Earthquake-Resistant Design Concepts

An Introduction to the NEHRP Recommended Seismic Provisions for New Buildings and Other Structures

FEMA P-749 / December 2010
Earthquake-Resistant Design Concepts
An Introduction to the NEHRP Recommended Seismic Provisions for New Buildings and Other Structures

FEMA P-749 / December 2010

Prepared for the
By the National Institute of Building Sciences Building Seismic Safety Council

National Institute of Building Sciences
Building Seismic Safety Council
Washington, DC
2010

Cover photo: Office Building, Walnut Creek, California, by William G. Godden.
©Godden Collection, NISEE, University of California, Berkeley
NOTICE: Any opinions, findings, conclusions, or recommendations expressed in this publication do not necessarily reflect the views of the Federal Emergency Management Agency of the Department of Homeland Security. Additionally, neither FEMA nor any of its employees make any warranty, expressed or implied, nor assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, product, or process included in this publication.

This report was prepared under Contract HSFEHQ-06-C-1139 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 (www.bssc.online) or write the Building Seismic Safety Council, National Institute of Building Sciences, 1090 Vermont, Avenue, N.W., Suite 700, Washington, D.C. 20005; phone 202-289-7800; fax 202-289-1092; e-mail bssc@nibs.org. Copies of this report may be obtained from the FEMA Public Distribution Facility at 1-800-480-2520. The report can also be downloaded in pdf form from the FEMA website or the BSSC website.

About The Building Seismic Safety Council

The Building Seismic Safety Council (BSSC) was established in 1979 under the auspices of the National Institute of Building Sciences as a forum-based mechanism for dealing with the complex regulatory, technical, social, and economic issues involved in developing and promulgating building earthquake hazard mitigation regulatory provisions that are national in scope. By bringing together in the BSSC all of the needed expertise and all relevant public and private interests, it was believed that issues related to the seismic safety of the built environment could be resolved and jurisdictional problems overcome through authoritative guidance and assistance backed by a broad consensus.

The BSSC is an independent, voluntary membership body representing a wide variety of building community interests. Its fundamental purpose is to enhance public safety by providing a national forum that fosters improved seismic safety provisions for use by the building community in the planning, design, construction, regulation, and utilization of buildings.

2010 BSSC BOARD OF DIRECTION

Chair – William Holmes, Rutherford & Chekene
Vice Chair – James Cagley, Cagley and Associates (representing the Applied Technology Council)
Secretary – Curtis Campbell, J. E. Dunn Construction Company (representing the Associated General Contractors of America)
Ex Officio – David Bonneville, Degenkolb Engineers

Members – Bradford Douglas, American Wood Council; Cynthia J. Duncan, American Institute of Steel Construction; John E. Durrant, American Society of Civil Engineers; Melvyn Green, Melvyn Green and Associates (representing the Earthquake Engineering Research Institute); Jay W. Larson, PE, FASCE, American Iron and Steel Institute; Joseph Messersmith, Portland Cement Association; Ronald E. Piester, RA, New York State Department, Division of Code Enforcement and Administration (representing the National Institute of Building Sciences); Timothy Reinhold, Institute for Building and Home Safety; R. K. Stewart, FAIA, Hon. Fraic, Hon. Jai, LEED AP, Perkins + Will (representing the National Institute of Building Sciences); Gregory Schindler, KPFF Consulting Engineers (representing the National Council of Structural Engineers Associations); Charles Spitz, NCARB, AIA, CSI, Architect/Planner Code Consultant (representing the American Institute of Architects); S. Shyam Sunder, National Institute of Standards and Technology (representing the Interagency Committee for Seismic Safety in Construction); Robert D. Thomas, National Concrete Masonry Association

BSSC MEMBER ORGANIZATIONS: AFL-CIO Building and Construction Trades Department, American Concrete Institute, American Consulting Engineers Council, American Wood Council, American Institute of Architects, American Institute of Steel Construction, American Iron and Steel Institute, American Society of Civil Engineers, American Society of Heating, Refrigeration, and Air-Conditioning Engineers, American Society of Mechanical Engineers, American Welding Society, APA - The Engineered Wood Association, Applied Technology Council, Associated General Contractors of America, Association of Engineering Geologists, Association of Major City Building Officials, Brick Industry Association, Building Owners and Managers Association International, California Seismic Safety Commission, Canadian National Committee on Earthquake Engineering, Concrete Masonry Association of California and Nevada, Concrete Reinforcing Steel Institute, Division of the California State Architect, Earthquake Engineering Research Institute, General Services Administration Seismic Program, Hawaii State Earthquake Advisory Board, Institute for Business and Home Safety, Interagency Committee on Seismic Safety in Construction, International Code Council, International Masonry Institute, Masonry Institute of America, Metal Building Manufacturers Association, Mid-America Earthquake Center, National Association of Home Builders, National Concrete Masonry Association, National Conference of States on Building Codes and Standards, National Council of Structural Engineers Associations, National Elevator Industry, Inc., National Fire Sprinkler Association, National Institute of Building Sciences, National Ready Mixed Concrete Association, Portland Cement Association, Precast/Prestressed Concrete Institute, Rack Manufacturers Institute, Steel Deck Institute, Inc., Structural Engineers Association of California, Structural Engineers Association of Central California, Structural Engineers Association of Colorado, Structural Engineers Association of Illinois, Structural Engineers Association of Kansas and Missouri, Structural Engineers Association of Kentucky, Structural Engineers Association of Northern California, Structural Engineers Association of Oregon, Structural Engineers Association of San Diego, Structural Engineers Association of Southern California, Structural Engineers Association of Texas, Structural Engineers Association of Utah, Structural Engineers Association of Washington, The Masonry Society, U.S. Army Corps of Engineers Engineer Research and Development Center–Construction Engineering Research Laboratory, Western States Clay Products Association, Wire Reinforcement Institute

Foreword

One goal of the Federal Emergency Management Agency (FEMA) and the National Earthquake Hazards Reduction Program (NEHRP) is to encourage design and building practices that address the earthquake hazard and minimize the resulting risk of damage and injury. Publication of this document, which is a companion guide to the 2009 edition of the *NEHRP Recommended Seismic Provisions for New Buildings and Other Structures* (FEMA P-750), reaffirms FEMA’s ongoing support of efforts to achieve this goal. First published in 1985, the 2009 edition of the *Provisions* marks the seventh in a series of updates to the document.

The *Provisions* and the building codes and consensus standards based on its recommendations are technical documents used primarily by the professionals who design and construct buildings and other structures. Understanding the basis for the seismic regulations in the nation’s codes and standards is nevertheless important to others outside the technical community including elected officials, decision-makers in the insurance and financial communities, and individual building or business owners and other concerned citizens. This document is intended to provide these interested individuals with a readily understandable explanation of the intent and requirements of seismic design in general and the *Provisions* in particular.

FEMA wishes to express its deepest gratitude for the significant efforts of the over 200 volunteer experts as well as the BSSC Board of Direction, member organizations, consultants, and staff who made possible the 2009 *NEHRP Recommended Seismic Provisions* and, by extension, this report. Americans unfortunate enough to experience the earthquakes that will inevitably occur in the future will owe much, perhaps even their lives, to the contributions and dedication of these individuals. Without the expertise and efforts of these men and women, this document and all it represents with respect to earthquake risk mitigation would not have been possible.

*Federal Emergency Management Agency of the
U. S. Department of Homeland Security*
# Table of Contents

**Forward** .................................................................................................................. iii

**Preface and Acknowledgements** ................................................................................. v

**Executive Summary** ..................................................................................................... 1

**Chapter 1 | The U.S. Building Regulatory Process and Its Approach to Seismic Risk** 3

1.1 Model Building Codes ............................................................................................. 4
1.2 Consensus Standards ............................................................................................... 5
1.3 Code Adoption and Enforcement ............................................................................ 6
1.4 The NEHRP and the NEHRP Recommended Seismic Provisions ......................... 7

**Chapter 2 | Seismic Risk and Performance** ................................................................ 13

2.1 Basic Concepts ....................................................................................................... 13
2.2 Acceptable Risk ...................................................................................................... 13
2.3 Geologic Earthquake Effects ................................................................................... 14
2.4 Seismic Hazard Analysis ........................................................................................ 20

**Chapter 3 | Design and Construction Features Important to Seismic Performance** 35

3.1 Stable Foundations ................................................................................................... 35
3.2 Continuous Load Path ............................................................................................. 36
3.3 Adequate Stiffness and Strength ............................................................................. 37
3.4 Regularity ................................................................................................................ 38
3.5 Redundancy ............................................................................................................ 39
3.6 Ductility and Toughness .......................................................................................... 40
3.7 Ruggedness ............................................................................................................. 41

**Chapter 4 | Buildings, Structures, and Nonstructural Components** 43

4.1 Buildings ................................................................................................................. 43
   4.1.1 Structural Systems ........................................................................................... 43
   4.1.2 Nonstructural Components ............................................................................ 48
4.2 Nonbuilding Structures ........................................................................................... 49
4.3 Protective Systems .................................................................................................. 51
4.4 Existing Buildings and Structures ......................................................................... 52

**Chapter 5 | Design Requirements** ............................................................................ 57

5.1 Seismic Design Categories ....................................................................................... 57
5.2 Site Class .................................................................................................................. 60
5.3 Design Ground Motion ............................................................................................ 66
5.4 Structural System Selection ..................................................................................... 70
5.5 Configuration and Regularity ................................................................................... 73
EARTHQUAKE-RESISTANT DESIGN CONCEPTS

5.6 Required Strength ................................................................. 75
  5.6.1 Seismic Design Category A .............................................. 76
  5.6.2 Seismic Design Category B .............................................. 77
  5.6.3 Seismic Design Category C .............................................. 83
  5.6.4 Seismic Design Categories D, E, and F ................................. 84
5.7 Stiffness and Stability .......................................................... 85
5.8 Nonstructural Components and Systems .................................... 87
5.9 Construction Quality Assurance ............................................. 89

Chapter 6 | Future Directions

6.1 Rationalization of Design Parameters ...................................... 91
6.2 Manufactured Component Equivalence ..................................... 91
6.3 Nonbuilding Structures ......................................................... 92
6.4 Nonstructural Components .................................................. 92
6.5 Performance-based Design .................................................... 92
6.5 Damage-tolerant Systems ...................................................... 93

Glossary ................................................................................. 95

Selected References and Bibliography ......................................... 103

FIGURES

Chapter 1

Figure 1 Examples of how NEHRP-funded basic research and application activities stimulate earthquake risk mitigation (image courtesy of NIST). ............................................ 9

Chapter 2

Figure 2 Major tectonic plates (courtesy of U.S. Geological Survey). For a more complete explanation of plate tectonics, see http://pubs.usgs.gov/gip/dynamic/dynamic.pdf/15

Figure 3 Fault movements can break the ground surface, damaging buildings and other structures. This fence near Point Reyes was offset 8 feet (2.5 m) when the San Andreas Fault moved in the 1906 San Francisco (magnitude 7.8) earthquake (photo courtesy of USGS). .......................................... 16

Figure 4 Vertical fault offset in Nevada resulting from the 1954 Dixie Valley earthquake (photo by K. V. Steinbrugge). ....................................................... 16

Figure 5 Earthquakes can trigger landslides that damage roads, buildings, pipelines, and other infrastructure. Steeply sloping areas underlain by loose or soft rock are most susceptible to earthquake-induced landslides. The photo on the left shows Government Hill School in Anchorage, Alaska, destroyed as a result of a landslide induced by the 1964 earthquake; the south wing of the building collapsed into a graben at the head of the landslide (photo courtesy of USGS). The home shown on the right was destroyed when the hillside beneath it gave way following the 1994 magnitude 6.7 Northridge earthquake (FEMA photo). .......................................... 17
### Table of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Top photo shows liquefaction-induced settlement of apartment buildings in the 1964 earthquake in Nigata, Japan (photo courtesy of the University of Washington). The bottom photo shows one of many manholes that floated to the surface as a result of soil liquefaction caused by the 2004 Chuetsu earthquake near Nigata, Japan (photo courtesy of Wikimedia Commons).</td>
</tr>
<tr>
<td>7</td>
<td>Lateral spreading damage to highway pavement near Yellowstone Park resulting from the 1959 Hegben Lake earthquake (photo courtesy of the USGS).</td>
</tr>
<tr>
<td>8</td>
<td>Locations of earthquakes in the continental United States between 1750 and 1996. Although not shown in this map, Alaska, Hawaii, Puerto Rico, and the Marianas also experienced earthquakes during this period.</td>
</tr>
<tr>
<td>9</td>
<td>Acceleration response spectrum for the 1940 Imperial Valley earthquake, north-south component.</td>
</tr>
<tr>
<td>10</td>
<td>Generalized shape of smoothed response spectrum.</td>
</tr>
<tr>
<td>11</td>
<td>Hazard curve for spectral acceleration at a site in Berkeley, California.</td>
</tr>
<tr>
<td>12</td>
<td>1940 Imperial Valley earthquake north-south and east-west spectra.</td>
</tr>
<tr>
<td>13</td>
<td>Collapse fragility curve for a hypothetical structure.</td>
</tr>
<tr>
<td>14</td>
<td>Distribution of short-period risk-targeted maximum considered earthquake response acceleration, ( S_1 ), for the conterminous United States.</td>
</tr>
<tr>
<td>15</td>
<td>Distribution of 1-second period risk-targeted maximum considered earthquake response acceleration, ( S_1 ), for the conterminous United States.</td>
</tr>
<tr>
<td>16</td>
<td>Collapse of a tilt-up building in the 1971 San Fernando earthquake (photo by P. Yanev).</td>
</tr>
<tr>
<td>17</td>
<td>Houses in Watsonville, California, that fell off their foundations in the 1989 Loma Prieta earthquake.</td>
</tr>
<tr>
<td>18</td>
<td>First story of an apartment building in San Francisco, California, leaning to the side after the 1989 Loma Prieta earthquake.</td>
</tr>
<tr>
<td>19</td>
<td>Imperial County Services Building, El Centro, California (courtesy of USGS). The photo on the right shows the crushed columns at the base of the building.</td>
</tr>
<tr>
<td>20</td>
<td>Failure of an unreinforced masonry wall in a building in Santa Cruz, California, in the 1989 Loma Prieta earthquake.</td>
</tr>
</tbody>
</table>

---

**Chapter 3**

---

**Table of Contents**
# TABLE OF CONTENTS

## EARTHQUAKE-RESISTANT DESIGN CONCEPTS

### Chapter 4
- Figure 21 Wood studs and structural panel sheathing of typical wood frame bearing wall construction. 44
- Figure 22 Typical low-rise concrete bearing wall building. 44
- Figure 23 A three-story masonry bearing wall building. 45
- Figure 24 A high-rise braced frame building in San Francisco, California. 46
- Figure 25 A tall steel moment-frame structure under construction. 47
- Figure 26 Structures commonly found in petroleum refineries and chemical plants. 49
- Figure 27 Seismic design criteria for steel storage racks of the type used in large warehouses and big-box retail stores are included in the Provisions. 50
- Figure 28 The San Bernardino County Justice Center in California was one of the first base-isolated buildings in the United States. 52

### Chapter 5
- Figure 29 Seismic Design Categories for low-rise buildings of ordinary occupancy on alluvial soils. 62
- Figure 30 Generalized design response spectrum. 67
- Figure 31 Map of long-period transition period, $T_L$, for the continental United States. 68
- Figure 32 Re-entrant corner irregularity. 73
- Figure 33 Diaphragm discontinuity irregularity. 73
- Figure 34 Out-of-plane offset irregularity. 73
- Figure 35 Examples of buildings with a soft first story, a common type of stiffness irregularity. 74
- Figure 36 Examples of in-plane discontinuity irregularities. 75
- Figure 37 Required seismic design forces for Seismic Design Category A structures. 76
- Figure 38 Continuity forces for Seismic Design Category A structures. 77
- Figure 39 Distribution of lateral earthquake force in three-story structure. 79
- Figure 40 Eccentric application of story forces. 82
- Figure 41 Deflection of diaphragm under lateral loading. 83
- Figure 42 Interstory drift. 86
TABLES

Chapter 2
Table 1  Modified Mercalli Intensity Scale  22

Chapter 5
Table 2  Seismic Design Categories, Risk, and Seismic Design Criteria  58
Table 3  Occupancy  59
Table 4  Site Class and Soil Types  61
Table 5  Values of Site Class Coefficient $F_a$ as a Function of Site Class  67
Table 6  Values of Site Class Coefficient $F_v$ as a Function of Site Class  67
Preface and Acknowledgements

This document reflects very generous contributions of time and expertise on the part of the many individuals who participated in the development of the 2009 NEHRP Recommended Seismic Provisions for New Building and Other Structures. The Building Seismic Safety Council (BSSC) is particularly grateful to Ronald O. Hamburger, SE, PE, SECB, Senior Principal, Simpson Gumpertz and Heger, San Francisco, California. Not only did Mr. Hamburger serve as chair of the Provisions Update Committee responsible for both the 2003 and 2009 editions of the Provisions, but he also drafted this report. The BSSC also wishes to acknowledge the conscientious support and assistance of Michael Mahoney, Geophysicist, FEMA, Mitigation Directorate, Building Science Branch, and the project officer overseeing development of this introduction to the concepts presented in the Provisions.
Executive Summary

Of the 500,000 or so detectable earthquakes that occur on Planet Earth each year, people will “feel” about 100,000 of them and about 100 will cause damage.1 Although most earthquakes are moderate in size and destructive potential, a severe earthquake occasionally strikes a community that is not adequately prepared and thousands of lives and billions of dollars in economic investment are lost.

For example, a great earthquake and the fires it initiated destroyed much of San Francisco in 1906 and a significant portion of Anchorage, Alaska, was destroyed by a large earthquake in 1964. Within the past 200 years, major destructive earthquakes also occurred in Charleston, South Carolina, and Memphis, Tennessee. Within the past 50 years, smaller but damaging earthquakes occurred several times in both Los Angeles and Seattle. Overall, more than 20 states have a moderate or high risk of experiencing damaging earthquakes. Earthquakes are truly a national problem.

One of the key ways a community protects itself from potential earthquake disasters is by adopting and enforcing a building code with appropriate seismic design and construction standards. The seismic requirements in U.S. model building codes and standards are updated through the volunteer efforts of design professionals and construction industry representatives under a process sponsored by the Federal Emergency Management Agency (FEMA) and administered by the Building Seismic Safety Council (BSSC). At regular intervals, the BSSC develops and FEMA publishes the NEHRP (National Earthquake Hazards Reduction Program) Recommended Seismic Provisions for New Buildings and Other Structures (referred to in this publication as the NEHRP Recommended Seismic Provisions or simply the Provisions). The Provisions serves as a resource used by the codes and standards development organizations as they formulate sound seismic-resistant design and construction requirements. The Provisions also provides design professionals, building officials, and educators with in-depth commentary on the intent and preferred application of the seismic regulations.

The 2009 edition of the Provisions (FEMA P-750) and the building codes and consensus standards based on its recommendations are, of necessity, highly technical documents intended primarily for use by design professionals and others who have specialized technical training. Because of this technical focus, these documents are not clearly understandable to those not involved in design and construction. Nevertheless, understanding the basis for the seismic regula-

---

1For more information, see http://earthquake.usgs.gov/learning/facts.php.
tions contained in the nation’s building codes and standards is important to many people outside this technical community including elected officials, decision-makers in the insurance and financial communities, and individual business owners and other citizens. This introduction to the NEHRP Recommended Seismic Provisions is intended to provide these interested individuals with a readily understandable explanation of the intent of the earthquake-resistant design and requirements of the Provisions.

Chapter 1 explains the history and purpose of building regulation in the United States, including the process used to develop and adopt the nation’s building codes and the seismic requirements in these codes. Chapter 2 is an overview of the performance intent of the Provisions. Among the topics addressed are the national seismic hazard maps developed by the U.S. Geological Survey (USGS); the seismic design maps adopted by the Provisions as a basis for seismic design; and seismic risk, which is a function of both the probability that a community will experience intense earthquake ground shaking and the probability that building construction will suffer significant damage because of this ground motion. Chapter 3 identifies the design and construction features of buildings and other structures that are important to good seismic performance. Chapter 4 describes the various types of structures and nonstructural components addressed by the Provisions. Chapter 5 is an overview of the design procedures contained in the Provisions. Chapter 6 addresses how the practice of earthquake-resistant design is likely to evolve in the future. A glossary of key technical terms, lists of notations and acronyms used in this report, and a selected bibliography identifying references that may be of interest to some readers complete this report.