seismic content in ASCE 7 and thence into the International Building Code, is not the same as with the case of the non-federal building getting a local building permit. Instead, the federal government has adopted building code requirements for its buildings, including earthquake design provisions, via Presidential executive orders (President of the United States 1990, 1994, 2016). The *NEHRP Recommended Seismic Provisions* was the set of seismic provisions which provided the basis for those federal regulations.

The critical importance of dealing with the federal inventory can be concisely summarized with these three points:

- Consider the immense size of the federal government's inventory of buildings owned, leased, or financed: 267,000 buildings with a total square footage of 2.8 billion square feet (General Services Administration 2016). For comparison, the entire non-residential building square footage in the 19 counties of Northern California (greater San Francisco Bay region) is only 85% of that, 2.4 billion square feet (Kircher et al. 2006, p.38).
- There is a vast diversity of agencies with sizable building inventories, which emphasizes the point that a standard applicable to all was necessary to manage a consistent national program. The 27 agencies represented in the Interagency Committee for Seismic Safety in Construction (ICSSC) indicate that diversity, a daunting list from the standpoint of trying to ensure a consistent federal approach without one set of seismic regulations. The ICSSC "was established in 1978 to assist the Federal agencies involved in construction to develop and

incorporate earthquake hazard-reduction measures in their programs." (Wright 1992, p. 12)

- A number of critical roles are played by agencies relying on the serviceability of their buildings, including law enforcement, medical, and other emergency services functions.

Three executive orders are briefly discussed below.

1. **Executive Order 12699 Seismic Safety of Federal and Federally Assisted or Regulated New Building Construction (President of the United States 1990)**

This executive order, issued in 1990, required seismic-resistant design for federal agencies owning, leasing, or regulating buildings as well as buildings receiving federal assistance (e.g., via mortgage financing). The executive order did not specifically require the use of the *NEHRP Recommended Seismic Provisions*. The seismic design provisions used must be deemed adequate by the responsible agency or the ICSSC. The ICSSC recommends model codes and standards that are substantially equivalent to the *NEHRP Recommended Seismic Provisions*.

A structural engineering evaluation of the various seismic regulations in building codes in existence as of 1995 (Melvyn Green & Associates 1995) found that there was substantial equivalence among the seismic regulations of the UBC, BOCA, and SBCCI building codes but that they varied in a number of ways and "each is constantly changing and being updated to incorporate the latest research findings, standards and methodologies." The report's comparative analysis of the dozens of specific aspects of those seismic regulations indicates the complexity of trying to evaluate equivalence among them and the simplicity of having one model set of provisions. The *NEHRP Recommended Seismic Provisions* became the solution to that problem. The lead entity moving the federal agencies in unison toward adoption and implementation of seismic regulations was the ICSSC (ICSSC 1992).

2. **Executive Order 12941 Seismic Safety of Existing Federally Owned or Leased Buildings (President of the United States 1994)**

The second executive order addresses that while constructing federal buildings with adequate earthquake protection is forward-looking, the vast number of existing buildings is much greater than the number built to a new edition of the code. Thus, Executive

Order 12941 was needed to deal with that existing building problem, which is intrinsically more difficult than dealing with new construction. Standards of the American Society of Civil Engineers (ASCE 31, ASCE 41) were used to guide that process. *The NEHRP Recommended Seismic Provisions* do not currently contain provisions for the evaluation and upgrading of existing buildings.

3. **Executive Order 13717 Establishing a Federal Earthquake Risk Management Standard (President of the United States 2016)**

The third executive order establishes a risk management standard for the inventory of federal buildings superseded Executive Order 12699 and Executive Order 12941 by including the essence of their content and updating it. The scope of Executive Order 13717 cast a broad net, as did the previous executive orders. It specified the use of the International Building Code or equivalent, and with the *NEHRP Recommended Seismic Provisions* embedded in that code, a national consistency was achieved across the seismic programs of the more than two dozen federal agencies. The International Residential Code was specified for use with buildings within its scope, namely one- and two-family residences and townhouses not exceeding three stories in height.

In an effort to go beyond the goal of designing for life safety, content in Executive Order 13717 also recommends the adoption of higher levels of seismic protection. In most cases, the life safety goal of the *NEHRP Recommended Seismic Provisions* and the IBC does not explicitly provide for post-earthquake functionality or rapid recovery. However, under moderate shaking, buildings designed to the IBC can experience damage that disrupts functions. Interagency Committee on Seismic Safety in Construction, an ICSSC Recommended Practice document published in 2017, gives guidance on the Executive Order 13717. Executive Order 13717 also provides the current requirements for biennial reporting by the agencies on their progress in implementing the Executive Order.

Chapter 5

NEHRP Recommended Seismic Provisions, Resilience-Based Design and the Future

The *NEHRP Provisions* has become a well-known brand name in the earthquake field and has pervasive influence.

5.1 Staying Up to Date

The *NEHRP Provisions* continue to be updated by FEMA and BSSC today through evaluation of large volume of new seismic information produced every year from analytical studies, laboratory testing, earth science research, new construction products and methods, input on practical seismic design aspects from the building industry and design practitioners, and by the lessons learned from recent earthquakes.

5.2 Community-Based Design

Conceptual ideas have been proposed to consider the seismic protection of an entire community instead of an individual structure, especially considering the lifelines/utilities systems, e.g., electricity, water, and transportation. Earthquake Resistant Lifelines: NEHRP Research, Development and Implementation Roadmap (NIST, 2014) recommends that the development of appropriate guidelines and standards for recovery-based seismic design be developed.

The BSSC considered post-earthquake functional and economic performance in the 2015 *Provisions* through a Part 3 Resource Paper that was built on a NIST report titled Community Resilience Planning Guide for Buildings and Infrastructure Systems, (NIST 2016). The NIST report outlines a planning process to help communities set priorities and allocate resources to improve their resilience. The resource paper provides performance objectives at each risk category in terms of life safety, function, and economic risk using multiple earthquake ground motion intensities.

Since the 2015 *Provisions*, the issue of earthquake resilience has received significant attention nationally, and there is considerable interest in the post-earthquake function for buildings of many

The *NEHRP Recommended Seismic Provisions* can help explore and provide technical resources for design of new buildings to include recovery-based objectives.

uses, not only those assigned to the more essential occupancies in Risk Category IV. The NEHRP Reauthorization Act of 2018 contains language related to community resilience as well as seismic risk. Specifically related to seismic standards, it requires recommendation of options for improving the built environment and critical infrastructure to reflect goals stated in terms of post-earthquake re-occupancy and functional recovery time. In response to the legislation, NIST and FEMA have engaged with a committee of experts that developed a special report: Recommended Options for Improving the Built Environment for Post-Earthquake Reoccupancy and Functional Recovery Time, FEMA P-2090/ NIST SP-1254.

In the 2020 *Provisions*, a conceptual resource paper has been developed that addresses the relationship between future *NEHRP Recommended Seismic Provisions* and resilience-based seismic design. The paper recognizes that the current codes-and-standards model is adaptable to resilience-based design, with the standard providing technical definitions and design criteria and the code setting policy goals. It acknowledges the lead role played by the *NEHRP Recommended Seismic Provisions* in setting seismic design criteria and that future criteria will need to address both life safety and functional recovery. There is an increasing trend that design standards need to incorporate the element of recovery time, which is not currently done.

The development of recovery-based resilience provisions, codes, and standards will be an evolution of current practice. The coming 2026 *Provisions* may help explore comprehensive recovery-based seismic design for new buildings. It will play an important role in setting seismic design criteria to address both life safety and resilience.

5.3 Outreach, Education, and Dissemination

The FEMA program is not limited to the development and publication of each new edition of the *NEHRP Recommended Seismic Provisions*. The *NEHRP Recommended Seismic Provisions* are widely referenced throughout the United States and globally as a university-level earthquake engineering teaching resource. Outreach, education, and dissemination activities to support the application of the *NEHRP Recommended Seismic Provisions* will continue to be an important objective within the development process. More engagement with stakeholders and users of the *NEHRP Recommended Seismic Provisions* will also be beneficial.

Appendix A

Abbreviations

ANSI	American National Standards Institute
ATC	Applied Technology Council
ASCE	American Society of Civil Engineers
BOCA	Building Officials and Code Administrators
BSSC	Building Seismic Safety Council
FEMA	Federal Emergency Management Agency
IBC	International Building Code
ICC	International Code Council
ICSSC	Interagency Committee on Seismic Safety in Construction
ICBO	International Congress of Building Officials
IRC	International Residential Code
NEHRP	National Earthquake Hazards Reduction Program
NIBS	National Institute of Building Sciences
NIST	National Institute of Standards and Technology
NSF	National Science Foundation
PUC	Provisions Update Committee
R	Response Modification Factor
SBCCI	Southern Building Code Congress International
SBC	Standard Building Code
SDC	Seismic Design Category
SEAOC	Structural Engineers Association of California
UBC	Uniform Building Code
USGS	U.S. Geological Survey

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Appendix B

Brief History of Seismic Regulations in American Building Codes

Earlier, this document explained the evolution of the *NEHRP Recommended Seismic Provisions* from the time of the ATC-3 project and the 1978 publication of ATC-3 (Applied Technology Council 1978) up through the present. This short appendix highlights some of the earlier milestones in the development of seismic regulations in the building codes of the United States. This brief review is not meant to be a comprehensive treatment of this topic. Interested readers will find the references cited useful for obtaining further information.

First, it must be noted that both Italy and Japan adopted building code regulations for earthquakes decades before any regulations were adopted in the United States. For example, in Italy there were regulations promulgated after the 1783 Calabria Earthquake to require prescriptive (non-engineered) construction measures in the affected southern region of the country (Tobriner 1983, 1984a, 1984b). Use of diagonal bracing embedded in masonry walls after the 1755 Lisbon Earthquake also occurred. Sorrentino (2006) has combined an engineer's and historian's analysis of several early Italian earthquakes, including the intentional seismic retrofitting of Malfi Castle after a 1694 earthquake damaged it. Iron diaphragm-wall ties and iron tie rods were used. (Note that iron tie rods were frequently used to deal with the lateral thrust of arches, but it is well documented that in the retrofitting of Malfi Castle, the purpose was unrelated to arches. The contemporary correspondence of the designer, Francesco Canevaro, also documents verbally and graphically his seismic intent). Such construction features later became part of the evolving building codes in Italy.

It is sometimes said that several centuries prior to approximately the 1900s "earthquake engineering" was employed in various places around the world, but the term "engineering" can be misleading because only non-engineered construction techniques were involved. Engineering theory that enabled mathematical representations of structures so that calculations could be conducted was only possible after structural engineering in general developed in the eighteenth and nineteenth centuries.

In 1908, the Reggio-Messina Earthquake affected the region on both sides of the strait separating Sicily from the mainland of Italy, causing 80,000 fatalities (still the greatest life loss in a European earthquake since the 1755 Lisbon Earthquake).

Not only were regulations adopted, but they were of a modern engineered type. A committee of engineers made calculations and used principles of structural engineering to devise the rules. An international competition held for engineers in 1909 elicited 240 submissions—the world's first such compilation of design and analysis papers on seismic engineering (Sorrentino 2011). Some of the thinking was extremely advanced for its time, such as the work of Arturo Danusso that mathematically related ground motion to structural response (Sorrentino 2007). At this time in Japan, a doctoral degree in structural engineering as applied to the earthquake engineering had already been conferred by the University of Tokyo on Riki Sano, which devised a similarly modern-looking equation for determining earthquake loads (Reitherman 2012). "Modern-looking" does not mean those developments from the turn of the nineteenth-twentieth centuries look up-to-date today. However, they were based on the insight that earthquake forces are inertial forces, and thus forces represented by the earthquake shaking times the mass (Newton's Second Law of Motion, $F = m * a$) could be calculated. These early Japanese and Italian codes were modern in the sense that an engineer could use them to make calculations to produce a design based on quantitative structural engineering methods.

In the United States in the late nineteenth century, there were some techniques used in San Francisco to embed iron bars in brickwork and make other construction improvements explicitly because of the earthquake threat (Tobriner 2006). Prior to the 1906 San Francisco Earthquake, San Francisco had experienced a significant damaging earthquake in 1865, and the East Bay, particularly Hayward, was damaged by another one in 1868. When the 1906 earthquake occurred, it was the most disastrous natural disaster in U.S. history, primarily because of the spread of fires caused by the earthquake. In spite of the devastation caused by the earthquake, it did not lead to seismic regulations in the building code as advanced as what had already been developed in Japan or

Italy. Although there was extensive discussion among architects and engineers about the earthquake damage, the only overall structural measure put into the code was to increase the design wind load. (Wind loading and seismic loading are quite different; hence this was not on the modern path toward effective seismic design.) A few piecemeal requirements were added to the code for anchoring parapets and cornices, though later these were found to be inadequate, and in 1969, a new ordinance was passed to deal with those appendages, about fifteen years after Los Angeles had done so. While the Japanese and Italians were on the accurate trail toward effective seismic design, with equations relating the mass of the building at various levels to a defined level of shaking, the 1906 earthquake that devastated San Francisco did not spur similar developments in the United States There were some scientific, engineering, and university education developments inspired by the earthquake (Reitherman 2006), but no seismic regulations in building codes in California or elsewhere in the United States were adopted. Although smaller in magnitude and resultant destruction, the earthquake that would initiate ongoing development of seismic regulations in a building code in the United States did not occur until almost thirty years later.

The March 10, 1933 Long Beach Earthquake (6.3 magnitude) was centered in a heavily urbanized part of the Los Angeles metropolitan area. Although two or three municipalities in California had adopted some earthquake regulations in their building codes based on a non-mandatory appendix to the 1927 Uniform Building Code, the 1933 earthquake was the important watershed event separating the pre- seismic-code era from seismic-code era. As of that date, engineers in the United States learned about the Japanese seismic building code requirements and underlying theory, which they used as a model to follow. California adopted the Field Act for public schools and the Riley Act for other buildings. Although the provisions of the laws appear crude by today's standards, they are forerunners of all later U.S. seismic regulations. The 1933 regulations were primarily modeled on the Japanese regulations passed ten years earlier after the 1923 Great Kanto or Tokyo-Yokohama Earthquake. Turkey, New Zealand, and India also adopted their first seismic building regulations in the 1930s. Reitherman (2012) provides details on the evolution of earthquake engineering knowledge and the development of earthquake regulations that are only briefly touched on here.

Of note is the introduction of the accelerograph, a strong-motion seismograph by the U.S. Coast and Geodetic Survey. Over the following years , this type of instrument recorded a number of instances of strong shaking at particular sites, such as during the 1940 El Centro, California Earthquake. For many years, the 1940 record was the primary record used in research and seismic code development. However, the innovation was not motivated by the 1933 earthquake; the first instrument had already been designed, built, and installed as of 1932. By the time of the 1971 San Fernando Earthquake, ordinances passed in the City and in the County of Los Angeles required the installation of accelerographs in tall buildings, and the number of records obtained (241) was ten times the number of all other records obtained since 1940. Later records revealed that the peak acceleration of an earthquake could be more than three times the 1940 record's peak of 1/3 g. Since then, increased worldwide efforts have been made to install and operate such instruments, and the data they provide is extensively used in the updating of building codes. The *NEHRP Recommended Seismic Provisions* have been comprehensively analyzed with regard to new earthquake records to refine the way the hazard of ground shaking is treated.

While the San Fernando Earthquake in 1971 was extremely significant in improving U.S. seismic codes, there was important earlier progress made in the post-World War II era. Very briefly cited here are the following:

- Separate 66 (Anderson et al. 1952), an ASCE publication that combined the latest thoughts of Southern and Northern California engineers
- the first Structural Engineers Association of California "Blue Book," Recommended Lateral Force Requirements and Commentary, (SEAOC Seismology Committee 1959)
- the textbook on ductile reinforced concrete frame design by Blume, Newmark, and Corning (1961)
- lessons from the structural performance of buildings in the 1964 Alaska Earthquake (Steinbrugge et al. 1967)
- establishment of the Joint Committee on Seismic Safety by the California Legislature in 1969.

In 1952, to resolve differences between seismic regulations in the Los Angeles and San Francisco building codes, a publication was produced to reconcile inconsistencies, (Anderson et al. 1952). However, by 1957 the differences remained and the Structural Engineers Association of California (SEAOC) charged a committee with producing one uniform standard, the Recommended Lateral

Figure B-1. The March 10, 1933 Long Beach Earthquake in Southern California was the impetus for development and adoption of building code regulations in the United States. (Source: *Los Angeles County Library*)

Forces and Commentary, or Blue Book (SEAOC 1959). This benchmark inaugurated a three-decade-long process of updating the SEAOC document that would then be incorporated into the Uniform Building Code, which is not only used California but throughout the western United States. While this was a big step toward providing consistency in many U.S. codes, because it was a California-based process and was embedded in the UBC, it was not deemed to be a suitable vehicle for nationwide code development. As described earlier, the SEAOC provisions and the UBC were supplanted by the merger of the ICBO with the other two regionally based model codes organizations in 2000 to form the ICC. At this point, the BSSC had been established and had a consensus-based national process developing editions *NEHRP Recommended Seismic Provisions* ready to provide the seismic regulations for the new International Building Code.

The 1971 San Fernando Earthquake in the Los Angeles metropolitan region can be cited as the most significant earthquake in this period from the issuance of Blue Book in the 1950s up to the ATC- 3 project that produced the previously discussed Tentative Provisions for the Development of Seismic Regulations for Buildings in 1978. The 1964 Alaska Earthquake should also be cited, as modern UBC-conforming buildings in Anchorage were damaged in ways that highlighted needed improvements. The 1964 earthquake also motivated the federal government to be involved in earthquake loss mitigation activities.

The 1971 earthquake that affected numerous buildings in the Los Angeles area was significant in many ways to include, including the design of dams and bridges, but from the standpoint of the development of seismic regulations for buildings, the 1971 earthquake can be singled out for two reasons. First, a number of buildings designed up to current or recent editions of the Uniform Building Code were badly damaged and exhibited types of damage and failures that contradicted some of the engineering thinking of the day (Harris 1992). More research and code development were obviously needed, and one result of this required the establishment of the Applied Technology Council. Second, because both the County of Los Angeles and the City of Los Angeles had instituted laws that required the installation of strong motion instruments in many buildings, the number of strong motion records was greatly increased.

Recall that the 1940 El Centro Earthquake was the first accurate recording obtained of intense earthquake shaking and was often used in research. Along with a record collected in the 1952 Kern County, California Earthquake, it was one of only a handful of records obtained worldwide that was useful in gaining a valid picture of the way the ground can shake. The collection and analysis of strong motion records remains an important way that seismic regulations are updated today. Although as of 2000, there were between 10,000 and 20,000 strong motion instruments around the world (Anderson 2003, Part B, p. 938), we have yet to obtain a number of records close to the causative fault of a great (approximately magnitude 8 or greater) earthquake. Observations of building performance and records of ground motions from such an event in an urbanized area of the United States thus could lead to revisions and refinements of seismic regulations in the future.

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