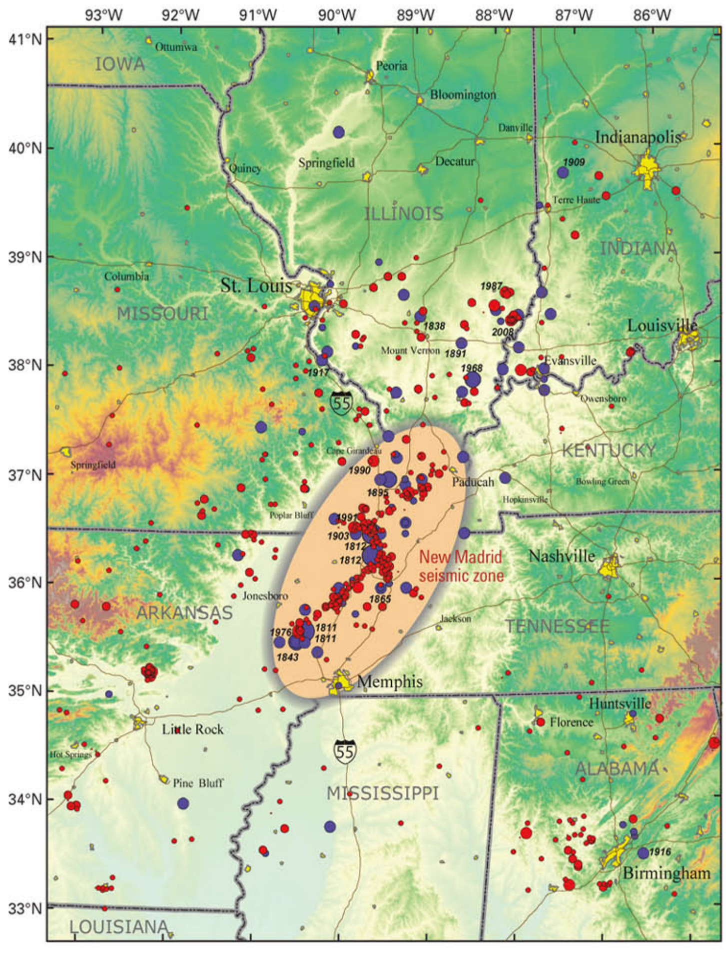
SEISMIC HAZARD DESIGN ISSUES IN THE CENTRAL UNITED STATES

Edited by James E. Beavers, Ph.D., P.E.; and Nasim Uddin, Ph.D., P.E.



ASCE Council on Disaster Risk Management
Monograph No. 7

ASCE

Seismic Hazard Design Issues in the Central United States

Edited by
James E. Beavers, Ph.D., P.E.
Nasim Uddin, Ph.D., P.E.

ASCE Council on Disaster Risk Management Monograph No. 7

ASCE AMERICAN SOCIETY OF CIVIL ENGINEERS

Library of Congress Cataloging-in-Publication Data

Seismic hazard design issues in the central United States / edited by James E. Beavers, Ph.D., P.E.; Nasim Uddin, Ph.D., P.E.
pages cm – (ASCE Council on Disaster Risk Management ; Monograph No. 7)
This collection contains nine papers on seismic design issues in the central United States, specifically in the New Madrid Seismic Zone, presented at the CDRM workshop held April 10, 2012 in Memphis, TN.
Includes bibliographical references and index.
ISBN 978-0-7844-1320-3 (print : alk. paper) – ISBN 978-0-7844-7822-6 (ebook) 1. Earthquake resistant design–Middle West. 2. Earthquake resistant design–New Madrid Seismic Zone. I. Beavers, James E., editor of compilation. II. Uddin, Nasim, editor of compilation. III. ASCE Council on Disaster Risk Management.
TA658.44.S415 2014
693.8'520977–dc23
2013048348

Published by American Society of Civil Engineers
1801 Alexander Bell Drive
Reston, Virginia, 20191-4382
www.asce.org/bookstore | ascelibrary.org

Errata: Errata, if any, can be found at http://dx.doi.org/10.1061/9780784413203.

ISBN 978-0-7844-1320-3 (paper)
ISBN 978-0-7844-7822-6 (PDF)
Manufactured in the United States of America.

21 20 19 18 17 16 15 14 1 2 3 4 5

Cover photo credit: Geological Survey, Fact Sheet 2009–3071

Table of Contents

Preface

During the 1990s, when the Council for Disaster Risk Management (CDRM) of the American Society of Civil Engineers (ASCE) was founded, one of its activities was staying abreast of the development of the International Building Code and the seismic hazard mapping process, especially what was called by the United States Geological Survey (USGS), Federal Emergency Management Agency (FEMA), and Building Seismic Safety Council (BSSC) as Project 97. Project 97 was basically completed in the mid-1990s with the publication of the new National Seismic Hazard maps. However, as the USGS mapping process continued into the next decade and the IBC seismic hazard design requirements began to become an ASCE standard, members of CDRM began to realize that the advancements in the seismic hazard mapping process were still troubling to practicing engineers, especially those in the Midwest. Practicing engineers perceived, as late as 2010, that the IBC imposed concepts for seismic design of buildings in the Midwest were very similar or higher than design requirements in California.

As a result of the discussion above, members of the CDRM started talking about having a workshop on seismic hazard issues to address concerns of practicing engineers in the Midwest in council meetings as early as 2009. Then following publication of ASCE/SEI 7-10 in May, 2010, and the Advisory Committee on Earthquake Hazard Reduction (ACEHR) of the National Earthquake Hazards Reduction Program (NEHRP) meeting in Memphis, Tenn. in November, 2010 members of CDRM approved the concept of a seismic hazard workshop to be held in Memphis, Tenn. in 2011 or 2012. This time frame coincided with the Earthquake Engineering Research Institute (EERI) and the National Earthquake Conference (NEC) meeting scheduled for the first part of April in 2012. As a result CDRM worked with EERI and NEC to have the workshop on the eve of the EERI/NEC meeting of April 11 thru 13, 2012, in Memphis, Tenn. on April 10, 2012.

Background

The Council for Disaster Risk Management (CDRM) of the American Society of Civil Engineers (ASCE) was first formed as a committee, i.e., Committee on Natural Disaster Reduction (CNDR), under ASCE's Technical Activities Committee on October 1, 1994. Then on October 1, 1997, CNDR became a Technical Council. Later, on July 25, 2004, the name was changed to what it is today.

Table 1. Monographs of CDRM

Mon. No.	*Title/Editor*	*Date*
1	Infrastructure Risk Management Processes Natural, Accidental, and Deliberate Hazards – Editors: Craig Taylor and Erik VanMarcke	May, 2005
2	Disaster Risk Assessment and Mitigation Arrival of the South Asia Tsunami Wave in Thailand – Editors: Nasim Uddin and Alfredo Ang	October, 2008
3	Multihazard Issues in the Central United States Understanding the Hazards and Reducing the Losses – Editor: James E Beavers	December, 2008
4	Wind Storm and Storm Surge Mitigation – Edited: Nasim Uddin	September, 2009
5	Quantitative Risk Assessment for Natural Hazards – Editors: Nasim Uddin and Alfredo Ang	June, 2011
6	Sea Level Rise and Coastal Infrastructure – Editors: Bilal Ayyub and Michael Kearney	February, 2012
7	Seismic Hazard Design Issues in the Central United States – Editor: James E Beavers and Nasim Uddin	July, 2013

Since its inception in 1994, the vision of CDRM has basically remained the same, i.e., "CDRM is to be ASCE's primary resource for disaster-related issues and to establish national leadership in disaster risk management". One important and successful product of the Council's activities has been the creation of the successful multidisciplinary journal, *Natural Hazards Review*. This journal was created in concert with the Natural Hazards Center at the University of Colorado in Boulder. In addition to the journal, CDRM has also published seven monographs. These monographs focus on key subject areas of natural hazards as shown in Table 1.

Objectives of the Seismic Hazard Workshop

Instead of having another workshop on just specific seismic hazard issues, the organizers felt that this workshop would also present an opportunity to address other issues that would seem to be very pertinent in today's world. As a result, two major goals of this workshop were: 1) To address seismic design issues that many practitioners in the central U.S. have been having with implementing the International Building Code and the ASCE-7 Standard; and 2) To address issues that may occur in the natural hazards arena in the future that are often not considered. Although some may disagree, a good example of this latter objective is the 2011 Tohoku earthquake and tsunami, where two natural hazard events did occur, albeit one caused the other. As result, this and other issues led the organizers to expand the original concept of the workshop to include other aspects of natural hazards as noted in the Preface. For example, the multi-hazard workshop presentation by Mr. Phil Schneider of the National Institute of Building Sciences and looking at long term concepts that might lead to changes in the way engineers treat natural hazards today.

ACKNOWLEDGMENTS

The editors greatly appreciate the support of William J. Hall, Professor Emeritus, Department of Civil and Environmental Engineering, University of Illinois and R. Joe Hunt, Civil, Structural and Architect Engineer, Y-12 National Security Complex, Oak Ridge, Tenn. in the development of the Workshop and preparation of the Monograph.

Council on Disaster Risk Management

Executive Committee

Yumei Wang, P.E., F.ASCE, *Chair*

Nasim Uddin, Ph.D., P.E., F.ASCE, *Past Chair*

Vilas, Mujumdar, D.P.A., P.E., Dist.M.ASCE*, Vice Chair*

Bilal Ayyub, Ph.D., P.E., F.ASCE, *Member*

Keith Porter, Ph.D., M.ASCE, *Member*

Board of Advisors

Alfredo Ang, Ph.D., S.E., Hon.M.ASCE

Bilal Ayyub, Ph.D., P.E., F.ASCE

Amar Chaker, Ph.D., M.ASCE

Anne Kiremidjian, Ph.D., M.ASCE

Craig Taylor, Aff.M.ASCE

Erik Vanmarcke, Ph.D. M. ASCE

Committee Chairs

Forrest J. Masters, Ph.D., P.E., M.ASCE

Nii O. Attoh-Okine, P.E., M.ASCE

Javier F. Moncada, A.M.ASCE

This page intentionally left blank

CHAPTER 1

Introduction to the 2012 Seismic Hazard Workshop

INTRODUCTION

Background

At the Advisory Committee on Earthquake Hazards Reduction (ACEHR) meeting on November 9–10, 2010 area engineers and geologist made presentations concerning the seismic hazard and policy in the Central U.S. (CUS). During one presentation, it was pointed out that seismic hazard design values in the International Building Code (IBC) (1) and the American Society of Civil Engineers (ASCE) Standard 7–10 (2) were too high; in many cases higher than that of California. It was also pointed out that the National Earthquake Hazards Reduction Program (NEHRP) Provisions Design Map (3), for the 0.2 Spectral Response Acceleration for the U.S., had an S_{DS} point value in Northwest Tennessee of 4.08 g. When this value was compared to the highest value shown for the West Coast, i.e., 1.88 g, the 4.08 g value is more than a factor of two higher, which did not make sense to many engineers and seismologist in the CUS. As a result, the contrasting difference between these S_{DS} values along with other variations in the IBC and ASCE Standard 7–10 between seismic design in the CUS and seismic design on the West Coast led to recommendations presented to the Advisory Committee, some of which were: 1) "The United States Geological Survey (USGS) National Seismic Hazard Maps portray the Central U.S. as a worst case," and 2) "Kentucky should not be placed in a hazard category twice as dangerous as California or China – not reasonable!"

In another presentation at the November 2010 meeting titled: "Should Memphis Adopt IBC/NEHRP for Seismic Safety?", the following points were made about the IBC: 1) Overstates earthquake risks during the useful life of a building; 2) Designates the New Madrid Seismic Zone (NMSZ) as the most hazardous/highest risk in the lower 48 states; 3) Not cost effective for life safety, as it includes elements of property loss reduction; 4) Does not reflect safety, economic, and political realities of the community; and 5) Will not promote voluntary compliance. In addition, concerning impact on cost for building construction following the adoption of IBC, it was stated that: "Anticipated cost increases above the Southern Building Code (SBC) 99, for new buildings in the following categories are: 1) Residential, 10% to 15%, 2) Commercial, 10% to 15%, 3) Light industrial, 15% to 25% and 4) Heavy industrial, 25% to 35%."

Outcome

Following the invited presentations and additional discussion among other members of the ACEHR and attendees at the meeting, Dr. Beavers began to work with the ASCE Council for Disaster Risk Management (CDRM) to plan and organize the workshop.

As a result of the issues that were presented at the ACEHR meeting, the CDRM of ASCE decided to host a workshop on seismic hazard issues in the CUS in concert with the Earthquake Engineering Research Institute (EERI)/National Earthquake Conference (NEC) in April, 2012.

Workshop Concept

Instead of having another workshop on just specific seismic hazard issues, the workshop organizers felt that this workshop would also present an opportunity to address other issues that would seem to be very pertinent in today's world resulting in the following two objectives: 1) the primary goal is to educate engineers in the Midwest about new seismic design procedures that exist in the IBC and ASCE/SEI 7 Standard and 2) to address issues that may occur in the natural hazards arena in the future that are often not considered today. A good example of this is the 2011 Tohoku earthquake and tsunami, where two natural hazard events did occur, albeit one caused the other. As a result, it was decided to expand the original concept of the workshop to include other aspects of natural hazards. For example, the multi-hazard paper prepared by Mr. Phil Schneider of the National Institute of Building Sciences looking at long term concepts that might lead to changes in the way engineers treat natural hazards today.

SUMMARY OF WORKSHOP SPEAKER PRESENTATIONS

Introduction

To provide the reader with some insights about the papers that were presented in the workshop, a brief summary of each paper is provided below. These discussions are in the order of the presentations at the workshop as shown below in Table 1-1.

Since several of the papers had multiple authors, only the author presenting the paper is shown in Table 1-1; however, all authors participating in each paper are shown in the Table of Contents of the monograph and in the title of each paper.

Workshop Introduction

In Chapter 1, an introduction to the workshop is provided to explain why the workshop occurred and the organization of the workshop.

The Seismic Design Values, S_{DS}, History and Issues; Beavers, Hall, and Hunt

In Chapter 2, Beavers, Hall and Hunt discuss the background of seismic history in the US with a focus on the development of codes in the Central and Eastern U.S. Beavers, Hall and Hunt also discuss the seismic design advances made in the IBC and ASCE 7 since 2000, and highlight some of the work that came from Project 97 (4) which resulted in seismic design guidelines in the first issue of the IBC in 2000. They also discuss Project 07

Table 1-1. Workshop presentation agenda

	SEISMIC HAZARD DESIGN ISSUES IN THE CENTRAL UNITED STATES AN ASCE SYMPOSIUM, Peabody Hotel, Memphis, Tenn., April 10, 2012
Time	Presentation/Speaker
8:10 a.m.	**The Seismic Design Values, S_{DS}, History and Issues**, Dr. James E. Beavers, James E Beavers Consultants, Knoxville, Tennessee,
8:30 a.m.	**What is Today's Seismic Risk in the Central US**, Dr. Arch Johnston, Center for Earthquake Information and Research, University of Memphis, Tennessee
8:55 a.m.	**Seismic Design for Schools in the Midwest, Lessons from the State of Oregon**, Ms. Yumei Wang, State of Oregon
9:20 a.m.	**The 2008 Sichuan earthquake in China and Implications for the Central US**, Dr. Craig Taylor, Managing Partner, Baseline Management Co Inc., Torrance California
9:45 a.m.	**Break**
10:10 a.m.	**A Multi-Hazard Perspective for the Central US**, Mr. Phil Schneider, National Institute of Building Sciences, Washington D.C.
10:35 a.m.	**Geotechnical Issues and Site response in Central US**, Dr. Youssef Hashash, Professor of Civil Engineering, University of Illinois, Urbana, Illinois
11:00 a.m.	**Major Changes in Spectra shapes for Critical Facilities**, Mr. Joe Hunt, BWXT, Oak Ridge, Tennessee
11:25 a.m.	**The International Building Code and the Tennessee Adoption Process**, Mr. Ron Mauer, Chief Plan Examiner, Knox County, Knoxville, Tennessee
11:50 a.m.	**Lunch**
1:20 p.m.	**Seismic Design in Western Kentucky**, Dr. Zhenming Wang, University of Kentucky, Lexington, Kentucky
1:45 p.m.	**Seismic Design and ASCE 7**, Dr. Jim Harris, JR Harris & Company, Denver, Colorado
2:10 p.m.	**Seismic Design in Memphis is not Designing to California, The Risk Targeted Approach**, Dr. Nico Luco, U.S. Geological Survey
2:35 p.m.	**Break**
3:00 p.m.	**New Directions, i.e., Design Costs of the National Earthquake Hazards Reduction Program**, Dr. Jack Hayes, National Institute of Standards and Technology
3:25 p.m.	**Developing Resiliency Measures to Reduce Seismic Hazard Impact in the Central United Sates**, Dr. Vilas Mujumdar, Consultant, Vienna, VA
3:50 p.m.	**Summary**, Dr. James E. Beavers, James E Beavers Consultants, Knoxville, Tennessee
4:00 p.m.	**Close of Workshop**

(5) that represents some of the major advances that have resulted in what is now considered as ASCE 7-2010.

What is Today's Seismic Risk in the Central US; Johnston

In his presentation Johnston updated the status of the seismicity in the NMSZ, and showed the seismic risk as depicted in the latest USGS seismic maps, i.e., there is a seismic hazard and new construction in the area should be designed for seismic loads.

Seismic Design for Schools in the Midwest, Lessons from the State of Oregon; Wolf and Wang

To provide the public in the Central and Eastern US information on how to initiate a program that will result in schools safe from damages resulting from an earthquake, Wolf and Wang, in chapter 3, discuss the approach that has been taken in the State of Oregon. They point out that the United States lacks a national policy affirming the right to learn in school buildings that are safe from earthquakes. In Oregon, Wang and Wolf reviewed the status of school seismic safety in five high-seismic-hazard zones identified on the USGS National Seismic Hazard Map. Efforts to support progress on school assessment and mitigation in the highly decentralized U.S. public education sector are reviewed, and Wang and Wolf propose a three-part national agenda to make schools safer in high-seismic-hazard regions, centered on a common goal: "URM-Free by 2060," i.e., Oregon being free of unreinforced masonry constructed schools by 2060. As we all know, numerous school buildings in the CEUS are constructed of unreinforced masonry and will not survive well during an earthquake. This poor performance was greatly demonstrated in the August 23, 2011 Virginia Earthquake of only magnitude 5.8. The epicenter of this event occurred in Louisa County, Virginia that had five public schools: Louisa County High School; Jouett Elementary School, Thomas Jefferson Elementary School, Louisa County Middle School, and Trevilians Elementary School. The high school and Thomas Jefferson Elementary School where damaged to the point of having to be closed for an indefinite period. Fortunately, none of the students or teachers experienced serious injury.

The 2008 Sichuan earthquake in China and Implications for the Central US; Taylor, Uddin, et al.

The 2008 Sichuan earthquake in China has many similarities to a repeat of one of the New Madrid earthquakes of 1811 and 1812. As a result of several visits to China following that earthquake, Taylor, Uddin, et al. discuss, in chapter 4, a number of implications for the CUS. Striking abruptly, earthquake disasters create destruction, urgency, and confusion, as symbolized by the stopped clock at Hanwang town after the May 12, 2008 Wenchuan earthquake in the Sichuan Province of China. Prior decision making is over. The event fits the definition of a "Black Swan" occurrence: nearly unpredictable, having a massive impact, and followed by numerous post-disaster explanations. The destruction and injuries result not only from the sudden jolt, but from multiple generations of building and habitation practices as well as very long-term geological processes. The CUS faces similar issues before the earthquake: what earthquakes and magnitudes to expect, what massive impacts may occur, and lots of ready but conflicting explanations that may be used after a possible major event should the "clock stop" as occurred in China. Taylor and his co-authors' paper explores the temporal dimensions of the Wenchuan event and that applicable to the CUS, decision procedures that fit such events before they occur. As stated by Taylor and his co-authors: "Whatever is done before the event provides a "premium" that protects against the massive impacts of a catastrophe. When the jolt strikes, as in a region of moderate seismicity but high catastrophic potential, time has run out for those tragically impacted. The future very much depends on the past positive near- and long-term developments in the capacity to resist future jolts."

A Multi-Hazard Perspective for the Central US; Schneider

As noted above in the Introduction of this paper under Workshop Concept two objectives of this workshop were mentioned: 1) the primary goal is to educate engineers in the

Midwest about new seismic design procedures that exist in the IBC and ASCE/SEI 7 Standard, and 2) is to address issues that may occur in the natural hazards arena in the future that are often not considered today. In chapter 5, Schneider addresses the second objective. Schneider starts out by saying: The CUS has experienced major flooding, including the two major Mississippi River floods in 1993 and 2011, frequent devastating tornadoes, for example, the Joplin, Missouri and the Tuscaloosa, Alabama tornados in 2011, and periodically catastrophic earthquakes, including three in 1811–1812 in the New Madrid area that exceeded 7.5 in magnitude. What would be the consequences of two natural hazards occurring in the Central U.S. about the same time? What could area residents expect? And, what would be the response? Schneider asks some good questions here, and following the 2011 Japan earthquake and tsunami such questions need to be asked and the answers should be provided.

Geotechnical Issues and Site response in Central US; Hashash, Kim, et al.

In chapter 6, Hashash, Kim, et al. state that this article highlights the results of recent studies dealing with key seismic geotechnical issues in the Central United States including:

1) Significance of using the Conditional Mean Spectrum for seismic design at the periphery of the New Madrid Seismic Zone: The commonly used Uniform Hazard Response Spectrum does not represent any specific earthquake event in these regions whereby the seismic hazard is a composite of two or more distinct sources. Treatment of these sources separately is needed.
2) Site response of deep soil deposits in the Mississippi Embayment: there is a need to use depth dependent site amplification factors instead of commonly used depth independent NEHRP site coefficients.
3) Unique aspects of liquefaction in the Central United States, particularly in the New Madrid Seismic Zone: Currently used liquefaction triggering analysis has been developed for plate margin setting which is different from the tectonic setting in the Central United States.

Major Changes in Spectra shapes for Critical Facilities; Hunt

State-of-the-art for development of earthquake response spectra to be used for the analyses and design of critical facilities in the central United States is discussed by Hunt in chapter 7. The need for changes as new earthquakes have occurred providing new data is also considered. This paper addresses the major changes in the earthquake response spectra beginning in the 1960's up to 2010, and anticipated changes in the near future.

The International Building Code and the Tennessee Adoption Process; Mauer and Beavers

In chapter 8, Mauer and Beavers present the reader some history of the seismicity of East Tennessee and the building code process in Knox County, Tennessee, and how the State of Tennessee and the various jurisdictions at the local levels operate when it comes to seismic design. All jurisdictions in Tennessee do not operate in the same manner as Knox County, for couple of key reasons: 1) other jurisdictions are not as large as Knox County and as a result does not have the resources for being an "exempt jurisdiction", and 2) other jurisdictions in the State of Tennessee do not have the seismic threat of Knox County. However, the authors have provided in this paper information to allow the people of other states and Tennesseans to take a peek into Tennessee to see how one state and one county handles its seismic hazard and its seismic design process with the goal that when a future earthquake occurs the losses will be minimized as a result.

Seismic Design in Western Kentucky; Wang

In chapter 9, Wang discusses better seismic design for buildings and other structures providing the most effective way to reduce seismic risk and avoid earthquake disaster. Wang also discusses the fact that adoption and implementation of new seismic safety regulations and design standards have caused serious problems in many communities in the New Madrid region, including western Kentucky. The main reasons for these problems are: (1) misunderstanding of the national seismic hazard maps, and (2) confusion between seismic hazard and seismic risk. Both are caused by probabilistic seismic hazard analysis (PSHA).

Seismic Design in Memphis is not Designing to California; The Risk Targeted Approach, Luco

Luco presented the development of the: "Risk Targeted Approach." The background information for the development of the Risk Targeted Approach was three publications. The first one by Dr. Luco and his colleagues was "Risk-Targeted versus Current Seismic Design Maps for the Conterminous United States." The Risk Target Approach was then published by the Federal Emergency Management Agency (3) as part of FEMA's duty for the seismic provisions updates, and finally it was published by the American Society of Civil Engineers as part of its development of national standards, i.e., ASCE/SEI 7-10 (2).

New Directions, i.e., Design Costs of the National Earthquake Hazards Reduction Program; Hays and Harris

As part of NIST's ongoing seismic hazard studies Jack Hays introduced Jim Harris to bring the attendees up to speed on the NIST study to determine the cost of seismic design in the CEUS, especially the Memphis, Tennessee area.

Developing Resiliency Measures to Reduce Seismic Hazard Impact in the Central United States; Mujumder

In chapter 10, Mujumder addresses resiliency issues that result in the reduction of damage when a major earthquake occurs. It also provides reduced day to day operational interruptions as part of good business. When a damaging seismic event occurs in an area, fatalities & injuries happen; damage to building structures and infrastructure systems occurs resulting in short-term and long-term economic losses and disruptions to societal systems. Given a particular damaging seismic event, the consequences of the event on a community depend on several factors: primary among them are the vulnerabilities of physical and socio-economic systems, and exposure to the damaging seismic event. The seismic risk to a community is a function of hazard, vulnerability, and consequences. The author is of the opinion that the total seismic risk comprises of *technical, economic and* *societal components*. Thus, the seismic hazard impact reduction needs a community systems-level approach that necessarily includes interaction of technical systems, economic systems, and societal systems within the constraints of existing organizational systems.

WORKSHOP SUMMARY

As summarized above and shown throughout the workshop papers in this monograph, the two main objectives and/or goals were to educate engineers in the Midwest about new seismic design procedures that exist in the IBC and ASCE/SEI 7 Standard, and to address issues that may occur in the natural hazards arena in the future of the CUS that are often not considered today.

The participants and attendees of this workshop recognized the seismic hazard issue facing the CUS, and will continue to strive to educate the public on the seismic hazard that all citizens in the CUS face.

In conclusion, the workshop organizers express their appreciation to the workshop paper authors and/or workshop speakers for their contributions to these important topics. They appreciated the participants who took time away from their daily schedules to participate in the important workshop and hope that the readers gain a better understanding of some of the technical and political issues that can arise when developing design procedures and standards for natural phenomena events.

The material in this chapter is adapted from introductory material prepared by Dr. J. E. Beavers following the workshop.

References

1. IBC (International Building Code) 2009. "International Building Code," International Code Council, Inc. 500 New Jersey Avenue, NW, 6th Floor, Washington, DC.
2. ASCE (American Society of Civil Engineers) 2010. "Minimum Design Loads for Buildings and Other Structures," American Society of Civil Engineers, ASCE/SEI 7-10, 1801 Alexander Bell Drive, Reston, Virginia.
3. FEMA (Federal Emergency Management Agency), 2009. "NEHRP Recommended Seismic Provisions for Buildings and Other Structures," Federal Emergency Management Agency, FEMA P-750, 2009 Edition, 500 C Street S.W., Washington D.C.
4. Hunt R.J. and Beavers, J.E., 1996. "Development of the 1997 Update of the Recommended Provisions for the Seismic Regulations of New Buildings," Eleventh World Conference on Earthquake Engineering, Acapulco, Mexico, June 23–28.
5. Luco, N., Ellingwood, B.R., Hamburger, R.O., Hooper, J.D., Kimball, J.E., and Kircher, C.A., 2007. "Risk-Targeted versus Current Seismic Design Maps for the Conterminous United States," Convention Proceedings, Structural Engineers Association of California, 1020, 12th Street, Suite 303, Sacramento, California.

This page intentionally left blank

CHAPTER 2

History of Seismic Design in the Central United States

J. E. Beavers, Ph.D., P.E.
William J. Hall, Ph.D., P.E.
R. J. Hunt, P.E.

INTRODUCTION

Background

In 2002 Beavers (1) published the paper: "A review of seismic hazard description in US design codes and procedures," that followed the history of seismic code development in the United States (US) from the early 1900s through 2000. In that paper, it becomes evident that seismic design for new building construction in the US primarily started in the State of California following the 1925 Santa Barbara earthquake when seismic design provisions were placed in the 1927 edition of the Uniform Building Code (UBC) (2), although, John R. Freeman in "Earthquake Damage and Earthquake Insurance" (3) noted that some seismic design for new building construction was ongoing before 1927, but that movement did not really start until seismic design requirements were adopted into the UBC in 1927.

Also, at that time, the seismic load in the UBC was a simple equation as shown in Equation (2-1) where, F was the lateral load on a building and W was the building's weight. This simple equation form remained in the UBC until the 1961 edition of the UBC was published (4). By then seismic hazard maps had been developed, the first one for the western US was published in 1928 by Heck (1 and 5). Then in 1948 the first seismic hazard map for the contiguous US was published by the US Coast and Geodetic Survey (USCGS) and developed by E. B. Roberts and F. P. Urich (6 and 7). Once the mapping of seismic hazard began occurring and the seismic zones were classified with alphanumeric characters the seismic design force equations became of the form as shown in Equation (2-2) where Z was a numerical coefficient based on the seismic zone, K was a numerical coefficient based on building type and C was a numerical coefficient based on the inverse of the cube root of the structure's (building's) period.

$$F = 0.075\ W \qquad (2\text{-}1)$$

$$F = ZKCW \qquad (2\text{-}2)$$

However, as Beavers and others (1 and 5) have pointed out the USCGS withdrew its national seismic hazard map in January, 1952 (8) by stating: "The Seismic Probability Map of the United States, SMC-76, issued by the US Coast and Geodetic Survey in 1951, has been withdrawn from circulation because it was found to be subject to misinterpretation and too general to satisfy the requirements of many users". However, as noted by Beavers (1) the International Conference of Building Officials (ICBO) had adopted the revised 1948 map, now the 1949 map, into the 1952 edition of the UBC (9) and it remained in the UBC following the USCGS withdrawal of the map in 1952. There were continual minor updates of the original 1948 USCGS map until 1969 when Algermissen (10) of the USCGS published a major revision to the 1948/1949 map which the ICBO adopted into the 1970 edition of the UBC (11). One of the biggest differences in the updated 1969 map was that many areas that were originally in Zone 1 were now in Zone 2, especially areas in the central and eastern United States.

The terms Central and Eastern United States (CEUS) and Eastern United States have often been used synonymously, as herein, i.e., meaning the area east of the Rocky Mountains. In 1996 the USGS (12) defined this boundary between the Western U. S. (WUS) and CEUS as an overlap area where the CEUS was extended westward to 115° W and the WUS was extended eastward to 100° W.

Seismic Design in the CEUS

For most construction in the CEUS, seismic design for new construction did not really start until the 1970s, when the ICBO adopted the 1969 Algermissen seismic hazard map (10) into the 1970 UBC (11), and at that time the UBC was primarily adopted in the western states.

In the 1970s the "Tentative Provisions for the Development of Seismic Regulations for Buildings" (13) and National Earthquake Hazards Reduction Program (NEHRP) (14) were developed resulting in seismic design being what it is today in the US.

However, it still took almost 10 years before the Building Officials and Code Administrators International (15) and the Southern Building Code Congress International (16) adopted seismic design provisions in the National Building Code in 1993 and the Southern Building Code in 1994, which were the two codes adopted by most states in the CEUS.

THE EVOLUTION OF SEISMIC DESIGN 1990S THRU 2000S

In his paper, Beavers (1), talked about two paradigm shifts in the history of seismic design development in the US, the first paradigm shift was in the 1970s following the poor performance of buildings during the 1971 San Fernando earthquake. The second paradigm shift occurred in the 1990s following the failure, of what Beavers (1) called: "Design Values Panel" of the NEHRP Provisions, to reach consensus. To be specific, the so called "Design Values Panel" referred to by Beavers (1) really consisted of the failure of Technical Committees (TCs) 1 and 2 (17) of the 1994 NEHRP Provisions Update Committee to reach consensus in the early 1990s. The Design Values Panel actually replaced TCs 1 and 2 and their failure to reach consensus was one of several reasons that resulted in the Building Seismic Safety Council (BSSC), FEMA, and USGS joining together to resolve the problem, which resulted in Project 97 (1 and 18). Project 97 had two primary goals: 1) to develop national seismic hazard maps that represent a consensus baseline for seismic hazard description throughout the U.S., and 2) to develop national seismic risk design values for use as consensus input for the 1997 update of the National Earthquake Hazards Reduction Program (NEHRP) *Recommended Provisions for the Development of Seismic Regulations for New Buildings* (19) using the seismic hazard maps as the baseline.

The authors cite four major advances in seismic hazard understanding during the 1990s thru 2000s: 1) the development of Project 97 (1 and 18); 2) the concept of "Maximum Considered Earthquake" (19); 3) the development of the "Risk-Targeted" Approach (20 and 21); and 4) the "High Frequency" issue (22). These four major advances are briefly discussed below:

(1) **Project 97**. As stated by Beavers (1): "In December 1993, the first author (at the time Chairman of BSSC) and Dr. Walter Hays of the USGS developed a concept for resolving the Design Values Panel issues called: "Project 97." The corresponding execution of Project 97 was an extremely successful project that helped lead the way to the new consensus seismic hazard standards that entered the first issue of the new International Building Code (23) and are now part of the ASCE 7 Standard (24). The authors consider the establishment of Project 2007 (20 and 21) as an indication of the success of Project 97.

(2) **Maximum Considered Earthquake**. While the Design Procedures Group was developing various aspects of the seismic design process the term maximum considered earthquake was developed for establishing a baseline to provide uniform levels of performance for structures depending on their occupancy, use and risk to society inherent in their failure (19).

(3) **Risk Targeted Approach**. The risk-targeted approach is explained in more detail in Luco, et al. (20) and its update in these workshop proceedings by Luco (21). Thus, only the main principle is discussed here. The first paper (20) states that it: 1) explains the basis for proposed adjustments to the uniform-hazard portions of seismic design maps currently in the NEHRP Provisions that result in uniform estimated collapse probability and 2) provides examples of the adjusted ground motions for a selected target collapse probability (or target risk)." The second paper represents an update of the first paper.

(4) **High Frequency Ground Motion**. Much of today's seismic design procedures, in particular the response spectra, are still based on the fundamental design response spectra developed during the 60s and early 70s for the design of nuclear power plants, i.e., Regulatory Guide 1.60 (25) using seismic records from the west coast of the US and other countries, e.g., Japan (26). Review of response spectra for hard rock sites in the CEUS indicate the hard rock site amplifies the motion in the 15 to 100 Hz range,

where engineers had previously considered no amplification of the motion in the response spectra that were primarily based on Type B Site Class soil types. The reader is referred to the paper by R. J. Hunt, (22) in these proceedings for more detailed discussion.

A TOUCH OF REALITY—TENTATIVE DESIGN/EVALUATION SUGGESTIONS FOR VIOLENT NATURAL HAZARDS

It is appreciated that those individuals who design, detail and construct infrastructure, of all kinds, by law, must meet code rules and other applicable regulations that apply to the project. However, in the past few years climate and geologic conditions seem to be changing, and violent natural hazards of many kinds occur worldwide with great loss of life and major damage to infrastructure and the environment. Herein we offer several tentative suggestions as to a design/evaluation approach, focusing on protection against loss of life, and to reducing damage/destruction of infrastructure.

Normally today economic considerations generally preclude major upgrades in design/construction practice to meet infrequent extreme hazard loadings and deformations. The authors believe that what is needed at an early stage of siting or preliminary design is **a period of deep thinking** by the design/construct team (or owner-operators), about what will happen to the project, or elements thereof, if it is impacted by a violent natural hazard action of some type as noted later. Foremost though would naturally be "… is the site an acceptable site?" They need to ask themselves questions such as "… are we providing for protection of people and property by this design to the degree possible for severe hazards under the existing fiscal and physical conditions? What small or large modifications can we make under the budget to enhance protection, improve the structural behavior, and reduce damage?" The focus should not just be on the probabilistic risk of the natural hazards, but should also consider changes that could be made with reasonable costs to increase the structural behavior regardless of the probabilistic risk of the hazard. Some other suggestions appear at the end of this piece.

Noting that the authors of this paper all come from the CEUS, we focus here on four natural hazards with potential for extreme effects peculiar to the CEUS. Obviously herein we are not suggesting any specific physical changes in design, as that approach would entail study of a mass of data and references.

Earthquakes: Earthquakes larger than MMI VI generally cause significant danger to people and infrastructure. Someday an earthquake the size of the 1811 New Madrid earthquake, well documented, will occur; with major disruption to the whole region (27 and 28). Landslides and liquefaction may be major features. In the meantime lesser but still large earthquakes will occur, as they have in recent history with shaking and ground disruption over regions of significance.

High Velocity Winds and Tornados: Right now (2012) the Midwest is being ravaged by serious storms spawning scores of tornados and much death and destruction. These current storm trends suggest that major education of the public and owner/operators, as well as architects and engineers, is needed as to methods to increase safety of people and reduction in damage.

Snow and Ice: Snow and ice are difficult to predict, but extreme snows in Alaska and the Balkans this year suggest that they could happen anywhere.

Floods: Runoff from rain, snow, ice and frozen ground into the Ohio, Missouri and Mississippi rivers and their many tributaries lead to spring, summer, and fall long-term flooding in the Midwest. This flooding has led in recent years to immense damage to infrastructure, crops and quality of farm land.

It must be noted here that the role of probabilistic estimates for such extreme hazards and remediable actions remains somewhat unclear at this moment by virtue of a lack of applicable statistical data.

It is suggested that appropriate agencies and design/construct bodies focus in the near term on issuing, in written form, remedial (and economically possible) upgrade suggestions for reducing injury to people and for reduction in infrastructure damage for specific regions. For the longer term we suggest that well thought out research/ development programs be undertaken with the same goals, especially for new construction or re-construction.

References

1. Beavers, J. E., 2002. "A Review of Seismic Hazard Description in US Design Codes and Procedures," Progress in Structural engineering and Materials, Wiley InterScience, John Wiley & Sons, Ltd, Vol. 4, No. 1, January-March.
2. ICBO (International Conference of Building Officials), 1927. "Uniform Building Code," 1927 edition, International Conference of Building Officials.
3. Freeman, J. R., 1932. Earthquake Damage and Earthquake Insurance, 1st edition, New York, McGraw Hill.
4. ICBO (International Conference of Building Officials), 1961. "Uniform Building Code," 1961 edition, International Conference of Building Officials.
5. Mittler, E., Taylor, C. and Petak, W., 1996. National earthquake Probabilistic Hazard Mapping Program: Lessons for Knowledge Transfer, Working Paper 92, Natural Hazards Research and Applications Information Center, University of Colorado, Boulder, April.
6. Roberts E. B. and Urich F. P., 1948. "Seismic Probability Map of the United States," U.S Coast and Geodetic Survey, 1948.
7. Roberts E. B. and Urich F. P., 1950. "Seismological activities of the US Coast and Geodetic Survey in 1948." Bulletin of the Seismological Society of America, 1950: 40(3): 195–216.
8. USCGS (U.S. Coast and Geodetic Survey), "Earthquake Risk in the United States," Bulletin of the Seismological Society of America, January, 1952, Vol. 42. p.110.
9. ICBO (International Conference of Building Officials), 1952. "Uniform Building Code," 1952 edition, International Conference of Building Officials.
10. Algermissen, S.T., 1969. Seismic risk Studies in the United States, Proceedings of the 4th World Conference on Earthquake engineering, Santiago, Chili, 1969.
11. ICBO (International Conference of Building Officials), 1970. "Uniform Building Code," 1970 edition, International Conference of Building Officials.
12. Frankel, A., Mueller, C., Barnhard, T., Perkins, D., Leyendecker, E. V., Dickman, N., Hanson, S. and Hooper, M., 1996. "National Seismic-Hazard Maps – Documentation June 1996," United States Geological Survey, Open-File Report 96-532, Denver, Co.

13. ATC (Applied Technology Council), “Tentative Provisions for the Development of Seismic Regulations for Buildings,” Applied Technology Council, Report ATC 3-06, Redwood City, CA 1978.
14. NEHRP (National Earthquake Hazard Reduction). Earthquake Hazards Reduction Act of 1977, Public Law 95-124, 95th Congress, 7 October 1977.
15. BOCA (Building Officials and Code Administrators International, 1993. National Building Code, Country Club Hills, Illinois.
16. SBCCI (Southern Building Code Congress International) 1997. Standard Building Code, Southern Building Code Congress International, Inc., 900 Montclair Road, Birmingham, Alabama.
17. BSSC (Building Seismic Safety Council), 1994. NEHRP Recommended Provisions for eh Development of Seismic Regulations for New Buildings, Appendix B, BSSC 1994 Update Program Participants, pp. 269 thru 290 http://www.nibs.org/client/assets/files/bssc/94NEHRP/AppendixB.pdf.
18. Hunt, R. J. and Beavers, J. E., 1996. “Development of the 1997 Update of the Recommended Provisions for the Seismic Regulations of New Buildings, Eleventh World Conference on Earthquake Engineering,” Acapulco, Mexico, June 23–28.
19. FEMA (Federal Emergency Management Agency), 1998. “NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures,” Parts 1 and 2, Provisions and Commentary, 1997 Edition. Federal Emergency Management Agency. FEMA 303/February, Building Seismic Safety Council, 1090 Vermont, Avenue, N.W., Suite 700, Washington. DC 1997.
20. Luco, N., Ellingwood, B. R., Hamburger, R. O., Hooper, J. D., Kimball, J. E., and Kircher, C. A., 2007. “Risk-Targeted versus Current Seismic Design Maps for the Conterminous United States,” Convention Proceedings, Structural Engineers Association of California, 1020, 12th Street, Suite 303, Sacramento, California.
21. Luco, N. 2010. “Risk-Targeted versus Current Seismic Design Maps for the Conterminous United States and Update,” Council on Disaster Risk Management, American Society of Civil Engineers, Monograph No. 6, 1801 Alexander Bell Drive, Reston, Virginia.
22. Hunt, R. J., 2014. “Major changes in spectral shapes for critical facilities in central and eastern United States,” Seismic Hazard Workshop, Council on Disaster Risk Management, American Society of Civil Engineers, Monograph No. 7, 1801 Alexander Bell Drive, Reston, Virginia, April 10.
23. IBC (International Building Code) 2009. “International Building Code,” International Code Council, Inc. 500 New Jersey Avenue, NW, 6th Floor, Washington, DC.
24. ASCE (American Society of Civil Engineers) 2010. “Minimum Design Loads for Buildings and Other Structures,” American Society of Civil Engineers, ASCE/SEI 7-10, 1801 Alexander Bell Drive, Reston, Virginia.
25. AEC (Atomic Energy Commission) 1973. “Design Response Spectra for Seismic Design of Nuclear Power Plants,” Directorate of Regulatory Standards, October, 1973.
26. Newmark, N. M. and Hall, W. J., 1987. “Earthquake Spectra and Design, ” Earthquake Engineering Research Institute Monograph, Library of Congress Catalog Card Number 82-71183 ISBN 0-943198-22-4.
27. Hamilton, R.M. and Johnston, A. C., 1989. Editors, “Tecumseh’s Prophecy: Preparing for the Next New Madrid Earthquake,” U. S. Geological Survey Circular 1066, 30p.
28. Hays, W. W., 1981. “Facing Geologic and Hydrologic Hazards – Earth-Science Considerations,” Geological Survey Professional Paper 1240-B, 108p.

CHAPTER 3

URM-Free By 2033: Toward A National Safe Schools Agenda

Edward C. Wolf and Yumei Wang, P.E.*

Abstract: *The United States lacks a national policy affirming the right to learn in school buildings that are safe from earthquakes. The authors review the status of school seismic safety in five high-seismic-hazard zones identified on the USGS National Seismic Hazard Maps. Efforts to support progress on school seismic assessment and mitigation in the highly decentralized U.S. public education sector are reviewed, and the authors propose a three-part national agenda to make schools safer in high-seismic-hazard regions, centered on a common goal: "URM-Free by 2033."*

INTRODUCTION

"Schoolchildren have a right to learn in buildings that are safe from earthquakes" (ACEHR, 2012). These words from a recommendation to the National Institute of Standards and Technology (NIST) by a national advisory committee in a report on the National Earthquake Hazards Reduction Program (NEHRP) would strike most parents of school-age children as simple common sense. To date, the United States has no national policy that affirms this right.

Responsibility for K-12 education in the United States is highly decentralized, with great variation from state to state and a broad range of sophistication at the level of local elected school boards who bear ultimate responsibility for the condition of school facilities. With respect to structural risks, children who attend schools in earthquake zones are at the mercy of local building codes, the age of the school buildings they attend, and the willingness of local school boards to seek capital bonds to pay for seismic retrofits and upgrades.

Meanwhile, advances in the science of seismic hazard show that elevated hazard is more widespread in the United States than previously understood, and far more prevalent than commonly recognized by policymakers or the general public. An earthquake during

***Edward Wolf** is a writer, policy advocate, and co-founder of Oregon Parents for Quake-Resistant Schools based in Portland, Oregon. **Yumei Wang, P.E.** chairs the executive committee of the ASCE Council on Disaster Risk Management and served as a member of the NEHRP Advisory Committee on Earthquake Hazard Reduction from 2007 to 2012.

school hours that is likely to result in significant or even mass casualties is a real possibility in areas of sixteen states that account for more than one-third of the U.S. population. The case for a national response to this widespread hazard is building steadily.

Seismic policy organizations are increasingly engaged with the issue of at-risk schools, and working to advance it on policy agendas. The Western States Seismic Policy Council (WSSPC), for example, representing 13 U.S. states, 3 U.S. territories, a Canadian territory, and a Canadian province, adopted a policy recommendation on "Identification and Potential Mitigation of Seismically Vulnerable School Buildings" in July 2010, and the Council will review and renew that policy recommendation in 2013. (WSSPC, 2010)

The Council's recommendation emphasizes a three-part approach: Identify the seismic vulnerability of schools, rank facilities, and enact programs to reduce the vulnerability of schools at greatest risk. In this paper, we review five U.S. regions with high seismic hazard for evidence of progress on such steps and programs, and we propose a national framework to promote the more efficient exchange of experience and policy between regions and jurisdictions whose school buildings and school children share common vulnerabilities to high seismic hazard.

PROBLEM STATEMENT

Seismic risk combines considerations of hazard probability, vulnerability, and consequences. The National Seismic Hazard Maps, prepared by the U.S. Geological Survey and updated each six years, provide a comprehensive view of seismic hazard in the United States based on the best available science. The maps display the probability levels of earthquake ground motions, and they are used to update building codes, revise insurance rates, and inform public policies based current understanding of active faults, seismicity and ground motions. The maps provide a general picture of the regions at risk for dangerous ground shaking. (USGS, 2008)

Schools in areas of high seismic hazard can take several approaches to manage the risk. Efforts to teach and practice self-protective behavior ("Drop, Cover, and Hold On"), to address non-structural falling hazards, and to retrofit or replace non-ductile school buildings all help reduce the probability of injury or death when an earthquake strikes during school hours. Of the three, children and school staff members can be trained at modest cost, and falling hazards can be mitigated affordably if the task is integrated into preventive maintenance programs, but mitigating structural vulnerabilities requires significant capital investment. In this paper, we focus on efforts to remove the barriers to that capital investment.

Non-ductile school buildings, which are under-reinforced buildings prone to catastrophic collapse, are unfortunately common in many areas of high seismic hazard. Unreinforced masonry (URM) and under-reinforced concrete were commonly used in school construction in many parts of the United States during the early twentieth century. Non-ductile precast concrete structures are common in mid century school construction in parts of the U.S. These structural types have inherent vulnerabilities to ground shaking particularly in places where local building codes lagged behind current scientific understanding of the seismic environment.

Public school buildings constructed prior to adequate seismic building codes share seismic deficiencies common to other buildings of the same structural types in the same setting, but several considerations set school buildings apart from their peers in terms of priority for seismic assessment and retrofit:

- First, schools are the only high occupancy public buildings other than prisons and courthouses whose occupants are compelled by legal mandate to be inside them.
- Second, school buildings in many communities tend to remain in use longer than comparable structures in private ownership, and tend to receive less frequent and less consistent capital renewal investment.
- Third, community members and public officials often hold a high (if unfounded) expectation that schools will provide community shelter or host public services in the wake of a natural disaster.

In seismic zones where time intervals between damaging earthquakes are shorter than the average lifetime of building stock, earthquakes test buildings – causing damage, necessitating repairs or retrofits, and applying almost Darwinian selection pressures to the inventory of existing buildings. Frequent earthquakes also drive a rapid improvement in building codes and standards, ensuring that turnover in the built environment advances the protection of students and other building occupants.

In zones where earthquakes are infrequent compared with the average lifecycle of buildings, including places where no earthquakes have struck during recorded history, the tendency is to complacency. Buildings unsuited to ground shaking persist without retrofit despite advances in building codes. Scientific understanding of the risk, no matter how robust, is seldom enough to drive change in such settings. Earthquakes in regions facing similar seismic risks can promote awareness, but far-away disasters do not automatically trigger changes in policies or repairs to existing infrastructure.

Despite steady advances in science and engineering, it typically takes a serious local earthquake to trigger the local changes needed to offer adequate protection to schools and children. This pattern has been repeated time after time, in the United States and throughout the world.

The challenge of adopting proactive policy with respect to earthquake safety of schools has not been fully met anywhere, but promising precedents can be shared and built upon. One of the biggest challenges is financial: correcting structural deficiencies requires capital investment, and projects that do not generate some form of financial return are difficult for public authorities, from school boards to state legislatures, to justify to the public. Projects that provide operating cost savings (*e.g.*, energy efficiency investments) often are prioritized. This risks a misallocation of capital away from hazard mitigation investments that have compelling societal value.

Assessing inventories of school buildings to characterize their vulnerability is neither costly nor time-consuming, but such assessments may be delayed by complacency. Organizing engineering evaluations to diagnose structural problems and estimate the cost of correcting them is a more complicated step requiring action by school districts and coordination and logistical support from engineering professionals. Deploying engineering and construction talent to retrofit or repair schools at risk is still more complex and costly, requiring significant capital investment and close coordination with local school districts and facilities managers. Policies are needed to overcome complacency, facilitate logistics, and expand access to capital for retrofits.

The typical default position – to allow the natural turnover of building stock to set the pace of modernizing schools – leaves districts two alternatives: Either force the closure of facilities that lack sufficient ductility or lateral strength, or leave large numbers of students at risk in deficient structures. Neither alternative is desirable, but both remain common in regions of high seismic hazard in the United States.

Each of the five regions of high seismic hazard discussed below offers examples of ways to address complacency, facilitate logistics, or expand access to capital. By combining promising approaches from different regions into a deliberate strategy, a national agenda to accelerate progress on school safety may be brought into clearer focus.

FIVE REGIONS AT RISK

In the continental U.S. (excluding Alaska and Hawaii), five regions possess the highest level of hazard identified on the USGS National Seismic Hazard Maps: California and Nevada, Cascadia (Washington, Oregon, and Northern California), Utah (along the Wasatch Front), coastal South Carolina, and the New Madrid Seismic Zone encompassing part of an eight-state region of the central U.S. (Figure 3-1.). Alaska and Hawaii each possess high seismic hazard areas as well, but lie outside the scope of this paper. Each of these five regions possesses distinct seismic hazards, and each presents unique obstacles to the "assess, rank, and mitigate" approach that the Western States Seismic Policy Council recommends for improving school safety.

California: The state that ranks Number 2 in number of earthquakes sets the U. S. benchmark for earthquake awareness and earthquake policy. The magnitude (M) 7.8 Great San Francisco earthquake of April 18, 1906 remains the iconic modern earthquake in American consciousness, but several more recent California earthquakes have triggered significant policy innovations that have yet to be emulated by other states. Nevada, whose seismic hazard resembles California's, is omitted from this discussion in the interest of simplicity.

With respect to school safety, the most important California earthquake of the 20th Century was the M6.4 Long Beach earthquake of March 10, 1933, which left more than 230 school buildings destroyed, significantly damaged, or judged unsafe to reoccupy. The earthquake struck on a Friday afternoon after school hours. One month later, the California State Assembly adopted the Field Act, which mandated that new public schools must be earthquake resistant and established the Office of State Architect (now known as the Division of State Architect) to oversee the safety of school construction (California Seismic Safety Commission, 2007).

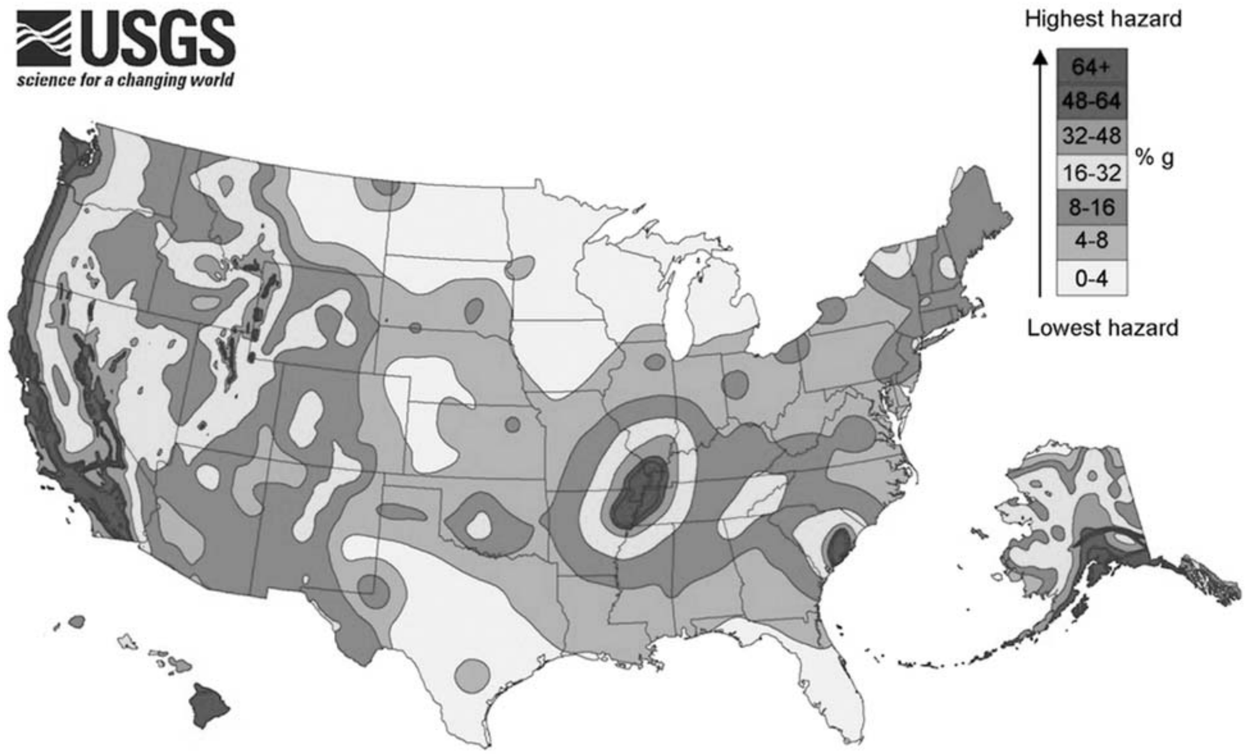


Figure 3-1. National Seismic Hazard Map showing peak ground accelerations
SOURCE: Petersen et al., 2008

One outcome of the Field Act was the banning of unreinforced masonry (URM) construction, the structural type that sustained the heaviest damage in the Long Beach earthquake. Although some URM buildings that predate 1933 remain in operation in California school districts, they are not in classroom use. Non-classroom uses do not fall under the jurisdiction of the Division of State Architect.

No injuries or deaths have occurred in a post-Field Act school building, and no school constructed according to Field Act standards has suffered partial or complete collapse in subsequent earthquakes. During the 1989 M6.9 Loma Prieta earthquake, two public schools in San Francisco's otherwise heaviliy damaged Marina District served as emergency shelters and disaster assistance centers (California Seismic Safety Commission, 2007). Legislative mandates and building code revisions triggered by recent earthquakes including Loma Prieta and the 1994 M6.7 Northridge earthquake have steadily advanced earthquake engineering practice in California.

California remains an innovator in the civil society response to the risk of earthquakes to educational facilities. The California Parent-Teacher Association (CAPTA), for example, adopted a statewide resolution on non-structural falling hazards and schools in May 1989 (5 months BEFORE the Loma Prieta earthquake) (California State PTA, 1989). The Great Southern California ShakeOut of November 2008, the largest voluntary earthquake drill in the U.S. up to that point, has inspired similar large-scale drills in many parts of the U.S. including all of the states and regions discussed in this paper.

New initiatives in California, including the voluntary efforts by the Concrete Coalition (sponsored by the nonprofit Earthquake Engineering Research Institute and focused on the seismic performance of non-ductile concrete buildings), continue to assess and propose mitigation for non-ductile structures including schools, with primary emphasis on compiling inventories of potentially hazardous buildings. A Pulitzer Prize-nominated investigative reporting project, "On Shaky Ground," exposed failures in the regulation of seismic safety at California public schools, suggesting that school safety remains an unrealized goal even in this innovative state (California Watch, 2011).

Cascadia: Washington and Oregon share a moderate to high seismicity (Washington and Oregon rank #5 and #10 respectively on a USGS list of states with the most frequent earthquakes) and the regional seismicity of Northern California is well-known, but the regional vulnerability to an earthquake along the Cascadia Subduction Zone (CSZ) megathrust (fault) that parallels the coast of both states has been recognized for only 25 years (Figure 3-2). The last full rupture of the CSZ occurred on January 26, 1700. Much of the existing built environment in the regions of all three states adjacent to the CSZ

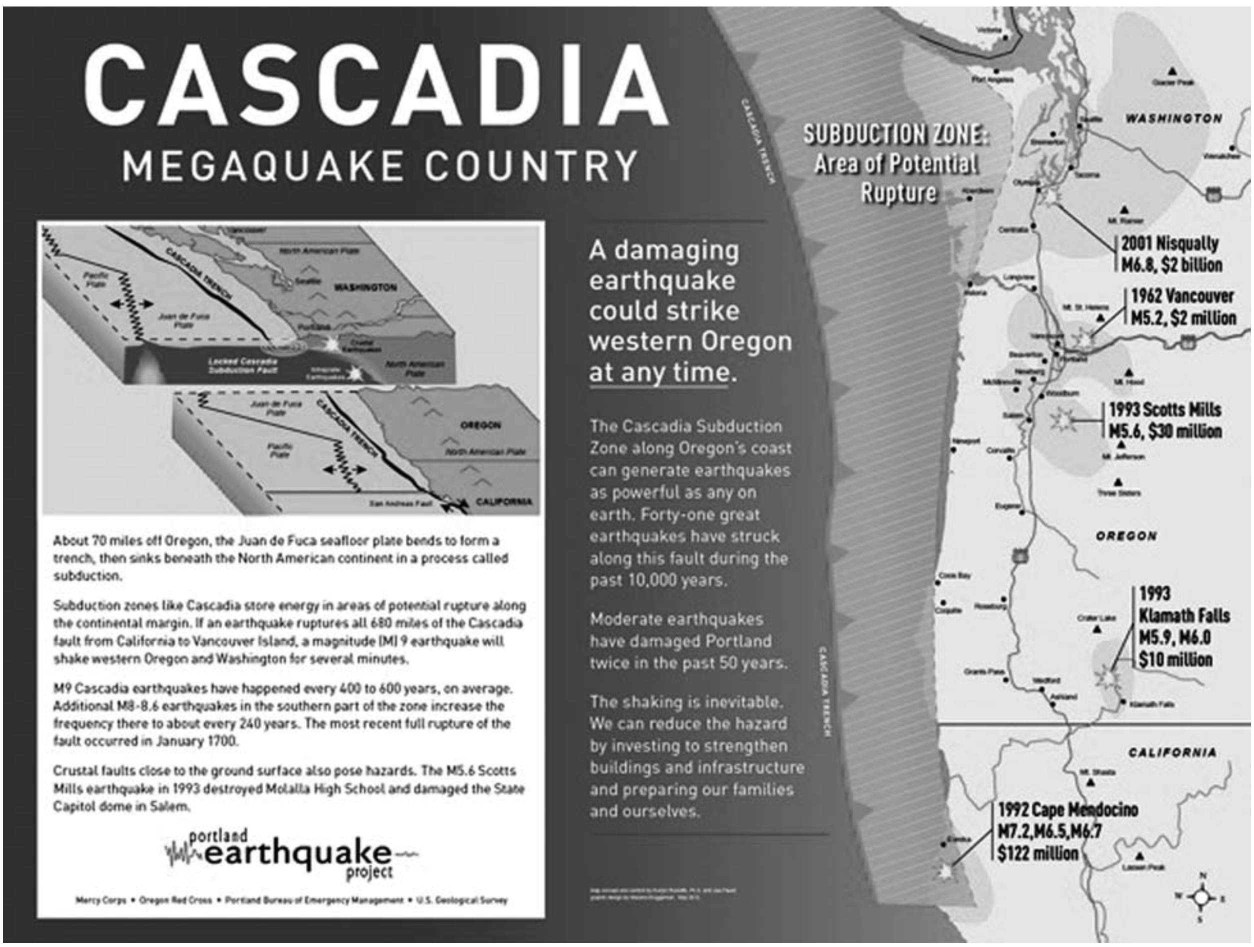


Figure 3-2. The Cascadia Subduction Zone
SOURCE: The Portland Earthquake Project

predates scientific understanding of the subduction zone risk. Policy and practice are slowly catching up to contemporary scientific assessments of the earthquake and tsunami hazard associated with the CSZ. Our discussion emphasizes initiatives in Oregon and Washington, states where the seismic policy environment is less advanced than in California.

Public awareness, informed by science, shaped relatively few policy initiatives relating to the subduction zone hazard in Cascadia before the March 2011 M9.0 Tohoku earthquake and tsunami generated by the megathrust off northeast Japan, often described as the "mirror image" of the CSZ. The immediacy of video images from that disaster, as well as tsunami warnings and the trans-Pacific tsunami wave that made impacts along the U.S. West Coast (including the arrival of marine debris beginning in spring 2012), have buoyed new initiatives, including a Resilient Washington State effort coordinated by Washington Emergency Management, and a legislatively directed statewide resilience planning effort directed by Oregon's Seismic Safety Policy Advisory Commission.

School inventories in Oregon and Washington include large numbers of non-ductile school facilities built before seismic building codes, and retrofits to older structures have been largely piecemeal affairs driven by the interest of local school boards and the receptivity of local voters to school bond measures that finance replacement of existing schools. Both states have experience with large-scale risk assessments, Oregon with a statewide assessment of schools and emergency response facilities completed in 2007 (Lewis, 2007), and Washington with a seismic safety pilot project in two school districts designed to produce affordable building-specific assessments that can be used directly for engineering design for mitigation (Walsh et al., 2011).

Statewide progress on mitigation of at-risk schools is not proceeding quickly in these two states, because responsibility for school facilities is highly decentralized and state resources for mitigation remain limited. Oregon has policies in place, including a statewide database of seismic ratings for schools built prior to 1994 and voter authorization to use general obligation bonding to finance retrofits for schools at risk, but legislators have shown little inclination so far to use that authority to address the problem at a large scale.

Washington State has a larger state economy, a somewhat different system for funding public education, and a tax system more favorable for passage of local school bonds, so the rate of replacement of older school buildings is probably higher than in Oregon. But no coordinated effort is yet in place to identify and prioritize the replacement of the most hazardous school buildings in Washington's inventory of 3,000 or so public schools.

Civil society in Washington and Oregon is increasingly engaged with the risk of significant earthquakes as well as tsunami. Both states have hosted, or are planning, large-scale ShakeOut earthquake drills that introduce large numbers of people, including students, to Drop, Cover, and Hold On practices that will save lives in the event of an earthquake. Both states are engaged in resilience planning exercises that aim to expand the policy menu beyond public safety to broader considerations of business continuity and economic recovery. The growing engagement of the business community in resilience planning and policy could lead to a new emphasis on the seismic safety of schools as one element of the integrity of the educational system, often singled out as a key priority on the business agenda.

Utah: The state of Utah ranks ninth in frequency of earthquakes, just ahead of Oregon, but the sparsely populated state has a concentrated region of high seismic hazard along the western base of the Wasatch Range. Although it has not generated a major earthquake since Mormon pioneers settled in the Great Salt Lake Valley in 1847, the 240-mile multi-segment Wasatch fault is believed capable of producing earthquakes of M7 and larger. Today the Wasatch Front is a rapidly growing metropolitan region stretching north and south from Salt Lake City along the Wasatch Range, accounting for about 80 percent of Utah's 2.8 million residents (Utah Seismic Safety Commission, 2008).

Because no major earthquakes have struck along segments of the Wasatch fault in historic times, awareness of the seismic hazard did not shape modern settlement patterns, and according to the Utah Geological Survey, many urbanized areas along the Wasatch Front today are built on soft lake sediments expected to be highly vulnerable to earthquake ground shaking. Construction did not take seismic hazard into account until recently, and over 150,000 URM structures may be at risk. Vulnerable buildings include many of Utah's 1,094 K-12 school buildings.

School safety has been a focus of the Utah Seismic Safety Commission, which led a pilot assessment of 128 public and charter school buildings using a Rapid Visual Screening method (FEMA 154) designed to identify structures in need of detailed seismic evaluation due to estimated probabilities of collapse associated with certain visual features of the structures assessed. The pilot assessment, completed in February 2011, identified 77 schools in need of further assessment, including 46 with scores indicating greater than ten percent probability of collapse in a strong earthquake and 10 considered highly likely to collapse. The high proportion of schools identified with significant risk factors supported the Commission's call for a comparable survey of all of Utah's 1,094 public schools and establishment of a systematic program to improve the seismic safety of Utah's older and seismically unsafe schools (Siegel, 2011).

Little progress toward that goal had been achieved at the time of this writing (June 2012). A bill to initiate the statewide survey (HB 279) was unsuccessful in the 2012 legislature (Utah State Legislature, 2012a). Legislators also took action during that session to weaken an existing requirement to make seismic improvements including bracing chimneys and parapets in unreinforced masonry buildings during re-roofing (Utah State Legislature, 2012b).

Civil society is shining a new spotlight on the hazard. In April 2012, Utah participated for the first time in ShakeOut events with the Great Utah ShakeOut, in which more than 940,000 Utahns participated. The statewide Drop, Cover, and Hold On drill was organized by Be Ready Utah, a statewide emergency preparedness campaign run by Utah's Department of Public Safety. In May 2012, Utah PTA members gave unanimous support to a resolution on earthquake-safe schools at their state convention. The resolution urges the legislature to fund a statewide rapid visual screening of all public school buildings and calls on the State Office of Education to support new efforts to address schools at greatest risk (Utah PTA, 2012). Utah PTA represents more than 135,000 local members at 650 schools. More must be done to turn this public awareness into political support for action to assess and retrofit Utah's unsafe school buildings.

South Carolina: Though the state is not widely known for its seismicity, the Charleston earthquake of 1886, estimated M7.3, was the most damaging earthquake ever to strike the southeastern United States. The earthquake caused extensive damage in an area with little or no known historical earthquake activity, and generated powerful aftershocks for months after the event. Shaking and liquefaction caused damage to more than 2,000 buildings in Charleston, some of the damage visible to this day (Coté, 2006).

The Charleston County School District, an urban district serving 45,000 students in 80 schools, made an unprecedented decision in May 2010 to close six schools after receiving engineering evaluations indicating the buildings' inability to withstand an earthquake of M5.0, considerably smaller than the 1886 earthquake. The decision involved the proposed relocation of 1,331 students served by four downtown schools for up to three years, a complex logistical challenge for any school district, and one that met with inevitable community resistance (Courrégé, 2010).

The second-largest of South Carolina's 85 school districts, Charleston County's inventory of schools probably reflects structural types and building ages found in many of the state's other cities and towns, but there is no indication that Charleston's historic earthquake or the "Relocate, Rebuild, Return" project the district initiated amid controversy in 2010 has triggered broader statewide concern about the vulnerability of school facilities. URM schools and other non-ductile structures probably account for a significant proportion of the state's 1,123 public schools, and a considerable share of the state's K-12 enrollment of roughly 700,000 students may be at risk.

Lacking a statewide seismic commission or an organized constituency for safer schools, it is difficult to see where the initiative might arise to advocate for assessment and mitigation of South Carolina schools, and how concern might translate into political support for public investment in seismic retrofits. The South Carolina Seismic Network, hosted at the University of South Carolina in Columbia, has a program of outreach to middle school and high school teachers to promote earth science education, but no focus on structural engineering. The College of Charleston hosts the South Carolina Earthquake Education & Preparedness Program, also with a focus on geology and not on engineering or the state's built environment. The Structural Engineers Association of South Carolina has been in existence for less than a decade and has had little time to undertake public policy advocacy. The South Carolina Earthquake Awareness Project, founded by the author of a history of the Great Charleston Earthquake, is one effort to raise awareness and improve policy (Coté, undated).

More than 260,000 South Carolinians reportedly did participate in the first Great Central U.S. ShakeOut drill in April 2011 (Central U.S. Earthquake Consortium, 2011). Although South Carolina is not a member state in the Memphis-based Central U.S. Earthquake Consortium, participation in ShakeOut was promoted and coordinated by South Carolina Emergency Management Division.

The New Madrid Seismic Zone (NMSZ): The NMSZ covers parts of an eight-state region centered on the town of New Madrid, Missouri. Over the winter of 1811–1812, a sequence of intraplate temblors shook the region with magnitudes between M7 and M8. The three major earthquakes that struck during the three-month period between December 1811 and February 1812 rank among the largest earthquakes in the recorded history of continental North America. Aftershocks followed for a period of at least five years, but because the region was sparsely populated at the time, casualties and recorded property damage were light (USGS, N.D.).

Today the region is home to approximately 11 million people and comprises some of the most densely urbanized and populated parts of the central U.S. including the city of Memphis, Tennessee. Damages caused by a repeat of the 1811–1812 temblors would be severe. FEMA has taken a keen interest in the NMSZ, and warned that a serious earthquake could result in the highest economic losses ever attributable to a natural disaster in the U.S., lasting impact due to disruption of lifeline infrastructure, and thousands of fatalities (FEMA, 2008; Frankel et al., 2009).

The City of Memphis has been a focus of special concern in the NMSZ, due to the city's location, population, and large numbers of non-ductile and unreinforced masonry buildings. Memphis City Schools, Tennessee's largest urban district with over 200 K-12 schools and enrollment of over 113,000 students (now in the process of merging with the Shelby County School District), has long alarmed geologists and engineers because of its large inventory of URM school buildings.

In 1997, Howard Hwang and Yang-Wei Lin of the Center for Earthquake Research and Information at the University of Memphis conducted a study titled "Expected Seismic Damage to City School Buildings." Their survey of 542 Memphis City School buildings identified some 286 URM structures, over half the district's inventory. White Station High School, one of the state's highest-performing high schools with a current enrollment of over 2,200 students, was identified to have five URM structures (the newest constructed as recently as 1967) on its nine-building campus. (Hwang and Lin, 1997).

Despite the comprehensive assessment of Memphis schools and the concentration of earthquake engineering expertise in Memphis, no action has been taken to carry out subsequent engineering assessments or to mitigate the risk to older Memphis schools, and no similar efforts have yet been proposed or carried out elsewhere in the NMSZ. The building code governing new construction in Memphis was significantly weakened by amendment, meaning that newly constructed schools also remain at risk. (Mike Mahoney, FEMA, personal communication, October 23, 2012).

Memphis City Schools was an enthusiastic participant in the first Great Central U.S. ShakeOut (Central U.S. Earthquake Consortium, 2012). The district scheduled its drill, the first-ever district-wide safety drill, for March 11, 2011 – by coincidence, the date of the M9.0 Tohoku earthquake and tsunami in northeast Japan (other Shelby County schools and other central U.S. states staged the ShakeOut drill on April 28, 2011). Tens of thousands of Memphis students participated in the minute-long Drop, Cover, and Hold On drill, many of them in aging URM schools never strengthened to withstand earthquake shaking. Memphis school authorities have yet to acknowledge the structural risk posed by their schools; the district's current five-year capital plan makes no mention of the word "earthquake" (Bailey et al., 2011).

REDUCING RISK IN SCHOOLS

This survey of risk and response in the five high-seismic-hazard zones identified on the 2008 National Seismic Hazard Maps suggests several common themes in these widely disparate regions of the United States.

First, URM and non-ductile school structures remain common in the high-seismic-hazard zones of the continental United States. Unreinforced masonry took hold in school architecture in the early twentieth century, in many cases because of its "fireproof" advantages compared with the wood-frame schools it replaced. Ironically, the "fireproof schools" effort accelerated after the San Francisco earthquake of 1906 (Wolf and Bailey, 2011).

Only in California was the trend toward URM construction interrupted by the 1933 Long Beach earthquake, and even in that state undamaged URMs remained in service, although gradually shifted out of classroom use. Masonry structures, in locations untested by ground shaking, tend to remain in use; URM schools have particular longevity. Thus the exposure to risk in these structures is also long-lived.

Second, despite assessments indicating high seismic hazard, outside of California the low frequency of significant earthquakes in the recent history of other U.S. high-seismic-hazard zones makes it easy for jurisdictions and school authorities to dismiss the risk as hypothetical. Building inventories are not tested and weeded out by ground shaking, existing structures remain in use without upgrades, and communities continue to expand. People move in to areas with significant seismic risk, with relatively few opportunities to learn how that risk relates to their lives.

This helps to explain the widespread appeal of earthquake drills and the growing popularity and success of large-scale efforts like ShakeOut. Drills impart useful information that can save lives. At comparatively modest cost, such drills give people the satisfaction of participation and the feeling they have taken a significant step to reduce risk and augment their personal safety. ShakeOut drills have attracted significant participation in each of the five regions discussed in this article, and they may represent a preliminary step toward broader public constituencies for an earthquake safety agenda that includes safe schools, residential retrofits, etc. The momentum toward constituencies with the capacity to influence policy is not yet clearly established, and so the contrary possibility must be considered: that authorities encourage public participation in safety drills as an affordable alternative to more costly commitments to earthquake safety.

Our survey also suggests that assessment, ranking, and mitigation efforts are very difficult to initiate at the individual school district level. School boards, even when motivated by a concern for student safety, are highly responsive to local electorates, which are typically deeply conservative when it comes to changes proposed for local schools. Charleston County Schools has found it very difficult to close and rebuild a small number of schools even when the risk and rationale for the school board's decision to close them were well documented. Memphis City Schools leadership has never acknowledged the results of the comprehensive assessment of school facilities performed fifteen years ago. Finding ways to bring the issue to the attention of decision makers at higher levels of authority is key.

State legislation appears to be a better way to begin and sustain school assessment and mitigation efforts. California has the advantage of a history of legislative initiatives dating back to the 1933 Long Beach earthquake and advanced by the many subsequent earthquakes that the state has experienced. Oregon has a double advantage (described below): legislative mandate of a statewide assessment of schools and voter authorization of a funding mechanism to pay for needed mitigation. The Utah legislature has so far resisted efforts to build on the preliminary assessment of school buildings completed by the Utah Seismic Safety Commission, but has at least considered and debated legislative proposals on the topic (Utah State Legislature, 2012).

The key element needed to move legislation and enact policies is public constituencies informed, activated, and in a position to apply pressure to the policy processes that direct public investment. Public safety constituencies such as the preparedness advocates that promote and support safety drills appear to be necessary but not sufficient. These constituencies typically focus on policy implementation rather than policy formulation. Preparedness constituencies that brought ShakeOut drills to South Carolina, the states of the NMSZ, and Utah have so far failed to advance policy on assessment, ranking, and mitigation of schools in those regions. To a certain extent, their goals provide a non-controversial alternative to the policy debate.

Informed, engaged advocates with the ability to represent the interest of groups at risk are needed. For school safety, this means advocates who represent parents with children in school. National PTA is the oldest and most respected of these advocates; parents' involvement in the reconstitution of public education after the 1906 San Francisco earthquake was one significant thread in the creation of the modern PTA. At the state level, PTAs have weighed in on seismic safety objectives by adopting resolutions in California, Oregon, and Utah, and that initial policy commitment can pave the way to advocacy. At the national level, the PTA structure is highly decentralized, with few systematic means to share initiatives among states.

Finally, implementation challenges may be encountered at the state, district, or even individual school level. California, where a commitment to school seismic safety has been institutionalized for 80 years, still receives criticism for inadequate implementation and oversight of its programs for schools at risk (California Watch, 2011). Oregon has enacted strong policies but has lacked the political will to implement them and to commit funds at the scale needed. Charleston County Schools has found it difficult, even in a situation with adequate funding for retrofits in hand, to temporarily close four schools (out of an inventory of 80 schools) in the face of public opposition. Even when the policies and resources are in place, mitigation of seismic risk may remain elusive.

CASE STUDY: OREGON

Oregon is further along the road toward significant public investment in seismic retrofits than most other states and regions, but the state struggles with policy obstacles and lack of political will that keep the goal of safer schools more aspirational than attainable.

Significant milestones included passage of a 2001 law (ORS 455.400) that set an aspirational target date of January 1, 2032 for the seismic rehabilitation of school buildings, subject to available funding, and a 2002 referendum adopted by Oregon voters that amended the state's constitution to allow General Obligation bonding to fund seismic rehabilitation of public education facilities (Wang and Burns, 2006; Wang, 2010; DOGAMI, 2010).

Enabling legislation (Senate Bills 2, 3, 4, and 5) passed in 2005 created a funding mechanism, the Seismic Rehabilitation Grants Program, to make seismic retrofit grants to eligible school districts and community colleges, and directed the state's Department of Geology and Mineral Industries (DOGAMI) to conduct a statewide Rapid Visual Screening (RVS) survey of public education and emergency response facilities and to make a comprehensive database of seismic ratings available to the public. The results, published in July 2007, were intended to help guide priorities in the allocation of seismic retrofit grant funds (Lewis 2007, Wang 2010).

The extent of risk revealed was perhaps larger than most policymakers had anticipated. According to the DOGAMI study, the RVS risk analysis identified over 1,000 school buildings whose RVS scores indicated a High or Very High probability of collapse in a strong earthquake (Lewis, 2007). The data revealed large numbers of public school facilities of all structural types constructed prior to Oregon's adoption of statewide building codes in 1974; well over half the school buildings assessed by the project are more than fifty years old.

The seismic grant program established by statute in 2005 was not staffed and operational until 2008. The first opportunity to authorize a bond sale for an inaugural round of seismic retrofit grants came in the 2009–2011 budget cycle. With the global financial crisis in full swing, it was the worst possible time in many years to launch a significant new program of public investment.

Nonetheless, the Oregon Legislature authorized $30 million for seismic grants, divided equally between the program for K-12 schools and a companion program to retrofit emergency response facilities. The first K-12 school grants, totaling $5.6 million for projects at twelve schools in eight school districts, were awarded in spring 2010. At around the same time, as the recession deepened and the state encountered fiscal difficulties, Governor Ted Kulongoski unilaterally rescinded $7.5 million of the original authorization for the program, limiting additional granting during 2009–2011.

Three K-12 schools (including two URM buildings) were awarded an additional $3.8 million for seismic retrofits in early 2011. These grants marked the end of the first funded cycle of the seismic grant program. A total of $9.4 million of the anticipated $15 million had been awarded to fifteen K-12 schools. The decision to continue or expand the program would be up to the 2011–2013 Legislature.

During this period, the State Treasurer advised a hiatus in issuing new General Obligation bonds, because state revenues were declining and he judged the state's credit rating to be at risk. This policy seriously undermined legislative interest in authorizing new seismic retrofit grants.

On March 11, 2011, the Tohoku earthquake and tsunami in Northeast Japan put Oregon's vulnerability to subduction zone risks back on the table, in the early weeks of a new legislative session. In April, the legislature passed House Resolution 3, sponsored by Rep. Deborah Boone (D-Cannon Beach), which directed Oregon's Seismic Safety Policy Advisory Commission (OSSPAC) to lead a statewide resilience study to recommend state policies designed to reduce the impact and accelerate the recovery from a region-wide Cascadia earthquake and tsunami. The resolution did not appropriate new state funds, but did emphasize public schools as a highly vulnerable component of Oregon's public infrastructure and a place where smart retrofit investments could mitigate the risk of mass casualties (Oregon Legislative Assembly, 2011).

During the same period, new voices began to emerge in Oregon's civil society. The Oregon PTA considered and adopted a resolution on earthquake-safe schools at its statewide convention in April 2011, putting this respected statewide advocate for children and schools on record in favor of new investments in public safety (Oregon PTA, 2011). Legislative advocates of energy efficiency in schools, a key priority of Governor John Kitzhaber, broadened their message to point out that state-supported energy and seismic retrofits could go hand in hand (Wolf and Bailey 2011). On the final day of the legislative session in June 2011, thanks to the efforts of staunch seismic safety advocate Sen. Peter Courtney, the legislature authorized $7.5 million in new seismic grants for the 2011–2013 biennium, keeping the seismic grant program on life support.

The new grants, announced in Fall 2011 and funded by a bond sale in July 2012, directed $7.2 million to seven more K-12 schools, bringing the total seismic retrofits funded by the state to 22 in a state in which over 1,000 school buildings have been identified as possessing high risk, or about 2 percent of the identified need. Oregon has made a start on school safety, and approved public investments that provide additional protection to approximately 8,500 schoolchildren. But future funding for the program is not assured, leadership interest has proved inconsistent at best, and the state is not on track to meet its 2032 target for seismic retrofit of all schools at risk.

One of the obstacles, despite visionary policy, remains a failure to appreciate the seriousness of the threat to life safety. In Oregon (as in most states), independent local school boards are responsible for school facilities, and few boards and local school districts have the expertise or capacity to manage the risks associated with their school facilities. Few seek assistance in understanding "new" problems like seismic vulnerability.

The statewide seismic assessment completed by DOGAMI was communicated to the public via release on the Internet, but the seismic ratings were not shared directly with Oregon's 197 school boards or with district superintendents. Nor were those groups, or the state's Department of Education, consulted about how the statewide screening results could be packaged and presented in a form most useful to the education community. This ultimate "constituency" for the seismic ratings – the group whose decisions the ratings were intended to inform – was not treated as a constituency.

Recognizing that a communications breakdown may have limited demand for the seismic retrofit grants, Sen. Peter Courtney introduced legislation in the 2012 session of the Oregon Legislature designed to raise the visibility of the data in the state's possession. Senate Bill 1566, passed with bipartisan support, directs the state's Department of Education (which communicates with parents about student achievement and school performance via an annual "report card") to include information on that annual report letting the public know that the database of seismic ratings exists and sharing a Web link to the ratings (Oregon Legislative Assembly, 2012). Further, the bill asks school districts to advise the state's Department of Geology and Mineral Industries when they rebuild or renovate schools, so that the state can share information about the upgrades.

These steps, although imperfect, will help to expand public awareness of the existence of the school seismic ratings. As a result, parents concerned about their children's schools may initiate new conversations with principals, superintendents, and elected school boards. Their questions will draw attention to the existence of the grant program, so that legislators may find it harder to ignore the need for significantly increased public investment to address the schools that remain at risk.

Another barrier, related to the highly decentralized responsibility for school facilities in Oregon, is that even school districts aware of hazardous buildings may lack the engineering assessments needed to prescribe fixes. School districts, even large urban districts, typically lack discretionary funds to hire consulting engineers for comprehensive assessments of their existing school buildings.

One proposal under consideration in Oregon offers a novel approach to this problem. Voluntary teams of structural engineers, with (as yet unconfirmed) support from the state's Department of Education, would deploy to perform ASCE-31 seismic evaluations and prepare preliminary retrofit cost estimates at the top-priority schools identified by the state's RVS assessment. A voluntary effort is not a viable way to address more than a limited sample of schools at risk, but the hope, as with SB 1566, is that by directing new attention to the problem and engaging professionals in a real effort to address it, public interest and support for state investment in the seismic retrofit grant program will grow.

Despite innovative policies and more than a decade of effort, Oregon is barely making progress toward school seismic safety. Some of the lessons from Oregon's experience for states and regions just beginning this journey are clear: Comprehensive assessment of schools at risk is necessary, but not sufficient. New requests for public investment can expect to compete with existing priorities and to encounter economic setbacks. Leadership attention is limited, and cannot be taken for granted. Constituencies that command real influence with policymakers must be recruited or created, and kept engaged. All these steps take time. And in zones of high seismic hazard around the United States, time may not be on our side.

URM-FREE BY '33: A NATIONAL AGENDA FOR SAFE SCHOOLS

The principle that schoolchildren have a right to learn in buildings that are safe from earthquakes remains unfulfilled in each of five high-seismic-hazard areas in the continental United States. Yet each region can point to some progress toward school safety, and common themes suggest progress could be accelerated by better efforts to share experience and build capacity for the three-part strategy of risk assessment, ranking, and mitigation.

What's missing is a shared goal to unite the efforts underway so that "assess, rank, and mitigate" can be seen to serve a larger-than-local purpose. Our proposal: Make public school districts in the country's high-seismic-hazard zones URM-free by 2033.

Why frame this as a national goal? Access to public education is a fundamental tenet of American life. Public education remains the most local of Americans' common responsibilities, but in a globalized world, educational performance and achievement have come to be accepted as national concerns. Earthquakes and other natural hazards may help Americans embrace the condition of school facilities as a national concern as well, and advance a U.S. agenda for safe schools. We selected the year 2033, just twenty years from the date of this writing, to set an aggressive aspirational goal and to mark the centennial of California's Field Act, the first statewide legislation to require earthquake-resistant design and construction of all public school facilities.

As NEHRP's Advisory Committee on Earthquake Hazard Reduction points out in its 2012 recommendation to NIST, "school buildings tend to remain in use longer than comparable structures in private ownership and tend to receive less frequent and less predictable capital renewal investment to address maintenance issues that can jeopardize structural performance. Schools also can play a critical role in a community's recovery from disaster" (ACEHR, 2012). These twin attributes – a tendency to longevity and underinvestment, and a role in community resilience – supply themes for a national conversation about school facilities.

At the local level, school administrators and elected school boards owe it to themselves and to their constituencies to be well informed about the condition of school facilities in their care, and to take steps to prioritize safe facilities. At a minimum, school districts in earthquake hazard zones should conduct comprehensive assessments of all their buildings, identify the URMs and other non-ductile buildings, and disclose the findings in reports meaningful to parents and other school constituencies. In a society where education remains compulsory, "guilty until proven innocent" should be the presumptive standard for school facilities in which children are obligated to spend their days. URMs, widely considered the top-priority subset of non-ductile structures, are a natural place to begin (Figure 3-3) (Reitherman, 2009). Some URMs of historic significance and exceptional community value will merit special approaches to mitigation, but no URM hazard to schoolchildren should be left unaddressed.

At the state level, departments of education can serve districts and parents by acting as clearinghouses of information about the condition of school facilities, just as they act as clearinghouses of information on student achievement and educational outcomes. In this

Figure 3-3. Portland, Oregon's Franklin High School is one of three URM high schools that will be rebuilt thanks to a school bond approved by Portland voters in November 2012
Photo by Yumei Wang.

way, departments of education can support school districts that take proactive steps to address seismic hazards, encourage school districts to do more to document or address the hazard, and assist parents in understanding the issue.

State education departments can also help legislators to see the merit of state investment in seismic retrofits, a capital expense that may exceed the local means available to small rural school districts in seismic hazard zones. The vulnerability of U.S. schools cannot be reduced without capital, and states must share the responsibility for this type of public investment if local districts cannot marshal the resources to assure student safety.

At the federal level, FEMA, its parent the Department of Homeland Security, and the Department of Education can do more, together and separately, to support schools as key elements of resilient communities. If funding from the federal level remains limited, then information sharing and coordination must play larger roles. FEMA could assemble information on school districts and jurisdictions that have performed RVS surveys and develop a joint strategy with the Department of Education to publicize the results, highlight best practices, and track mitigation progress. Districts that have performed such assessments can receive some credit for their accomplishment; districts and jurisdictions just encountering the problem can find examples to follow.

A national school safety goal has proved elusive because local circumstances – seismicity, the age of buildings, building codes, and the condition of building stock – vary. Each region, however, shares the common vulnerability of unreinforced masonry. "URM-free by '33" sets a goal, specifies a date, and defines a target in the interest of millions of public school students and their families, beginning with high-seismic-hazard areas in sixteen states**.

Removing URMs from the inventory of public schools makes sense from a safety standpoint, because URMs possess structural deficiencies that are difficult and costly to mitigate. Removing URMs from the inventory also makes sense from a community resilience standpoint, because URM buildings are unlikely to be usable for community purposes after an earthquake even if the structural damage they sustain causes no casualties.

With the addition of a clear goal, a national message can begin to unite fledgling efforts that need to grow. Identify and rank schools at risk. Mitigate high-priority schools. Remove URMs from school inventories by 2033. A national agenda built on these priorities would affirm the right of schoolchildren to learn in buildings that are safe from earthquakes. Policy will follow the principle.

ACKNOWLEDGMENTS

The authors thank Mike Mahoney, Barry Welliver, and Ivan Wong for thoughtful review comments, the National Earthquake Hazard Reduction Program and its Advisory Committee on Earthquake Hazard Reduction, the Schools Committee of the Earthquake Engineering Research Institute, and our colleagues Nancy Bailey, James Beaver, Philip Gould, Mike Mahoney, and Barry Welliver for opportunities to explore these ideas together. We are particularly grateful to Mike Mahoney for suggesting the title of this paper.

References

Advisory Committee on Earthquake Hazards Reduction (ACEHR). 2012. *Effectiveness of the National Earthquake Hazards Reduction Program: A Report on NEHRP Effectiveness*. Washington, D.C. Online: http://www.nehrp.gov/pdf/2012ACEHRReportFinal.pdf

Bailey, Nancy, Welliver, Barry and Wolf, Edward. 2011. "Buildings, Not Drills, Hold Key to Disaster Proof Schools," *Education Week*, July 18. Online: http://www.edweek.org/ew/articles/2011/07/18/37bailey.h30.html?tkn=VTUFrkA6FwryYe03Tjx%2FXyOjWf9q6I3xI%2FhV&intc=es

**The sixteen states with high-seismic-hazard areas include Alaska, California, Hawaii, Nevada, Oregon, South Carolina, Utah, Washington, and the states of the New Madrid Seismic Zone: Alabama, Arkansas, Illinois, Indiana, Kentucky, Mississippi, Missouri, and Tennessee. The total population of these states is 107.6 million (U.S. Census Bureau, July 2011 estimates; online: http://www.census.gov/popest/data/state/totals/2011/index.html).

California Seismic Safety Commission. 2007. *Field Act and Public School Construction: A 2007 Perspective.* CSSC 2007-03. Sacramento, Calif. Online: http://www.seismic.ca.gov/pub/CSSC_2007-03_Field_Act_Report.pdf

California State PTA. May 1989. "Mitigating Earthquake Hazards in Public Schools," Resolution on Earthquake Hazards and Schools. Sacramento, Calif. Online: http://www.capta.org/sections/advocacy/resolutions.cfm

California Watch. 2011. "On Shaky Ground" (multi-part investigative series). Center for Investigative Reporting, Berkeley, Calif. Online: http://californiawatch.org/earthquakes

Central U.S. Earthquake Consortium. 2011. The Great Central U.S. ShakeOut – Overview and Final Report. Memphis, Tenn. On-line: http://www.cusec.org/documents/shakeout/2011_ShakeOut_Final_Report.pdf

Coté, Richard N. Undated. "Preparing for Earthquakes in South Carolina," Website of the South Carolina Earthquake Awareness Project www.scearthquakes.com (last revised February 1, 2012), Charleston, S.C.

Coté, Richard N. 2006. *City of Heroes: The Great Charleston Earthquake of 1886* (Mt. Pleasant, S.C.: Corinthian Books).

Courrégé, Diette. 2010. "Board votes to move students," *The Post and Courier* (Charleston, S.C.), May 11. Online: http://www.postandcourier.com/article/20100511/PC1602/305119947

Department of Geology and Mineral Industries (DOGAMI). 2010. "Oregon's Seismic Safety Legislative Timeline," *CASCADIA* (newsletter, winter issue), Portland, Ore. Online: http://www.oregongeology.org/sub/quarpub/CascadiaWinter2010.pdf

Federal Emergency Management Agency (FEMA). 2008. "New Study Examines Impact of Magnitude 7.7 Earthquake on States in New Madrid Seismic Zone." Press release No. HQ-08-249. Washington, D.C. On-line: http://www.fema.gov/news/newsrelease.fema?id=46853

Frankel, A.D., Applegate, D., Tuttle, M.P., and Williams, R.A. 2009. Earthquake hazard in the New Madrid Seismic Zone remains a concern. U.S. Geological Survey Fact Sheet 2009–3071, Memphis, Tenn. Online: http://pubs.usgs.gov/fs/2009/3071/

Hwang, Howard and Yang-Wei Lin. 1997. "Expected Seismic Damage to City School Buildings." Memphis, Tenn.: Center for Earthquake Research and Information, University of Memphis.

Lewis, Don. 2007. *Statewide Seismic Needs Assessment: Implementation of Oregon 2005 Senate Bill 2 Relating to Public Safety, Earthquakes, and Seismic Rehabilitation of Public Buildings* (Open File Report 07-020). Portland, Ore.: Department of Geology and Mineral Industries. Online: http://www.oregongeology.org/sub/projects/rvs/default.htm

Oregon Legislative Assembly. 2011. House Resolution 3. Sponsored by Rep. Deborah Boone. Online: http://www.leg.state.or.us/11reg/measpdf/hr1.dir/hr0003.en.pdf

Oregon Legislative Assembly. 2012. Senate Bill 1566, Relating to Seismic Information About Schools, Sponsored by Senate President Peter Courtney. Online: http://www.leg.state.or.us/12reg/measures/sb1500.dir/sb1566.en.html

Oregon PTA. April 2011. "Making Oregon Schools Earthquake Safe." Resolution adopted at Oregon PTA Convention, Portland, Ore. Online: http://www.oregonpta.org/docs/advocacy/seismicUpgradesRes.pdf

Petersen, Mark D., Frankel, Arthur D., Harmsen, Stephen C., Mueller, Charles S., Haller, Kathleen M., Wheeler, Russell L., Wesson, Robert L., Zeng, Yuehua, Boyd, Oliver S., Perkins, David M., Luco, Nicolas, Field, Edward H., Wills, Chris J. and Rukstales, Kenneth S. 2008. Open-File Report 2008–1128. "Documentation for the 2008 Update of the United States National Seismic Hazard Maps." Washington, D.C.: U.S. Geological Survey.

Reitherman, Robert. 2009. *Unreinforced Masonry Buildings and Earthquakes: Developing Successful Risk Reduction Programs*. FEMA P-774. Washington, D.C.: Federal Emergency Management Agency.

Siegel, Lee J. 2011. *Utah Students At Risk: The Earthquake Hazards of School Buildings.* Salt Lake City: Utah Seismic Safety Commission and Structural Engineering Association of Utah. Online: http://ussc.utah.gov/students_at_risk.html

U.S. Geological Survey (USGS). 2008. United States National Seismic Hazard Maps (Fact Sheet 2008-3017), Washington, D.C. Online: http://pubs.usgs.gov/fs/2008/3017/pdf/FS08-3017_508.pdf

U.S. Geological Survey (USGS). Undated. "New Madrid 1811–1812 Earthquakes," Washington, D.C. Online: http://earthquake.usgs.gov/earthquakes/states/events/1811-1812.php/

Utah PTA. 2012. "Utah Students At Risk, Need for Rapid Visual Screening Seismic Survey," Safety Resolution SAF 2012-1. Salt Lake City, Utah. Online: http://www.utahpta.org/safety-resolutions

Utah Seismic Safety Commission. 2008. *Putting Down Roots in Earthquake Country*. Salt Lake City, Utah. Online: http://geology.utah.gov/utahgeo/hazards/eqfault/index.htm

Utah State Legislature. 2012a. HB 279 – Utah Schools State Seismic Hazard Inventory. Introduced by Rep. Larry B. Wiley. On-line: http://le.utah.gov/~2012/htmdoc/hbillhtm/HB0279.htm

Utah State Legislature. 2012b. HB 305 Substitute – Construction Code Revisions. Introduced by Rep. Gage Froehrer. Online: http://le.utah.gov/~2012/htmdoc/hbillhtm/HB0305S01.htm

Walsh, Timothy J., Schelling, John D. and the Washington State Seismic Safety Committee. 2011. *Washington State School Seismic Safety Pilot Project – Providing Safe Schools for Our Students.* Open File Report 2011-7. Olympia: Washington Division of Geology and Earth Resources. Online: http://www.dnr.wa.gov/publications/ger_ofr2011-7_school_pilot_project.pdf

Wang, Yumei. 2010. "Oregon's Seismic Rehabilitation Grants Program: a.k.a. Courtney Grants" (Paper No. 1816). Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering. Toronto, Ontario, Canada, July 25–29.

Wang, Yumei, and Burns, W.J.. 2006. "Case History of the Oregon G.O. Bond Task Force: Promoting Earthquake Safety in Public Schools and Emergency Facilities," in Proceedings of the 100th Anniversary Earthquake Conference, Commemorating the 1906 San Francisco Earthquake. San Francisco, Calif.

Western States Seismic Policy Council (WSSPC). 2010. "Identification and Potential Mitigation of Seismically Vulnerable School Buildings," Policy Recommendation 10-8. Broomfield, Colo.: WSSPC Annual Business Meeting.

Wolf, Edward and Bailey, Jules. 2011. "Cascadia's Seismic Certainty: Putting Earthquake Safety on the Green Schools Agenda," *Trim Tab* (on-line quarterly journal of the Cascadia Green Building Council, fall issue). Online: http://issuu.com/ecotone/docs/trimtabv11_fall2011

CHAPTER 4

The 2008 Sichuan Earthquake in China and Implications for the Central United States

Craig Taylor, Ph.D., Aff. M.ASCE
Nasim Uddin, Ph.D., P.E., F.ASCE
Yajie (Jerry) Lee
Kent Yu, Ph.D., S.E., M.ASCE
Chris Poland, S.E., F. SEAOC, M.ASCE
William Graf, P.E., M.ASCE

Abstract: *Striking abruptly, earthquake disasters create destruction, urgency, and confusion, as symbolized by the stopped clock at Hanwang town after the May 12, 2008, Wenchuan earthquake in the Sichuan Province of China. Prior decision making is over. The event fits the definition of a "Black Swan" occurrence: nearly unpredictable, having a massive impact, and followed by numerous post-disaster explanations. The destruction and injuries result not only from the sudden jolt, but from multiple generations of building and habitation practices as well as very long-term geological processes. The Central Eastern United States (CEUS) faces similar issues before the earthquake: what earthquakes and magnitudes to expect, what massive impacts may occur, and lots of ready but conflicting explanations that may be used after a possible major event should the "clock stop" as occurred in China. This paper explores the temporal dimensions of the Wenchuan event and, applicable to the CEUS, decision procedures that fit such events before they occur.*

INTRODUCTION

On Monday May 12, 2008 at 02:28:01 PM near the epicenter of the Wenchuan earthquake, the clock stopped (Figure 4-1). Intraplate earthquakes such as this one (and events in the Central Eastern United States) are less common and hence less anticipated than earthquakes in those interplate regions of California, Alaska, Turkey, Japan, Chile, and elsewhere. For those in need of immediate help, as is common in all emergencies, rescue within two minutes can seem like ten minutes. For those in the disaster region not in need of immediate care and not first responders, the daily bustle of life slows down since routes

Figure 4-1. The Stopped Clock at Hanwan Town

are impassable or cleared for emergency vehicles, commercial and industrial buildings are damaged, and telecommunication modes are disabled or saturated.

As first responders rapidly mobilized after the earthquake – within two hours after the magnitude 7.9 to 8.0 earthquake struck eastern Sichuan – the Chinese Premier Wen Jiabao was on route to the damaged region for a two-day visit. (China Daily, 2008) Not long after the disaster, a team from the Technical Council on Lifeline Earthquake Engineering of the American Society of Civil Engineers (TCLEE/ASCE) was mobilized to survey damaged infrastructure systems and to summarize damage totals developed by Chinese authorities (see Edwards, 2009; Yashinksy, 2009; Eidinger, 2009; Shannon, 2009; Lo, 2009; Lee, 2009; Tang, 2009).

This paper first summarizes different perspectives on temporal dimensions of decision-making for this intraplate earthquake as first based on an October visit by a team from the Council of Disaster Risk Management (CDRM) of ASCE, and joined by others from ASCE. This team first attended the Kwang-Hua World Forum Secretariat on the Wenchuan Earthquake and Post-quake Reconstruction. Some team members also gave presentations at the 14th World Conference on Earthquake Engineering (14WCEE) held concomitantly in Beijing. Five authors of this paper also surveyed the damaged region. In addition to visits with Chinese authorities, attendance at the Forum and World Conference, respectively, and site visits, the team benefitted enormously from the many internet contributions on this disaster. Comparison of the Wenchuan event with issues in the new Madrid Seismic Zone (NMSZ) comes through (a) a discussion of "Black Swan" events and (b) discussion of advanced procedures that assist in clarifying the seismic decision process in seismic regions. (See Taylor et al., 2009)

THE KWANG-HUA WORLD FORUM AND REFLECTIONS ON FUTURE AND PAST SEISMIC PRACTICES

The ASCE team attended and participated in a two-day Tongji University forum, chaired by Xilin Lu and K. C. Tsai, on the earthquake and its reconstruction. This forum stressed on the one hand assessments of damages in the earthquake and on the other hand engineering approaches stressing new seismic design and retrofit. Speakers included not only engineers from within China, but engineers from elsewhere, such as Japan, Australia, Korea, Taiwan, Canada, and the United States. Through this effort, China could learn about effective techniques from elsewhere and so adopt those engineering practices that withstand tests in practice as well as in the laboratory.

Selected Key Activities Before the Forum

On June 4, 2008, before the forum began, the State Council of the People's Republic of China had passed the "Wenchuan earthquake disaster recovery and reconstruction act," a very comprehensive approach to the huge tasks to be undertaken. Along with requiring safety from such hazards as flooding and landslide, even apart from earthquakes, this act considered ecological, aesthetic, social, cultural, psychological, administrative, economic, regional, agricultural, infrastructural, and a host of other factors in its guidelines for how recovery and reconstruction was to be undertaken. (State Council of People's Republic of China, 2008)

In addition, according to Tongi University's Vice President, Yongshang Li, the university's efforts to assist on the earthquake began rapidly after the earthquake as volunteers assisted on medical care rescue and support and soon afterwards on structural examinations of buildings, led by Xilin Lu, Director of Tongji University's Civil Engineering Research Institute of Structural Engineering and Disaster Reduction. This effort was undertaken from May 16 to May 23, during a period of five aftershocks with magnitudes greater than 5.0. Proposed as a result of this effort were: (1) Urgent safety assessments for important buildings are critical, (2) since masonry construction is widespread in China, seismic provisions need to be improved, especially for large-bay and large-space buildings, and including schools, hospitals and other public buildings and (3) the entire process of design, construction, management, and unauthorized modifications should be subject to quality assurance. Past building seismic practices needed to be upgraded. (see Lu and Ren, 2008; see also Edwards, 2009).

For the reconstruction process as a whole, Tongji University undertook a leadership role in urban planning and architecture, design and materials, and building codes and schools.

OVERVIEW OF DAMAGES AND CHANGED PRACTICES

At the forum, Chuhan Zhang of the Chinese Academy of Sciences summarized statistics: 125,000 sq. km had been impacted, 7M buildings had collapsed, 24M buildings were damaged, 10,000 landslides occurred and 36 big barrier lakes formed. Other data have suggested that 69,000 people were known dead and another 18,000 missing or buried in ubiquitous landslides, 370,000 people injured, 6900 schools destroyed, 125 M m^2 of buildings collapsed, 152 M m^2 of buildings damaged and many hospitals and other critical facilities damaged or destroyed. Between three to five million people were being relocated as some towns were being abandoned. Although early macro-statistics tend to be corrected over time, these statistics have remained fairly stable – save that one estimate has eight million people relocated, and early estimates of direct damages at about $100B appear to be on the very low side given the combined damages to buildings and infrastructure facilities. (See Wei, 2008, Shannon, 2009, Lekkas, 2008)

The First Building Code Issue: Importance Factors

Importance factors are used in seismic codes to increase seismic design forces for "important buildings." Before the earthquake, the Chinese code had used a factor of 1.0 for ordinary buildings, schools, and hospitals. The 1995 Standard for Classification of Seismic Protection of Buildings, for instance, had considered the school buildings as Class III (i.e., standard occupancy). Government buildings had been designed with an importance factor of 2.0. Many participants in the forum discussed importance factors. Songtan Xue (the Kwang-Hua World Forum Secretariat on the Wenchuan Earthquake and Post-quake Reconstruction, 2008) contended that China like Japan should treat schools as shelters and the large spaces in schools, including gymnasiums, as likely evacuation centers. Thus, schools should have high importance factors for their critical post-disaster uses.

Since the earthquake, the China Seismic Code had increased importance factors to 2.0 (Class II representing substantial hazard to human lives) for schools (including dormitories and cafeterias) and hospitals. The China Seismic Code thus now requires much more stringent seismic detailing for the school structures. Multistory masonry buildings, if used for hospitals or schools, must meet more stringent height limitations and are required to have cast-in-place concrete floor slabs as opposed to traditional precast concrete hollow core planks. Furthermore, detailing stairs to ensure stability of emergency egresses is required. It is thus expected that the new schooland hospital buildings will have better seismic deformation capacity to resist major earthquakes.

The Building Code Issue of Intensities Used for the Sichuan Intraplate Region

Another set of issues pertained to the seismic intensities used in China's three-level protection, two-level design approach. This issue can be hotly debated in intraplate regions of moderate seismicity but high catastrophic loss potential, including the New Madrid region, the Wasatch front region, and the Charleston, South Carolina region. In such regions, statistics pertaining to larger earthquakes are scarcer than are found for estimating earthquake occurrences and their attenuation and site conditions in interplate regions such as Alaska and California. (Z.Wang et al., 2008)

The China Seismic Code uses an intensity scale from 6 to 9 termed the seismic fortification intensity to describe seismicity for a region. The seismic fortification intensity is defined as "seismic effect, which has 10% probability of exceedance in a 50-year period." Intensity 9 is equivalent to traditional UBC Zone 4, and Intensity 7 is approximately equivalent to traditional UBC Zone 2A. The seismic acceleration values double as the seismic requirement increases by one intensity. The China Seismic Code uses a three-level protection, two-phase design approach. The three-level protection means no damage under the action of a minor earthquake of frequent occurrence, reparable damage under the action of an earthquake of the seismic fortification intensity (with a return period of 475 years), and no collapse under the action of a major and severe earthquake of rare occurrence (with a return period of 1975 years). In the China Seismic Code, the ground acceleration of a minor earthquake is 35% of the ground peak acceleration of an earthquake of the seismic fortification intensity. The intensity of a major earthquake is approximately one degree higher than the seismic protection intensity. Before the earthquake, the seismicity of the affected cities including those near the epicentral region and along the ruptured faults was assigned with Intensity 7 by the code. However, the earthquake intensity map of this Wenchuan earthquake indicated actual intensity in those cities was two to three degrees higher than the seismic protection intensity.

One set of issues raised in the Kwang-Hua World Forum pertained to how the Chinese probabilistic site hazard analysis maps (PHSA) should be modified in light of this massive earthquake. As the ASCE team learned a few days later from Jiancheng Lei, Director of the Institute of Engineering Seismology, Seismological Bureau of Sichuan Province, a new seismic design map had been rapidly developed after the earthquake in order to be useful in the new construction that was underway. At the same time, ongoing investigations are being undertaken to account for the intraplate region being re-mapped.

The Wenchuan earthquake occurred on a known fault system, known as the Longmen Shan Fault Belt, consisting of three faults (the Rear Longmenshan fault, the Central Longmenshan fault, or Yingxiu Beichuan fault, and the Guanxian-Anxia fault). The fault system extends from north-east to south-west about 470 km, formed as part of the tectonic movement between the Indian plate and the Eurasia plate, and marking the boundary between the Sichuan Basin to the east and Tietan plateau to the west. (See Qing et al., 2008, and Xiaojun et al., 2008)

The May 12 event ruptured more than 300 km of the fault. Historically, no events greater than 7 have been recorded along the fault, according to Yuntai Chen, an academic of Chinese Academy of Science, even though the nearby fault systems in the same tectonic region have produced events with larger magnitudes, as recently as in 1976. There have been 3 earthquakes with magnitudes from 6 to 6 ½ recorded along the Longmen Shan fault zone during more than 2000 year documented history of the Sichuan province (Zhang et al., 2008).

According to Yanxiang Yu, a lead researcher on the PSHA work in China with the China Earthquake Administration, evidences that would otherwise suggest mega-magnitude events like the May 12 event, which would impose great seismic risks to the region, were generally not believed to be observed before the May 12 event. The maximum magnitude for the fault had been set at 7.0 in the most recent PSHA map that was used in seismic design in China, with a return interval of about 3000 years. Newer estimates of recurrence intervals for a major earthquake like the Wenchuan event currently range from 1,000 years according to Chuhan Zhang to 10,000 years, with slip rates varying between 5–8 mm/year to 1 mm/year. In the general tectonic region, there is a north-east movement of 4 cm/year. (Burchfiel et al., 2008; Chavez et al., 2008) At the forum,Yaoru Lu of the Chinese Academy of Engineering added that one must also examine the very long geologic record and stress the role and changes in the Earth's Rheosphere. After the

Wenchuan event, as an effort to revise the seismic design map for post-earthquake reconstruction, the maximum magnitude of the Longmen Shan fault was increased to 8, together with a slightly reduced return interval, according to Yanxiang Yu.

Ground motion prediction equations (GMPEs) – modeling how the earthquake shaking spreads – became more publicly developed some time after the earthquake (see for instance D. Wang et al., 2010) As with significant divergences in NMSZ GMPEs, so significant divergences are expected from different investigators examining strong ground motions in the Sichuan province.

For structural engineers on the ASCE team, determination of the Maximum Credible Earthquake (MCE) was a critical issue in considering new design of buildings. Did the records from the Wenchuan quake represent the MCE event, or was its recurrence interval longer than the 2000 years in the new Chinese code? How risk averse should seismic codes be in this region of moderate seismicity with high catastrophic potential? Should a longer return interval be used to assure that buildings do not collapse?

The Building Code Issue of Quality Assurance

A third set of building code issues – already mentioned – pertained to practices of quality assurance relating to the designer, contractor, manager, and occupants, and unauthorized modifications. In the Kwang-Hua World Forum, Yuan Feng, Chief Engineer, China Southwest Architectural Design and Research Institute Corp., Ltd., provided many examples of how improper detailing had led to damages. Xilin Lu likewise gave a presentation that emphasized as well how many buildings had not been designed in accordance with the building code as it existed before the earthquake. Rural areas were a special emphasis along with seismic design coefficients and geologic setting. Government enforcement supervision and education to assure the implementation of building codes were critical. Because many of those being relocated were to move to densely populated areas, there was special concern about large-span/large-space buildings. That is, many of those relocated were to be housed in engineered structures between three- and six-stories.

Building Code Changes Summarized

In response to the Great Tangshan earthquake of 1976, Chinese Seismic Building Codes were developed in 1978. These codes were improved in 1989 and 2001. Buildings constructed before 1978, mostly masonry structures, were damaged most severely. (Leiping et al., 2008)

At the Kwang-Hua World Forum, Yayong Wang, head of developing the new Chinese building code that had only recently been released, presented his findings on the new seismic code in response to the 2008 earthquake. (See Y. Wang, 2008) He suggested that instruments limited peak ground accelerations to a maximum of 1g. In terms of major features of the new code, he discussed (1) land-use restrictions relative to earthquake faults, landslides, severe liquefaction zones, and other local hazards, (2) the three levels of no damage in 50 years, reparable damage in 475 years and no collapse in 2000 years, and (3) "multiple lines of defense" for buildings, with a special emphasis on secondary earthquake countermeasures that improve building performance even if seismic design coefficients are exceeded by the actual ground motions in an earthquake. Currently, the seismicity used for the post-earthquake reconstruction has been raised for several cities near the fault rupture including Dujiangyang, Wenchuan, and Baichuan to Intensity 8.

One of these secondary countermeasures that received much attention throughout the seminar was the concept of "strong column, weak beam." For instance, Yan-Gang-Zhou maintained that the weak-beam strong-column theory needs a total probabilistic study including an investigation of how various stories may collapse in an earthquake.

VISIT TO SICHUAN PROVINCE – CHENGDU AND HEAVILY DAMAGED REGIONS

As well as visiting the Seismological Bureau of Sichuan Province, the ASCE team visited the China Southwest Architectural Design and Research Institute Corp., Ltd. Gang Liu, Chief Architect of the Urban Design Research Center, and his associates presented two projects being undertaken at the Center. The first was an urban plan proposal for redoing the plan for Dujiangyan. Located 30 km east of the earthquake epicenter, 30% of the buildings collapsed and 70% suffered considerable damage. Many building collapses were founded on ground composed of remnants of river deposits and debris of limited thickness on the rocky background. (Lekkas et al., 2008) Severe infrastructure damage has already been mentioned.

Dujiangyan is known for its Dujiangyan Irrigation System designed around 2,300 years ago and that was only slightly damaged in the earthquake. Several other irrigation systems developed such vast times ago have been replaced well before the earthquake. The proposal on redoing the urban plan for Dujiangyan is one of ten proposals evaluated at Tongji University.

The proposed reconstruction of Dujiangyan revises a proposed plan that was adopted by the City shortly before the earthquake. Instead of the previous plan that had emphasized the development of a big city, the new plan stressed the role of Dujiangyan as a green, safe, harmonious city emphasizing tourism, science and education. The existing traffic loop system with a highway to Chengdu is to become enhanced through the development of three city cores, all further interconnected through a grid system. There will be a new industrial area and a new town, a government center, with freeways nearby and a light-rail system. The old town center, severely damaged, will be restored for heritage and tourist purposes and open space will be used in the landslide-prone region. Limitations of water resources as well as such hazards as earthquakes provide reasons for limiting growth in this proposed urban plan.

After such visits in Chengdu, the cities that the ASCE team visited are generally located in the seismicity intensity range from VII to X. The ASCE team first proceeded to the very badly damaged Manzou. Gu Chuan Hong, General Manager and Chief Engineer of the Si Chuan Mian Zhu Municipal Tap Water Company and his chief assistant Yan Yuan Chun presented details on the system, its damages, and its actions going forward. At the time, a tent city of people temporarily relocated was being served along with existing customers. Near the tent city are various high rise structures being designed for more permanent accommodations for those who have been relocated. The water system itself had severely damage to its pipelines, with 7.8 km of cast iron piping with rigid connections suffering over 50% damage as a result of settlement and 27 km of concrete piping with soft rubber ring connections being destroyed. Polyvinyl chloride (PVC) piping had been prohibited as being too brittle.

In the reconstruction process of the Mianzhu Water System, all new larger diameter piping (>300mm in diameter) was being replaced by ductile iron piping with rubber gasketed joints. Polyethylene piping used for smaller diameter uses was being increased to accommodate the additional number of customers. Thus, the water system had decided to emphasize total seismic improvement in joints used. Other facilities in the water system, four wells, five buried distribution storage facilities, and booster pumps were virtually undamaged. At the time of the ASCE visit, 60%–70% of the water supplied is still lost before delivery, with reductions in pressures. Thus, incomplete reconstruction and additional demands have caused temporary strains on the maximum water supply for the system. Power outages, whether caused by earthquakes or by lightning, create problems for the system for which supply itself and pressures within the pipelines are dependent on continuous flows of power. Regional water system managers have determined, though, that water supplies in the future are adequate to meet future growths in demand, including recent growth planned for people being relocated.

On the final day of the trip, the project team visited the most heavily damaged region, Shi Fang and Hanwang, part of Mianzhu City, both the town(s) and the precarious canyons. Temporary housing consists of pre-fabricated units, tents, or assemblages of wood and brick. The regions away from the mountains include some of the rich farmland that is a general feature known about Sichuan.

The canyon exhibited all the features of severe damages and the untiring attempt to reconstruct mountainous regions so critical in providing hydro-power, minerals, and other resources in China. The ASCE team was in search of two stations that had recorded strong ground motions and possibly served to provide invaluable records for determining strong ground motions for seismic design.

A two-lane paved highway had turned into a one-lane road, sometimes unpaved and a much more daunting drive than the disrupted portions of the landslide-impacted roads of Portugese Bend in Southern California. In spite of very heavy trucks hauling rocks and other very heavy vehicles, a spring was flowing along an unpaved portion of the road. Along the road, one witnessed not only considerable reconstruction of the river below, but also workers at some height on the top of a damaged penstock and lofting small boulders down the hill. Below was a damaged hydroelectric facility. Landslides, bridge structure damage, and other building damage were all apparent in this region being worked on assiduously as China undertakes its huge reconstruction (see Figure 4-2).

Mianzhu is a town that was impacted by greater seismic waves inasmuch as the greater slip on the faults moved toward the northeast headed for Mianzhu. (Lekkas, 2008) Many of the collapsed buildings in the Hanwang township of Minazhu (with a population of more than 60,000) are of recent construction, having been built in the 1990s. Hanwang is at the foot of the Dragon Gate Mountains, home of the giant pandas. The fault rupture was very close (within 10 kilometers) and in the mountains. Nearly all the buildings that

Figure 4-2. A house damaged and buried during landslides

Figure 4-3. Concrete structures with many walls stands well (left) and totally collapsed brick wall structures

collapsed were constructed with very little seismic resistance, and non-ductile, vulnerable construction is found everywhere. Some four-story buildings observed has some serious damage and failed components, but had not yet collapsed during our trip (see Figure 4-3). Construction consisted of non-ductile cast-in-place concrete columns and beams; walls are also unreinforced masonry–URM (see Figure 4-4). Many of the shear walls cracked extensively, and many columns failed. Columns failed mainly where the infill walls butted up against the concrete columns because the walls shorten the columns, causing them to attract more seismic force and subsequently fail in shear rather than flexure. One building was found collapsed, but an adjacent building of similar construction did not. Both structures were probably built in 1990s. They were supported by URM walls, with precast concrete floor planks. The survived building had many interior shear walls and shorter

Figure 4-4. Collapsed URM Hospital building structures

floor spans, which is probably why that building is still standing and the main school building collapsed.

Some five-story building structures consist of non ductile cast-in-place concrete columns and beams supported by unreinforced brick walls. The first-floor, soft story garage collapsed, turning the five story into four stories. The upper floors of the building did not collapse, other than to drop down to top of the first floor garage. Few three-story office buildings were standing well with very little damage evident. This type of concrete structure has many walls, and appears to be well designed and constructed. The only visible damage is to the wood roof.

Most of the buildings built of brick walls and wood frame roofs with lightweight black roofing tiles collapsed as discussed in Miyamoto report. These tiles are very light and actually helped reduce the seismic force to the building by falling off. However, walls made of unreinforced brick have little stability against earthquake forces. Several apartment buildings are made of unreinforced brick walls and concrete slabs. Many diagonal shear cracks occurred in the walls between the windows, but the building did not collapse. Each room is very small, which results in a lot of walls. The more walls that exist, the higher the seismic capacity of the structure is. Several older residential buildings performed well enough to prevent collapse because of this design feature. The Miyamoto report observed many ground floor collapses even without soft-story storefront conditions. Other observations of the performance of this building type include: building “ends” with severe damage, perhaps coinciding with stairwell construction; “end of block” effects; and severe damage or partial collapse at zones of detailing or material defect. Defects include poor ductile detailing, insufficient concrete cover over reinforcing steel, improper size and shape of aggregate in concrete, quality of cement, and poor quality of brick. Not as common in the Longmenshan Mountain region, concrete moment frame buildings appeared to perform much better than adjacent brick buildings; however, we did not have the opportunity to observe many of them. Although it was noted that some concrete moment frame buildings suffered from weak column/strong beam behavior, there were some buildings that performed remarkably well.

A light industrial plant constructed of precast roof panels over steel trusses supported by concrete columns performed well, except for the collapsed entrance canopy as reported by a Miyamoto report. A steel fabricating plant constructed with lightweight steel roof, steel trusses, and steel braces were observed to perform well with little damage. The concrete water tower where no major damage was observed was constructed of cast-in-place concrete, and no damage was observed. The shape and weight of this structure may have had a lower frequency than the structures nearby. This water tower also likely has a strong structural system and foundation for supporting daily operational loads.

As observed by many experts during the forum, the immense damage seen in the Wenchuan Earthquake could have been avoided through seismic risk management-particularly in identifying and rehabilitating buildings and in protecting nonstructural components. Lessons learned from the earthquake are already included in a major revision in GB50011 China Code based on damage data of buildings. These include: (1) School and hospital buildings are ranked one "importance" grade higher; (2) multi-defense lines for seismic design of buildings are stressed; (3) RC frame structures are required to contain a certain number of braces or shear walls that can be treated as the first defense line to protect the frame structure from collapse; (4) confined masonry structures are required to have RC tie-columns and tie-beams to ensure the integration of buildings; (5) the seismic design for "strong column and weak beam" of RC frame structures requires careful determination of proper size and detailing for column and beam in consideration of the rigidity and strength of floor slabs; (6) the safety of the stair shaft of masonry buildings requires taking account of the rigidity and strength of RC step beam and the slab; and (7) stricter limits of height and stories for masonry school and hospital buildings are included in the new code.

THE EARTHQUAKE AS A "BLACK SWAN" EVENT: A QUANTITATIVE ACCOUNT OF SEISMIC DECISION-MAKING IN INTRAPLATE REGIONS

The foregoing discussion illustrates how the 2008 earthquake fits the definition of a "Black Swan" event: (1) an outlier with an extremely low predictability; (2) carries a massive impact; (3) after the fact, reasons are concocted to make it appear less random, and more predictable, than it was (see Taleb, 2007, pp. xvii, xiii).

Seismic decisions are in general challenging. Especially in regions of moderate seismicity but high catastrophic potential, these decisions are controversial. To quantify these and many other decisions, Taylor et al. (2009) have modified Levy (2006) to describe the applicability of "Almost Stochastic Dominance" (aSD) methods. For a detailed application to the NMSZ, the authors have developed an illustration of seismic design alternatives. A new building constructed according to the recent seismic code is contrasted to the same building with no explicit seismic design. The building in question is five stories in height, with a reinforced concrete moment resisting frame. The fundamental structural question is 0.72 s. The alternative without seismic design has low

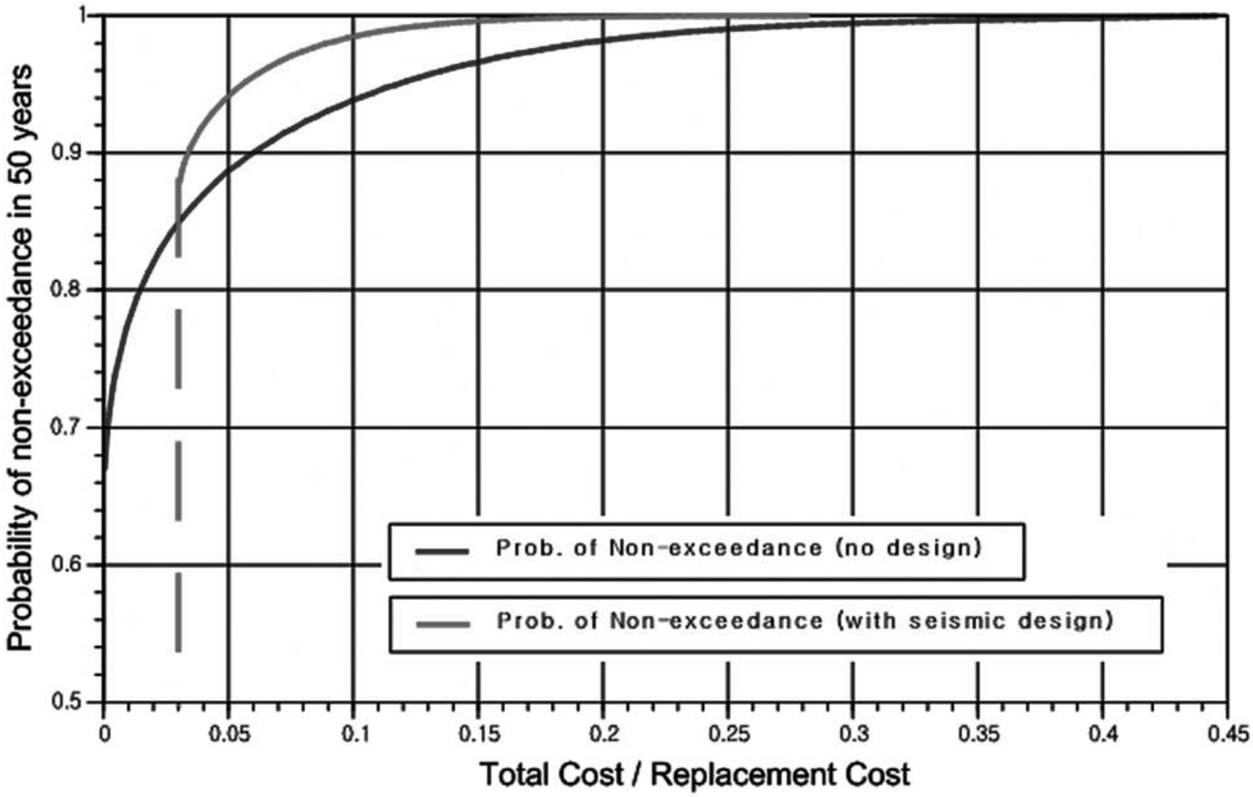


Figure 4-5. Illustration Contrasting Alternative Seismic Design Decisions for a Five-Story Memphis Building

lateral strength (Cs = 0.05) and low ductility (R = 3). The alternative with seismic design is somewhat stronger (Cs-0.07) and more ductile (R = 8.5). In the example, a mean 4% discount rate is applied to a 50-year useful structural life-span.

Figure 4-5 summarizes the comparison of these two alternatives in terms of distributions of their "total costs," or initial costs plus losses. On the one hand, there is a significant probability that within a fifty year building life-span, no major damaging earthquake will impact the building. In this case, one would prefer the lesser seismic design owing to its lower initial outlay. On the other hand, if a major damaging earthquake occurs, then the seismic design will provide protection against a major loss. In this case, one would prefer having made the decision to provide this protection as insurance against property loss as well as against deaths and injuries. Thus, seismic decisions in this case tend to be a matter of whether or not the seismic design "premium" against high-level property losses and casualties is worthwhile. For building officials, the premium required in a region of high catastrophic potential is a premium protecting against massive impacts as seen in the 2008 Wenchuan earthquake.

SUMMARY

The ASCE trip first began with a visit to a forum attended by professionals from many countries and engaged in discussing various key reconstruction alternatives as Tongji

University is taking a lead in urban planning and architecture, design and materials, and building codes and schools. ASCE team members then went to Chengdu where they witnessed one of the competing presentations to redo the famous city of Dujiangyan and visited the Director of the Institute of Engineering Seismology, Seismological Bureau of Sichuan Province. These visits as well as visits to the heavily damaged area–where workers and heavy machinery were ubiquitous even in the precarious canyons – emphasized the detailed and even competitive planning and activities in the long-term reconstruction project.

Punctuated by a stopped clock at Hanwan Town, the field visit covered a water system whose piping was being systemically replaced, and canyons with damaged roads and landslides, and ghost towns.

Before the clock stopped, China had engaged in multi-generational efforts to improve seismic construction and planning processes. Since the 1976 Great Tangshan earthquake, China has engaged in significant efforts to improve seismic protection and response and the supporting expertise and instrumentation. Many national laws, codes, standards, and regulations had been established before the 2008 earthquake. As a result, many structures fared much better in the 2008 quake, but only some portion of the older building stock had been replaced and some buildings lacked quality assurance during a period of rapid expansion. (see Chen, 2008, Wei, 2008)

Even longer before, some structures constructed about two thousand years ago had survived the earthquake, and China is known for the first seismograph instrument about eighteen hundred years ago, along with a very long-term catalog of earthquake occurrences. (Chen, 2008)

Phenomenologically speaking, the earthquake's jolt and the resulting disaster should be seen in the context of much longer processes involving the very slow changes in the building stock, design and construction practice, and instrumentation. Positive long-term changes diminish the extent of the disaster and render it possible to develop a long-term reconstruction project as well as long-term seismic protection activities that can further reduce the extent of future disasters. Whatever is done before the event provides a "premium" that protects against the massive impacts of a catastrophe. When the jolt strikes, as in a region of moderate seismicity but high catastrophic potential, time has run out for those tragically impacted. The future very much depends on the past positive near- and long-term developments in the capacity to resist future jolts.

ACKNOWLEDGEMENTS

We appreciate and express our sincere gratitude to the Kwang-Hua World Forum Secretariat on Wenchuan Earthquake and Post-quake Reconstruction for their financial support and hospitality during our trip to China. We are also grateful to Prof. Jie Li of Tongji University and his graduate students to make all the contacts and make our trip a success. Thanks are also due to Prof. Al Ang of University of California at Irvine to help us to start up the process. Special thanks to ASCE to make the trip possible.

References

Burchfiel, B. C., L H. Royden, R. D. vander Hilst, B. H. Hager, Z. Chen, R. W. King, C. Li, J. Lu, H. Yao, and E. Kirby, 2008, "A geological and geophysical context for the Wenchuan earthquake of 12 May 2008, Sichuan, People's Republic of China," http://www.gsajournals.org, the Geological Society of America, Online Publications, June 7.

Chavez, M., E. Cabrera, H. Chen, N. Perea, A. Salazar, D. Emerson, M. Ashworth, Ch. Moulinec, M. Wu, and G. Zhao, 2008, "3D Wave Models of the 12 05 2008 Sichuan Ms7.9 Earthquake," *The 14th World Conference on Earthquake Engineering*, October 12–17, Beijing, China.

Chen, Jiannim, 2008, "Earthquake Disaster Reduction in Developing China," *The 14th World Conference on Earthquake Engineering*, October 12–17, Beijing, China.

China Daily, 2008, "Premier moves Chinese amid quake effort," May 15.

Edwards, Curtis L., 2009, "Emergency Response and Recovery after the May 12, 2008 Wenchuan Earthquake," pp. 1342–1348, *TCLEE 2009, Lifeline Earthquake Engineering in a Multihazard Environment*, ed. by Alex K. K. Tang and Stuart Werner.

Eidinger, John, 2009, "Wenchuan Earthquake Impact to Power Systems," pp. 1359–1370, *TCLEE 2009, Lifeline Earthquake Engineering in a Multihazard Environment*, ed. By Alex K. K. Tang and Stuart Werner.

Lee, David D., 2009, "Potable Water System Damager and Recovery for M8.0 Wenchuan, Earthquake, China," pp. 1395–1406, *TCLEE 2009, Lifeline Earthquake Engineering in a Multihazard Environment*, ed. By Alex K. K. Tang and Stuart Werner.

Lekkas, E. L., 2008, "Wenchuan Earthquake (Mw7.9, 12 May 2008) Sichuan, China, Geotectonic Regime and Macro-Distribution," *The 14th World Conference on Earthquake Engineering*, October 12–17, Beijing, China.

Levy, Haim, 2006, Stochastic Dominance: Investment Decision Making under Unceertainty, 2nd Edition, New York: Springer.

Lo, Robert C., 2009, "May 12, 2008 Wenchuan Earthquake – Geoscience Aspect, Earthquake Impact, Response, and Recovery," pp. 1383–1394, *TCLEE 2009, Lifeline Earthquake Engineering in a Multihazard Environment*, ed. By Alex K. K. Tang and Stuart Werner.

Lu, X. L. and X. S. Ren, 2008, "Site Urgent Structural Assessment of Buildings in Earthquake-Hit Area of Sichuan and Preimary Analysis on Earthquake Damages," *The 14th World Conference on Earthquake Engineering*, October 12–17, Beijing, China.

Qing, Jiao, Yang Xuanhui, Xu Liqing, and Wang Bo, 2008, "A Preliminary Study of the Motion Characteristics of the Longmenshan Fault Before and After the M8.0 Wenchuan Earthquake," *The 14th World Conference on Earthquake Engineering*, October 12–17, Beijing, China.

Shannon, Del A., 2009, "Dam Damage: Evaluating and Learning from the Wenchuan Earthquake's Impact to China's Dams," pp. 1371–1382, *TCLEE 2009, Lifeline Earthquake Engineering in a Multihazard Environment*, ed. By Alex K. K. Tang and Stuart Werner.

State Council of People's Republic of China, 2008, "Wenchuan earthquake disaster recovery and reconstruction act," passed into law June 4, 2008, and promulgated and become effective June 8, 2008.

Taleb, Nassim Nicholas, 2007, *The Black Swan: The Impact of the Highly Improbable*, New York: Random House.

Taylor, Craig, Glenn Rix and Fang Liu, 2009, "Exploring Financial Decision-Making Approaches for Use in Earthquake Risk Decision Processes for Ports," *Journal of Infrastructure Systems*, Volume 15, Number 4, pp. 406–416, December 1, 2009.

Wang, Yayong, 2008, "A New Round of Update of Seismic Design Code of China," *The 14th World Conference on Earthquake Engineering*, October 12–17, Beijing, China.

Wang, Z., E. W. Woolery, and L. Wang, 2008, "Cooperative Research in Earthquake Engineering and Hazards Mitigation: The Central United States and Northwestern China," *The 14th World Conference on Earthquake Engineering*, October 12–17, Beijing, China.

Wei, Huang, 2008, "Review and Prospect of Earthquake Relief Work in Urban and Rural Construction of China," *The 14th World Conference on Earthquake Engineering*, October 12–17, Beijing, China.

Xiaojun, Li, Zhou Zhengua, Huang Moh, Wen Ruizhi, Yu Haiyin, Lu Dawei, Zhou Yougnian, and Cu Jianwin, 2008, "Introduction and Preliminary Analysis of Strong Motion Recordings from the 12 May 2008 Ms 8.0 Wenchuan Earthquake of China," *The 14th World Conference on Earthquake Engineering*, October 12–17, Beijing, China.

CHAPTER 5

A Multihazard Perspective for the Central U.S.

Philip J. Schneider, AIA, MCITPM

INTRODUCTION

The Central U.S. has experienced major flooding, including the two major Mississippi River floods in 1993 and 2011, frequent devastating tornadoes, for example, the Joplin, Missouri and the Tuscaloosa, Alabama tornados in 2011, and periodically catastrophic earthquakes, including three in 1811–1812 in the New Madrid area that exceeded 7.5 in magnitude (USGS, May 2011). What would be the consequences of two natural hazards occurring in the Central U.S. about the same time? What could area residents expect? And, what would be the response?

This paper will explore the effects on Central U.S. communities when two Midwest hazards occur in proximity to one another. Four scenarios will be discussed as shown in Table 5-1.

Many consequences could be considered for these combined events, including building damage, lifeline functionality, effects on critical facilities, casualties, shelter requirements, and economic loss. This paper only considers one to two major effects for each of these events.

Each scenario was developed from a combination of historic data gleaned from websites and contemporary periodicals, and FEMA's loss estimation program Hazus (Federal Emergency Management Agency, *HAZUS®MH*, 2011), which was used to conduct the earthquake and flood analysis, and generate the resulting consequences.

Hazus is a software program that models earthquakes, floods, hurricanes, and coastal surge and in the future will model tsunamis. Hazus characterizes these hazards and estimates resulting building, infrastructure, social and economic losses. GIS technology in Hazus allows for the production of maps for displaying hazards and loss, and a national database supports out-of-the-box analysis of any part of the U.S. for earthquake and flood analysis.

Loss reduction strategies for strengthening buildings and infrastructure can be assessed by rerunning an analysis with one or more mitigation techniques in place. For emergency management before disasters, Hazus guides resource allocation, such as shelter and trucks for debris hauling. For response and recovery it identifies vulnerable areas

Table 5-1. Multihazard Scenarios

Location	*Hazard 1*	*Hazard 2*
Shelby County, TN	Major earthquake	Flooding
Cape Girardeau, MO	Major earthquake	Tornado
Tuscaloosa, AL	Minor earthquake	Tornado
St. Louis City, MO	Major earthquake	Extreme Cold

Figure 5-1. Mississippi River Flooding Adjacent to Memphis in Shelby County, TN May 10, 2011
SOURCE: NASA, May 2011

during disasters that require resources, and guides effective relief. Use of Hazus is supported by 39 Hazus Users Groups, an extensive training program, and a FEMA Hazus website (FEMA, March 2012).

EARTHQUAKE AND FLOOD – SHELBY COUNTY, TN

The first scenario involves the largest of the historic New Madrid earthquakes as defined by Hazus coinciding with the Mississippi River flooding that occurred on May 10, 2011 in Shelby County, TN, where Memphis is located. (See Figure 5-1).

Flooding as shown in green in Figure 5-2 occurred as the Mississippi River crested at 48.03 feet (NOAA, April 2012), and a backwater/levee broke (*The Commercial Appeal*,

Table 5-2. Losses from a Hazus 500-Year Flood Simultating the 2011 Event in Shelby County, TN

Type of Loss	*Loss in Millions of $*
Building – Direct Economic	1,179
Vehicles (Day)	138.1
Transportation	.218
Utilities	73.84
Agriculture	4.73
Total	1,395.89

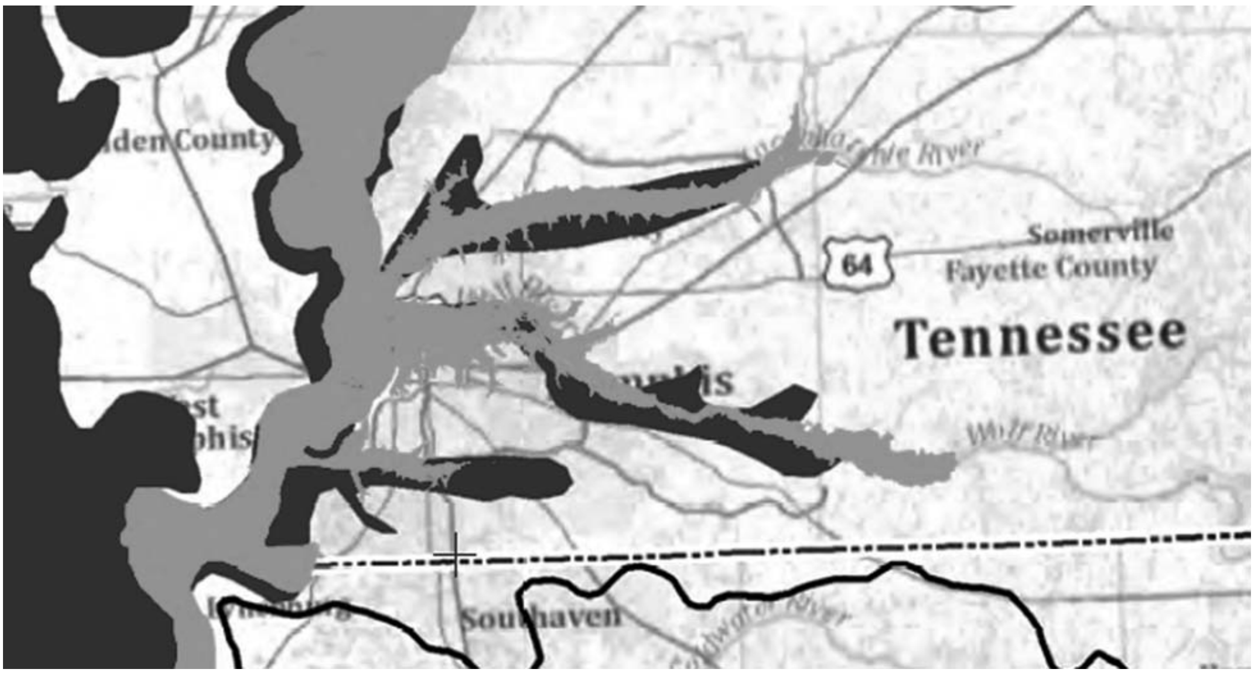


Figure 5-2. Shelby County, TN 2011 Flood Inundation Extent in Green; 1927 Mississippi Flood Inundation Extent in Blue
SOURCE: U.S. Army Corps of Engineers, June 2011

May 2011). It is estimated that $2 billion in losses were incurred (National Weather Service Weather Forecast Office, *Great Mississippi River Flood of Spring 2011*, May 2012).

A Hazus simulation of the 2011 event based on a 500-year flood as seen in Figures 5-3 and 5-4 generates an estimated crest of 52.95 feet near Memphis and $1.396 billion in building, vehicle, transportation, utility and agricultural losses as shown in Table 5-2.

Losses for the actual event are 1.43 times greater than the simulated event ($2/$1.396 billion) primarily because the river reaches for the Hazus event do not parallel the extent of flooding for the actual event. A smaller flood boundary can leave out a significant part of a community or utilities that might account for lesser losses.

The levees that protect Shelby County left many areas dry during the May 2011 Flood (*The Commercial Appeal*, May 2011). But what would happen if the levees were to partially

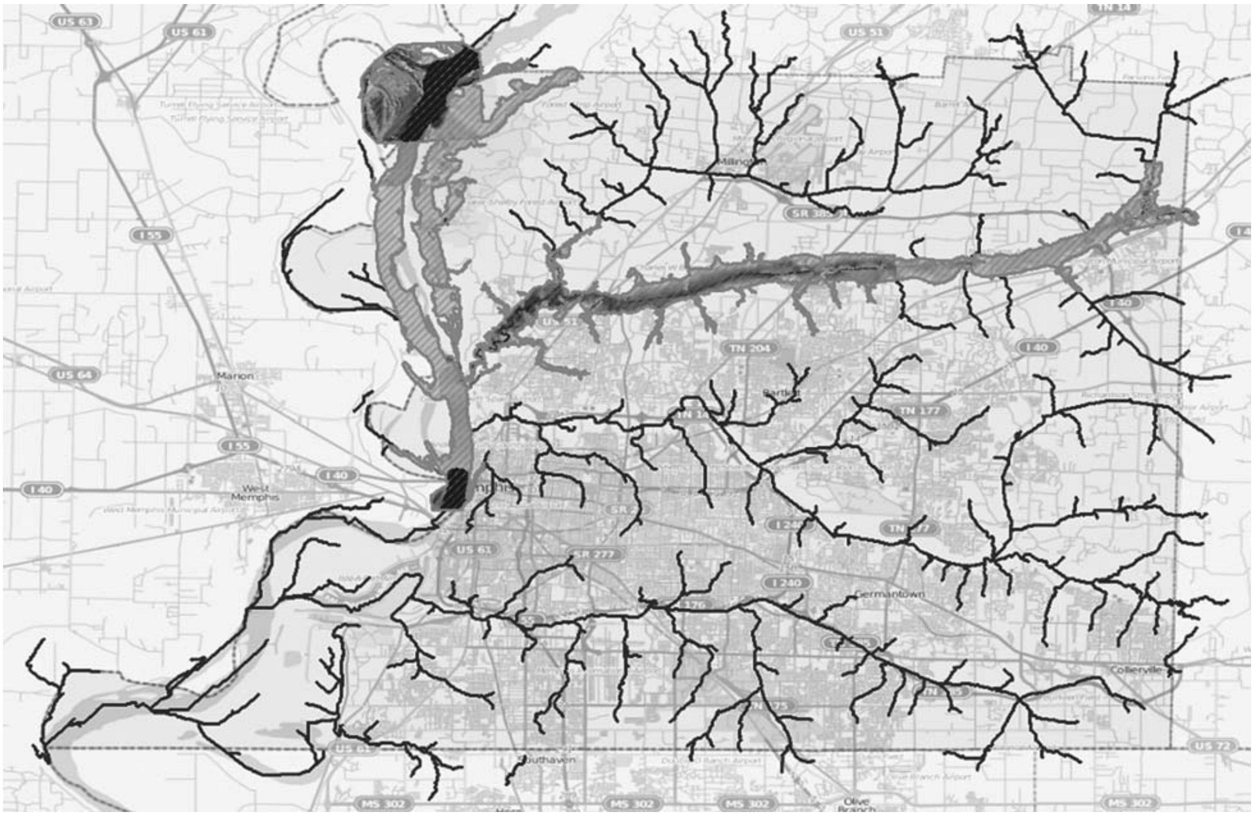


Figure 5-3. Hazus 500-Year Flood Simulating the Northern Portion of the 2011 Mississippi Flood

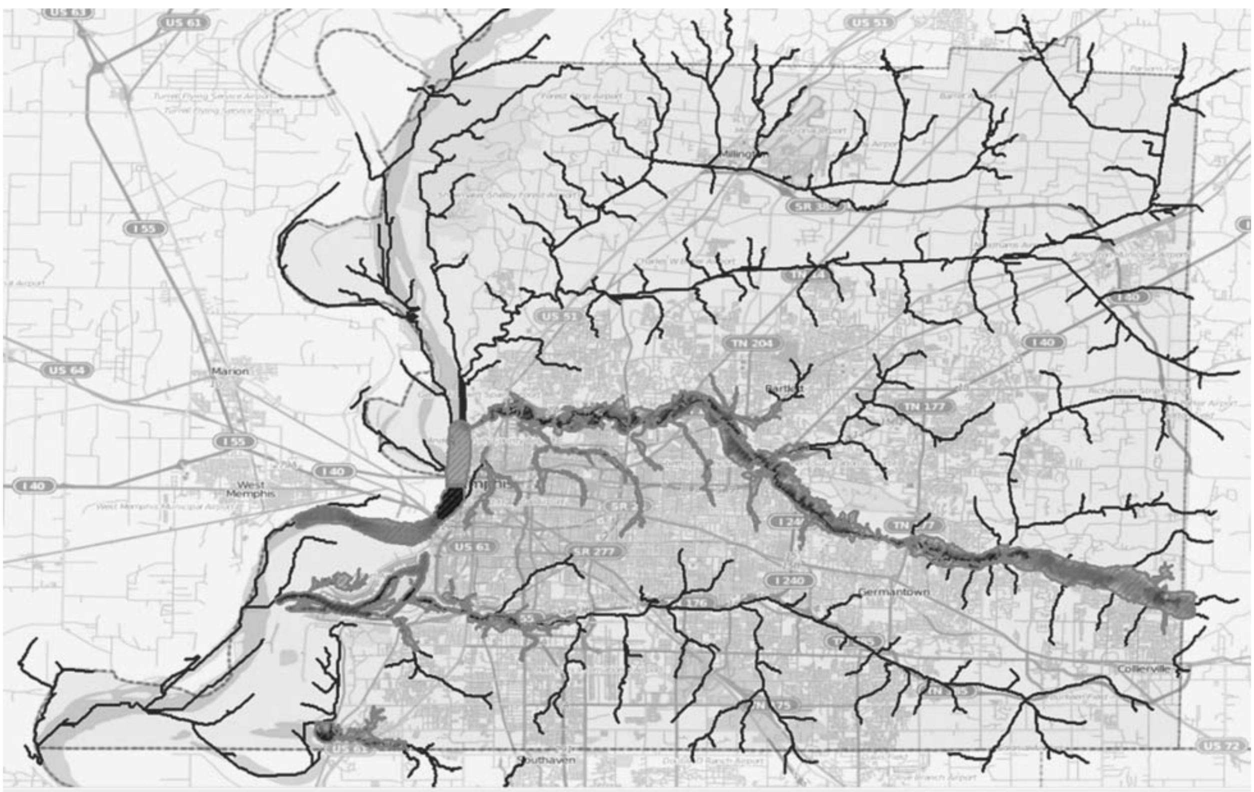


Figure 5-4. Hazus 500-Year Flood Simulating the Southern Portion of the 2011 Mississippi Flood

Note: The overlap just to the west of Memphis in Figures 5-3 and 5-4 do not create double counting, since no inventory is located there.

Table 5-3. Historic New Madrid Earthquakes (USGS, May 2011)

Date	*Estimated Magnitude*
December 16, 1811	7.7
January 23, 1812	7.5
February 7, 1812	7.7

Table 5-4. Losses from a Hazus 500-Year Flood Simulating the 1927 Event in Shelby County, TN

Type of Loss	*Loss in Millions of $*
Building – Direct Economic	1,962
Vehicles (Day)	236.7
Transportation	.218
Utilities	114.4
Agriculture	5.63
Total	2,318.95

fail? This could happen, not necessarily due a Mississippi high-water flood event, but with a major earthquake occurring either before the Mississippi crests without time for restoration, or shortly after cresting.

The Memphis area experienced three such earthquakes in the winter of 1811–1812 as listed in Table 5-3.

The levees that protect Memphis are earthen structures as seen in photo and the cross section in Figure 5-5.

Figure 5-6 shows how earthen levees can fail by riverine forces in four scenarios: overtopping, breaching, seepage/wet spots/sand boils, and erosion/slumping.

A large enough earthquake as has occurred historically in the New Madrid region can also cause these types of failures. Overtopping can occur through levy subsidence (decrease in elevation) or seiche (horizontal sloshing of the Mississippi River). Earthquake shaking can produce breaching by opening cracks in the levy. Liquefaction can weaken the wet soils underneath the levy. And, shaking can cause both erosion and slumping.

If levees fail by a future earthquake that occurs in conjunction with a crest as high as the 2011 Mississippi River flood inundation would likely be similar to the 1927 flooding (shown in blue in Figure 5-2) that occurred with a crest of 45.08 feet (NOAA, April 2012) and poorly constructed levees (RTBOT).

Hazus was used to simulate the extent of the 1927 flooding. The northern reaches in Figure 5-3 using the 2011 flood event, and a separate run for southern reaches shown in Figure 5-7 were used to characterize the flood.

The Hazus 500-year flood event losses in Shelby County assuming poorly constructed or partially failed levees due to a New Madrid scale earthquake are estimated to be as high as $2.3 billion (Table 5-4).

Multiplying this loss with the factor of 1.43 previously derived from a comparison of Hazus 500-year losses with the estimated losses from inundation during the 2011

Mississippi River flood generates possible losses of \$3.3 billion (\$2.3 billion × 1.43). The 1927 event losses with partially failed levees would be \$1.3 billion higher than the 2011 event losses or 3.9% (\$3.3/\$84.78 billion) of exposure in Shelby County (see Table 5-5). The 1927 losses would be even higher if Hazus could fully model the flood boundaries of all of the river reaches.

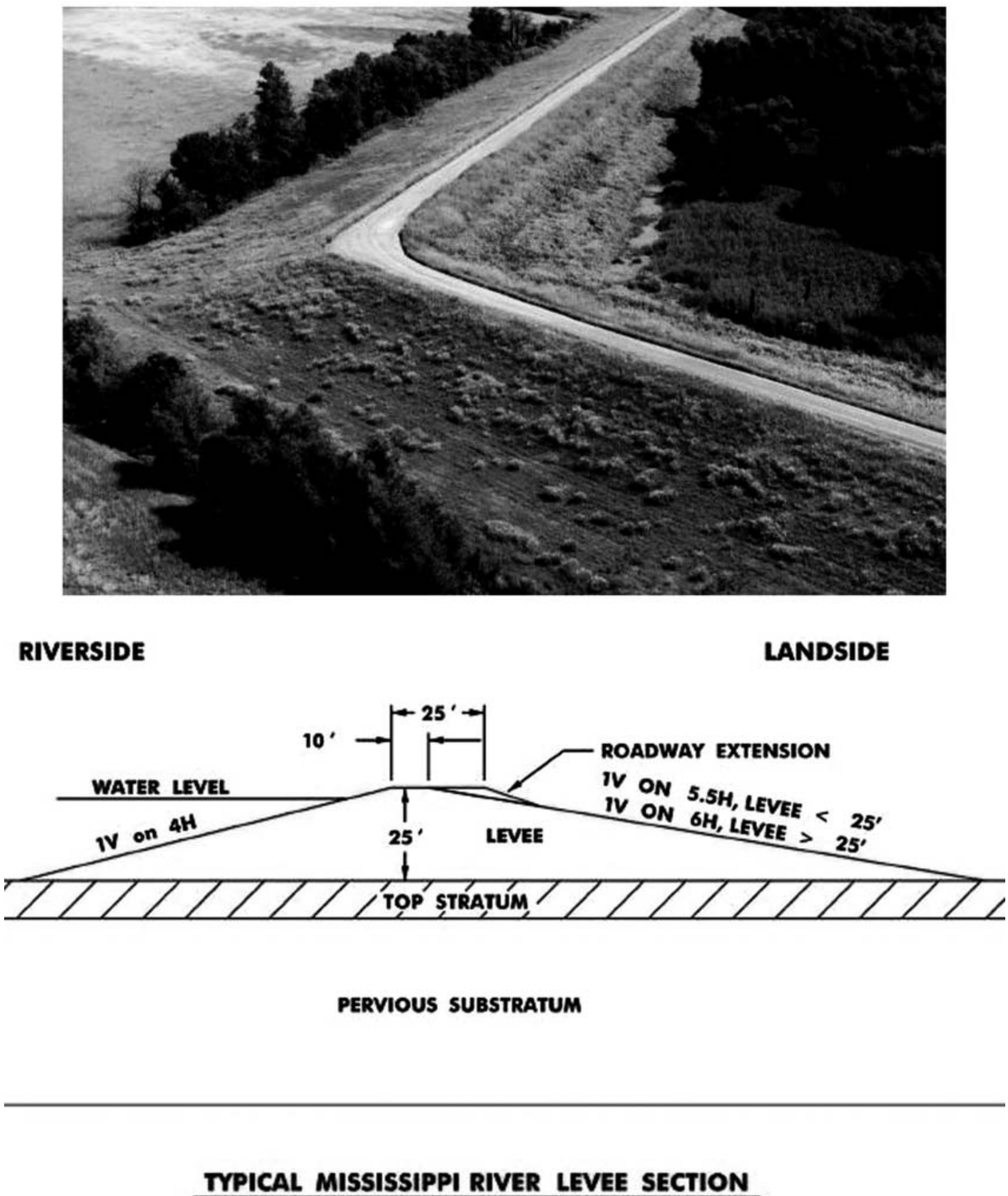


Figure 5-5. Memphis, TN Levee

SOURCE: U.S. Army Corps of Engineers, 2010

A 7.4 magnitude historic New Madrid earthquake generated by Hazus has the potential to generate losses of $2.58 billion apart from flood losses. The upper bound of total loss could be as high as $5.88 billion (6.9% of exposure), however, it is likely to be less since earthquake loss would occur in areas that overlap flood loss.

Table 5-5. Inventory Exposure for Shelby County, TN

Exposure	*Value in Millions of $*
Building – Direct Economic	70,358
Vehicles (Day)	6,293
Transportation	6,580
Utilities	1,349
Agriculture	199
Total	84,779

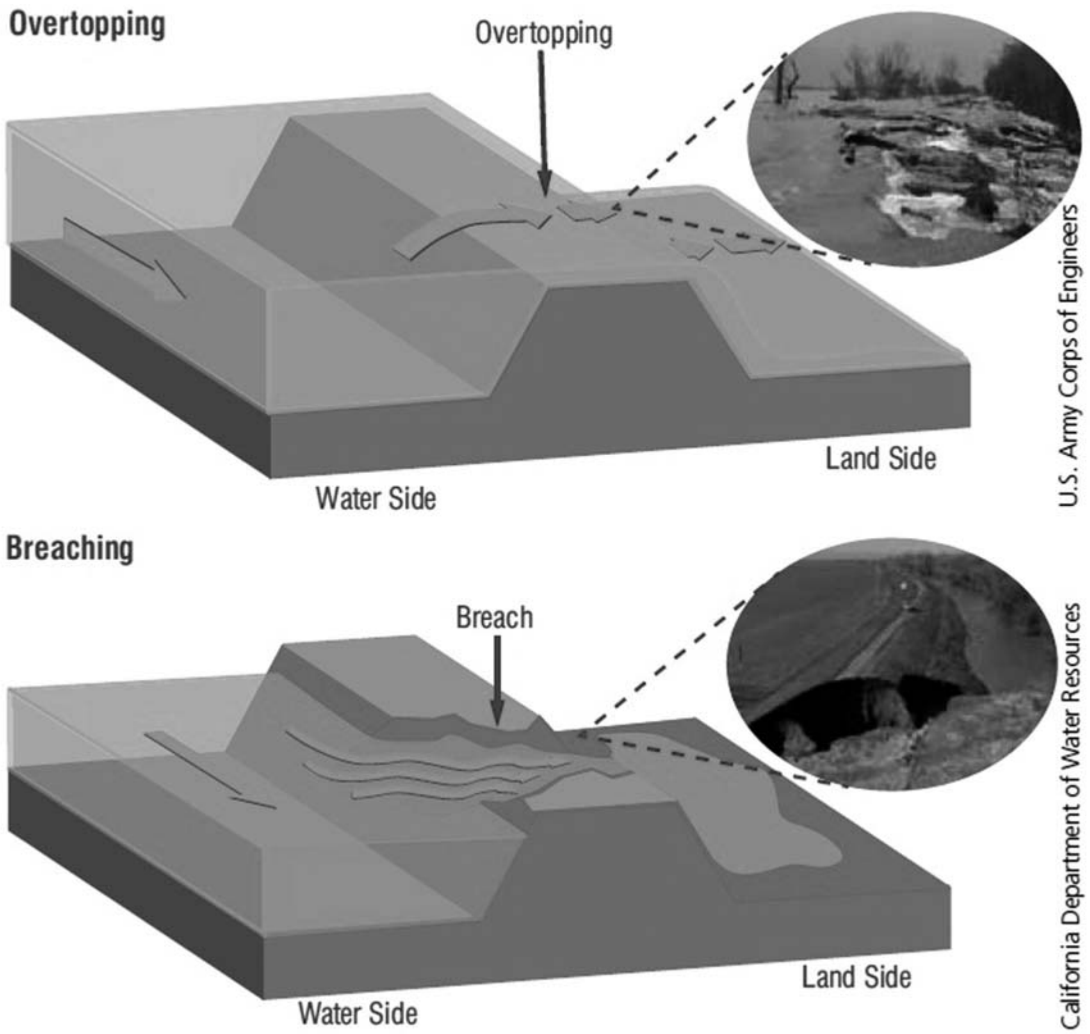


Figure 5-6. Methods for Potential Levee Damage
SOURCE: American Society of Civil Engineers, 2010

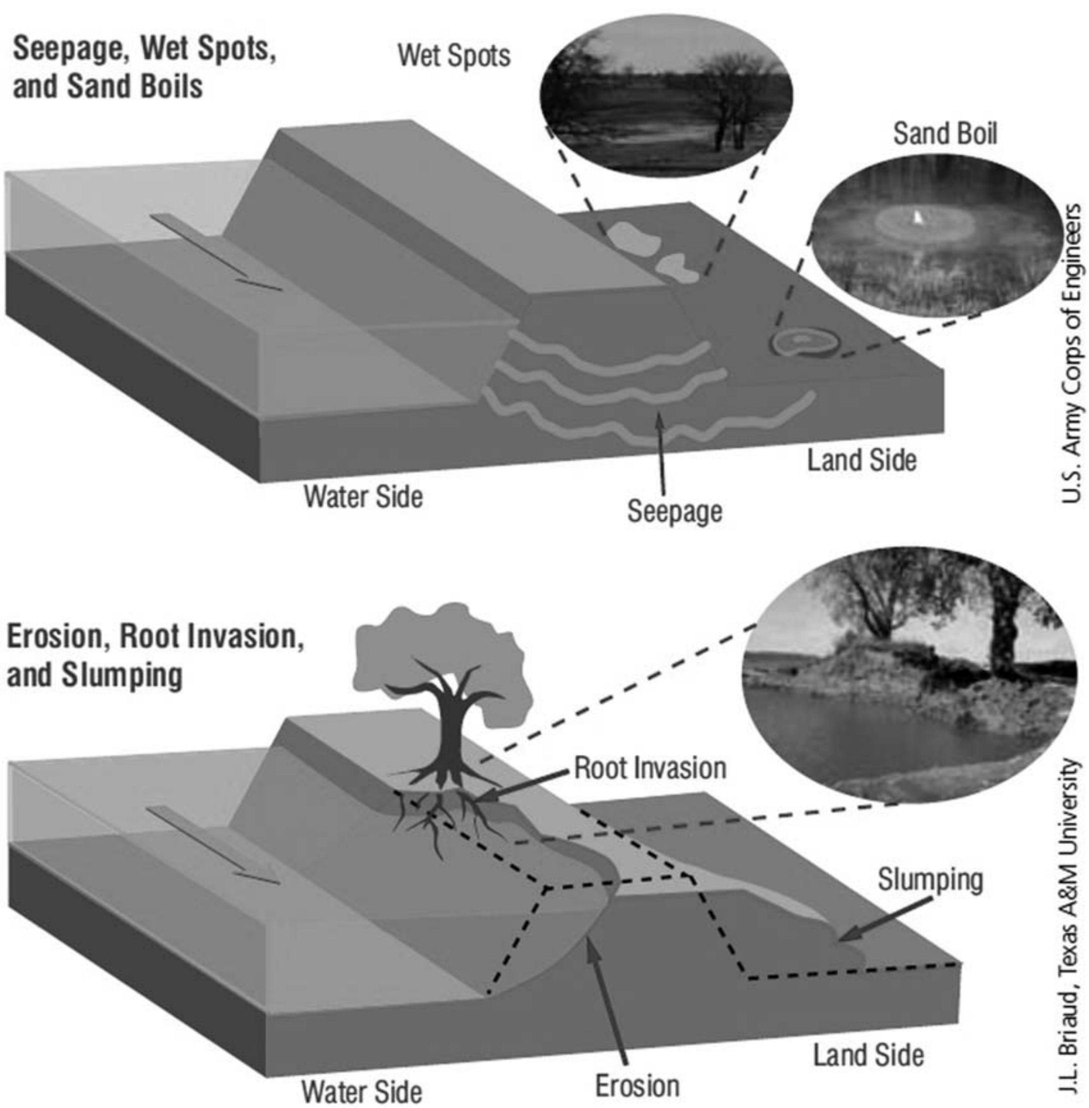


Figure 5-6. continued

EARTHQUAKE & TORNADO – CAPE GIRARDEAU, MO

On May 21, 1949 a tornado touched down at 6:56 p.m. in Cape Girardeau, MO. There were 22 deaths, 72 sent to three hospitals, and hundreds injured. Two hundred two homes were destroyed, 231 other houses damaged, 19 businesses leveled and 14 other businesses damaged (*Southeast Missourian*, May 21, 2009). Since this damage affected the downtown, it can be easily assumed that similar damage would result from the same type of Fujita-scale tornado striking today. If a repeat of the historic 7.4 magnitude New Madrid earthquake modeled by Hazus strikes around the same time it could produce many as 24 deaths, 48 with life threatening injuries and 49 requiring hospitalization. Two hundred forty-three buildings would be destroyed with 938 extensively damaged. As with the previous scenario, casualties and damage from the earthquake would be expected to overlap those from the tornado.

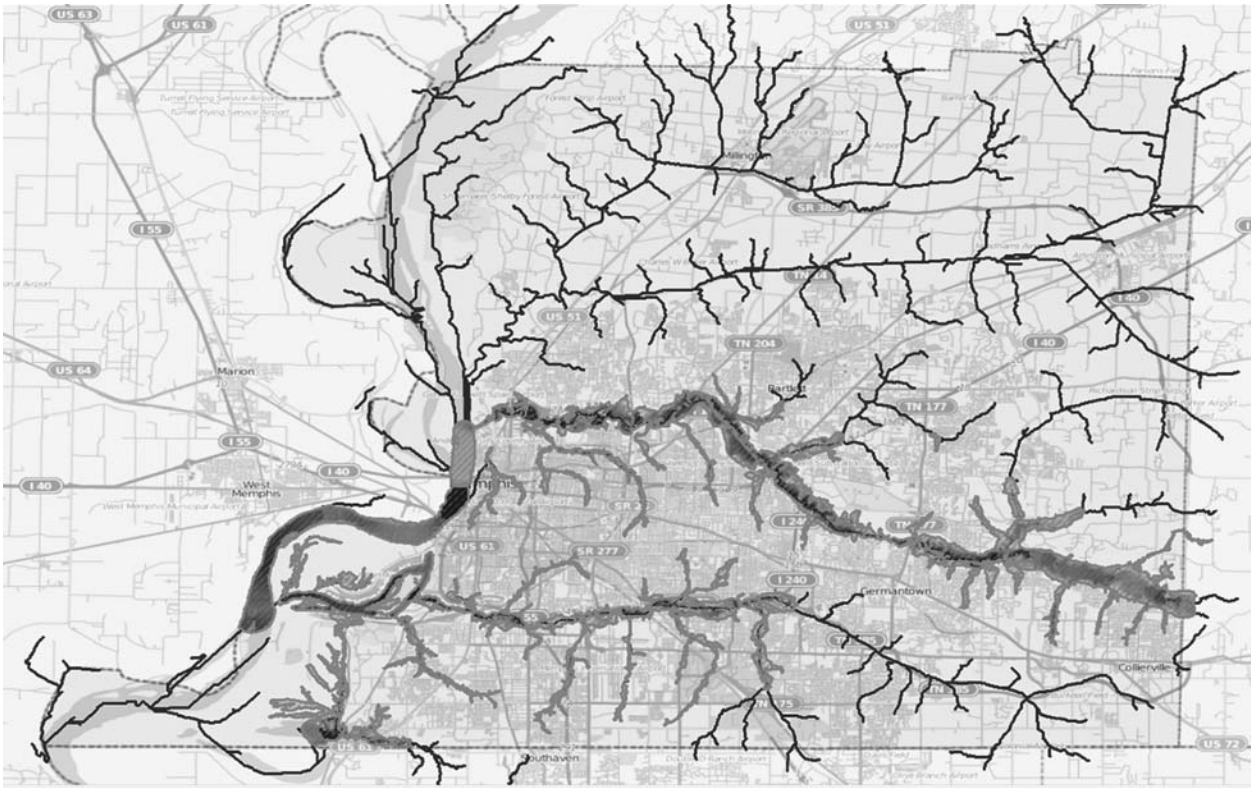


Figure 5-7. Hazus 500-Year Flood Simulating the Southern Portion of the 1927 Mississippi Flood

In addition to losses within Cape Girardeau, Hazus demonstrates that the earthquake would heavily damage bridges. With bridge functionality estimated to be less than 65%, regional access to the city would be limited as shown in Figure 5-8. Figure 5-9 shows that every highway bridge in the vicinity of Cape Girardeau also is heavily damaged. The primary connection across the Mississippi would likely be down. (On the map in Figure 5-9, the bridge for Route 146 shown in green crossing the Mississippi is mislocated to the north.) For those injured and rendered homeless by the dual tornado and earthquake event, overland response would be compromised since only 41% of the bridges would be functional on Day 1 and 60% on Day 30. Roads rendered impassable due ground failure are not included this analysis.

EARTHQUAKE & TORNADO – TUSCALOOSA, AL

In the evening of April 27, 2011, a tornado struck Tuscaloosa, Alabama with winds of 190 miles per hour (Earth Observatory, May 2011) and produced 1000 injuries and 65 deaths (Tuscaloosa News.com, May 2011). If only a deterministic 5.5 magnitude earthquake located 12 miles northwest of Tuscaloosa struck around 5:00 p.m. as modeled by Hazus it could result in 543 injuries requiring paramedics/clinics, 150 injuries requiring hospitalization, 52 injuries that are life threatening, and 41 deaths. Ignoring double counting the total injuries requiring hospitalization could be as high as 1202. As shown in

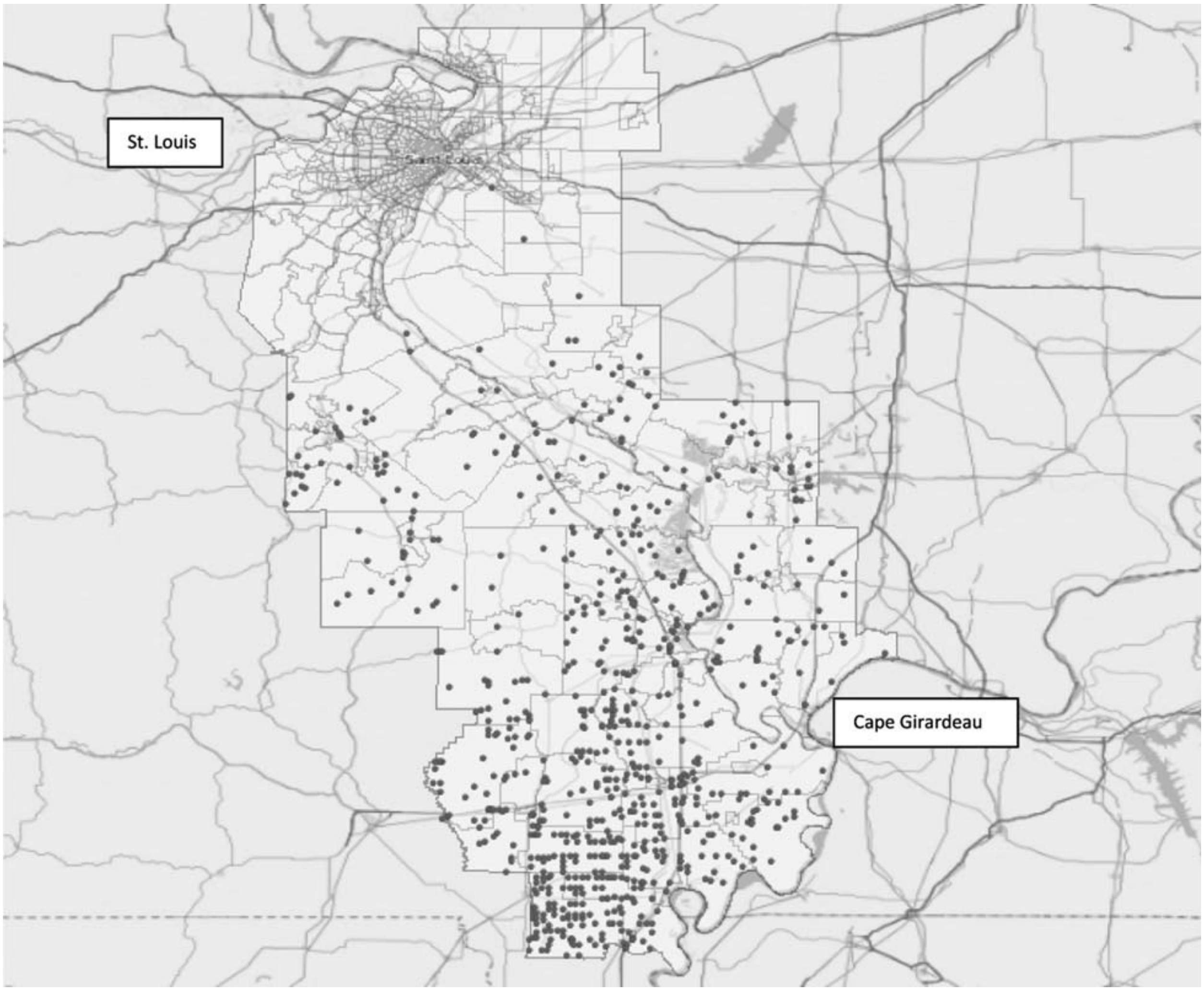


Figure 5-8. Missouri-Illinois Region Bridges with Functionality Less than 65% Due to Earthquake Damage as Estimated by Hazus

Table 5-6 all of the hospitals in Tuscaloosa would be heavily damaged by this relatively minor earthquake. On Day 3 the local hospitals could handle less than a third of the tornado injuries alone. Figure 5-10 shows that the nearest functional hospital is 25 miles away with five more 30-40 miles away. All five of the distant hospitals are estimated by Hazus to be more than 85% functional on Day 3. Even with a high level of hospital damage, bridge damage, unlike the Joplin, MO scenario, is extremely low and likely would not affect medical responders.

EARTHQUAKE AND EXTREME COLD – ST. LOUIS CITY, MO

The last scenario couples a major earthquake event with extreme cold that periodically occurs in St. Louis City. The Missouri Department of Natural Resources, Geological Survey Program has estimated that a Magnitude 7.6 New Madrid Earthquake with a

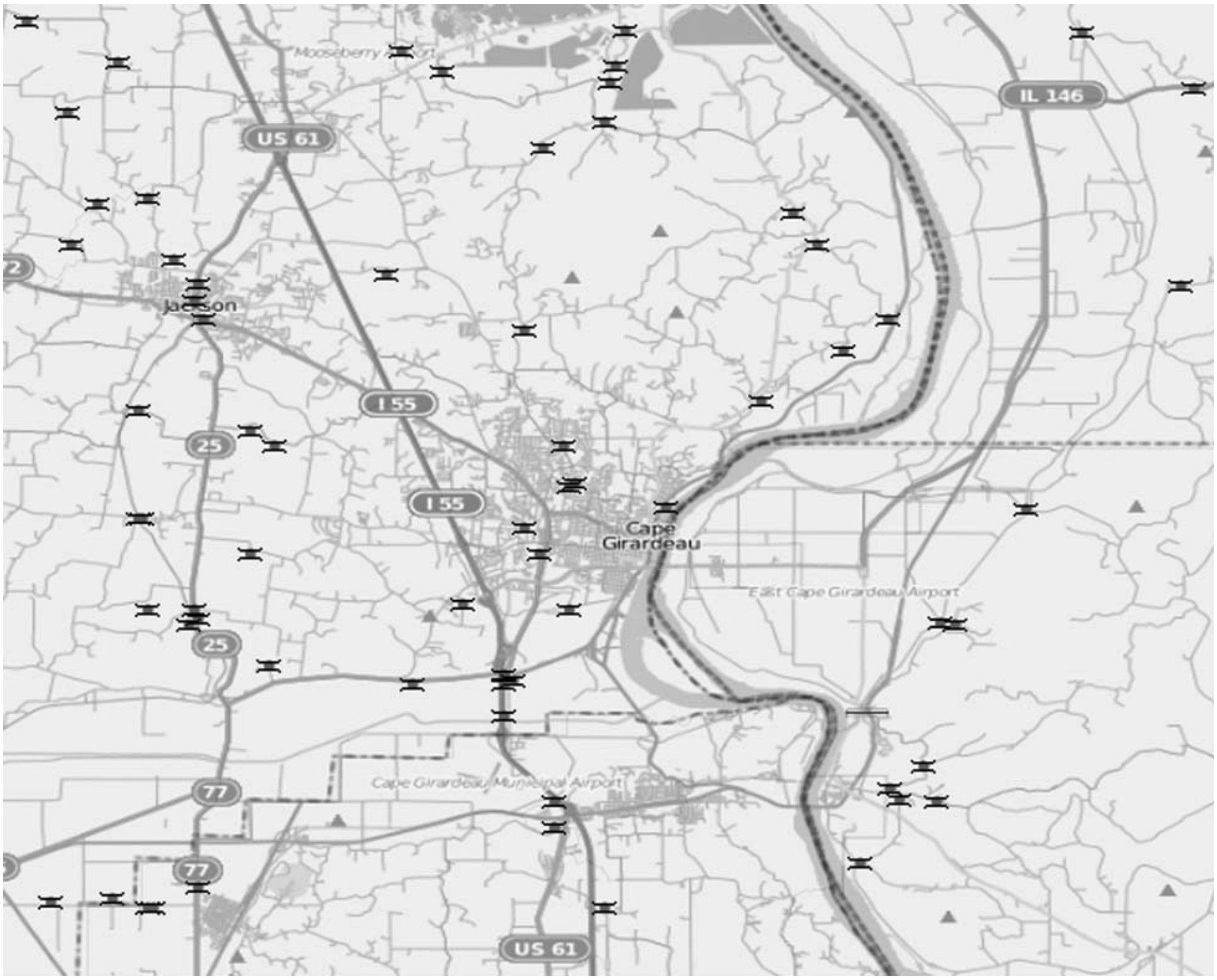


Figure 5-9. Cape Girardeau, MO Bridges with Functionality Less than 65% Due to Earthquake Damage as Estimated with Hazus

Table 5-6. Hospital Damage in Tuscaloosa, AL from a Hazus Magnitude 5.5 Earthquake

Tuscaloosa Medical Center Functionality					
		Day 3		*Day 7*	
Hospital	*Total Beds*	*% Functional*	*Beds*	*% Functional*	*Beds*
Northport	156	14%	22	32%	50
VA	582	29%	171	52%	301
DCH	610	22%	131	42%	257
Total Beds	1348	24%	324	45%	609

7–10% probability of repeating would generate shaking in St. Louis City at Modified Mercalli Intensity (MMI) VIII (Missouri Department of Natural Resources). According to the USGS, equivalent peak ground acceleration would range between .34 g and .65 g (USGS, March 2011). In Figure 5-11 a Hazus generated map shows shaking within this range.

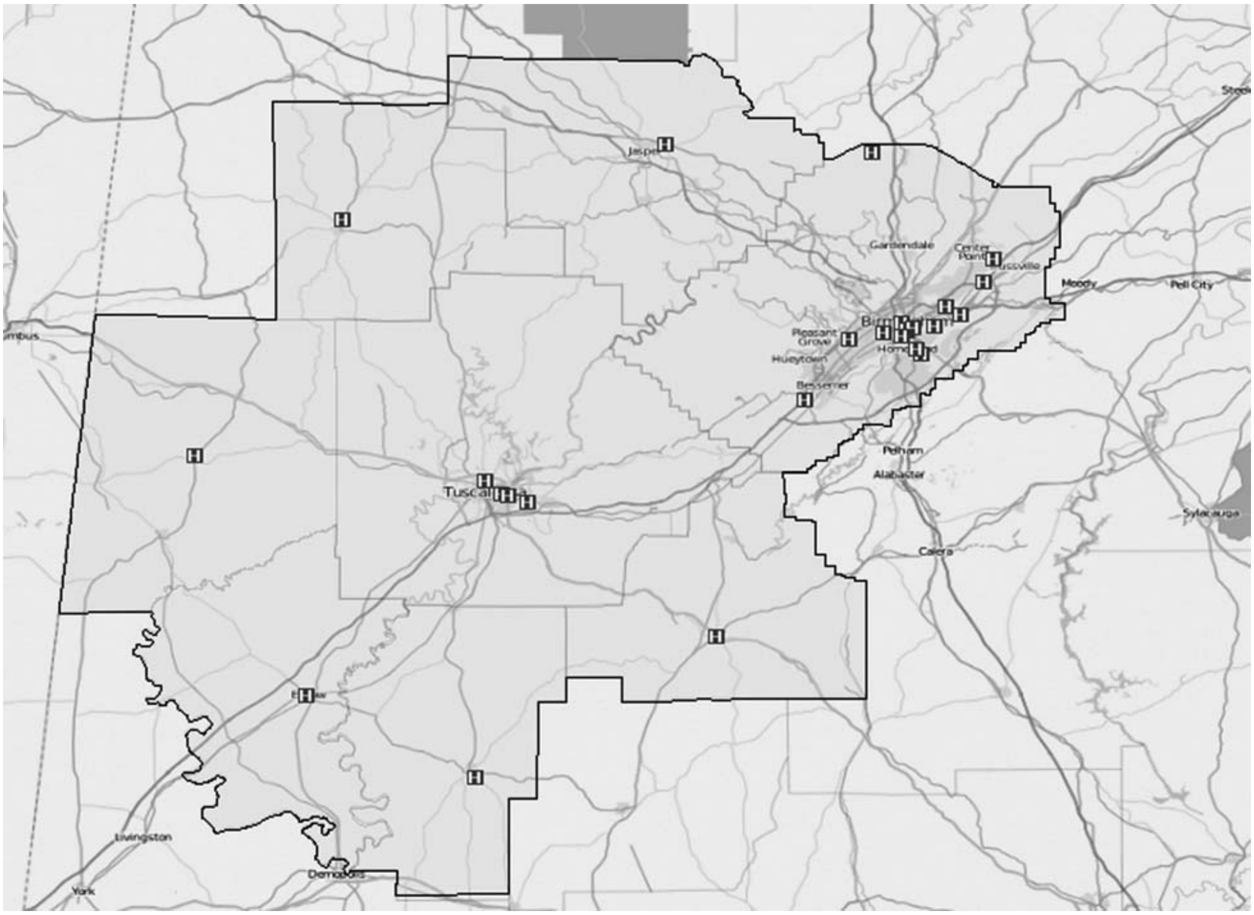


Figure 5-10. Hospitals in the Vicinity of Tuscaloosa, AL

Building damage from this level of shaking would be high as shown by Table 5-7.

Extensive and complete structural damage for steel moment frame buildings is defined in the Hazus Technical Manual as follows. Other structural types are similarly defined.

Extensive Structural Damage: Most steel members have exceeded their yield capacity, resulting in significant permanent lateral deformation of the structure. Some of the structural members or connections may have exceeded their ultimate capacity exhibited by major permanent member rotations at connections, buckled flanges and failed connections. Partial collapse of portions of structure is possible due to failed critical elements and/or connections.

Complete Structural Damage: Significant portion of the structural elements have exceeded their ultimate capacities or some critical structural elements or connections have failed resulting in dangerous permanent lateral displacement, partial collapse or collapse of the building. Approximately 8%(low-rise), 5%(mid-rise) or 3%(high-rise) of the total area of steel moment-framed buildings with complete damage is expected to be collapsed (Federal Emergency Management Agency, *Hazus – MH 2.1 Technical Manual, Earthquake Model*, 5-17 and 5-18, 2011.)

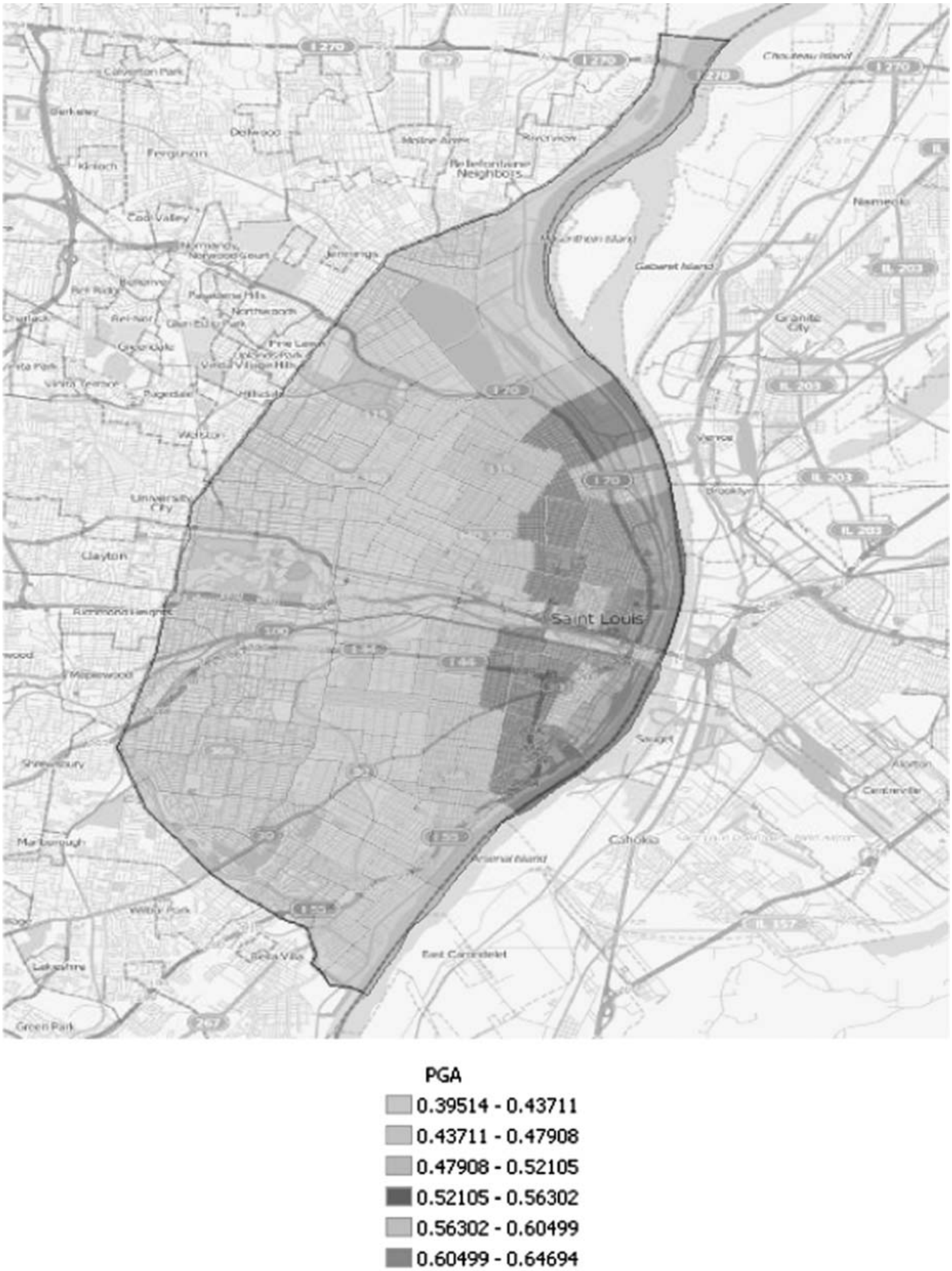


Figure 5-11. Hazus Generated Peak Ground Acceleration in St. Louis Equivalent to MMI VIII

Table 5-7. Extensive or Completely Damaged Structures in St. Louis City, MO from an MMI VIII Earthquake

Building Type	*% of Buildings Damaged*
Single Family Residences	20
Multi-Family Residences	23
Schools	70
Government Buildings	80
Commercial Buildings	72
Industrial Buildings	76

Table 5-8. Conditions for Onset of Hypothermia in 30 Minutes

Temperature (°F)	*Wind Speed (mph)*
5	30
0	15
–5	10
–10	0

To assess the effects of extreme cold with an MMI VIII earthquake, night time and day time scenarios are considered. In the night time scenario, short-term shelter requirements for 18,491 persons are estimated with Hazus in St. Louis City. This estimate assumes people will leave damaged residences to stay with friends and relatives or in the family car or public shelter (Federal Emergency Management Agency, *Hazus – MH 2.1 Technical Manual, Earthquake Model*, 14-4, 2011.)

The distribution of shelter requirements estimated by Hazus, based on PGA .395 g–.646 g, is shown in Figure 5-12.

However, for those who need to leave their residences in the city, the available shelter will severely diminished by earthquake damage to building as shown in Table 5-7. As much as 70% of schools and 80% of government buildings normally used as shelter will likely not be available after the earthquake. Nearby homes that could be available for shelter might be similarly damaged. Shelter availability also will depend on how residents interact with one other.

Since 1874 St. Louis has experienced 75 days with average *high* temperatures between minus five and seven degrees Fahrenheit. Another 75 days (with some overlap with the first 75) had low temperatures between minus 22 and minus eight degrees (NOAA, August 2008). Hypothermia becomes an issue at these temperatures depending on the wind speed. In light clothing hypothermia begins to develop in 30 minutes as per Table 5-8 (Ski-Adventure-Guide.com).

St. Louis also has experienced temperature extremes as seen in Table 5-9, at which the onset of hypothermia is ten minutes (Ski-Adventure-Guide.com).

If many of the over 18,000 people needing shelter have to leave their homes, or their homes are without power, and warm enough clothing is unavailable due to building

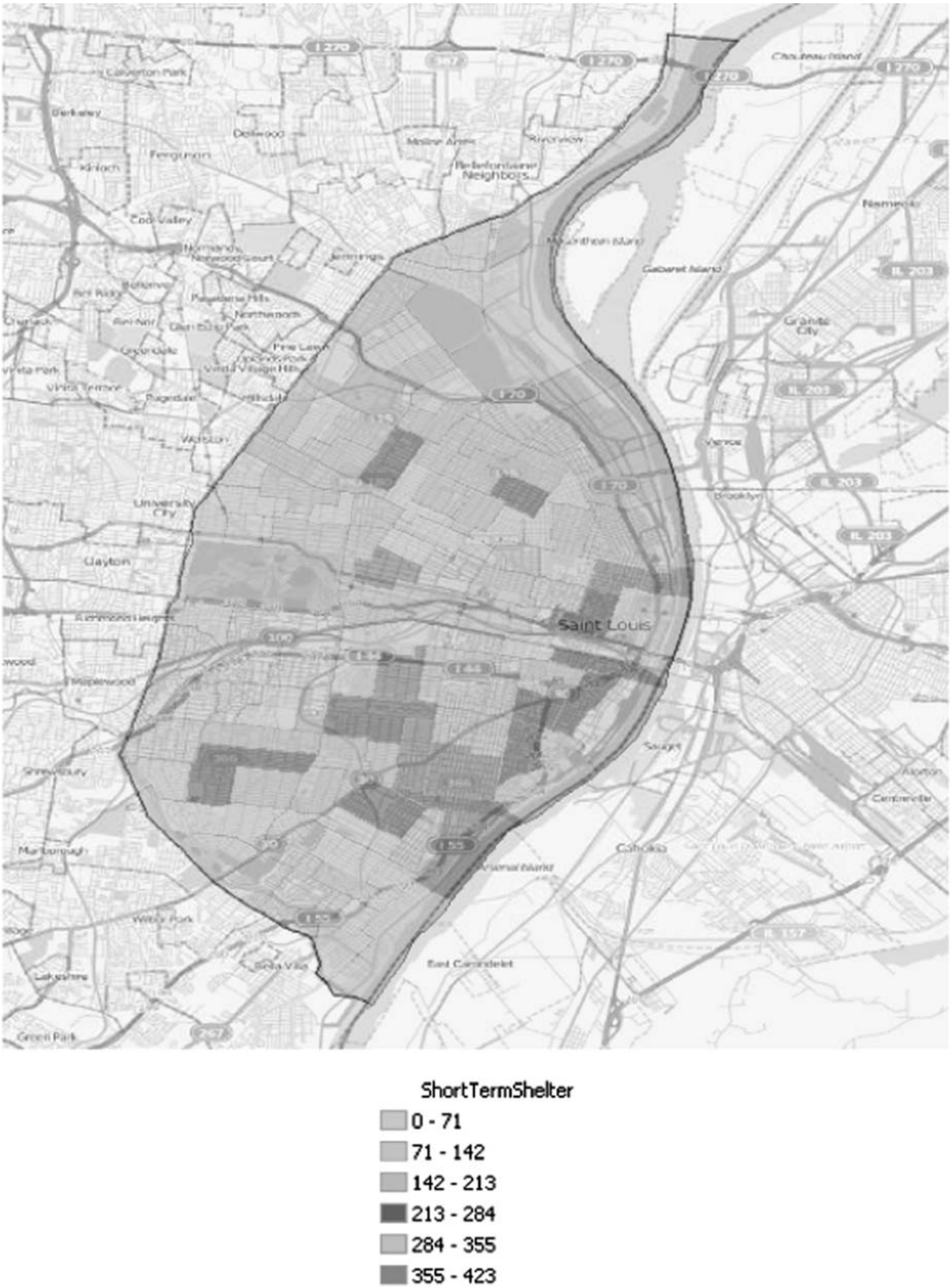


Figure 5-12. Short-Term Shelter Requirements Estimated by Hazus

Table 5-9. Recent Record Cold in St. Louis, MO (National Weather Service Weather Forecast Office, St. Louis Missouri, Climatology and Weather Records, May 2012)

Month/Day/Year	*Temp (°F)*	*Wind Chill (°F)*
January 16, 1977	–14	–38
January 17, 1977	–12	
January 19, 1985	–12	
January 20, 1985	–18	–48

damage, they could be subject to hypothermia given the ambient temperature and wind speed. People trapped in their homes without access to warm clothing are more at risk.

The second scenario in the daytime involves people, who are primarily at work in office and industrial buildings. According to the 2010 Census there are 168,720 workers in the St. Louis City labor force (US Census Bureau). In Table 5-7 between 72% and 76% of commercial and industrial buildings will be extremely or completely damaged and likely either partially or completely uninhabitable. This indicates that persons numbering as many as 100,000, as a rough estimate, could be in the streets following an earthquake. They will need to find shelter in the roughly 25% of school, government, commercial and industrial buildings moderately, slightly or not damaged. Available buildings might not be close by. As in the night time scenario, if warm enough clothing is unavailable when they leave their places of work, or if they are trapped in their workplaces, the likelihood of hypothermia increases.

As an end note, a Magnitude 7.5 New Madrid Earthquake occurred January 23, 1812 (USGS, May 2011) within the same time period as the coldest day that St. Louis City has experienced in the last twenty-five years.

CONCLUSIONS

Each of the four scenarios described above has a low probability of occurrence, but with higher potential losses, and consequences with greater complexity than for a single hazard event. More analysis is required to determine combined loss estimates and eliminate double counting, but it is certain that in each case the combined losses will exceed those for a single event.

For the Shelby County, Joplin and Tuscaloosa events, earthquakes have a window of time before and after a tornado or a flood to affect a multihazard event. In Shelby County, the flood stage for the May 2011 Mississippi River event lasted about one month (*The Commercial Appeal*, Memphis, May 27, 2011). If an earthquake had destroyed a number of levees before the river crested, flood levels would have depended on the speed of levee repair. If the earthquake had destroyed levees as the water levels receded flooding would have depended on the height of the water at that given time.

In Joplin, if enough bridges are not repaired before a tornado, land-based emergency response will be compromised. An earthquake after a tornado will retard the emergency response in progress, in addition to increasing its requirements for support. The same approach applies to the hospitals in Tuscaloosa before and after an earthquake. In St. Louis a two to three day extreme cold snap at less than 0 degrees has occurred 60 times since 1893. Fifteen other times this has lasted four or more days, and in one year it lasted ten days (National Weather Service Weather Forecast Office, St. Louis Missouri, Climatology and Weather Records, Ranked Occurrences of Temperatures <32 and 0 degrees (1893 – Present), May 2012).

These multihazard events, or what can be called "black swans" according to Nassim Nicholas Taleb's definition, have not yet occurred in U.S. history. However, they point to important implications for emergency management if they were to happen. First, in each of the events, the disaster victims will be relying on their own resources and each other for a period of time, since there will be a loss of facilities and infrastructure that support emergency response. If the levees are breached in Shelby County, people will find themselves cut off as were the victims of Hurricane Katrina. With many bridges down in Joplin, Mo, help will not be arriving by overland as quickly as expected. In Tuscaloosa people will need to wait longer for hospital support. In St. Louis City, people will be required to find warm clothing and shelter quickly on their own.

Fortunately, the Shelby County, Joplin and Tuscaloosa scenarios show that they can be alleviated with incrementally more disaster response planning than already exists. Even with the complexity and a wide range of consequences from a major flood event coupled with an earthquake, Federal and state emergency management agencies now have experience with large scale catastrophic flood and earthquake events that could serve in responding to a dual event in Shelby County. Airborne response if appropriately readied and rapid location of functional routes could provide support for disasters that feature failures of land-based transportation systems. Regional and state-wide hospitals can be included in plans for distance response efforts if local hospitals are damaged. The type of planning for the two latter events is necessary for earthquake response without other coincidental hazard events. A coincident tornado only increases the damage and casualties that would be encountered by first responders.

For the St. Louis City scenario, however, response would need to be studied, since there is less experience with this combination of hazards. Response would have to be fast enough to prevent elevated loss of life from hypothermia among a large number of potential victims. It would need to be planned to overcome debris in the roads and highway bridge damage. According to Hazus only 50% of the bridges would be functional on Day 1 of the event. Additionally, the possible presence of significant snowfall and its effect on access to the city has to be taken into account. For example, the year 2011 saw the ninth snowiest January since 1883 at 13.5 inches with 9.6 inches of that total falling in a single storm (Stltoday.com, January 2011).

The usefulness of public education for earthquakes coupled with other hazards might likely be compromised by the rarity of such events. However, these four scenarios show that despite expected higher levels of damage, preparing for and responding to multiple hazards fortunately is not necessarily beyond the resources of the emergency management and response community.

References

American Society of Civil Engineers, *So You Live Behind a Levee – What You Should Know to Protect Your Home and Loved Ones from Flood*, 2010.

Earth Observatory, *Tornado Track in Tuscaloosa, Alabama*, http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=50434&src=eorss-nh, May 2011.

FEMA, *Hazus*, http://www.fema.gov/plan/prevent/hazus/, March 2012.

Federal Emergency Management Agency, *HAZUS®MH, FEMA Risk Assessment System*, Version 2.1, 2011.

Federal Emergency Management Agency, *Hazus – MH 2.1 Technical Manual, Earthquake Model*, 5-17 and 5-18, 2011.

Federal Emergency Management Agency, *Hazus – MH 2.1 Technical Manual, Earthquake Model*, 14-4, 2011.

"Levee breach submerges Downtown Memphis airport; some streets in peril", The Commercial Appeal, Memphis, TN, Memphis Commercial Appeal May 2011.

"Mississippi River recedes; back below flood stage for first time since April 26", The Commercial Appeal, Memphis, TN, 27Memphis Commercial Appeal May, 2011.

Missouri Department of Natural Resources, Geological Survey Program, *Facts about the New Madrid Seismic Zone*, http://www.dnr.mo.gov/geology/geosrv/geores/techbulletin1.htm.

NASA Earth Observatory/United States Geological Survey, *Flooding in Memphis, May 11, 2011*, http://www.earthobservatory.nasa.gov/IOTD/view.php?id=50549, May 2011.

National Weather Service Weather Forecast Office, Memphis, TN, *Great Mississippi River Flood of Spring 2011*, http://www.srh.noaa.gov/meg/?n=2011riverflooding, May 2012.

National Weather Service Weather Forecast Office, St. Louis Missouri, Climatology and Weather Records, Extremes (1874 – Present) – Saint Louis, MO, May 2012.

National Weather Service Weather Forecast Office, St. Louis Missouri, Climatology and Weather Records, Ranked Occurrences of Temperatures <32 and 0 degrees (1893 – Present), May 2012.

NOAA, Advanced Hydrologic Prediction Service, *Historical Crests*, http://water.weather.gov/ahps2/hydrograph.php?wfo=meg&gage=memt, April 2012.

NOAA, National Weather Service Weather Forecast Office, St. Louis, MO, *Bi-State Area Weather Trivia*, http://www.crh.noaa.gov/lsx/?n=jan_trivia, August 2008.

RTBOT, Great Mississippi Flood of 1927, http://www.rtbot.net/Great_Mississippi_Flood_of_1927.

Ski-Adventure-Guide.com, *First Safety on the Snow*, http://www.ski-adventure-guide.com/firstsafety.html.

Stltoday.com, *Snow snarls traffic, pushes January into the records*, http://www.stltoday.com/news/local/metro/article_06a2c513-c8b9-5499-9f00-14ce002bb722.html#ixzz11MB6QE5j, January 2011.

"Survivors recall deadly 1949 tornado that struck Cape Girardeau", *Southeast Missourian*, May 21, 2009.

Tuscaloosa News.com, *Tornado that hit Tuscaloosa Wednesday declared an EF4*, http://www.tuscaloosanews.com/article/20110503/news/110509918?p=2&tc=pg, May 2011.

U.S. Army Corps of Engineers, Inundation Map, Lower MVD Estimated Inundation, http://www.mvd.usace.army.mil/docs/FloodMap_1927vs2011.pdf, June 16, 2011.

U.S. Army Corps of Engineers – Memphis District, *Mississippi River Levees, AR, IL ,KY, MS, MO, TN*, 2010.

U.S. Census Bureau, American Fact Finder, http://factfinder2.census.gov/faces/tableservices/jsf/pages/productview.xhtml?src=bkmk.

USGS, Historic Earthquakes, *Historic Earthquakes:New Madrid 1811–1812 Earthquakes*, http://earthquake.usgs.gov/earthquakes/states/events/1811-1812.php, May 2011.

USGS, *ShakeMap Scientific Background*, http://earthquake.usgs.gov/earthquakes/shakemap/background.php#wald99b, March 2011.

Bibliography

Blackwell, Brian, "Survivors recall deadly 1949 tornado that struck Cape Girardeau", *Southeast Missourian*, May 21, 2009.

Charlier, Tom, "Levee breach submerges Downtown Memphis airport; some streets in peril", The Commercial Appeal, Memphis, TN, Memphis Commercial Appeal Posted May 5, 2011 at 11:57 a.m., updated May 5, 2011 at 11:28 p.m.

Charlier, Tom, "Mississippi River recedes; back below flood stage for first time since April 26", The Commercial Appeal, Memphis, TN, Memphis Commercial Appeal Posted May 27, 2011 at 11:04 a.m., updated May 27, 2011 at 11:26 p.m.

Federal Emergency Management Agency, Earthquake Model HAZUS®MH Version 2.1 Technical Manual, Washington, DC, 2011.

Federal Emergency Management Agency, *HAZUS®MH, FEMA Risk Assessment System*, Version 2.1, Washington, DC, 2011.

CHAPTER 6

Geotechnical Issues and Site Response in the Central U.S.

Youssef M. A. Hashash*
Byungmin Kim*
Scott M. Olson*
Sungwoo Moon*

Abstract: *This article highlights the results of recent studies dealing with key seismic geotechnical issues in the central United States including:*

1) *Significance of using the Conditional Mean Spectrum for seismic design at the periphery of the New Madrid seismic zone: The commonly used Uniform Hazard Response Spectrum does not represent any specific earthquake event in this region whereby the seismic hazard is a composite of two or more distinct sources of significantly different characteristics. Treatment of these sources separately results in a more realistic assessment of seismic hazard.*
2) *Site response of deep soil deposits in the Mississippi Embayment: there is a need to use depth-dependent site amplification factors instead of commonly used depth-independent NEHRP site coefficients.*
3) *Unique aspects of liquefaction in the central United States, particularly in the New Madrid Seismic Zone: Currently used liquefaction triggering analysis has been developed for plate margin settings which differ from the tectonic setting in the central United States.*

INTRODUCTION

The New Madrid seismic zone (NMSZ) is the dominant seismic source in the central U.S. and straddles a number of states including Illinois, Missouri, Kentucky, Arkansas, and Tennessee. The NMSZ is a clustered pattern of earthquake epicenters between 5 and 15 km deep and lies mostly within the Reelfoot rift (Figure 6-1). The NMSZ is a right-lateral strike-slip fault zone with a restraining bend (Reelfoot reverse fault) (Csontos and Van Arsdale 2008). The fault system is approximately 200 km long and consists of five identified faults: New Madrid North (29°, 72°SE), Risco (92°, 82°N), Axial (46°, 90°), Reelfoot North (167°, 30°SW), and Reelfoot South (150°, 44°SW) (Csontos and Van

*University of Illinois at Urbana and Champaign, Illinois, USA

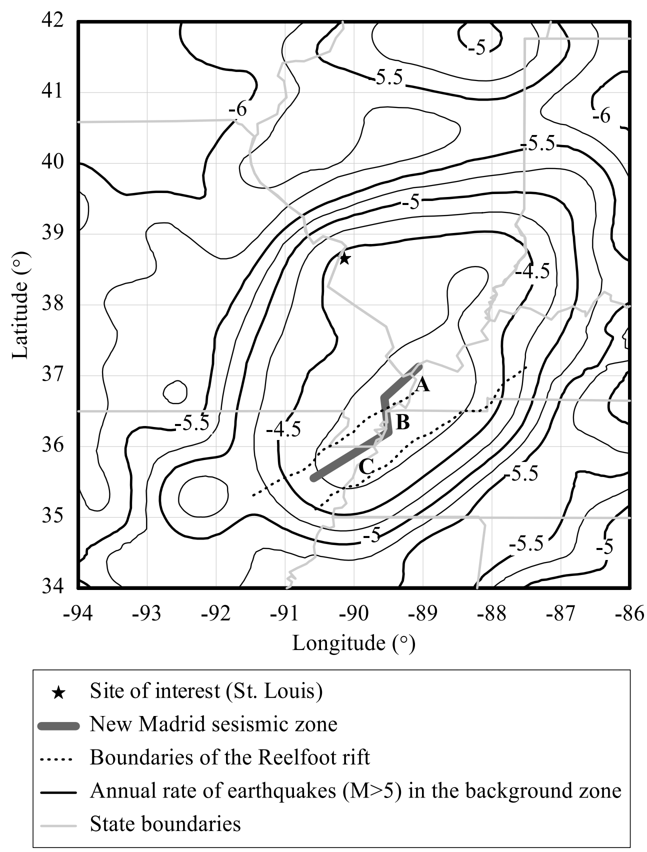


Figure 6-1. Map showing the location of St. Louis, the New Madrid Seismic zone with three segments (A, B, and C), and boundary of the Reelfoot rift. The contours show the annual rate of earthquakes with $M > 5$ for 0.1×0.1 degree grids in the background zone (in $\log_{10}$ units)

Arsdale 2008). At least one large earthquake occurring at about A.D. 300 and three sequences of large earthquakes occurring at about A.D. 900, A.D. 1450, and A.D. 1811–1812 have been recognized from crosscutting relationships and radiometric dating of charcoal and plant remains within and outside of liquefaction-induced sandblow feature (Tuttle *et al.* 2002b; Tuttle *et al.* 2005). Interpreted magnitudes for these earthquakes are still controversial, with a range from M7.0 to M8.1 (Bakun and Hopper 2004; Hough and Martin 2002).

The Mississippi Embayment, which overlies the New Madrid seismic zone, is shown in Figure 6-2. The embayment is approximately 1000 m deep at its center, and is filled with sediments of clay, silt, sand, gravel, chalk, and lignite ranging in age from Cretaceous to recent Holocene. The presence of the deep embayment deposits is a challenge for estimating local site effects on propagated ground motion.

The seismic hazard in the CUS is dominated by the NMSZ. Larger-magnitude, preinstrumental seismic activity typically is associated with extensive paleoliquefaction features. This article summarizes recent studies on seismic geotechnical issues in the CUS, including the use of the conditional mean spectra framework at the periphery of the

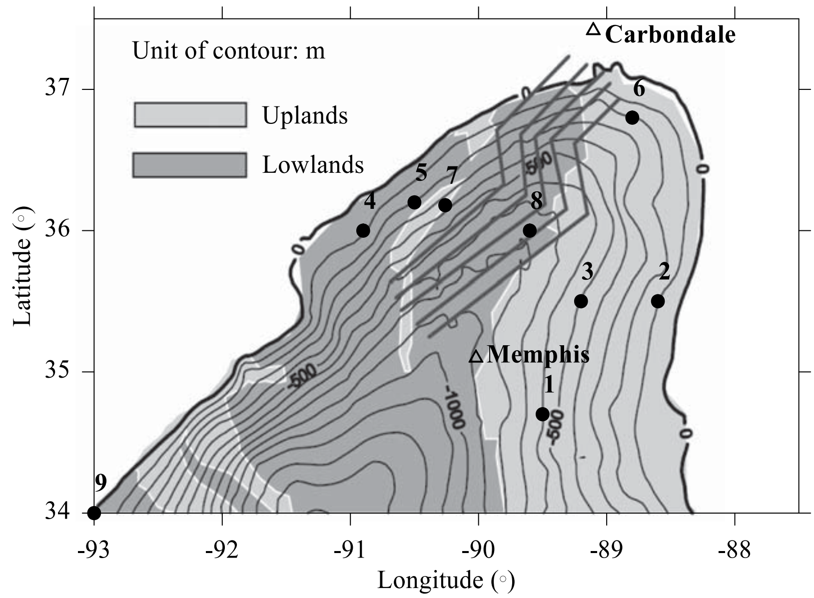


Figure 6-2. The Mississippi Embayment and the NMSZ. The selected sites for the PSHA-NL analysis for a 2475-year return period (described later) are shown as black circles
SOURCE: Hashash and Moon 2011

NMSZ, site amplification for deep soil deposits in the ME, and the unique aspects of liquefaction in the CUS.

SEISMIC HAZARD ALONG THE NMSZ PERIPHERY

The uniform hazard response spectrum (UHRS), developed from a probabilistic seismic hazard analysis, is often used to define seismic hazard for a given probability of occurrence. This approach is adopted in the widely used seismic hazard maps published by the U.S. Geologic Survey and adopted by various building codes. The UHRS implicitly includes motions from multiple earthquake sources, and the resulting spectrum represents an envelope of possible spectra yet does not represent a single event. As an alternative to using the UHRS, Baker and Cornell (2006a) proposed the conditional mean spectra (CMS) which provides target spectra that better represent controlling seismic sources while preserving the probabilistic framework of the UHRS.

Abrahamson (2009) performed a site-specific seismic hazard analysis for a site near St. Louis (38.646°N, 90.178°W), which is located approximately 200 km from the NMSZ. Abrahamson (2009) modeled the NMSZ with three segments (A, B, and C) shown in Figure 6-1, instead of using individual faults. He used a fault model and logic tree that maintain the basic elements (quiescent periods and clustering) of the source characterization for the NMSZ by the USGS 2008 National Hazard Mapping Project (Petersen et al. 2008). He assigned weights of 0.2 to the longer quiescent recurrence interval (1000 years) and 0.8 to the shorter recurrence interval (500 years) while the USGS (Petersen et al. 2008) assigned weights of 0.1 and 0.9 to these branches, respectively. The

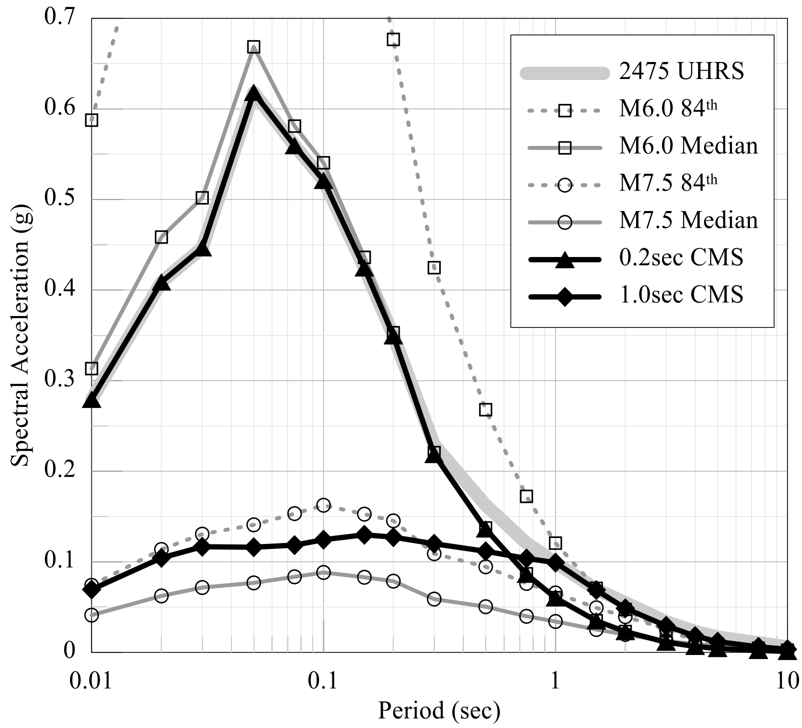


Figure 6-3. Rock outcrop ($V_s = 2.0$ km/sec) horizontal uniform hazard response spectra (UHRS) and conditional mean spectra (CMS) for T = 0.2 and 1.0 second for 2% in 50 years (2475-year return period), compared with median and 84th percentile deterministic spectra for M = 6.0 and M = 7.5

USGS (Petersen et al. 2008) gives equal weight to the clustering and non-clustering models, but Abrahamson (2009) included an alternative that the clustering occurs 75% of the time. He modeled background seismicity in addition to the NMSZ, using the smoothed seismicity model developed by the USGS (Petersen et al. 2008). The annual rate of M > 5 earthquakes for the background zone is shown in Figure 6-1. The maximum magnitude for the background zone ranges from 6.6 to 7.2, and that for the Wabash Valley region is increased to 7.5 (Petersen et al. 2008). Abrahamson (2009) employed three ground motion prediction models that represent the current understanding of ground motions in the CEUS: Atkinson and Boore (2006), Campbell (2003), and Silva et al. (2002). Using the standard approach for the probabilistic seismic hazard analysis described by Cornell (Cornell 1968), the bedrock Uniform Hazard Response Spectra (UHRS) shown in Figure 6-3 were computed for a 2475-year return period.

The magnitude-distance deaggregation for a 2475-year return period for spectral periods (T) of 0.2 and 1.0 sec are shown in Figure 6-4. For short spectral periods, the hazard is dominated by M5.0–6.5 earthquakes at distances of 0–30 km, corresponding to background seismicity sources. For long spectral periods, the hazard is dominated by M7.0 – 8.0 earthquakes at distances of 180–300 km, corresponding to earthquakes along the NMSZ. Therefore, the UHRS represents an envelope of the ground motions from these distinctly different earthquake sources.

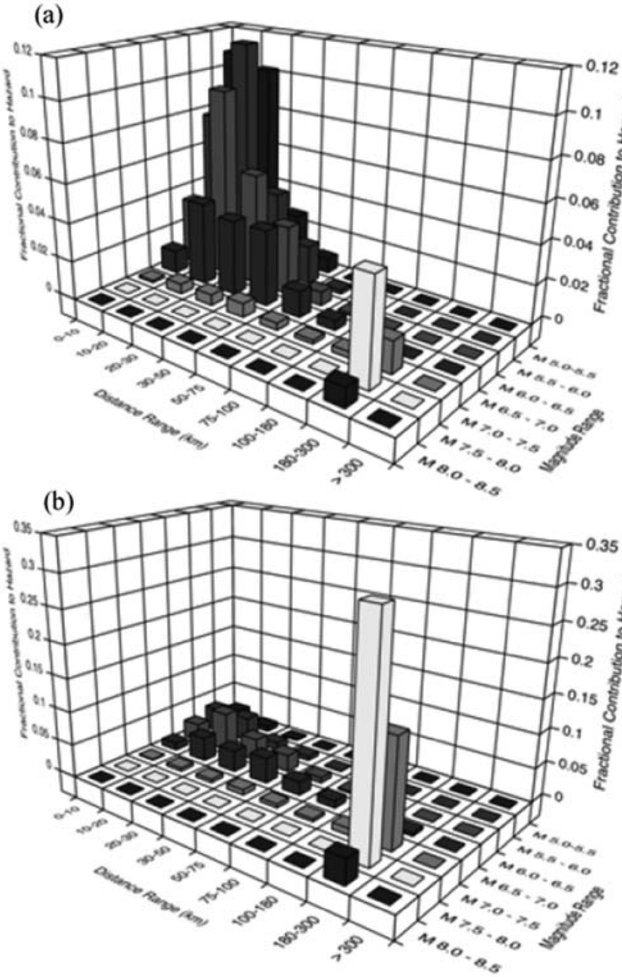


Figure 6-4. Seismic hazard deaggregation for (a) T = 0.2 sec and (b) T = 1.0 sec for a return period of 2475 years

An alternative to using the UHRS was developed by Baker and Cornell (2006b). They defined a conditional mean spectrum (CMS) that results in response spectra that are consistent with the controlling sources while maintaining the probabilistic framework of the UHRS. The CMS is based on the scenario spectrum concept. The main feature of the realistic scenario spectrum is that it matches the UHRS only at the period of interest, which is typically the expected fundamental period of the structure being designed (T_1). Basic steps in constructing a CMS begin with deaggregating the hazard for the period of interest (T_0) at a specified return period to determine the associated earthquake magnitude and distance. The median and standard deviation of the response spectrum are computed for the dominant magnitude-distance pair based on the deaggregation. Next, the number of standard deviations, ε, that the UHRS is above the median spectrum at spectral period T_0 is found. The mean value of ε at the other periods is then found, taking into account the correlation of the ground motion between different spectral periods.

Figure 6-3 presents the CMS for two target spectral periods (0.2 and 1.0 sec) as well as the deterministic spectra at a rock outcrop with V_s = 2.0 km/sec (Abrahamson 2009). The plot shows that CMS at T = 0.2 sec closely resembles the deterministic spectra from background sources and can be associated with such events. The CMS at T = 1.0 sec closely resembles the deterministic spectra for large, distant NMSZ events and can be associated with such events. Notably, the high frequency content of this spectrum is significantly less than that of the UHRS. The seismic hazard at the site is bi-modal, and the UHRS is ill-suited for representing the bi-modal seismic sources. Spectrally-matching a ground motion time series to the UHRS and associating it with a NMSZ event potentially can result in large seismic demands that do not reflect the tectonic setting and expected ground shaking at the site.

Olson and Hashash (2009) selected representative recorded and simulated ground motions which were matched to the target CMS, and performed 1-D equivalent-linear and nonlinear total stress ground response analyses. Sample site response analysis output in Figure 6-5 shows that the short period components of the input motion are attenuated while the longer period components are amplified due to the presence of thick soft soil deposits at the site. The ground motions for the T = 0.2 sec CMS (M = 6.0) have significantly higher accelerations than those for the T = 1.0 sec CMS (M = 7.5). Olson and Hashash (2009) performed liquefaction triggering analysis using the CMS-compatible ground motions and the guidelines proposed by Robertson and Wride (1998), Youd et al. (2001), and Idriss and Boulanger (2006). The analyses suggested that liquefaction is either not triggered or triggered only sporadically at the site using both design cases. In addition, no lateral spreading displacement was estimated using the procedures by Youd et al.

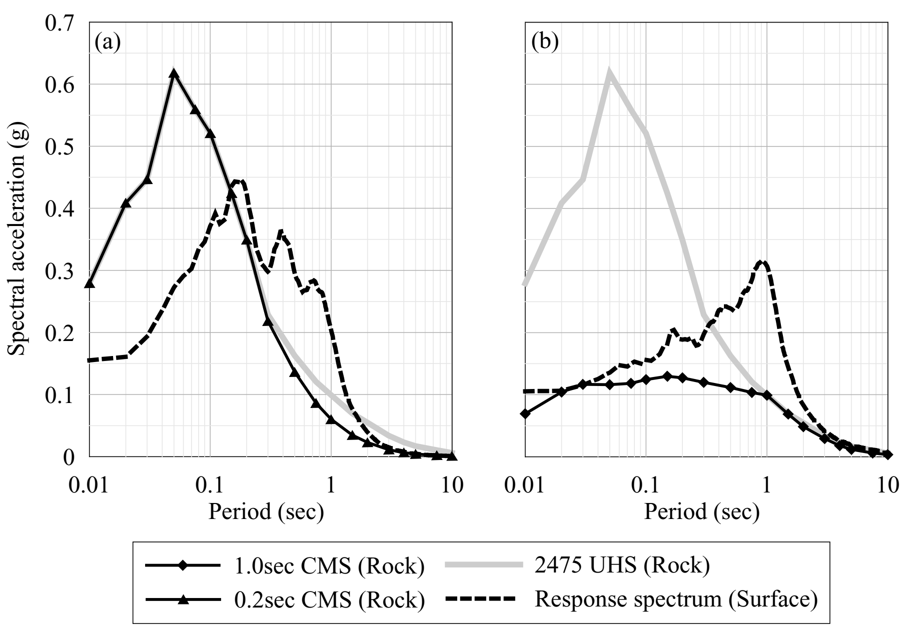


Figure 6-5. Response spectra at ground surface for (a) 0.2 sec CMS and (b) 1.0 sec CMS for 2475-year return period

(2002) and Zhang et al. (2004). These results are consistent with the observation of limited liquefaction in the St. Louis area during the 1811–1812 NMSZ events and other historical earthquakes (Obermeier 1988a; Street and Nuttli 1984). The use of UHRS-compatible motions with a high PGA associated with a M = 6.0 event and the large magnitude (M 7.5) associated with the NMSZ predicted pervasive and widespread liquefaction and lateral spreading. The use of CMS provided a sound and technically defensible approach to reduce the conservatism in UHRS based seismic design, particularly for the site where the seismic hazard is influenced by distinctly different sources. Hashash et al. (2014, in press) summarizes the seismic analysis using the conditional mean spectra at the Illinois approach of the new I-70 Mississippi River Bridge based on the updated information from previous studies (Abrahamson 2009; Olson and Hashash 2009).

SITE RESPONSE OF MISSISSIPPI EMBAYMENT DEPOSITS

Park and Hashash (2005) proposed a new integrated probabilistic seismic hazard analysis (PSHA) procedure that can consider nonlinear site effects in the seismic hazard calculation. The flowchart of the PSHA-NL procedure is shown in Figure 6-6. The procedure is composed of three main steps: (1) source characterization, (2) generation of ground-motion time histories, and (3) site response analysis. Steps 1 and 2 generate ground-motion time histories and uniform hazard response spectra (UHRS) at hard rock and B/C boundary, and step 3 characterizes the effect of the deep soil deposits of the

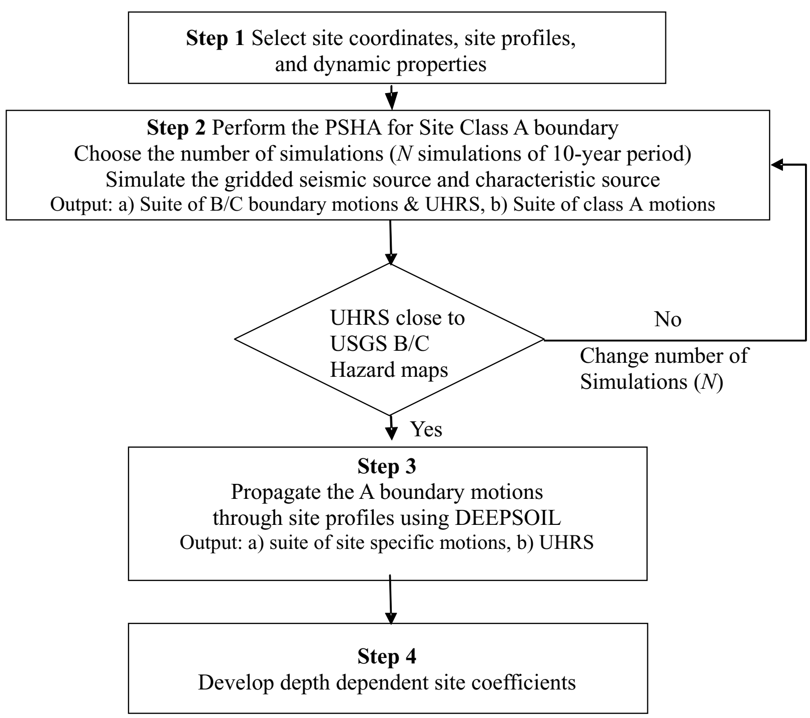


Figure 6-6. Procedure of the PSHA-NL for estimation of site coefficients

SOURCE: after Park and Hashash 2005

Table 6-1. Comparison of conventional USGS PSHA/NEHRP procedure and PSHA-NL to derive surface ground motions (Hashash and Moon 2011)

Step	*USGS PSHA/NEHRP*	*PSHA-NL*
1. Seismic source characterization	a. Identify seismic sources and geometry. b. Define recurrence parameters for each seismic source.	a. Identify seismic sources and geometry. b. Define recurrence parameters for each seismic source. c. Develop a synthetic earthquake catalog over a period of simulation years to reflect the sources and their recurrence rates.
2. Ground-motion parameters	a. Use attenuation relationships to derive ground-motion parameters. b. Develop spectral parameters corresponding to a given uniform hazard at NEHRP site-class A or B/C.	a. Use attenuation relationships to calibrate the Point Source (PS) and Finite Fault (FF) models for generation of synthetic ground-motion time histories. b. Develop UHRS from the aggregation of all acceleration time histories for NEHRP site-class A and B/C.
3. Site effects	a. Use NEHRP site coefficients to develop NEHRP spectrum at ground surface.	a. Propagate all synthetic motions through randomized soil profile properties to preserve the probabilistic nature of the surface ground-motion parameters. b. Develop UHRS at the ground surface.

Upper Mississippi Embayment (UME) through propagation of generated ground motions. Table 6-1 compares the steps in PSHA-NL to those of the conventional USGS PSHA/NEHRP procedure. The PSHA-NL generates synthetic ground motion time histories via ground motion simulation programs; whereas the traditional PSHA generates the ground motion parameters using ground motion prediction equations (i.e., attenuation relationships). The propagated ground motions through the soil column and the developed UHRS are used to determine depth-dependent NEHRP-style site coefficients. The PSHA-NL procedure suggested by Park and Hashash (2005) has two limitations: (1) the use of point source models and parameters to simulate characteristic earthquakes requiring an artificial cap to avoid unrealistically large ground motions in step 2, (2) the use of only two deterministic soil profiles to account for uncertainty in soil-column profiles that only represent site class D.

Cramer (2006) suggested a procedure to estimate the site-specific seismic hazard considering the effect of deep soil deposits of the UME. The developed UHRS from the USGS hazard map methodology is obtained on a grid pattern. Ten ground-motion time histories were selected from the M~7 strong motion time series (corresponding to a characteristic earthquake for the NMSZ) and scaled to match the USGS UHRS (with 2% probability of exceedance in 50 years) at each grid point. The site response analysis was performed using 1-D equivalent-linear site response analysis. The scaled ground motions were propagated through the 100 randomized soil profiles to account for the uncertainty and variability of soil profiles. However, this approach has important limitations. Scaling a motion to fit a UHRS is generally not recommended because it is not probabilistically rigorous (Baker and Cornell 2006b). The UHRS represents an aggregation of multiple earthquake sources while the ground motion used for site response analysis represents the motion from only a single earthquake. Furthermore, the sole use of the equivalent-linear method for site response analysis under strong shaking is generally insufficient because it does not consider the strongly nonlinear response of the soil (Field et al.1998).

Hashash et al. (2008) enhanced the PSHA-NL procedure suggested by Park and Hashash (2005) by incorporating finite fault models that generate ground-motion time histories for large earthquakes ($M_w > 7$) compatible with the USGS hazard maps (Petersen et al. 2008) without artificial caps, and by propagating the generated ground motions through the randomized soil-column properties. These improvements yielded a procedure that accounts for the site effects of UME deep soil deposits and overcomes the limitations in the studies by Cramer (2006) and Park and Hashash (2005).

Hashash and Moon (2011) added new shear wave velocity data collected for the UME soils to the data used by Hashash et al. (2008) to develop additional generic shear wave velocity profiles and evaluate soil amplification for site classes C, D, and E. The modulus reduction and damping curves proposed by Darendeli (2001) and Menq (2003) are combined with the curves for: (1) Mississippi Embayment (ME), and (2) Electric Power Research Institute (EPRI), which were used by Hashash et al. (2008). The selected modulus reduction and damping curves modified by the fitting procedure proposed by Phillips and Hashash (2009). Updated information regarding hypothetical faults and attenuation relationships for finite-fault (FF) and point-source (PS) were used, based on the 2008 USGS hazard map (Petersen et al. 2008) rather than the 2002 USGS hazard map (Frankel et al. 2002). The finite fault simulations used the program EXSIM (Extended Finite-Fault Simulation; Motazedian and Atkinson 2005) to generate the ground motion time series. SMSIM (version 3.1, Boore 2005) was used to simulate point sources and generate ground motion time series.

Ground motions for hard rock (NEHRP site-class A, representing Paleozoic bedrock) conditions were generated by both finite fault and point source models at nine selected sites (locations are listed in Figure 6-2), and were propagated to the ground surface to account for the effects of Mississippi embayment deposits. The seismic-wave propagation was simulated using both equivalent-linear and nonlinear approaches with the 1-D site response analysis code DEEPSOIL (version 4.0) (Hashash 2011; Hashash and Park 2001). To consider the uncertainty in the site response analysis due to variability in dynamic soil properties, two sets of shear-wave velocity profiles representing the upland and lowland profiles were randomized based on the methodology by Toro and Silva (2001) and Wong et al. (2004), as shown in Figure 6-7. The thickness of soil-column profile at each site was considered to be 30, 100, 200, 300, 500, and 1000 m to evaluate the effect of the soil deposit at each depth for which site response analyses were performed.

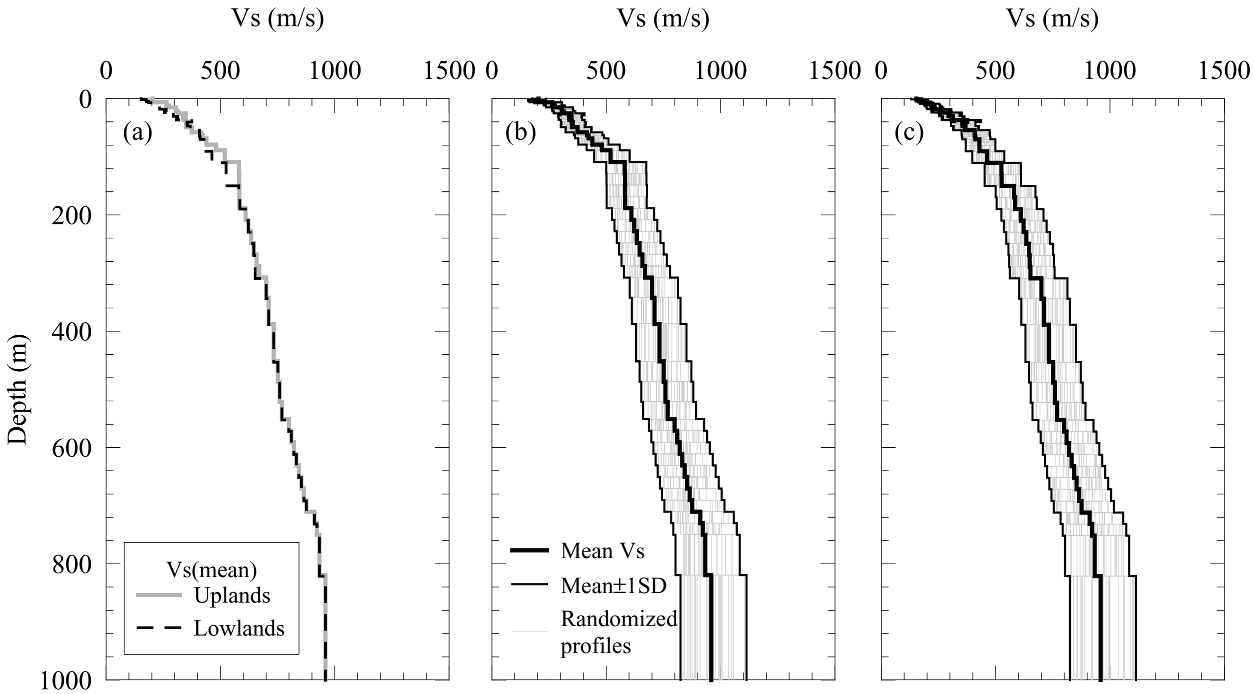


Figure 6-7. Shear wave velocity profiles for upland and lowland at site class D: (a) mean values; (b) 30 randomized profiles at upland; and (c) 30 randomized profiles at lowland
SOURCE: Hashash and Moon 2011

Figure 6-8 is an example of the derived NEHRP-style depth-dependent site coefficients for NEHRP site class D obtained from the PSHA-NL(FF) (Hashash and Moon 2011). The figure also shows the site coefficients in the NEHRP Provisions. The figure clearly shows a dependence of these site coefficients on embayment thickness up to a thickness of around 300–400 m. Readers are referred to Hashash and Moon (2011) for the depth-dependent site coefficients for site classes C and E.

Figure 6-9 shows the comparison of site coefficients (Fa, Fv) obtained from PSHA-NL(FF) (Hashash and Moon 2011) analyses and previous empirical studies using recorded ground data (Borcherdt 1994; 2002; Choi and Stewart 2005; Crouse and McGuire 1996; Dobry et al. 1999; Field 2000; Harmsen 1997; Joyner and Boore 2000; Rodriguez-Marek et al. 1999; Silva et al. 2000; Steidl 2000; Stewart et al. 2003) for a 30 m thick soil column for NEHRP site classes C, D, and E (Hashash and Moon 2011). In this figure, the relationship of site coefficients versus PGA is presented for short period (0.2 sec) and long period (1.0 sec) where Fa corresponds to the short-period amplification site coefficient and Fv corresponds to the long period amplification site coefficient. This figure shows wide ranges of site coefficients provided by previous studies, and moderately consistent trends of nonlinearity of site coefficients. The nonlinearity in site coefficients increases as the soil becomes softer. The site coefficients calculated from PSHA-NL(FF)(2011) show the same trends as the previous studies with respect to the nonlinearity according to site

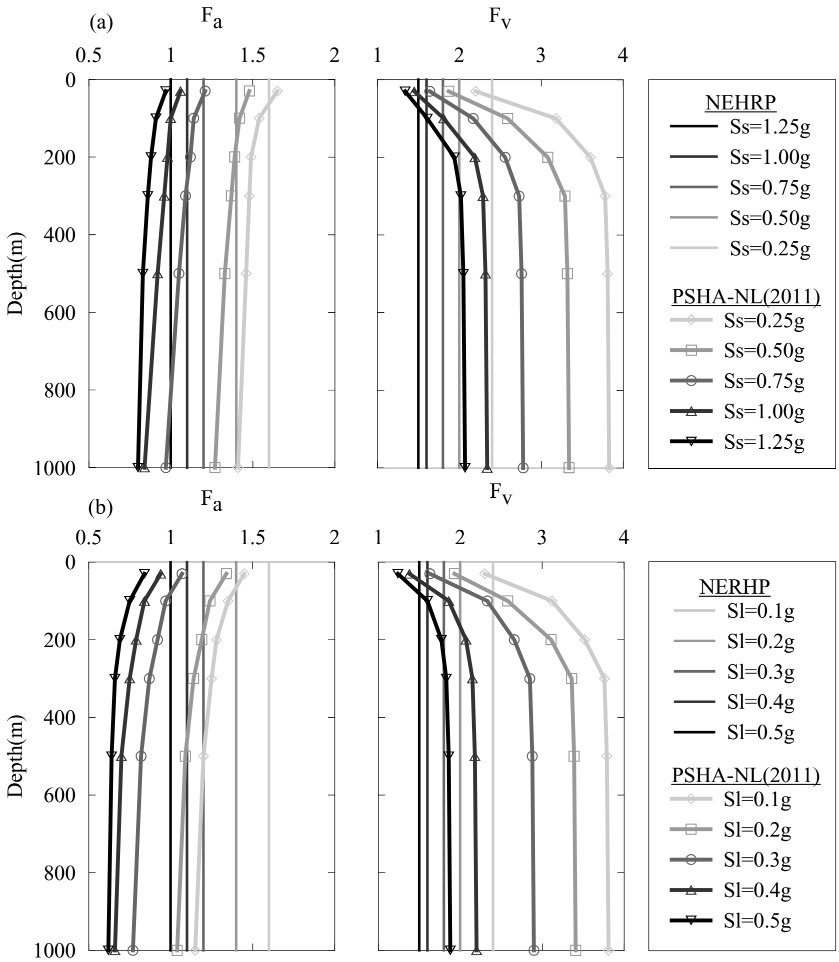


Figure 6-8. Comparison of depth-dependent site coefficients (Fa and Fv) obtained from PSHA-NL(FF) and NEHRP site coefficients at site class D for (a) Uplands (b) Lowlands
SOURCE: Hashash and Moon 2011

classes. The calculated Fa for the upland and lowland are located in the upper part within the range of other studies for site class C, in the middle part within the range of other studies for site class D, and in the lower part within the range of other studies for site class E. The developed Fv for both the upland and lowland are in the lower part of the range of these studies regardless of site class. Figure 6-10 compares the depth-dependent site coefficients at six soil-columns (30, 100, 200, 300, 500, 1000 m) for the upland and the lowland obtained from the PSHA-NL(FF)(2011) with other studies corresponding to site class D (Hashash and Moon 2011). The site coefficients clearly demonstrate the dependency on thickness of the embayment. The Fv values developed from the PSHA-NL(FF)(2011) increase with the thickness of the soil column, and cover the full range shown by previous studies. The Fa values show less dependency on thickness than the Fv values but they clearly decrease with thickness.

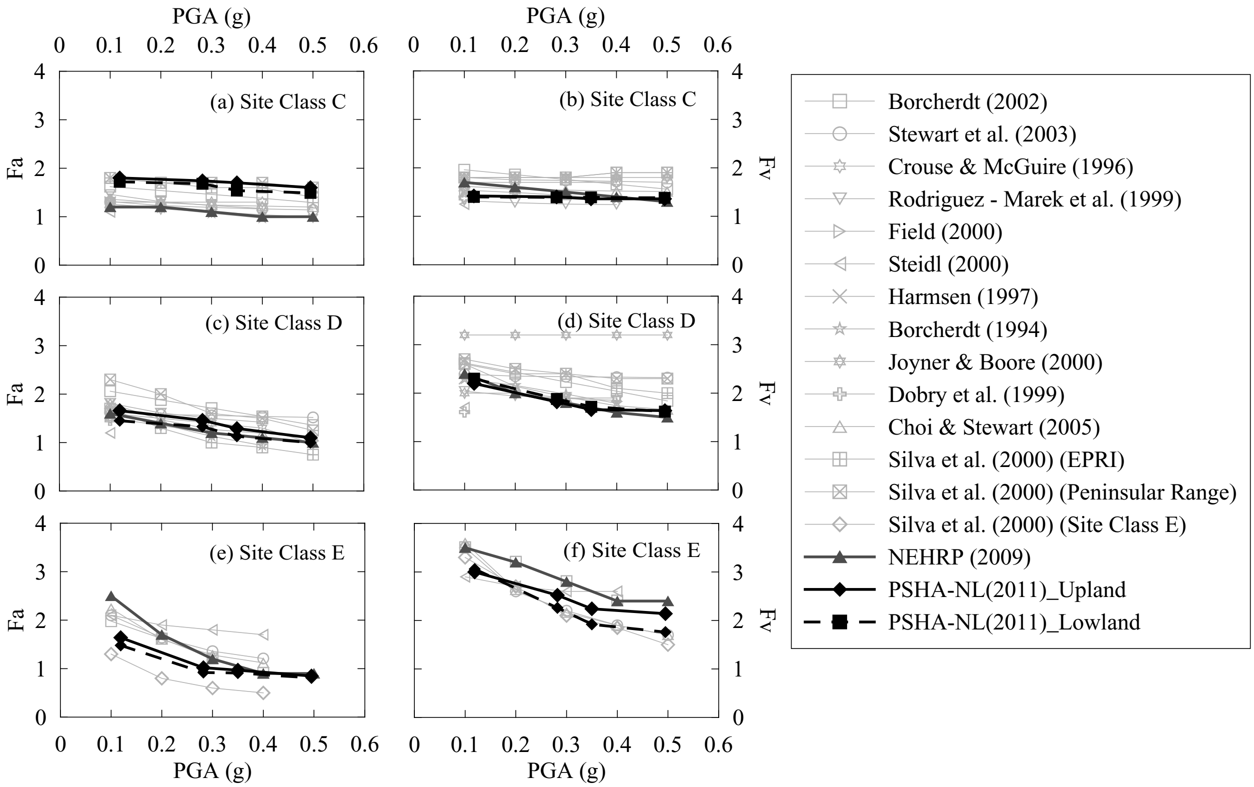


Figure 6-9. Comparison of the mean site coefficients (Fa and Fv) obtained from PSHA-NL(FF)(2011) and other empirical studies for 30 m thick soil column for site classes C, D, and E
SOURCE: Hashash and Moon 2011

UNIQUE ASPECTS OF LIQUEFACTION IN THE CENTRAL U.S.

Liquefaction analysis procedures for level-ground conditions are relatively well-established, despite on-going disagreements in the literature (e.g., Cetin et al. 2004; Idriss and Boulanger 2008; 2010) related to a few factors and particular case records. However, the field case histories used to develop liquefaction triggering and lateral spreading analyses are dominated by sites located in plate margin settings, e.g., western U.S. and Japan. As a result, there is some uncertainty in applying these liquefaction triggering relationships to intraplate settings such as the central U.S. Specifically, there are at least three aspects related to liquefaction and its effects that are relatively unique to the CUS, and in particular, the NMSZ. These aspects include:

1. The size of the liquefaction field and density of liquefaction features within the liquefaction field.
2. The size of individual liquefaction features.
3. Potential differences in seismic demand and site response factors, i.e., the magnitude scaling factor (MSF) and depth reduction factor (r_d).

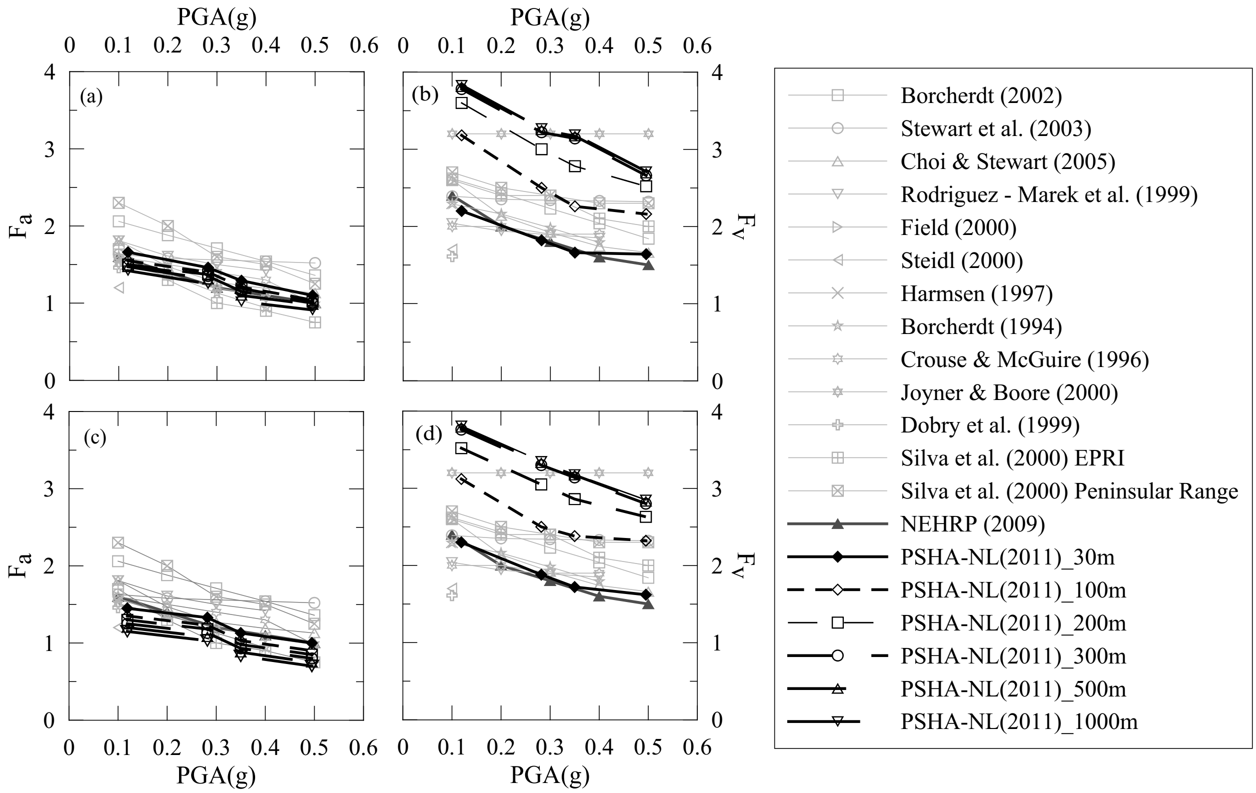


Figure 6-10. Comparison of developed depth-dependent site coefficients (a) Fa and (b) Fv for the Uplands, and (c) Fa and (d) Fv for the Lowlands, corresponding to 30 m, 100 m, 200 m, 300 m, 500 m, 1000 m depth soil column at site class D and other empirical studies
SOURCE: Hashash and Moon 2011

In addition, while most liquefaction sites in the CEUS involve relatively clean sands (fines content less than 5%), there are documented paleoliquefaction features involving gravel-rich soils in the Wabash seismic zone (WSZ) along the Indiana-Illinois border.

The size of the liquefaction field and the density of liquefaction features observed within the New Madrid seismic zone liquefaction field is one of the largest observed during modern earthquakes. For example, another intraplate earthquake, the 2001 Bhuj, India, earthquake (M 7.7) triggered liquefaction over an extensive area of about 10,000 km^2 (Thakkar and Goyal 2004). In comparison, the 1811–12 New Madrid earthquakes produced a liquefaction field covering about 10,000 to 12,000 km^2 (Obermeier 1988a)(see Figure 6-11). The size of the liquefaction field is largely a function of the extent of liquefiable sediments (the areal extent and thickness of the relatively clean sands throughout the upper Mississippi Embayment) as well as the significant strength of shaking. Although these liquefaction fields are similarly-sized, the liquefiable sediments in the Kachchh region of India were estimated to exhibit moderate to high liquefaction susceptibility (Tuttle et al. 2002a) while the sediments in the CUS generally exhibit moderate liquefaction susceptibility (Olson et al. 2005). However, the thickness of the sediments and strength of shaking resulted in severe liquefaction over a wide area, making the NMSZ liquefaction field relatively unique.

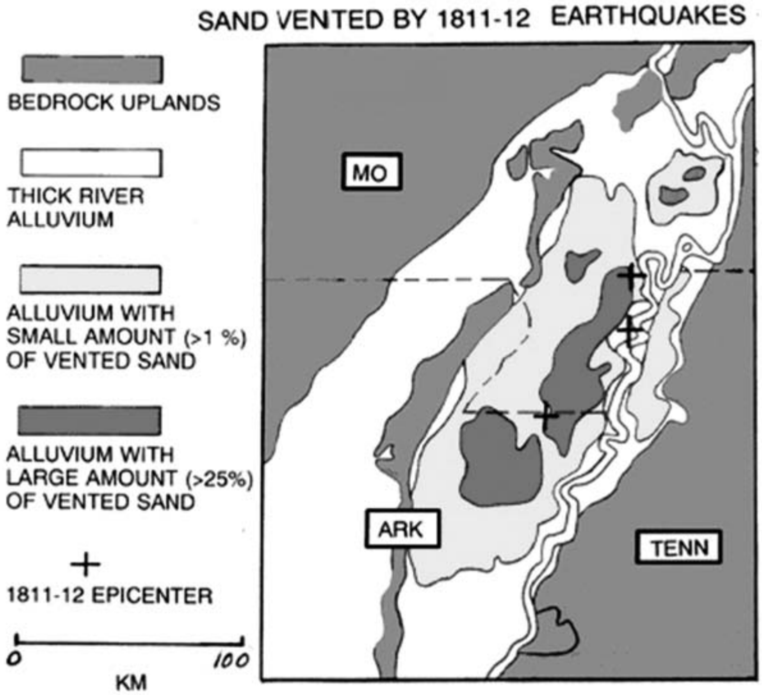


Figure 6-11. Liquefaction field and density of liquefaction features resulting from the 1811-12 New Madrid earthquakes
SOURCE: Obermeier 1988b

Liquefaction in the 1811–12 New Madrid earthquakes was reported at approximate epicentral distances of 250 to 275 km (Obermeier 1988b; Street and Nuttli 1984). While a few liquefaction features have been observed at distances greater than those associated with the 1811–12 events, these only occurred with significantly larger earthquakes (Ambraseys 1988). For similarly-sized earthquakes, the Bhuj earthquake again offers a good analog. Liquefaction during the 2001 Bhuj earthquake was confirmed at distances of 180 to 240 km from the earthquake epicenter (Thakkar and Goyal 2004; Tuttle et al. 2002a). Again, liquefaction during the New Madrid earthquakes appears fairly unique.

The size of the individual features (sand blows and lateral spreading features) has rarely been reported in modern earthquakes, worldwide. For example, again using the Bhuj earthquake as an analog, Tuttle et al. (2002a) reported that "most of the Bhuj sand are less than 60 m long, 10 m wide, and 15 cm thick …" The feeder dikes for the sand blows generally were 0.2 to 10 cm wide, with some up to 25 cm wide (Tuttle et al. 2002a). In contrast, liquefaction features in the NMSZ are typically 100 m long, 30 m wide, and 0.5 to 1 m thick (Tuttle 2001). Feeder dikes for the sand blows in the NMSZ typically are 0.5 to 2 m wide, with some up to 10 m wide (Tuttle et al. 2002b).

Similarly, some of the lateral spreading features in the meizoseismal region of the 1811–12 New Madrid earthquakes extend laterally over 2 km, and are over 1 kilometer back from the nearest free-face (e.g., Figure 6-12). The only similar-sized features have been reported in large magnitude (M > 8) subduction zone earthquakes (e.g., Arduino et al. 2010; Rodriguez-Marek et al. 2007).

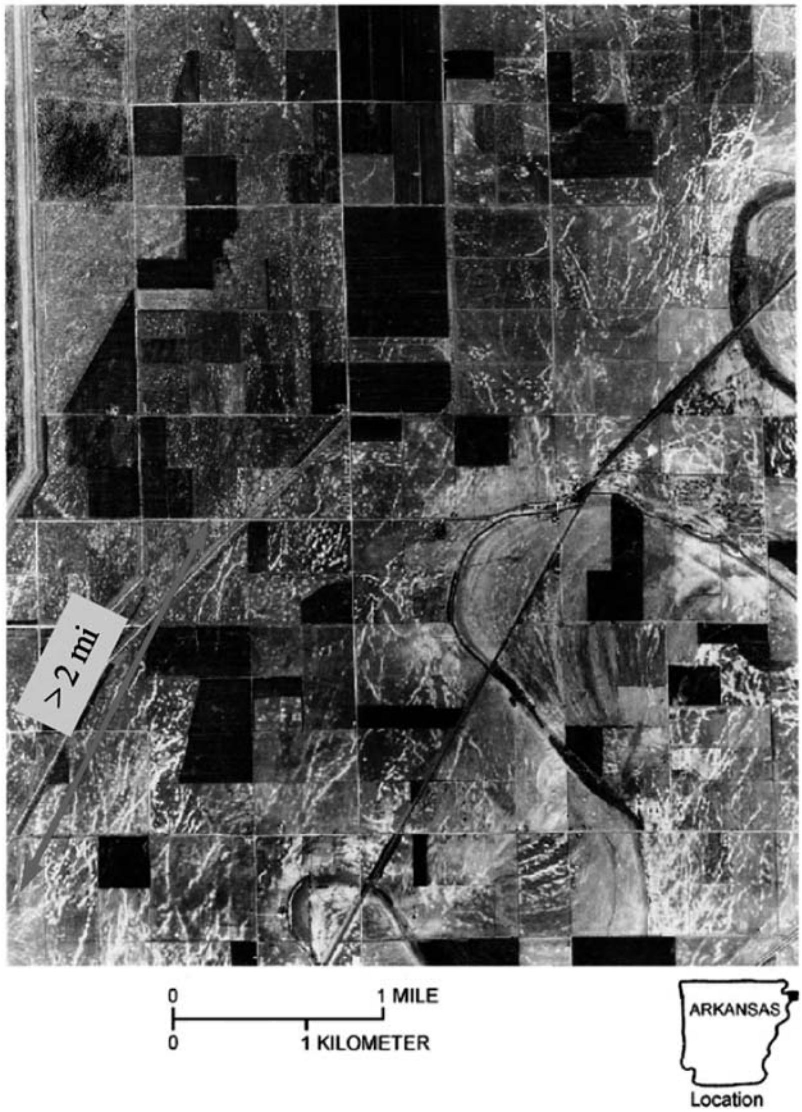


Figure 6-12. Aerial photograph showing effects of severe liquefaction in the meizoseismal zone of the 1811–12 New Madrid earthquakes. White linear features show sand that has vented through breaks in the cap caused by lateral spreading. Note the concentration of linear breaks in proximity to stream banks. Isolated white spots show sand that has vented through breaks in the cap caused by hydraulic fracturing

SOURCE: modified from Obermeier et al. 2005

As noted above, because common level-ground liquefaction triggering procedures (e.g., the cyclic stress method initially proposed by Seed and Idriss 1971; Whitman 1971) utilize liquefaction sites chiefly from the western U.S. and Japan, there are potential differences in seismic demand factors, such as MSF and r_d. The magnitude scaling factor accounts for differences in frequency content and duration among earthquakes of different magnitude. Because of the known differences in frequency content between earthquakes typically recorded in the western U.S. and those recorded in the CEUS, magnitude scaling factors developed for the western U.S. and Japan may not be appropriate for the CEUS. Recently, a number of studies (Cetin et al. 2004; Green and Terri 2005; Idriss and Boulanger 2008; Liu et al. 2001) have re-examined the magnitude scaling factor for liquefaction analysis; however, there has been little work published on potential differences in MSF for the CUS.

Similarly, there has been considerable research related to the depth reduction factor (r_d) for liquefaction analysis (Cetin et al. 2004; Idriss 1999; Idriss and Boulanger 2008). This work has illustrated that r_d is a factor of site stratigraphy, soil properties, and characteristics of the bedrock ground motions (Cetin et al. 2004) – the same factors that influence site response. As a result, it is reasonable to assume that the r_d factor may differ based on the seismological characteristics of a region. Thus, the r_d factor developed using motions from the WUS and Japan may not apply to the CUS.

Therefore, accurate site response analysis is crucial for properly estimating liquefaction potential at sites in the CUS. Furthermore, uncertainties related to the magnitude scaling factor and depth reduction factor (r_d) warrant the direct use of site response analysis results (i.e., profiles of cyclic stress ratio with depth) in evaluating liquefaction potential.

Lastly, while gravel-rich soils have liquefied during past earthquakes, e.g., 1987 Borah Peak (Andrus 1994) and 1990 Armenia (Yegian et al. 1994), liquefaction in the CUS often is considered to be an issue for sandy and silty deposits. However, paleoliquefaction features observed in the Wabash Valley seismic zone in the CUS have developed in gravel-rich soils (Pond 1996). Obermeier et al. (2005) concluded that liquefaction of gravel-rich soils rarely occurred unless the gravel-rich deposit is capped by a laterally-extensive low-permeability layer, and is shaken by a relatively strong earthquake ($PGA > 0.4\,g$ and $M > 7$). Nevertheless, liquefaction analyses in the CEUS should consider liquefaction in silty, sandy, and gravelly soils.

SUMMARY AND CONCLUDING REMARKS

The three unique seismic geotechnical issues in the Central United States discussed in this article were: (1) the importance of the Conditional Mean Spectra at the periphery of the New Madrid Seismic Zone; (2) the development of depth-dependent site coefficient that accounts the deep soil deposits in the Mississippi Embayment; and (3) the unique aspects of liquefaction.

The Uniform Hazard Response Spectrum has been most commonly used in seismic design. However, the UHRS represents an envelope of possible spectra by including motions from multiple earthquake sources. This may result in unnecessary conservatism in the estimate of seismic hazard at some locations in the NMSZ. The use of the Conditional Mean Spectrum framework permits the development of ground motions that are consistent with the seismic sources in the area while maintaining the probabilistic framework of a PSHA.

The presence of deep deposits of the Mississippi Embayment has an important influence of site response in the embayment. A new set of depth-dependent site coefficients for site classes of C, D, and E was recommended in lieu of the depth-independent coefficients.

Liquefaction features are unique in the NMSZ. The broad and thick liquefiable sediments and strong shaking intensity from the NMSZ resulted in severe liquefaction over a wide area. The size of individual liquefaction features such as feeder dikes and lateral spreading has also been observed to be exceptionally large. Site-specific evaluation including site response analysis is needed for evaluating liquefaction potential.

References

Abrahamson, N. A. (2009). Probabilistic seismic hazard analysis and time histories for the I-70 Mississippi River Bridge. Piedmont, CA, Norman A. Abrahamson, Inc.: 292 pages.

Ambraseys, N. N. (1988). Engineering seismology, Earthquake engineering and structural dynamics. Amsterdam, Elsevier.

Andrus, R. D. (1994). In situ characterization of gravelly soils that liquefied in the 1983 Borah Peak earthquake, University of Texas, Austin, TX: 533 pages.

Arduino, P., S. Ashford, D. Assimaki, J. Bray, T. Eldridge, D. Frost, Y. Hashash, T. Hutchinson, L. Johnson, K. Kelson, R. Kayen, C. Ledezma, R. Moss, G. Mylonakis, S. Olson, K. Rollins, N. Sitar, J. Stewart, A. Urzua, R. Verdugo, R. Witter and N. Zoa (2010). "Geo-Engineering Reconnaissance of the 2010 Maule, Chile Earthquake." GEER Association Report No. GEER-022.

Atkinson, G. M. and D. M. Boore (2006). "Earthquake ground-motion prediction equations for eastern North America." Bulletin of the seismological society of America 96(6): 2181–2205.

Baker, J. W. and C. A. Cornell (2006a). "Correlation of response spectral values for multicomponent ground motions." Bulletin of the Seismological Society of America 96(1): 215–227.

Baker, J. W. and C. A. Cornell (2006b). "Spectral shape, epsilon and record selection." Earthquake Engineering and Structural Dynamics 35(9): 1077–1095.

Bakun, W. H. and M. G. Hopper (2004). "Magnitudes and locations of the 1811–1812 New Madrid, Missouri, and the 1886 Charleston, South Carolina, earthquakes." Bulletin of the seismological society of America 94(1): 64–75.

Boore, D. M. (2005). SMSIM Fortran programs for simulating ground motions from earthquakes, version 2.3. A revision of U.S.Geol.Surv.Open-File Rept. 96-80-A.

Borcherdt, R. D. (1994). "Estimates of site-dependent response spectra for design (Methodology and Justification)." Earthquake spectra 10: 617–653.

Borcherdt, R. D. (2002). "Empirical evidence for site coefficients in building-code provisions." Earthquake spectra 18: 189–218.

Campbell, K. W. (2003). "Prediction of strong ground motion using the hybrid empirical method and its use in the development of ground-motion (attenuation) relations in Eastern North America." Bulletin of the Seismological Society of America 93(3): 1012–1033.

Cetin, K. O., R. B. Seed, A. Der Kiureghian, K. Tokimatsu, L. F. Harder Jr, R. E. Kayen and R. E. S. Moss (2004). "Standard penetration test-based probabilistic and deterministic assessment of seismic soil liquefaction potential." Journal of Geotechnical and Geoenvironmental Engineering 130(12): 1314–1340.

Choi, Y. and J. P. Stewart (2005). "Nonlinear site amplification as function of 30 m shear wave velocity." Earthquake spectra 21 (1): 1–30.

Cornell, C. A. (1968). "Engineering seismic risk analysis." Bulletin of Seismological Society of America 58: 1583–1606.

Cramer, C. H. (2006). "Quantifying the uncertainty in site amplification modeling and its effects on site-specific seismic-hazard estimation in the upper Mississippi embayment and adjacent areas." Bulletin of the seismological society of America 96(6): 2008–2020.

Crouse, C. B. and J. W. McGuire (1996). "Site response studies for purpose of revising NEHRP seismic provisions." Earthquake spectra 12: 407–439.

Csontos, R. and R. Van Arsdale (2008). "New Madrid seismic zone fault geometry." Geosphere 4(5): 802–813.

Darendeli, M. B. (2001). Development of a new family of normalized modulus reduction and material damping curves. Civil Engineering. Austin, University of Texas at Austin: 395.

Dobry, R., R. Ramos and M. S. Power (1999). Site Factors and Site Categories in Seismic Codes. Technical Report MCEER-99-0010: 81 pp.

Field, E. H. (2000). "A modified ground motion attenuation relationship for southern California that accounts for detailed site classification and a basin depth effect." Bull. Seism. Soc. Am. 90: S209–S221.

Field, E. H., S. Kramer, A.-W. Elgamal, J. D. Bray, N. Matasovic, P. A. Johnson, C. Cramer, C. Roblee, D. J. Wald, L. F. Bonilla, P. P. Dimitriu and J. G. Anderson (1998). "Nonlinear site response: Where we're at (A report from a SCEC/PEER seminar and workshop)." Seismological Research Letters (69): 230–234.

Frankel A., M. D. Pertersen, C. S. Mueller, K. M. Haller, R. L. Wheeer, E. V. Leyendecker, R. L. Wesson, S. C. Harmsen, C. H. Cramer, D. M. Perkins and K. S. Rukstales (2002). Documentation for the 2002 update of the national seismic hazard maps, US Geological Survey: 33.

Green, R. A. and G. A. Terri (2005). "Number of equivalent cycles concept for liquefaction evaluations – Revisited." Journal of Geotechnical and Geoenvironmental Engineering 131(4): 477–488.

Harmsen, S. C. (1997). "Determination of site amplification in the Los Angeles urban area from inversion of strong motion records." Bull. Seism. Soc. Am. 87: 866–887.

Hashash, Y. M. A. (2011). DEEPSOIL V 4.0, Tutorial and User Manual. 2002–2011., University of Illinois at Urbana-Champaign, Urbana Illinois.

Hashash, Y.M.A., N.A. Abrahamson, S.M. Olson, S. Hague and B. Kim (2014, in press). "Conditional mean spectra in site-specific seismic hazard evaluation for a major river crossing in the Central U.S." Earthquake Spectra. DOI: 10.1193/033113EQS085M

Hashash, Y. M. A. and S. Moon (2011). Site amplification factors for deep deposits and their application in seismic hazard analysis for Central U.S., USGS. USGS/NEHRP Grant: G09AP00123: 91 pages.

Hashash, Y. M. A. and D. Park (2001). "Non-linear one-dimensional seismic ground motion propagation in the Mississippi embayment." Engineering Geology 62(1–3): 185–206.

Hashash, Y. M. A., C.-C. Tsai, C. Phillips and D. Park (2008). "Soil column depth dependent seismic site coefficients and hazard maps for the Upper Mississippi Embayment." Bull. Seism. Soc. Am. 98(4): 2004–2021.

Hough, S. E. and S. Martin (2002). "Magnitude estimates of two large aftershocks of the 16 December 1811 New Madrid earthquake." Bulletin of the seismological society of America 92(8): 3259–3268.

Idriss, I. M. (1999). An update to the Seed-Idriss simplified procedure for evaluating liquefaction potential. TRB Workshop on New Approaches to Liquefaction, Federal Highway Administration, January.

Idriss, I. M. and R. W. Boulanger (2006). "Semi-empirical procedures for evaluating liquefaction potential during earthquakes." Soil Dynamics and Earthquake Engineering 26(2–4 SPEC. ISS.): 115–130.

Idriss, I. M. and R. W. Boulanger (2008). Soil liquefaction during earthquakes. Monograph MNO-12. Oakland, CA, Earthquake Engineering Research Institute.

Idriss, I. M. and R. W. Boulanger (2010). SPT-based liquefaction triggering procedures. Report UCD/CGM-10/02, Dept. of Civil and Environmental Engineering, Univ. of California, Davis, CA.

Joyner, W. B. and D. M. Boore (2000). Recent developments in earthquake ground-motion estimation. Sixth International Conference on Seismic Zonation, Palm Springs, California.

Liu, A. H., J. P. Stewart, N. A. Abrahamson and Y. Moriwaki (2001). "Equivalent number of uniform stress cycles for soil liquefaction analysis." Journal of Geotechnical and Geoenvironmental Engineering 127(12): 1017–1026.

Menq, F. Y. (2003). Dynamic Properties of Sandy and Gravelly Soils. Department of Civil Architectural and Environmental Engineering. Austin, University of Texas at Austin: 364.

Motazedian, D. and G. M. Atkinson (2005). "Stochastic finite-fault modeling based on a dynamic corner frequency." Bulletin of the Seismological Society of America 95(3): 995–1010.

Obermeier, S. F. (1988a). Liquefaction potential in the central Mississippi Valley, US Geological Survey Bulletin 1932.

Obermeier, S. F. (1988b). Seismic liquefaction features—examples from paleoseismic investigations in the continental United States. Open-File Report 98-488 (U.S. Geological Survey). CD-ROM. http://pubs.usgs.gov/openfile/of98-488/.

Obermeier, S. F., S. M. Olson and R. A. Green (2005). "Field occurrences of liquefaction-induced features: A primer for engineering geologic analysis of paleoseismic shaking." Engineering Geology 76(3–4): 209–234.

Olson, S. M., R. A. Green and S. F. Obermeier (2005). "Geotechnical analysis of paleoseismic shaking using liquefaction features: A major updating." Engineering Geology 76(3–4): 235–261.

Olson, S. M. and Y. M. A. Hashash (2009). Geotechnical seismic engineering New 1–70 Mississippi River Bridge St. Louis, Missouri to St. Clair County, Illiois, HNTB Corporation: 296 pages.

Park, D. and Y. M. A. Hashash (2005). "Estimation of seismic factors in the Mississippi Embayment: II. Probabilistic seismic hazard with nonlinear site effects." Soil Dynamics and Earthquake Engineering 25: pp. 145–156.

Petersen, M. D., A. D. Frankel, S. C. Harmsen, C. S. Mueller, K. M. Haller, R. L. Wheeler, R. L. Wesson, Y. Zeng, O. S. Boyd, D. M. Perkins, N. Luco, E. H. Field, C. J. Wills and K. S. Rukstales (2008). Documentation for the 2008 Update of the United States National Seismic Hazard Maps, USGS. Open-File Report 2008–1128: 60 pages.

Phillips, C. and Y. M. A. Hashash (2009). "Damping formulation for non-linear 1D site response analyses." Soil Dynamics and Earthquake Engineering 29(7): Pages 1143–1158.

Pond, E. C. (1996). Seismic parameters for the central United States based on paleoliquefaction evidence in the Wabash Valley, Virginia Polytechnical Institute and State University, Blacksburg, VA. PhD thesis: 583 pages.

Robertson, P. K. and C. E. Wride (1998). "Evaluating cyclic liquefaction potential using the cone penetration test." Canadian Geotechnical Journal 35(3): 442–459.

Rodriguez-Marek, A., J. D. Bray and N. Abrahamson (1999). Task 3: Characterization of Site Response, General Site Categories. Berkeley, Ca, Pacific Earthquake Engineering Research Center.

Rodriguez-Marek, A., J. A. Hurtado, B. Cox, J. Meneses, V. Moreno, M. Olcese, R. Sancio and J. Wartman (2007). Preliminary Reconnaissance Report on the Geotechnical Engineering Aspects of the August 15, 2007 Pisco, Peru Earthquake. GEER Association Report No. GEER-012.

Seed, H. B. and I. M. Idriss (1971). "Simplified procedure for evaluating soil liquefaction potential." ASCE J Soil Mech Found Div 97(SM9): 1249–1273.

Silva, W., R. Darragh, N. Gregor, G. Martin, N. Abrahamson and C. Kircher (2000). Reassessment of site coefficients and near-fault factors for building code provisions. USGS NEHRP program report 98-HQ-GR-1010.

Silva, W. J., N. Gregor and R. Darragh (2002). Development of regional hard rock attenuation relations for central and eastern North America. Pacific Engineering and Analysis Report.

Steidl, J. H. (2000). "Site response in southern California for probabilistic seismic hazard analysis." Bull. Seism. Soc. Am. 90: S149-S169.

Stewart, J. P., A. H. Liu and Y. Choi (2003). "Amplification factors for spectral acceleration in tectonically active regions." Bull. Seism. Soc. Am. 93 (1): 332–352.

Street, R. L. and O. Nuttli (1984). The central Mississippi Valley earthquakes of 1811–1812. The New Madrid Seismic Zone, US Geological Survey Open-File Report 84-770.

Thakkar, M. G. and B. Goyal (2004). "On the relation between magnitude and liquefaction dimension at the epicentral zone of 2001 Bhuj earthquake." Current Science 87(6): 811–817.

Toro, G. R. and W. J. Silva (2001). Scenario earthquakes for Saint Louis, MO, and Memphis, TN, and seismic hazard mpas for the Centraul United States Region including the effect of site conditions.

Tuttle, M. P. (2001). "The use of liquefaction features in paleoseismology: Lessonslearned in the New Madrid seismic zone, Central United States." Journal of Seismology 5(3): 361–380.

Tuttle, M. P., J. Hengesh, K. B. Tucker, W. Lettis, S. L. Deaton and J. D. Frost (2002a). "Observations and comparisons of liquefaction features and related effects induced by the Bhuj earthquake." Earthqu. Spectra (Suppl. A) 18: 79–100.

Tuttle, M. P., E. S. Schweig, J. D. Sims, R. H. Lafferty, L. W. Wolf and M. L. Haynes (2002b). "The earthquake potential of the New Madrid seismic zone." Bulletin of the seismological society of America 92(6): 2080–2089.

Tuttle, M. P., E. S. Schweig Iii, J. Campbell, P. M. Thomas, J. D. Sims and R. H. Lafferty Iii (2005). "Evidence for New Madrid earthquakes in A.D. 300 and 2350 B.C." Seismological Research Letters 76(4): 489–501.

Whitman, R. V. (1971). "Resistance of soil to liquefaction and settlement." Soils and Foundations 11(4): 59–68.

Wong, I., P. Thomas, W. Silva, R. Quittmeyer, G. Toro, M. Dober, C. L. Pattanapong, S. Upadhyaya, S. Logeswaran, S. Olig and F. Terra (2004). Development of Earthquake Ground Motion Input for Preclosure Seismic Design and Postclosure Performance Assessment of a Geologic Repository at Yucca Mountain. NV, Bechtel SAIC Company.

Yegian, M. K., V. G. Ghahraman and R. N. Harutiunyan (1994). "Liquefaction and embankment failure case histories, 1988 Armenia earthquake." Journal of Geotechnical Engineering – ASCE 120(3): 581–596.

Youd, T. L., M. H. Corbett and F. B. Steven (2002). "Revised multilinear regression equations for prediction of lateral spread displacement." Journal of Geotechnical and Geoenvironmental Engineering 128(12): 1007–1017.

Youd, T. L., I. M. Idriss, R. D. Andrus, I. Arango, G. Castro, J. T. Christian, R. Dobry, W. D. L. Finn, L. F. Harder Jr., M. E. Hynes, K. Ishihara, J. P. Koester, S. S. C. Liao, W. F. Marcuson, G. R. Martin, J. K. Mitchell, Y. Moriwaki, M. S. Power, P. K. Robertson, R. B. Seed and K. H. Stokoe (2001). "Liquefaction resistance of soils: summary report from the 1996 NCEER and 1998 NCEER/NSF Workshops on evaluation of liquefaction resistance of soils." Journal of Geotechnical and Geoenvironmental Engineering 127(10): 817–833.

Zhang, G., P. K. Robertson and R. W. I. Brachman (2004). "Estimating liquefaction-induced lateral displacements using the standard penetration test or cone penetration test." Journal of Geotechnical and Geoenvironmental Engineering 130(8): 861–871.

CHAPTER 7

Major Changes in Spectral Shapes for Critical Facilities in Central and Eastern United States

R. J. Hunt, P.E.

INTRODUCTION

The state-of-the-art for development of earthquake response spectra to be used for the analyses and design of critical facilities in the central United States has changed as new earthquakes have occurred providing new data to be considered. This paper will address the major changes in the earthquake response spectra beginning in the 1960's up to 2010, and anticipated changes in the near future.

EARTHQUAKE RESPONSE SPECTRA IN THE 1960–1970's

During the 1960–1970's, the earthquake ground motion response spectra to be used for the analyses and design of critical facilities in the central and eastern United States (CEUS) were based on the use of seismic tectonic provinces, historical earthquakes defined by Modified Mercalli (MM) intensities, MM intensity acceleration relationships to define the peak ground acceleration, and spectra shapes anchored to the peak ground acceleration.

The tectonic provinces were defined because the historical earthquakes could not be associated with specific known faults. The tectonic provinces were defined by considering the geology of the region and the pattern of the historical earthquakes. The tectonic provinces were defined as regions of similar geology, tectonics and seismicity. The Safe Shutdown design earthquake (SSE) (terminology used to define the design earthquake for commercial nuclear power plants) was determined assuming the largest historical earthquake, in the tectonic province where the site was located, could occur at the site. The MM intensity of the largest historical earthquake was then used with the MM intensity ground motion acceleration relationships to define the peak ground acceleration for this earthquake. For the adjacent tectonic provinces in which the site was not located, the largest historical earthquakes in those provinces were moved to the edge of the province to a point that was closest to the site. The peak ground acceleration at the site for these earthquakes were then determined using the MM intensity acceleration relationships considering the distance from the site. The largest peak ground acceleration was then used as the anchor for the spectra shape to define the SSE ground response spectra. This process is described in two Tennessee Valley Authority reports (1) (2).

The spectra shapes used during this time period were shapes developed by Housner and Newmark (3). Figure 7-1 shows the Housner and Newmark spectral shapes for the 5%

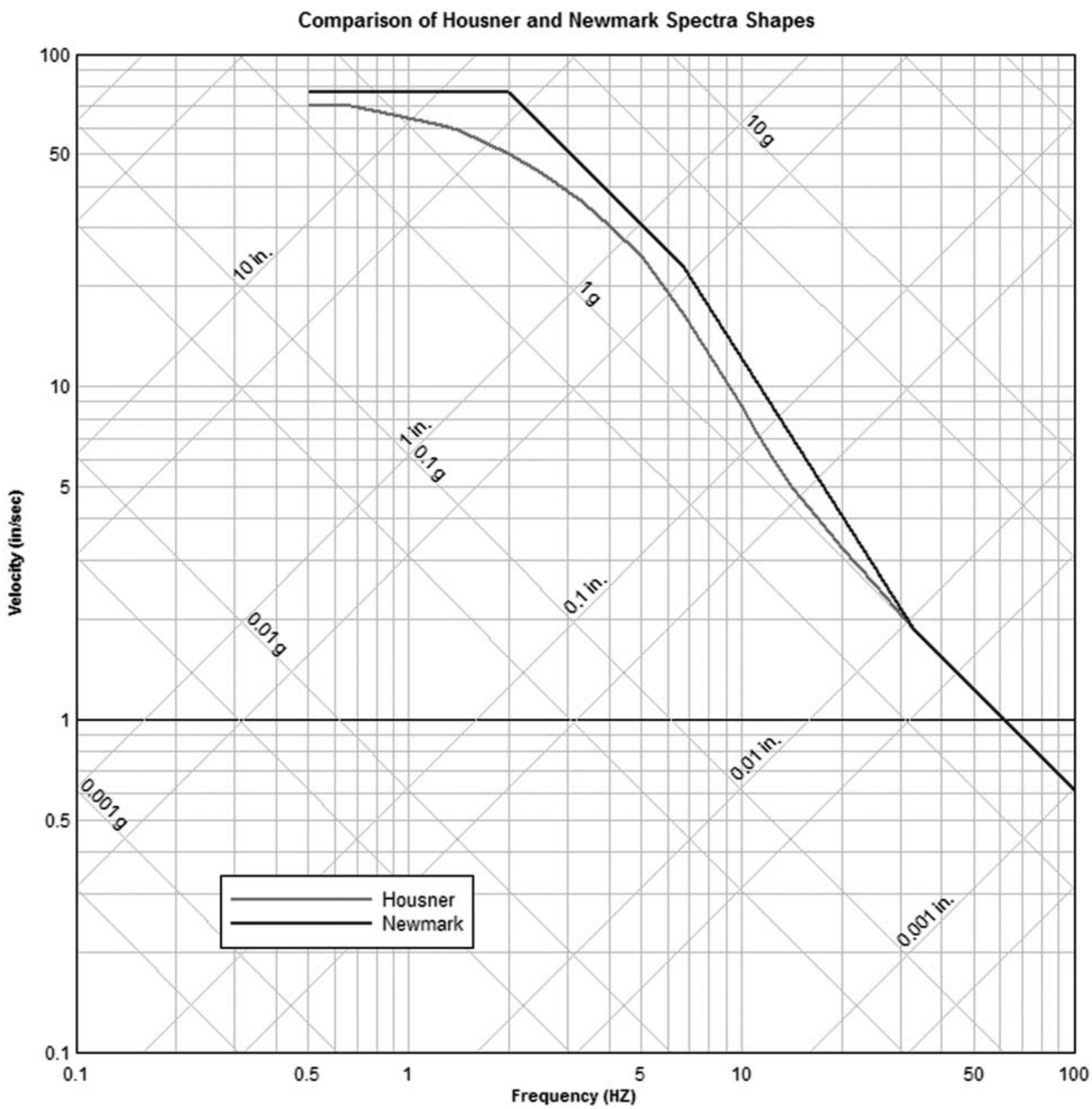


Figure 7-1. Comparison of Housner and Newmark Spectral Shapes

damping ratio anchored to 1g. The peak ground acceleration of 1g is the anchor for the spectral shapes and occurs at a frequency of 33 Hz.

EARTHQUAKE RESPONSE SPECTRA IN THE 1970–1980's

In the 1970–1980's, the 1971 San Fernando, California earthquake occurred which provided new ground motion data for evaluations. Based on this new data, new MM intensity acceleration relationships were developed which resulted in increases in the peak ground accelerations for MM intensities. Trifunac and Brady (4) and Murphy and O'Brien (5) developed new MM intensity ground motion acceleration relationships. In addition, the U. S. Atomic Energy Commission (AEC) developed Regulatory Guide 1.60 (6) which provided new response spectra shapes for use in defining the SSE ground motion response spectra. Figure 7-2 shows the comparison between the Housner, Newmark, and the Regulatory Guide (RG) 1.60 spectra shapes for 5% damping ration anchored to 1g.

EARTHQUAKE RESPONSE SPECTRA IN THE 1980–1990's

During the 1980–1990's, the Charleston, South Carolina earthquake issue was raised by the U.S. Nuclear Regulatory Commission (NRC). The concern was that an 1886 Charleston magnitude earthquake could reoccur anywhere in the Eastern seaboard. To address this issue, a significant amount of work was done, particularity in developing probabilistic seismic hazard assessments (PSHA) techniques and performing PSHA's at the nuclear power plant sites in the CEUS. The Lawrence Livermore National Laboratory (LLNL) (7) sponsored by the NRC and the Electric Power Research Institute (EPRI) (8) sponsored by the nuclear power industry developed the PSHA techniques and performed the PSHA's at the nuclear power plant sites.

In 1986, the Leroy Ohio earthquake (magnitude M_L 5.0) occurred and the ground motions were recorded at the Perry Nuclear Plant located near the epicenter of the earthquake. The recorded ground motion data exceeded the SSE design response spectra in the high frequency range (20 to 30 Hz). This earthquake and other small magnitude earthquakes which were recorded provided data that was used to develop new ground motion attenuation relationships based on magnitude and distance instead of the MM intensity relationships that had been previously used.

These new ground motion attenuation relationships provided information that could be used to develop site specific response spectra shapes instead of the previous standard shapes like the Housner, Newmark, and RG 1.60 spectra shapes. These new relationships also provided information which showed the CEUS earthquakes for hard rock and shallow soil sites contained high frequency motions (20–30 Hz) and the peak ground accelerations occurred in the 100 Hz range versus the 33 Hz range for the Housner, Newmark, and RG 1.60 spectra.

Also during this time frame, the Department of Energy (DOE) was developing new up-to-date earthquake analyses and design standards. Of particular note, the

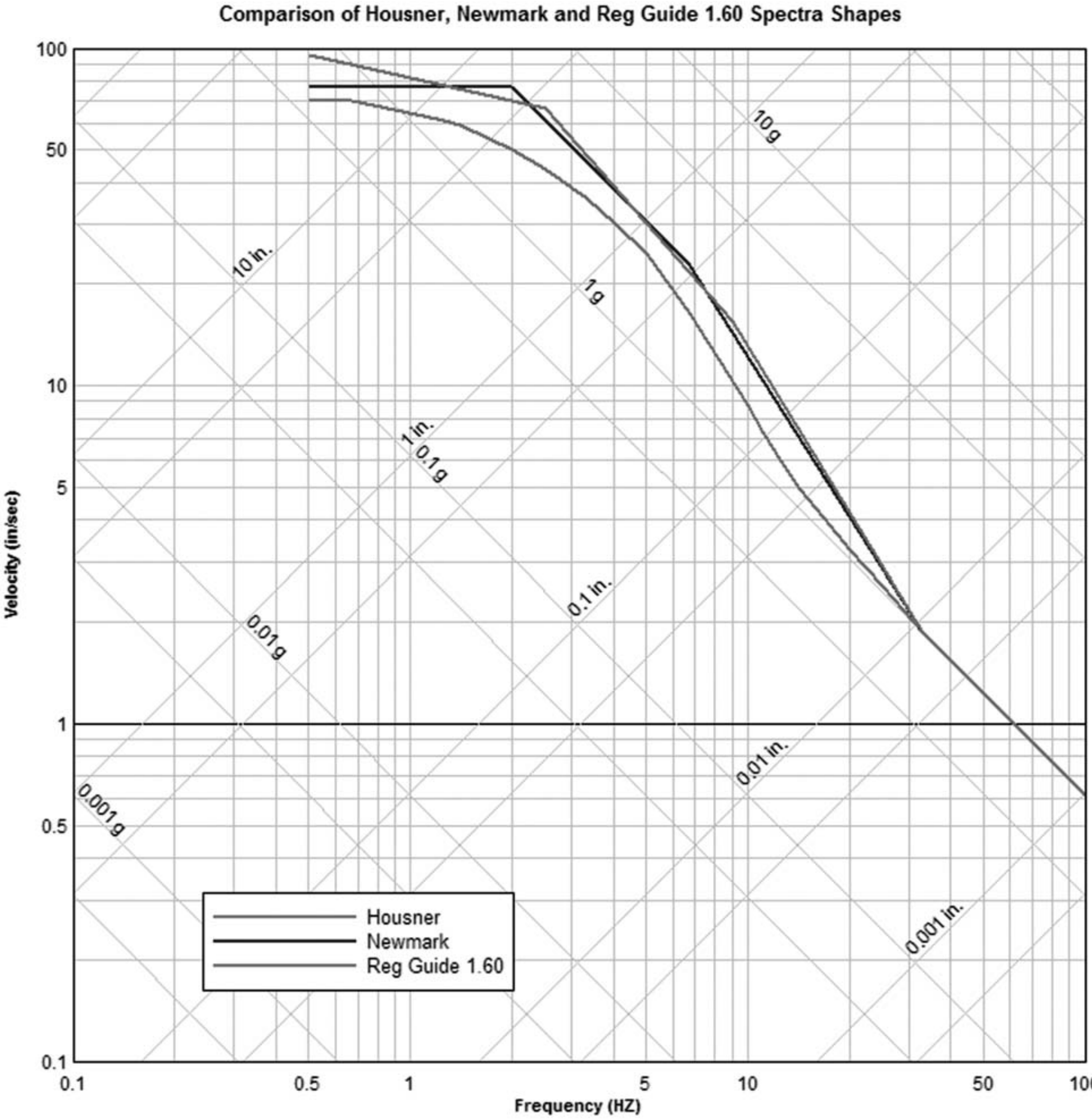


Figure 7-2. Comparison of Housner, Newmark, and RG 1.60 Spectral Shapes

DOE-STD-1020-2002, *Natural Phenomena Hazards Design and Evaluation Criteria of Department of Energy Facilities* (9), was developed which presented a graded performance based design approach to be used for the wide range of types of DOE facilities located in numerous places in the United States. In addition, based on the EPRI and LLNL PSHA's, the NRC issued the requirements for Individual Plant Examination for External Events (IPEEE) under Generic Issue (GI) 88–20 (10) which required a complete assessment and review of the operating nuclear power plants.

Figure 7-3 shows the EPRI and LLNL seismic hazard results for peak ground acceleration at an East Tennessee hard rock site.

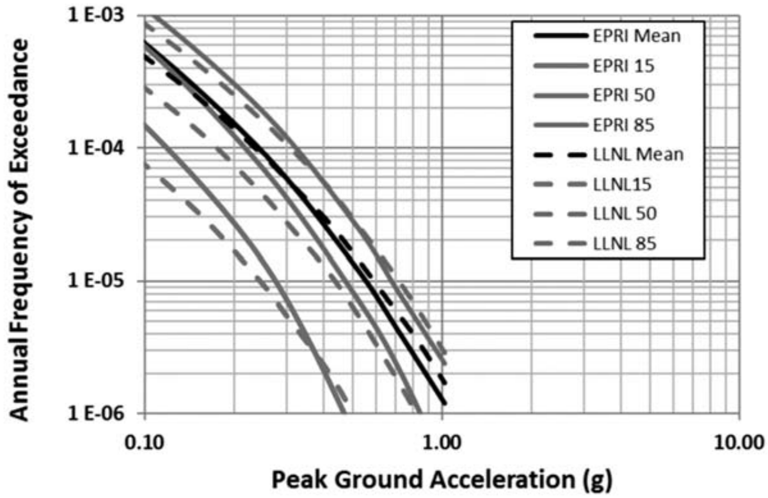


Figure 7-3. Comparison of the EPRI and LLNL Seismic Hazard Curves for an East Tennessee Hard Rock Site

EARTHQUAKE RESPONSE SPECTRA IN THE 1990–2010's

During the time frame from 1990–2010, numerous changes and developments occurred which had an impact on the earthquake response spectra used in the design of critical facilities. Some of the changes and developments resulted from the data obtained from 1986 Leroy Ohio earthquake and the results of the LLNL and EPRI seismic hazard results performed to address the Charleston earthquake issue.

As a result of the recorded ground motion from the Leroy Ohio earthquake at the Perry Nuclear Plant exceeding the SSE design response spectra, the EPRI performed a study to determine why these exceedances did not cause any damage at the plant. These studies determined that the high frequency ground motions did not have enough energy to cause any damage and led to defining the cumulative absolute velocity (CAV) as a better parameter for determining if the high frequency ground motions could cause damage. The CAV was defined in EPRI TR-100082, *Standardization of the Cumulative Absolute Velocity* (11).

Also based on the Charleston earthquake issue and the resulting LLNL and EPRI seismic hazard results, the NRC issued NUREG-1407, *Procedural & Submittal Guidance for the Individual Plant Examination for External Events (IPEEE) for Severe Accident Vulnerabilities* (12), which required all of the existing nuclear power plants to re-evaluate their facilities for the new seismic hazard results. In addition, NUREG/CR-6728, *Technical Basis for Revision of Regulatory Guidance on Design Ground Motion: Hazard- and Risk-Consistent Ground Motion Spectra Guidelines* (13), was issued which provided guidance on developing site-specific earthquake response spectra. Figure 7-4 compares the earthquake response spectra shapes of Housner, Newmark, R.G. 1.60, and site-specific spectra for a hard rock site in East TN following the guidelines in NUREG/CR-6728. This comparison shows that the site-specific spectra exceed the other spectra in the high frequency range.

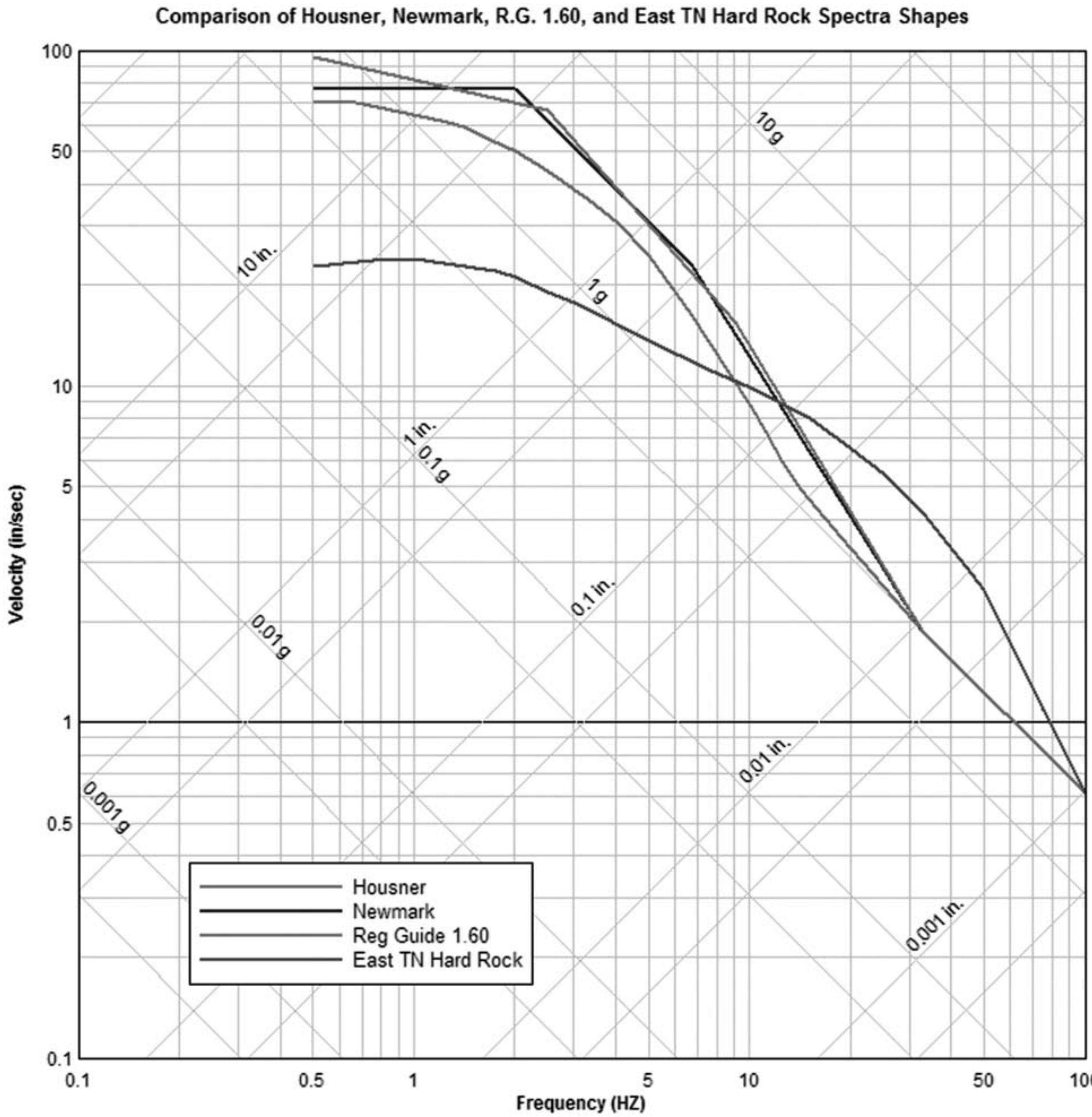


Figure 7-4. Comparison of the Housner, Newmark, RG 1.60, and Site Specific Spectral Shapes for an East Tennessee Hard Rock Site

During the 1990's, the Building Seismic Safety Council (BSSC) and the United States Geological Survey (USGS) initiated a major effort to update the national seismic hazard maps, which were incorporated into the design maps for the first edition of International Building Code in 2000. The results of these seismic hazard maps raised questions about the LLNL and EPRI seismic hazard results that were developed in the 1980's. The USGS results indicated higher seismic hazard results in general for sites in the CEUS. Figure 7-5

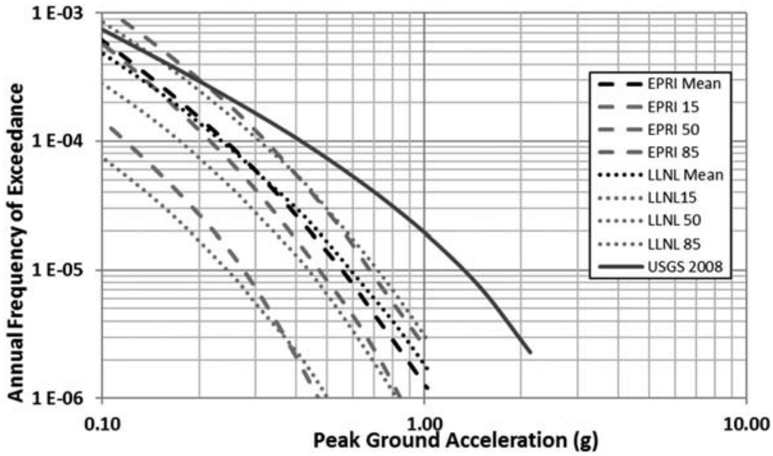


Figure 7-5. Comparison of the EPRI, LLNL and USGS Seismic Hazard Curves for an East Tennessee Hard Rock Site

compares the results of the USGS seismic hazard with the EPRI and LLNL seismic hazard for peak ground acceleration at a hard rock site in East Tennessee. The USGS results are from the 2008 USGS results which are slightly less than the results produced in 2000 for the seismic hazard maps, but the USGS results are significantly higher than the EPRI and LLNL results.

Based on the site-specific spectra shapes which exceeded the RG 1.60 spectra in the high frequency range and the increased seismic hazard results from the USGS, the NRC and EPRI issued several documents to evaluate the impact of the changes at existing and new nuclear power plants.

The NRC issued GI 194, *Implications of Updated Probabilistic Seismic Hazard Estimates* (14), GI 199, *Implications of Updated Probabilistic Seismic Hazard Estimates in Central and Eastern US for Existing Plants* (15), RG 1.165, *Identification and Characterization of Seismic Sources and Determination of Safe Shutdown Earthquake Ground Motion* (16) (now withdrawn), RG 1.208, *A Performance-Based Approach to Define the Site-Specific Earthquake Ground Motion* (17), and NRC Interim Staff Guidance on Seismic Issues Associated with High Frequency Ground Motion in Design Certification and Combined License Applications (18).

EPRI issued TR-1009684, *CEUS Ground Motion Project* (19), Technical Update Report 1012967, *Program on Technology Innovation: Effect of Negligible Inelastic Behavior on High Frequency Response* (20), Technical Update Report 1015108, *Program on Technology Innovation: The Effects of High-Frequency Ground Motion on Structures, Components, and Equipment in Nuclear Power Plants* (21), and Technical Update Report 1015109, *Program on Technology Innovation: Seismic Screening of Components Sensitive to High-Frequency Vibratory Motions* (22).

In addition, EPRI, NRC, and DOE sponsored a program to update the seismic source characterization in the CEUS and the next generation of CEUS ground motion attenuation relationships.

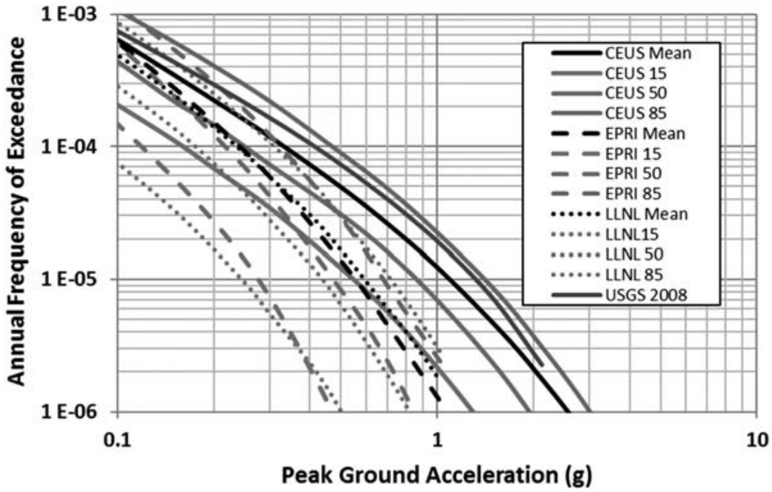


Figure 7-6. Comparison of the EPRI, LLNL, USGS, and CEUS Seismic Hazard Curves for an East Tennessee Hard Rock Site

EARTHQUAKE RESPONSE SPECTRA IN THE 2010 TO PRESENT

The results of the EPRI, NRC, and DOE program to update the seismic source characterization in the CEUS were published in NUREG-2215, *Technical Report: Central and Eastern United States Seismic Source Characterization for Nuclear Facilities* (23). Figure 7-6 compares the seismic hazard results for peak ground acceleration from the EPRI, LLNL, USGS, and the new CEUS at a hard rock site in East Tennessee. This comparison shows that the new CEUS hazard curves are higher than the previous EPRI and LLNL curves and are now comparable with the USGS results.

In March 2012, the NRC issued a request for information (24) which will require the existing CEUS nuclear power plants to update their seismic hazard assessments using the results in NUREG-2115 and if necessary to update their seismic vulnerability studies as previously done using NUREG-1407.

FUTURE CHANGES

As discussed above, EPRI, NRC, and DOE are also sponsoring a program to update the next generation of CEUS ground motion attenuation relationships. This program is expected to be completed in 2014 and will have an impact on the seismic hazard assessment for existing and new critical facilities.

In addition, the August 23, 2011, Mineral Virginia earthquake has provided additional ground motion data which needs to be evaluated and the data will be considered as the ground motion attenuation relationships are developed.

The existing critical nuclear facilities will be updating their seismic hazard studies considering the NUREG-2115 and performing seismic evaluations of their facilities. The seismic evaluations will consider the high frequency ground motions utilizing the guidance in the EPRI Technical Update Reports 1012967, 1015108, and 1015109.

SUMMARY

There have been significant changes in the development of the seismic design criteria for critical facilities in the last 50 years. These changes have come about based on experience and knowledge gained from earthquake occurrences and increased capabilities in analysis techniques. The changes have in general increased the earthquake ground motions used for the design of the critical facilities. Additional evaluations of the existing critical facilities will be required to address the increase in the ground motions and the high frequency ground motions for hard rock and shallow soil sites in the CEUS.

References

1. Tennessee Valley Authority (TVA), *Justification of the Seismic Design Criteria Used for the Sequoyah, Watts Bar, and Bellefonte Nuclear Power Plants*, Phase I, April 1978.
2. Tennessee Valley Authority (TVA), *Justification of the Seismic Design Criteria Used for the Sequoyah, Watts Bar, and Bellefonte Nuclear Power Plants*, Phase II, August 1978.
3. Earthquake Engineering Research Institute (EERI), *Earthquake Spectra and Design*, by N. M. Newmark and W. J. Hall, March 1982.
4. Trifunac, M. D. and A. G. Brady, *On the Correlation of Seismic Intensity Scales with the Peaks of Recorded Strong Motion*, Bulletin of the Seismological Society of America, Volume 65, No. 1, February 1975.
5. Murphy, J.R., and L. J. O'Brien, *Analysis of a Worldwide Strong Motion Data Sample to Develop an Improved Correlation Between Peak Acceleration, Seismic Intensity, and Other Physical Parameters*, U. S. Nuclear Regulatory Commission NUREG-0402, January 1978.
6. U. S. Atomic Energy Commission (AEC), Regulatory Guide 1.60, *Design Response Spectra for Seismic Design of Nuclear Power Plants*, December 1973.
7. U. S. Nuclear Regulatory Commission (NRC), NREG-1488, *Revised Livermore Seismic Hazard Estimates for 69 Nuclear Power Plants Sites East of the Rocky Mountains*, April 1994.
8. Electric Power Research Institute, EPRI NP-6395-D, *Probabilistic seismic hazard Evaluation at Nuclear Plant Sites in the Central and Eastern United States: Resolution of the Charleston Issue*, April 1989.
9. Department of Energy Standard, DOE-STD-1020-2002, *Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities*, January 2002.
10. U. S. Nuclear Regulatory Commission (NRC), NREG-0933, Resolution of Generic Safety Issues: Issue 88: Earthquakes and Emergency Planning, http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr0933/sec3/088.html.
11. Electric Power Research Institute, EPRI TR-100082, *Standardization of the Cumulative Absolute Velocity*, December 1991.
12. U. S. Nuclear Regulatory Commission (NRC), NREG-1407, *Procedural & Submittal Guidance for the Individual Plant Examination for External Events (IPEEE) for Severe Accident Vulnerabilities*, June 1991.
13. U. S. Nuclear Regulatory Commission (NRC), NREG/CR-6728, *Technical Basis for Revision of Regulatory Guidance on Design Ground Motion: Hazard- and Risk-Consistent Ground Motion Spectra Guidelines*, October 2001.
14. U. S. Nuclear Regulatory Commission (NRC), NREG-0933, Resolution of Generic Safety Issues: Issue 194: Implications of Updated Probabilistic Seismic Hazard Estimates, http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr0933/sec3/194r1.html.
15. U. S. Nuclear Regulatory Commission (NRC), NREG-0933, Resolution of Generic Safety Issues: Issue 199: Implications of Updated Probabilistic Seismic Hazard Estimates in Central

and Eastern U.S. for Existing Sites, http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr0933/sec3/199r1.html.

16. U. S. Nuclear Regulatory Commission (NRC), Regulatory Guide 1.165, *Identification and Characterization of Seismic Sources and Determination of Safe Shutdown Earthquake Ground Motion*, March 1997.
17. U. S. Nuclear Regulatory Commission (NRC), Regulatory Guide 1.208, *A Performance-Based Approach to Define the Site-Specific Earthquake Ground Motion*, March 2007.
18. U. S. Nuclear Regulatory Commission (NRC) Interim Staff Guidance on Seismic Issues Associated with High Frequency Ground Motion in Design Certification and Combined License Applications, http://pbadupws.nrc.gov/docs/ML0814/ML081400293.pdf.
19. Electric Power Research Institute, EPRI TR-1009684, *CEUS Ground Motion Project*, December 2004.
20. Electric Power Research Institute, Technical Update Report 1012967, *Program on Technology Innovation: Effect of Negligible Inelastic Behavior on High Frequency Response*, December 2005.
21. Electric Power Research Institute, Technical Update Report 1015108, *Program on Technology Innovation: The Effects of High-Frequency Ground Motion on Structures, Components, and Equipment in Nuclear Power Plants*, June 2007.
22. Electric Power Research Institute, Technical Update Report1015109, *Program on Technology Innovation: Seismic Screening of Components Sensitive to High-Frequency Vibratory Motions*, October 2007.
23. U. S. Nuclear Regulatory Commission (NRC), NREG-2115, *Technical Report: Central and Eastern United States Seismic Source Characterization for Nuclear Facilities*, January 2012.
24. U. S. Nuclear Regulatory Commission (NRC) Memorandum dated March 12, 2012: Subject: *Request for Information Pursuant to Title 10 of the Federal Code of Regulations 50.54(f) Regarding Recommendations 2.1, 2.3,and 9.3, of the Near-Term Task Force Review of Insights from the Fukushima Dai-Ichi Accident*, http://pbadupws.nrc.gov/docs/ML1205/ML12053A340.pdf.

CHAPTER 8

The International Building Code and the Tennessee Adoption Process

R.J. Mauer, Building Official
J.E. Beavers, Ph.D., P.E.

INTRODUCTION

Background

The State of Tennessee is locate in the Eastern United States (US) and is bordered in the West at its south-western point at approximately –90.3° long. by 35.0° lat. and in the East at its north-eastern point at approximate –81.6° long. by 36.6° lat. From this north eastern tip to the south-western tip the longitudinal and latitudinal distances are approximately 800 km by 200 km, making it a long, narrow state. As a result, the western part of the state includes the New Madrid Seismic Zone (NMSZ) discussed by other speakers at this workshop and the most active seismic zone in the contiguous US east of the Rocky Mountains. In addition, the eastern part of the state includes the East Tennessee Seismic Zone (ETSZ), possibly the second most seismically active zone in the contiguous US.

Powell and Beavers (1) described the NMSZ as: "… having abundant evidence … that the NMSZ generated at least three major earthquake sequences in the past (1450, 900, and 1811–1812 AD) with a 400–500 year recurrence interval." The ETSZ as discussed by Powell and Beavers (1) receives little publicity and is virtually unknown to the general population. However, Powell and Beavers state: "Although the ETSZ generates approximately 50 recorded earthquakes each year, none has exceeded magnitude 4.6 in recorded history." In their paper Powell and Beavers conclude the following: "It is evident that the ETSZ as currently understood represents a significant risk to the population and should be treated with more respect … research needs to be conducted … capable of producing a magnitude …7.9. A magnitude 7.9 would be catastrophic to the region." As just implied and discussed further below such an earthquake would result in significant losses.

Knox County

As shown and discussed by Powell and Beavers (1), the ETSZ includes Knox County, Tennessee. In addition, on January 19, 1982, the U.S. Geological Survey (USGS) wrote a letter (2) to Mr. Robert E. Jackson, Chief, Geosciences Branch of the U.S. Nuclear

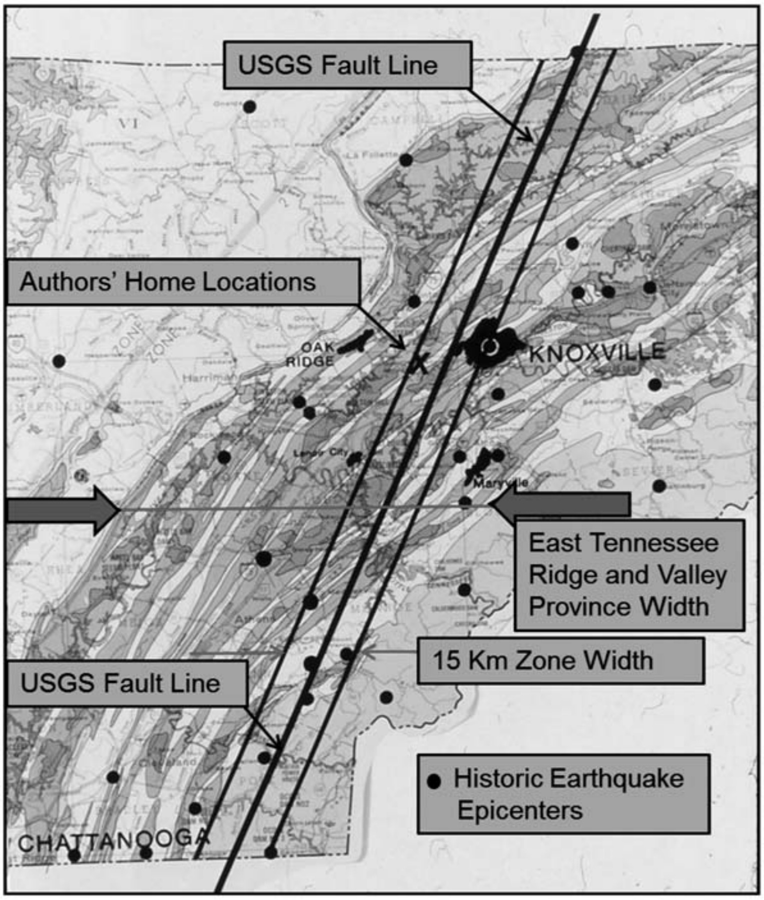


Figure 8-1. East Tennessee Geologic Map with the USGS Hypothesized Fault

Regulatory Commission stating the following: "Nine of these relocated earthquakes can be seen to make up a zone 15 km wide and 180 km long, extending from about 34° 57′ N lat., 84° 36′ W long., to 36° 25′ N lat., 83° 40′ W long. A line connecting these points runs through Knoxville and forms an azimuth of nearly 20 degrees more northerly than the surface trend of the Appalachians." Figure 8-1 shows a geologic map of East Tennessee with an overlay of this fault line showing it as 180 km long as defined by the USGS in 1982.

As an aside note, it might be interesting to the reader that both authors' home locations are just inside the western part of this 15 km zone width as shown by the "**X**" west of Knoxville. For what it is worth, the second author lives at the foot of the well-known Beaver Ridge Fault.

Powell and Beavers (1) showed a similar fault line in Figure 8-2. This hypothesized fault line data is based on a statistical analysis of epicenter locations and focal mechanisms solutions for 26 earthquakes (3). NE and EW Trending faults are indicated with maximum lengths of 300 and 30 km, respectively. Most of the seismic stations used in the analysis are operated by the Center for Earthquake Research and Information at the University of Memphis. As discussed above in the USGS letter (2) it was stated: "A line connecting these points runs through Knoxville and forms an azimuth of nearly 20 degrees more northerly than the surface trend of the Appalachians." Figure 8-2 shows a hypothesized fault line

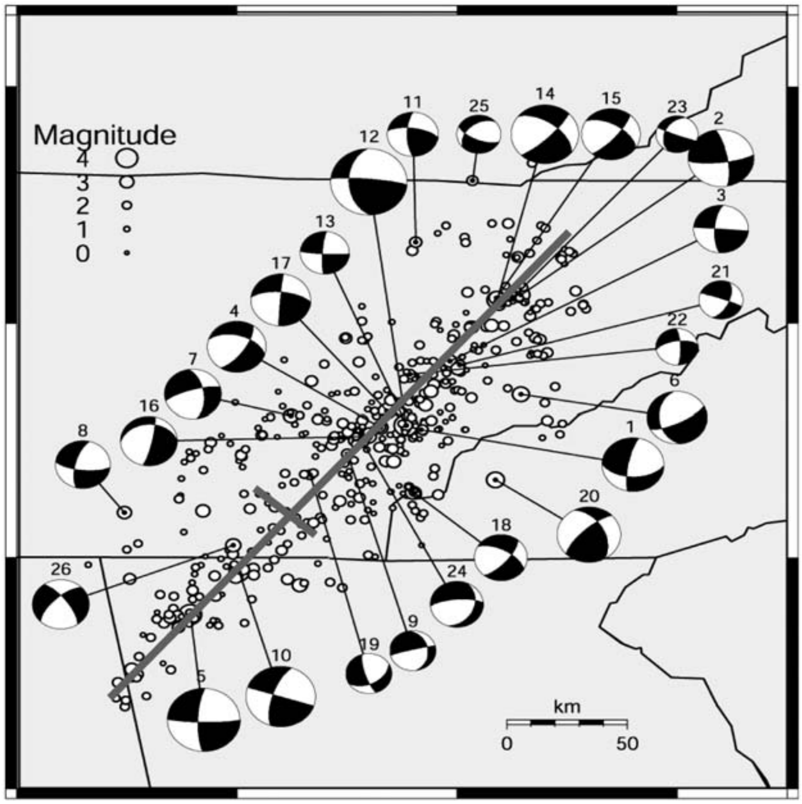


Figure 8-2. Fault line based on Chapman, et al. (3) data

that is more in line with the surface trend, especially in the northern part. However, the database collection of small earthquakes occurs at a minimum depth of 5 km, well below rocks forming the surface trend. Since the data for Figure 8-2 was collected at depth, this difference in fault line trend between Figures 8-1 and 8-2 are based on data collection and comparisons, Figure 8-2 being based on more recent data and the deference between the hypothetical fault line slopes will be resolved with future collections of data, however, both sets of data clearly show a possible large fault line.

The 300 km length in Figure 8-2 is considerably longer than the 1982 180 km length shown in Figure 8-1. Using the equation from Powell and Beavers (1), i.e., $\mathbf{M} = 5.16 + 1.12 \times (\log(\mathbf{L}))$ where **L** is the fault length and **M** is the moment magnitude one can determine the moment magnitude based on fault rupture length. In the case of the 1982 fault line (Figure 8-1) a complete fault rupture of 180 km would result in an earthquake having a moment magnitude of 7.7 and a complete rupture of the 2008 fault line (Figure 8-2) of 300 km would result in a moment magnitude of 7.9. Obviously, these large fault ruptures would be considered worst case scenarios, however a magnitude 6.0 event would not be. By conducting a reverse calculation, a magnitude 6.0 would only require 5.6 km of fault rupture, a significantly smaller rupture than required for a magnitude 7.0 or greater.

In the last 10 years the Federal Emergency Management Agency (FEMA) has developed the loss estimation methodology Hazard U.S. Multihazard (HAZUS-MH) (4). In 2008 Beavers and Powell (1) applied this methodology in Knox County assuming a magnitude 6.8 earthquake occurred at the epicentral location of the 1973 4.6 magnitude earthquake (5 and 6). The results of this assessment showed massive damage and loss of life. The total building related losses were $7.2 billion (30 percent of the Knox County building inventory value) with Level 1, 2, and 3 casualties for a 2:00 a.m. event of over 7,000 and with Level 4 casualties (deaths) of 462.

Summary

Based on the above knowledge, Knox County, Tennessee, with its major city Knoxville that hosted the 1982 World's Fair (7), represents a county and city that needs to have a seismic code. However, since its seismic hazard is not as high as its sister city, Memphis, in the western part of the state, the controversy that has and continues to occur in Memphis between builders and design engineers over the past 30 years; e.g., the introductory paper by Beavers, Hall and Hunt (8) in this monograph and other noted references (9), has not occurred in Knox County or Knoxville, the former being one major reason for this workshop. The remainder of this paper talks about Knoxville, and Knox County working together to assist the State of Tennessee in adopting seismic codes and to stay abreast of the changes that continue to occur in the area when it comes to the need for seismic design.

HISTORY OF KNOX COUNTY SEISMIC CODE ADOPTION PROCESS

In this paper, when the authors are discussing the seismic issues of Knox County this automatically includes the city of Knoxville, Tn. While it is true that, like many other areas of the US, a major county and its major city often have different governmental arms; however, in many cases when it comes to building code issues, the governments run hand in hand, i.e., when one adopts a code, the other entity follows suit to avoid confusion to the residents.

The first seismic code adopted in Knox County and Knoxville, Tennessee was the 1985 edition of the Southern Building Code (SBC) of the Southern Building Code Congress International (SBCCI). The SBC was created in 1940 (10) by the SBCCI to cover the southeastern US. This set of building codes was used for all aspects of structural design and implementation in that region, including foundation codes, until its integration into the International Building Code (IBC) of the International Code Council (ICC) in 2000 (11).

Governmental responsibilities for building codes and permits exist at the federal, state and local levels, each being unique. In the State of Tennessee law mandates the Architectural and Engineer Registration Law and the adoption of updated codes which must occur within a seven year period; however, local governments can adopt on an every 3 year cycle with the IBC, if they so choose.

Before adopting the seismic requirements from the SBC, Mr. Ron Mauer, the Knox County Building Official and coauthor held a meeting in Knoxville, Tennessee in 1985 to discuss various issues that needed to be considered before adopting these seismic requirements. Some of these issues were: 1) how much of the seismic provisions should be adopted, 2) should some of the provisions factors be modified and/or 3) should the seismic provisions be adopted in total. Mr. Mauer had invited Mr. Warner Howe, a practicing structural engineer from Memphis, Tennessee, who had been instrumental in seismic code development at the national level serving as Chairman of the Design Provisions Format Committee of the Tentative Provisions for the Development of Seismic Regulations for Buildings 1973 through 1978 (12) and later as Chairman of the Building Seismic Safety Council (BSSC) from 1987 through 1989 (13) and Mr. John Battle of the SBCCI. Mr. Battle is still an active employee of the ICC at the Birmingham, Alabama, office. Mr. Mauer also invited University of Tennessee structural engineering Professors Ed Burdette, David Goodpasture and Richard Bennett. In addition, the Mayor of Knox County at the time, the Honorable Dwight Kessel, attended part of the meeting and local practicing engineer Romeo Bayolsis also attended this meeting. Following a lengthily discussion about the pros and cons of the issues the group concluded the best thing for Knox County was to adopt the SBC seismic provisions of the code in total with no exceptions.

The Plan Examiner/Code Official qualifications are preferably an architecture or engineering education at the bachelor's level degrees and substantial related experience within industry having knowledge in planning, design, and construction including corporate and government areas.

Facilitating, assistance and cooperation by the code official is imperative because of the often encountered "bureaucracy," delays which discourages development. Excessive government interference can cripple the economy and future growth of an area. Interpretation of code issues by code officials is important in the design stages for architects, engineers, developers and contractors will facilitate the process. The ICC check list is an invaluable tool to the code officials and the designers and should be incorporated on the front sheets of the drawings with code analysis. The more detailed an analysis the more it reflects architectural and engineering professionalism.

The ICC families of codes with applicable National Fire Protection Association fire codes are to be referenced. The codes are written for the benefit of public safety and welfare, and are legally monitored by governments. Zoning laws are equally an important aspect as well. Storm water, Occupational Safety and Health Administration and air pollution codes must be reviewed by the code departments within that government.

KNOX COUNTY WORKING WITH THE STATE OF TENNESSEE

It is important that Knox County work with the State of Tennessee to minimize losses from natural disasters. As shown by Powell and Beavers (1) and discussed by Chapman-Henderson (9) earthquakes will occur in the State of Tennessee in the future, the only uncertainty is magnitude, location and losses. Powell and Beavers also ran the FEMA HAZUS-MH loss estimation methodology (4) in their 2008 study and showed that a credible magnitude 6.0 earthquake near Knox County would result in building related losses of $2.4 billion (10 percent of the Knox County building inventory), considerable smaller loses than a 6.8 magnitude earthquake. In addition, of the 128 schools in Knox

County 46 would experience more than 50 percent damage and total losses to Knox County would represent about $0.5 billion in a magnitude 6.0 event. To reduce these potential losses, Knox County must work with the State of Tennessee to have and maintain a competent building code to prevent such losses in the future.

The code adoption process in the state of Tennessee starts with the Department of Commerce and Insurance and is the responsibility of the State Fire Marshall's (SFM) office. The SFM mandates commercial and residential buildings, e.g., apartment complexes, drawings and calculations be submitted and reviewed. The architect/engineers design to the adopted code of the record and then submit that design for review and approval. This procedure also allows for "Exempt Jurisdictions" to review, approve and inspect projects themselves. Exempt jurisdictions are generally larger cities and counties, e.g., Knoxville, and Knox County which have competent staff with architect/engineering backgrounds to enforce the code of record.

The results of the 1985 meeting, mentioned in the previous section on the adoption of the seismic provisions from the 1985 SBC, that was held in Knoxville was instrumental in the State of Tennessee adopting the code without modifications.

At the state and local levels the management of projects dictate the architect/engineer and contractors must effectively work together free of conflicts resulting in design and construction success for code compliance.

There are procedures for building permits that are essential to the process for completion of projects. In Knox County and the state, all projects are initiated with the Architect/Engineer stamped drawings, including proper code review data and are submitted to the local government, i.e., the authority having jurisdiction. The jurisdictional government will then inspect the building and provide a written certificate of occupancy which finalizes the project.

The IBC has a requirement for "Special Inspections." In such cases the project design drawings most be followed and revisions submitted and issued to the general contractor of record. Third party inspections are now part of the IBC and reflect the complexity of steel, concrete, wood, masonry and foundation designs. Final inspection reports are filed with the code official; regrettable, these third party inspections are not being enforced by the state of Tennessee due to what the authors believe are perceived higher cost issues during economic recessions.

CONTINUED EDUCATION AND SEMINARS

Continued education and seminars are required for the future understanding of code requirements for both industry and design professionals so that all understand the complexity behind the current codes including the basis for their recent revisions. The University of Tennessee Civil and Architectural Academic Departments are valuable sources for instruction and seminars. Faculty at the University can meet with the practicing architects and engineers and determine their educational needs, and then go about developing the needed training programs for the practicing architects and engineers. The cost can be economical and benefit the industry. The more knowledge everyone, i.e., building officials and seismic design engineers is concerning building code requirements provides a much safer environment for the public. In addition to the building officials and seismic design engineers, contractors should know their respective areas of the codes. This acts as checks and balances and can eliminate serious and costly mistakes.

The future of the ICC codes and their complexity require continued education and seminars addressing code improvements vital to the professionals and the public. Previously, three codes existed within the US, these being the SBC of the SBCCI (10) discussed earlier, the BOCA* Basic Building Code of the Building Officials and Code Administrators (14) and the Uniform Building Code of the International Conference of Building Officials (15), representing the south, central and east, and west, respectively. The IBC which these three building codes consolidated into has existed from 2000 to 2012 and as it currently stands, will move on into the future.

The above efforts have resulted in superior building, mechanical, plumbing, and fire codes. However, they have evolved to "complex language" where interpretations may vary. To correct deficiencies, changes are proposed by various ICC committees which are then approved or rejected by the general membership reflecting in the next code issue at three years intervals. This action preserves a democratic process with checks and balances, but participation requires effort and funding by state and local governments. The procedure is typical with local government; however, variations and funding short falls still exist, but there are also opportunities for continued improvement.

With respect to this section, when the first author was President of the East Tennessee Building Officials Chapter of the Tennessee Building Officials Association, the first author put out a voluntary call for membership support in the form of a "Note from the President's Desk" dated April 1, 1996, that stated the following:

> I have recently attended the Certification meetings at the State Fire Marshall's office. I am convinced that continuing education is the single most important action each building inspector can take to further his future development and advancement. The complexity of the changing Standard Building Codes of the Southern Building Code Congress International adapted throughout the South Eastern United States, dictates the need for this continuing study. We must provide educational opportunities to improve our knowledge. In so doing we will also prove to our Governments that we protect the public with our knowledge and that the Building Inspector is a Professional who is current in his/her field.
>
> Natural Disasters have cost millions of dollars in loss of property and loss of life. Much of this damage is the result of inadequate implementation of codes. It is also incomprehensible that codes are not adapted in all of the various states. The ability of Governments and Insurance companies to protect from losses due to natural disaster is impossible without strong codes enforcement. Excusing enforcement because of "good old boy" friendships provides little help when nature strikes.

---

*BOCA is the acronym for Building Officials and Code Administrators.

> Natural disasters occur in all geographic areas; however, some areas are more likely to be a target of natures' wrath than others. Today a national effort designed to reduce these losses is in progress. Property owners, Insurance companies, and Governments who recognize their obligation to protect the public safety and welfare are becoming involved. Building officials who enforce the codes along with architects, engineers, and the building industry as a whole must be more active in this effort.
>
> Please, inform your governments and industry in your areas, and your associates with whom you interact on a daily basis, of the need for training on a continuing basis. Encourage them to participate in a political and monetary manner to insure the future of these training sessions. Make a concerted effort to attend your chapter meetings and take full advantage of the educational opportunities your chapter sets up. Then inform the public of our dedication to their welfare and of the issues which impact on their welfare.

While we no longer have the SBC, from both authors' perspective, these words are as true and important today as when they were written almost 20 years ago.

CONCLUSIONS

In conclusion, participation is the most important part of the code process. Regrettably, local governments typically do not have funds to support training and attendance to annual code hearings. These meetings are critical where changes to the codes are proposed and discussed. The local government representative must be in attendance to vote. The large jurisdictions fund and participate in these hearings and dominate voting whereas the small jurisdictions cannot vote. This inequality exists and the on-line voting process has not been implemented by ICC to correct this deficiency.

Conflicts created by NFPA 101 promote confusion and is not necessary because the ICC adequately covers most issues. The fire and building officials work counterproductive to each other because their loyalties are to NFPA and ICC, respectively.

All parties within industry need to cooperate for the betterment of all. Government agencies, architects, engineers, and construction material suppliers must recognize the code provides better building quality. Developers, real estate, and insurance companies know catastrophic economic losses have occurred during earthquake, hurricane and tornado disasters including substantial loss of life. Adoption of current building codes and their enforcement is imperative. Political infighting and the "blame game" accomplishes nothing. The future of the code world must be progressive.

Finally, the above discussion presents the reader some history of the seismicity of East Tennessee and the building code process in Knox County, Tennessee, and how the State of Tennessee and the various jurisdictions at the local levels operate when it comes to seismic design. All jurisdictions in Tennessee do not operate in the same manner as Knox County, this is for a couple of key reasons; 1) other jurisdictions are not as large as Knox County and as a result does not have the resources for being an "exempt jurisdiction" and 2) other jurisdiction in the State of Tennessee do not have the seismic threat of Knox County. However, the authors have provided this paper to allow the people of other states and Tennesseans to take a peek into Tennessee to see how one state and one county handles its seismic hazard and its seismic design process with the goal that when a future earthquake occurs the losses will have been minimized as a result.

References

1. Powell, C.A. and Beavers, J.E. 2008. "The 'Unknown' Seismic Hazard in East Tennessee and Potential Losses," Multihazard Issues in the Central United States-Understanding the Hazards and Reducing the Losses, ASCE Council on Disaster Risk Management, Monograph No. 3, American Society of Civil Engineers, 1801 Alexander bell Drive, Reston, Va., 2009.
2. Devine, J.F. 1982. "U.S. Department of Energy, Clinch River Breeder Reactor Plant," Oak Ridge, Tennessee NRC Docket N0. 50-537, United States Department of the Interior, Geological Survey, Reston Virginia, 22092, January 19, 1982.
3. Chapman, M. C., Powell C.A., Vlahovic, G., and Sibol M.S., 1997. "The nature of faulting in eastern Tennessee inferred from a statistical analysis of focal mechanisms and epicenter locations," Bulletin Seismological Society of America, v. 87, p. 1522–1536.
4. Federal Emergency Management Agency (2006). "Multihazard Loss Estimation Software (HAZUS-MH)," FEMA's Software Program for Estimating Potential Losses from Disasters, Version 1.0, January 2006.
5. Beavers, J.E., 1974. "Oak Ridge Strong Motion Recording of the Maryville Earthquake of November 30, 1973," K-D-3266, Oak Ridge Gaseous Diffusion, Oak Ridge, Tennessee, April.
6. Bollinger, G. A, Langer, C. J., and Harding, S. T. 1976 "The Eastern Tennessee Earthquake Sequence of October Through December, 1973," Bulletin of the Seismological Society of America, v. 66, No. 2, April.
7. World's Fair, 1982. http://www.worldsfairphotos.com/knoxville82/index.htm, December 15, 2012.
8. Beavers, J.E., Hall, W.J. and Hunt, R.J., 2012. "History of Seismic Design in the Central United States," Monograph No. 7, American Society of Civil Engineers, 1801 Alexander bell Drive, Reston, Va., 2012.
9. Chapman-Henderson, L., 2012. "Upgraded seismic code puts safety first," The Commercial Appeal, Memphis, Tennessee, Tuesday, December 18.
10. Southern Building Code (SBC), 2011. Southern Building Code Congress International http://www.ehow.com/list_6398674_southern-building-codes_-foundation-standards.html.
11. International Building Code (IBC), 2000. "International Building Code," International Code Council, Inc. 500 New Jersey Avenue, NW, 6th Floor, Washington, DC.
12. Applied Technology Council (ATC), 1978. "Tentative Provisions for the Development of Seismic Regulations for Buildings" U.S. Department of Commerce, National Science Foundation, and National Bureau of Standards, June 1978.
13. Building Seismic Safety Council (BSSC).
14. BOCA Basic Building Code, 1993. Building Officials and Code Administrators International, 1993. Country Club Hills, Illinois.
15. Uniform Building Code, 1997. International Conference of Building Officials, Whittier, California.

CHAPTER 9

Seismic Design in Western Kentucky: Issues and Alternatives

Zhenming Wang*

Abstract: *A better seismic design for building and other structures is the most effective way to reduce seismic risk and avoid earthquake disaster. Adoption and implementation of new seismic safety regulations and design standards have caused serious problems in many communities in the New Madrid region, including western Kentucky, however. The main reasons for these problems are (1) misunderstanding of the national seismic hazard maps and (2) confusion between seismic hazard and seismic risk. Both are caused by probabilistic seismic hazard analysis (PSHA).*

PSHA is a mathematical formulation derived from a probability analysis on the distribution of earthquake magnitudes, locations, and ground-motion attenuation. Some assumptions and distributions associated with PSHA have been found to be invalid in earth science, however. In addition, PSHA contains a mathematical error: equating a dimensionless quantity (the annual probability of exceedance – exceedance probability in one year) to a dimensional quantity (the annual frequency of exceedance with the unit of per year [1/yr]). Thus, PSHA is scientifically flawed and the resulting seismic hazard and seismic risk estimates are artifacts. The national seismic hazard curves and maps are artifacts because they were produced from PSHA, even though the inputs are scientifically sound.

Although seismic hazard and seismic risk have often been used interchangeably, they are two fundamentally different concepts. Seismic hazard describes the natural phenomenon *or* property of *an earthquake, whereas seismic risk describes the* probability of *loss or damage that could be caused by a seismic hazard. Seismic hazard and seismic risk play different roles in engineering design and other policy considerations. Furthermore, measures for seismic hazard mitigation are different from those for seismic risk reduction. The difficulties in the development of design ground motion for NEHRP provisions are caused by the use of the national seismic hazard maps which are neither seismic hazard nor seismic risk. The resulting design ground motions for building codes and other policy considerations are therefore problematic.*

California's experience proves that deterministic/scenario seismic hazard analysis is an appropriate approach for seismic hazard assessment, seismic risk assessment, as well as

*Kentucky Geological Survey, University of Kentucky, 504 Rose Street, Lexington, KY 40506; phone (859) 323-0564; fax (859)257-1147; e-mail: zmwang@uky.edu.

engineering design and other policy considerations. Deterministic/scenario seismic hazard analysis is also appropriate for engineering design and other policy considerations in the New Madrid region, as well as other regions.

INTRODUCTION

Development of seismic safety regulations and design standards for buildings and other structures, such as seismic provisions of building codes, is a complex process. This can be seen in the development of seismic safety regulations and design standards in the United States (Figure 9-1). The development began with the seismic hazard assessment – the national ground-motion hazard maps. Then a committee composed of engineers, seismologists, and others from the Building Seismic Safety Council developed a set of recommendations, particularly concerning the design ground motion, based on engineering science and experience. These recommendations were endorsed by the Federal Emergency Management Agency and thus became the NEHRP recommended seismic provisions for new buildings and other structures (e.g., FEMA P-750/2009 edition). The NEHRP recommended seismic provisions were adopted by other federal agencies, such as the U.S. Environmental Protection Agency, state and local governments, as well as nongovernment organizations, such as the American Association of Civil Engineers and the International Code Council, resulting in the ASCE/SEI 7-10 (2010) and International Building Code (2012).

Adoption and implementation of the seismic safety regulations and design standards have caused serious problems in many communities in the New Madrid region. For

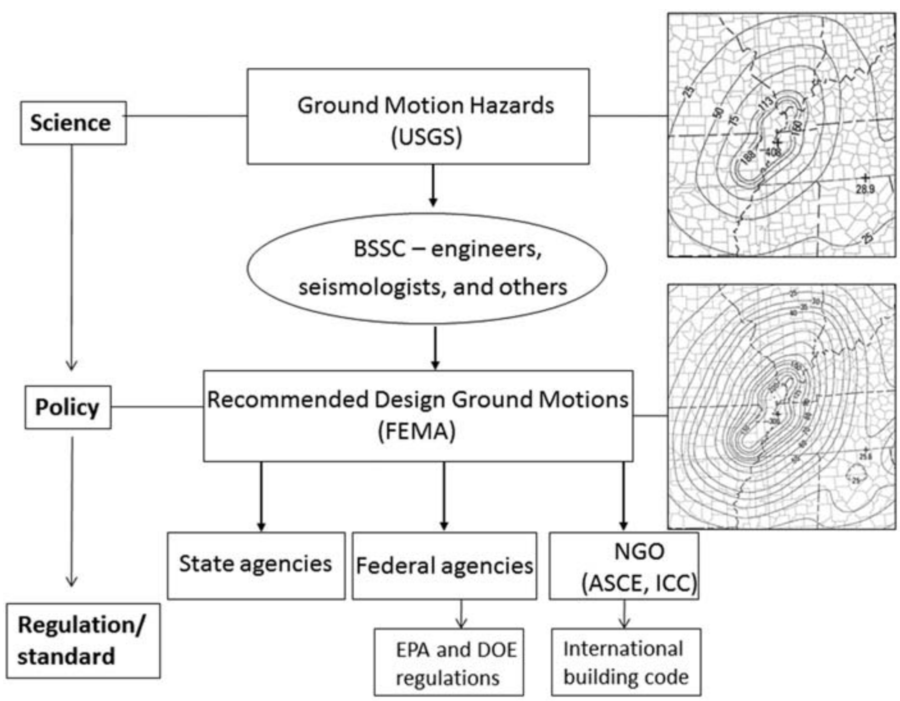


Figure 9-1. Development of seismic safety regulations and standards in the United States

example, peak ground acceleration of 0.8 g would have to be considered for seismic design of a landfill at the Paducah Gaseous Diffusion Plant near Paducah, Ky., if the NEHRP seismic hazard maps are considered (Beavers, 2010). This high ground motion (i.e., 0.8 g PGA) made it difficult for the U.S. Department of Energy to obtain a permit from federal or state regulators to construct the landfill (Beavers, 2010). The problems caused by the NEHRP provisions, as well as the resulting codes and regulations, have led to intense debate and discussion, especially about the national seismic hazard maps for the New Madrid area (Frankel, 2003, 2004, 2005; Stein and others, 2003a, b; Wang, 2003, 2005; Wang and others, 2005; Stein, 2010; Wang and Cobb, 2012). This debate has attracted national attention. The Advisory Committee on Earthquake Hazards Reduction convened a meeting on Nov. 9, 2010, in Memphis to address the concerns. In a statement, the Advisory Committee (2011) acknowledged "the local community concerns, and assigns a high priority to addressing the issues raised about the high hazard levels and attendant costs" and recommended that "the NEHRP agencies engage other earthquake professionals in making a clear and defendable statement of current seismic risk and goals for reducing that risk in the New Madrid region." The statement also specifically recommended an examination of "the high hazard levels in USGS maps via an independent review for the New Madrid area and explore ways to improve communication of the hazards and their effects on structural design."

In response, an independent expert panel, the Independent Expert Panel on New Madrid Seismic Zone Earthquake Hazards was chartered by the National Earthquake Prediction Evaluation Council to review the current high earthquake hazard assigned to the New Madrid Seismic Zone by the U.S. Geological Survey. The Independent Expert Panel (2011, p. 1) released a report stating that "the lack of knowledge concerning the physical processes that govern earthquake recurrence intervals in the Central US, and whether large earthquakes will continue to occur at the same intervals as the previous three clusters of events," is the fundamental problem. The panel concluded that "evolution in our knowledge will change the estimated hazard from New Madrid mainshocks in the next round of seismic hazard calculations; we infer that there are several factors that might reduce the estimated hazard." Furthermore, "it is likely that the estimated NMSZ hazard may decline moderately in the next hazard assessment due to improved knowledge of past earthquakes and current deformation." In other words, the panel expected the estimated hazard in the New Madrid Seismic Zone to be lower in the next round of hazard assessment.

The issues about seismic design in the CUS, the International Building Code (IBC) and ASCE 7 Standard in particular, have also attracted the attention of the Council for Disaster Risk Management (CDRM) of ASCE (Beavers and others, 2013). In concert with the Earthquake Engineering Research Institute (EERI)/National Earthquake Conference, a workshop on seismic issues in the Central U.S. was convened by CDRM in April 10, 2012 in Memphis, Tenn. (Beavers and others, 2013). One of the outcomes from this workshop is the ASCE Monograph No. 6. This chapter is a result from a presentation at the workshop and a contribution to the monograph.

As shown in Figure 9-1, the national ground-motion hazard maps are the basis for development of the design ground motion in NEHRP provisions and resulting building codes and other policies. Thus, at the heart of the debates is the simple question: How could the New Madrid region have a higher ground motion hazard than the San Francisco Bay area or Los Angeles? (Wang and Cobb, 2012). In this chapter, I will explore and discuss the basic concepts and assessments of seismic hazard and risk, as well their applications in design ground motion development, focusing on the national seismic hazard maps, the methodology being used to produce the maps, and resulting design ground-motion maps in the New Madrid region.

SEISMIC HAZARD AND RISK

In order to better understand the national seismic hazard maps as well as the resulting design ground-motion maps, two important concepts must be discussed: seismic hazard and seismic risk. Although the two terms have often been used interchangeably, they are fundamentally different (Wang, 2006, 2007, 2009, 2011a and b; Wang and Cobb, 2012). Seismic hazard is "a property of an earthquake that can cause damage and loss" (McGuire, 2004, p. 7), whereas seismic risk is "the probability that some humans will incur loss or that their built environment will be damaged" (McGuire, 2004, p. 8). In other words, seismic hazard describes the *natural phenomenon* or *property* of an earthquake, whereas seismic risk describes the *probability* of loss or damage that could be caused by a seismic hazard (Wang, 2006, 2007, 2009, 2011a and b; Wang and Cobb, 2012). Thus, seismic hazard is often referred to a physical measurement such as peak ground acceleration (PGA) and peak ground velocity (PGV) that is caused by an earthquake, whereas seismic risk is often referred to a probability such as 10 and 5 percent of an adverse consequences (e.g., a building collapse) resulted from an earthquake.

Seismic hazard and risk are also closely related, however. This is illustrated in Figure 9-2, which shows massive rockfalls (seismic hazards) triggered by the Wenchuan earthquake and its aftershocks. The driver and pedestrians (i.e., exposures) in Figure 9-2, who were exposed to and vulnerable to the hazards, were taking a risk (probability) of being struck by the rockfalls. In other words, seismic risk is a probable outcome (or consequence) from interaction between the rockfalls (seismic hazards) and exposures. Therefore, seismic risk can conceptually (qualitatively) be expressed as

$$Seismic\ Risk = Seismic\ Hazard \times Exposure. \qquad \text{Eq. 9-1}$$

This qualitative relationship demonstrates that seismic hazard is a critical component of seismic risk assessment; there is no risk if there is no hazard. But high hazard does not necessarily mean high risk. This qualitative relationship also demonstrates that engineering designs for seismic hazard mitigation may be different from those for seismic risk reduction. Seismic hazard may or may not be mitigated, but seismic risk can always be reduced by either mitigating seismic hazard, reducing exposure, or both. For example, earthquake fault rupture cannot be mitigated, but liquefaction can be mitigated by

Figure 9-2. The differences between seismic hazard and risk, and their relationships. Seismic hazard: rockfall triggered by an earthquake. Exposure: car, driver, and pedestrians. Seismic risk: the probability of being struck by a rockfall (adverse consequence) during the period that the car or pedestrians pass through the road section

engineering measures. As shown in Figure 9-2, seismic hazard (rockfalls) may be difficult, if not possible, to mitigate along this road section because of its steep slope, but seismic risk can always be reduced by either mitigating seismic hazard (i.e., building barriers or other measures), reducing exposure (i.e., limiting traffic or pedestrians), or both. There will be no risk if the driver decides not to drive or pedestrians decide not to walk on the road (i.e., no exposure).

Seismic Risk Assessment

The forgoing qualitative discussion, while instructive, is insufficient for decision-making. Quantitative descriptions are necessary. The aim of seismic risk assessment is to determine four parameters: *probability*, *level of severity*, and *spatial* and *temporal* measurements (Wang, 2009, 2011a and b; Wang and Cobb, 2012). However, seismic risk assessment is complex and somewhat subjective, and requires joint efforts from seismologists, engineers, and others. The assessment not only depends on the desired physical measurements (e.g., ground motion level, damage level, fatalities, or economic loss), but also on how the hazard and exposure interact in time and space. Hazard and exposure could interact at a specific site (site-specific risk) or over an area (aggregated risk) (Malhotra, 2008). In order to estimate seismic risk, a model has to be assumed to describe how the hazard and exposure interact in time. Several models, such as Poisson, empirical, Brownian passage time, and time-predictable, have been used in seismic risk assessment.

Different models result in different estimates. Currently, the most commonly used model in engineering risk assessment is the Poisson distribution (i.e. probability of occurrence is constant over time). Under the Poisson model, seismic risk, expressed in terms of a probability P_T that a seismic hazard of level y or greater could occur at the exposure site, can be estimated by

$$P_T = 1 - e^{-\frac{t}{\tau}}, \quad \text{(dimensionless)} \qquad \text{Eq. 9-2}$$

where τ is the return period (i.e., average recurrence interval) or $1/\tau$ is the average recurrence frequency of the seismic hazard with level y or greater at the site, t is the exposure's life in years. For small t/τ (<0.1), equation (9-2) can be approximated by using the first two terms of Taylor series ($e^x = 1 - x + x^2/2 - \ldots$) as

$$P_T \cong \frac{t}{\tau} \; or \; 1 - \left(1 - \frac{1}{\tau}\right)^t. \quad \text{(dimensionless)} \qquad \text{Eq. 9-3}$$

Equations (9-2) or (9-3) describe a quantitative relationship between seismic hazard, in terms of a hazard level y or greater with a return period τ or recurrence frequency of $1/\tau$, and seismic risk, in terms of the probability that the hazard level y or greater being exceeded over the exposure's life t at the exposure site. Equations (9-2) or (9-3) are widely used for risk calculation in earthquake engineering for a given hazard (Cornell, 1968; Milne and Davenport, 1969; McGuire, 2004; Luco and others, 2007), hydraulic engineering (Gupta, 1989), and wind engineering (Sachs, 1978). For example, for a ground motion hazard of 0.3 g PGA with a return period of 500 years (τ), equation (9-2) results in a risk of about 9.5 percent probability of ground motion exceeding 0.3 g PGA in 50 years (t), or a risk of about 10 percent probability of ground motion exceeding 0.3 g PGA in 50 years from equation (9-3). For a ground motion hazard of 0.4 g PGA with a return period of 2,500 years, equations (9-2) and (9-3) result in a risk of about 2 percent probability of ground motion exceeding 0.4 g PGA in 50 years. For a flood hazard of 10 m height with a return period of 100 years (the 100-year flood), equation (9-2) and (9-3) both result in a risk of about 1 percent probability of flood exceeding 10 m in 1 year.

Similarly, equations (9-2) or (9-3) are also used to estimate seismic hazard for a given seismic risk. For example, for a seismic risk of 10 percent probability of ground motion exceeding a given level in 50 years, equation (9-2) results in a return period of about 475 years, and about 500 years from equation (9-3) for the corresponding ground motion level. For a seismic risk of 2 percent probability of ground motion exceeding a given level in 50 years, equation (9-2) results in a return period of about 2475 years, and about 2,500 years from equation (9-3) for the corresponding ground motion. For the flood risk of 1 percent probability of flood exceeding a given level in 1 year, equations (9-2) and (9-3) result in a return period of about 100 years (i.e., the 100-year-flood). Thus, under certain conditions (e.g., the Poisson distribution and a given exposure time), seismic hazard and seismic risk can be converted from one to the other. However, seismic hazard and risk are not the same.

Equations (9-2) and (9-3) are derived from the interactions between hazard and exposure in time at a site only, without consideration of physical interactions. In other words, equations (9-2) or (9-3) can only determine the probability that an exposure could experience a certain level of hazard, without consideration of its vulnerability (i.e., inability to withstand the effects of a seismic hazard) or the related level of damage or economic loss. The physical interaction between seismic hazard and exposure is complicated and can be determined from a fragility analysis. For example, for certain buildings, there is a relationship between ground motion and damage level, expressed as a fragility curve (Kircher and others, 1997). The damage level can also be related to a level of economic loss or fatality. Thus, seismic risk, in terms of the probability P_D that a level of damage to the exposure could be caused by a seismic hazard, can be estimated from

$$P_D = P_T \cdot P_V = \left(1 - e^{-\frac{t}{\tau}}\right) P_V \cong \frac{t}{\tau} P_V \ or \left[1 - \left(1 - \frac{1}{\tau}\right)^t\right] P_V, \qquad \text{Eq. 9-4}$$

where P_V is the exposure's vulnerability to damage (i.e., probability of damage vs. a level of ground motion). As shown in equation (9-4), reducing vulnerability P_V through strengthening the built environment will reduce risk. This is why engineers play key role in reducing seismic risk through better design and construction of the built environment.

Equations (9-3) and (9-4) can be used to estimate the risks that the pedestrians and driver faced during their passage through the road section in Figure 9-2. If the rockfall occurrences follow a Poisson distribution and the rockfall hazard can be quantified as a mean diameter of 0.25 m or greater with an average occurrence frequency of once every 60 minutes along that section of the road, the risk for a car that take 3 minutes to pass through that section of the road is about a 5 percent probability of being struck by the rockfall; the risk is about a 33 percent probability for pedestrians who take 20 minutes to pass through the road section. Furthermore, pedestrians will almost certainly be killed if they are struck by a rockfall of 0.25 m or greater diameter, but the driver of the car might not be killed if the car is struck by a similar rockfall because the body of the car could protect the driver. In other words, a pedestrian is more vulnerable to rockfall hazard than a driver in the car. If we assume that pedestrians will surely be killed (vulnerability P_V is 100 percent) when they are struck by a rockfall and P_V is 25 percent that a driver will be killed if a car is struck by a rockfall, the risk of being killed is about 33 percent for pedestrians and only about 1.25 percent for the driver of the car.

Seismic Hazard Assessment

The aim of seismic hazard assessment is to determine *level of hazard* (physical measurement), and *spatial* and *temporal* measurements from instrumental, historical, and geologic observations (Wang, 2006, 2007, 2009, 2011a and b; Wang and Cobb, 2012).

Different kinds of hazards could be caused by an earthquake (fault rupture), and they can be separated into two categories: primary and secondary hazards. Primary hazards are surface rupture and ground motion that are caused directly by an earthquake. Strong ground motion could also trigger a secondary hazard, such as ground-motion amplification, liquefaction, or a landslide under certain site conditions at a specific site. As shown in Figure 9-2, the ground motions from the main shock and aftershocks of the Wenchuan earthquake (M7.9) triggered rockfalls along the road section. Ground-motion hazard normally affects large areas, whereas surface rupture is limited during an earthquake. Seismic hazard assessment discussed here focuses only on ground motions on rock caused directly by an earthquake.

Several methods are being used for seismic hazard assessment. The two most commonly used methods are probabilistic seismic hazard analysis (PSHA) and deterministic seismic hazard analysis (DSHA). PSHA and DSHA use the same seismologic and geologic information, but define and calculate seismic hazard differently. In PSHA, seismic hazard is defined as the ground motion with an annual frequency or rate of exceedance and calculated from a probability analysis based on statistical relationships of earthquakes and ground motion (Cornell, 1968; McGuire, 2004, 2008). In DSHA, seismic hazard is defined as the median or a certain percentile (e.g., 84 percent) ground motion from a single or set of scenario earthquakes and calculated from simple statistics of earthquakes and ground motion (Krinitzsky, 1995, 2002). A key component for both PSHA and DSHA is the ground-motion attenuation relationship or the so-called ground-motion prediction equation (GMPE).

Ground Motion Prediction Equation

GMPE is a statistical relationship between a ground-motion parameter Y (i.e., PGA, PGV, MMI, or PSA at different periods), earthquake magnitude M, source-to-site distance R, and uncertainty or residual δ as

$$\ln(Y) = f(M, R) + \delta. \quad \text{Eq. 9-5}$$

GMPE predicts ground motions in space (i.e., a spatial relationship), developed from a statistical analysis of ground-motion observations and/or theoretical ground-motion simulations (Atkinson and Boore, 2006; Pezeshk and others, 2011). The ground-motion uncertainty δ is modeled as a normal distribution with a standard deviation, σ (Atkinson and Boore, 2006; Pezeshk and others, 2011). Equation (9-5) can also be expressed as

$$\ln(Y) = f(M, R) + \varepsilon\sigma, \quad \text{Eq. 9-6}$$

where ε is the normalized residual, which is also a normal distribution with a constant standard deviation of 1 (Wang, 2011b). The source-to-site distance R is measured as the shortest distance either to the surface rupture (R_{RUP}) or to the surface projection of the

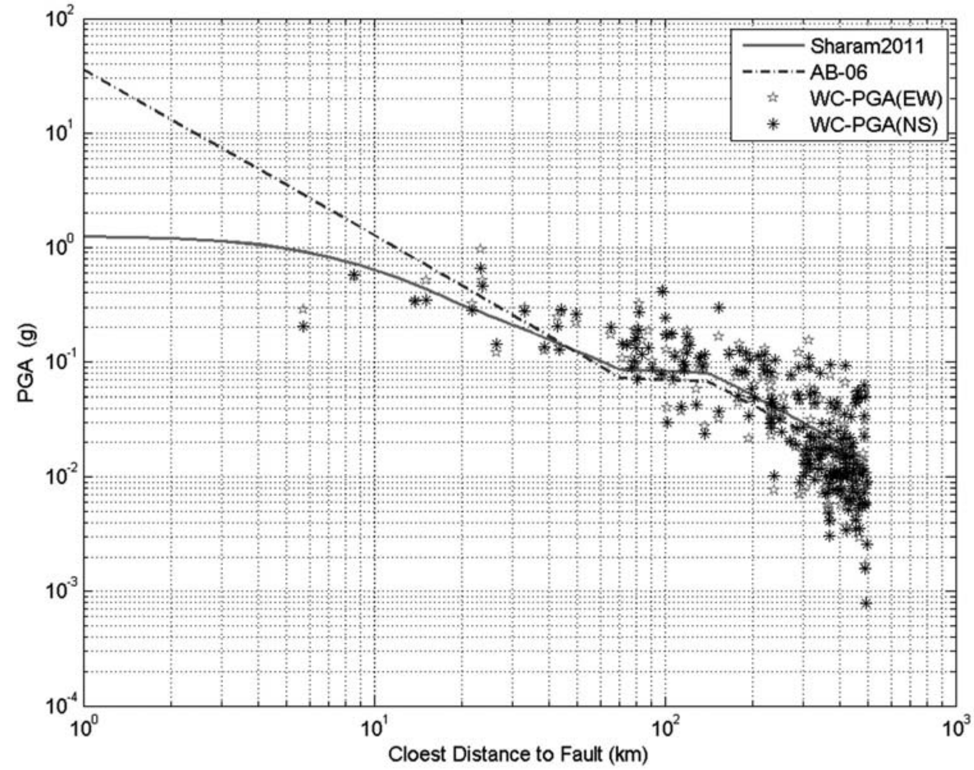


Figure 9-3. Median PGA attenuation curves of Atkinson and Boore (2006) and Pezeshk and others (2011) for an M7.9 earthquake, as well as the observed PGAs from the 2008 Wenchuan earthquake (M7.9)
SOURCE: Wang and Lu, 2011

rupture (R_{JB}) (Atkinson and Boore, 2006; Pezeshk and others, 2011). Figure 9-3 shows the median PGA prediction curves of Atkinson and Boore (2006) and Pezeshk and others (2011) for an M7.9 earthquake in the central United States. Also shown in Figure 9-3 are the observed PGAs from the 2008 Wenchuan earthquake (M7.9) which occurred in the western border of the South China stable continent region (SCR) that is similar to SCR of the central and eastern United Sates (Wheeler, 2011; Wang and Lu, 2011). As shown in Figure 9-3, both GMPEs of Atkinson and Boore (2006) and Pezeshk and others (2011) over-predict ground motion at near source ($R < 10$ km).

Probabilistic Seismic Hazard Analysis

PSHA is a mathematical formulation derived from a probability analysis of the distribution of earthquake magnitudes, locations, and ground-motion attenuation (Cornell, 1968; McGuire, 2004, 2008). The basic formulation of PSHA was introduced by Cornell in 1968 and computer coded by McGuire in 1976: the so-called Cornell-McGuire PSHA. Although it has been modified and advanced greatly, as pointed out by McGuire (2008), PSHA still depends, at its core, on the early formulation by Cornell (1968). Thus, examining the basic formulation of PSHA developed by Cornell (1968) is essential.

In his landmark paper, "Engineering Seismic Risk Analysis," Cornell (1968) made three fundamental assumptions: (1) equal likelihood of earthquake occurrence (single point) along a line or over an areal source, (2) constant-in-time average occurrence rate of earthquakes, and (3) Poisson (or "memory-less") behavior of earthquake occurrences in time. He then applied equation (9-2) to estimate seismic risk in terms of the probability of exceedance for a given intensity *i* at a site over an interval of time *t* from a seismic source as

$$1 - F_{I^t_{\max}}(i) = 1 - e^{-\nu P[I \geq i]t}, \quad \text{(dimensionless)} \qquad \text{Eq. 9-7}$$

where ν is the average occurrence rate (per year) of events (earthquakes) and $P[I \geq i]$ is the probability that intensity *I* exceeds the given *i*. For *t = 1 year*, the *annual probability of exceedance* for a given intensity *i* is equation 22 in Cornell (1968):

$$1 - F_{I_{\max}}(i) = 1 - e^{-\nu P[I \geq i]t(1\ year)}. \quad \text{(dimensionless)} \qquad \text{Eq. 9-8}$$

For a small probability (say, ≤ 0.05) (Cornell, 1968), equation (9-8) can be approximated by equation (9-3) (equation 23 in Cornell [1968]) as:

$$1 - F_{I_{\max}}(i) \cong 1 - (1 - \nu P[I \geq i])^1 = \nu P[I \geq i]. \quad \text{(dimensionless)} \qquad \text{Eq. 9-9}$$

Similarly, for a given ground motion *y*, Cornell (1968) estimated the *annual* (*t = 1 year*) *probability of exceedance* as equation 28 in Cornell (1968):

$$1 - F_{Y_{\max}}(y) \cong \nu P[Y \geq y]. \quad \text{(dimensionless)} \qquad \text{Eq. 9-10}$$

For a given ground motion *y* at a site from all seismic sources, Cornell (1968) determined the total annual probability of exceedance as equation 41 in Cornell (1968):

$$1 - F_{Y_{\max}}(y) \cong \sum \nu P[Y \geq y]. \quad \text{(dimensionless)} \qquad \text{Eq. 9-11}$$

In other words, "the basic formulation of PSHA was generalized in the 1970s using the 'total probability theorem'" (McGuire, 2008, p. 333):

$$P_a[Y \geq y] \cong \sum \nu P[Y \geq y] = \sum \nu \iint P[Y \geq y \mid M, R] f_{M,R}(m, r)\,dm\,dr,$$
$$\text{(dimensionless)} \qquad \text{Eq. 9-12}$$

where $P[Y \geq y \mid M,R]$ is the conditional exceedance probability and $f_{M,R}(m,r)$ is the probability density function (**PDF**) for magnitude *M* and distance *R*.

Thus, as defined by Cornell (1968), the *annual probability of exceedance* is the *probability* of exceedance in *1* year and a dimensionless quantity. The basic formulation of PSHA, equation (9-12), is valid only under three preconditions:

(1) Earthquake occurrence in time follows a Poisson distribution,

(2) Small probability of occurrence (say, ≤ 0.05),

(3) and **$t = 1$ year** (annual).

Cornell (1968) defined the reciprocal of the *annual probability of exceedance* for a given intensity *i* as the average return period as equation 24 in Cornell (1968):

$$T_i = \frac{1}{1 - F_{I_{\max}}(i)} \cong \frac{1}{\nu P[I \geq i]}. \quad \text{(dimensionless)} \qquad \text{Eq. 9-13}$$

Cornell (1968) also defined the average return period for a given ground motion *y* from a single seismic source as equation 29 in Cornell (1968):

$$T_y = \frac{1}{1 - F_{Y_{\max}}(y)} \cong \frac{1}{\nu P[Y \geq y]}, \quad \text{(dimensionless)} \qquad \text{Eq. 9-14}$$

or from all seismic sources as equation 42 in Cornell (1968):

$$T_y = \frac{1}{P_a[Y \geq y]} \cong \frac{1}{\sum \nu_i \iint P[Y \geq y \mid M, R] f_{M,R}(m, r) dm dr}. \quad \text{(dimensionless)} \qquad \text{Eq. 9-15}$$

Therefore, as defined by Cornell (1968), the return period is also a dimensionless quantity because the reciprocal of a dimensionless quantity is still dimensionless. For example, the reciprocal of 1 percent (0.01) is 100, which means that the chance is 1 in 100. Thus, as formulated by Cornell (1968), PSHA determines a relationship between ground motion and probability of exceedance in *1* year (the *annual probability of exceedance*) at a site. In other words, Cornell (1968) introduced a method for "the evaluation of the seismic risk at the site of an engineering project" in terms of a ground motion parameter (such as peak acceleration) versus the *annual probability of exceedance* (i.e., probability of exceedance in 1 year) or its reciprocal – the return period (dimensionless). However, Cornell (1968) erroneously interpreted the return period as a dimensional quantity with the unit of time in years. This can be seen in Figure 9-4 (modified from Figure 9-4 of Cornell [1968]), in which the return period T_i carries the unit of time in years.

Thus, a mathematical error: neglecting the precondition of *t = 1 year* (annual) in equations (9-9) through (9-15), was committed in the original formulation of PSHA. This mathematical error made the *annual probability of exceedance* becomes "the frequency (the number of events per unit of time) with which a seismic hazard will occur" (McGuire, 2004, p. 7), and its reciprocal (the return period) becomes "the mean (average) time between occurrences of a seismic hazard" (McGuire, 2004, p. 8). In other words, this mathematical error made "Engineering Seismic Risk Analysis" with result in terms of a *probability* with which ground motion exceeds a given level in *1 year* at a site becomes

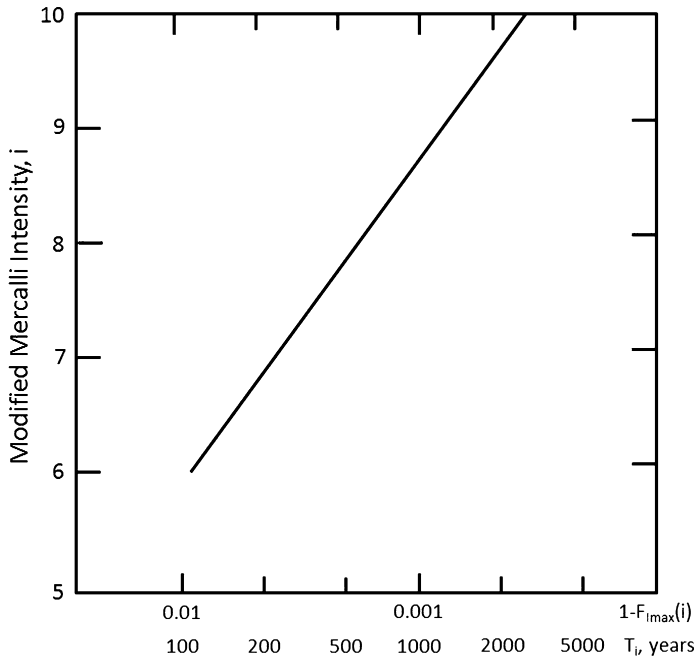


Figure 9-4. Intensity versus annual probability of exceedance or rerurn period
SOURCE: modified from Cornell (1968)

probabilistic seismic hazard analysis with result in terms of a *frequency* (per year) or an average recurrence time in years with which ground motion exceeds a given level at a site. Therefore, the annual probability of exceedance (i.e., a dimensionless quantity) has erroneously been used as a frequency (i.e., a dimensional quantity with unit of per year) in PSHA. In other words, a dimensionless quantity (i.e., the annual probability of exceedance) and a dimensional quantity (i.e., annual frequency of exceedance with the unit of per year [1/yr.]) have been used interchangeably in PSHA. This mathematical error led to the ergodic assumption (Anderson and Brune, 1999, p. 19): "PSHA treats that spatial uncertainty of ground motions as an uncertainty over time at a single point."

Recent studies have also found that PSHA has other inherent problems (Anderson and Brune, 1999; Wang and others, 2003, 2005; Wang, 2007, 2011b, 2012; Wang and Zhou, 2007). For example, PSHA is developed from the assumption that earthquake occurrence in time follows a Poisson distribution. But earthquake occurrence, for large earthquakes in particular, does not follow a Poisson distribution. Also, PSHA is based on a single point-source model for earthquakes (Cornell, 1968), which is not valid for large earthquakes that are of safety concern. A large earthquake is now considered a complex finite fault rupture in modern seismology. Therefore, PSHA has become a pure probability model or analysis, such as Monte Carlo simulation (Musson, 2012a, b), without earth science basis (Wang, 2011b, 2012; Wang and Cobb, 2012). The PSHA analysts have become experts in probability theory, not experts in earth sciences, who might not be better than "a monkey hitting keys on a typewriter" (Scherbaum and Kuehn, 2011, 2012).

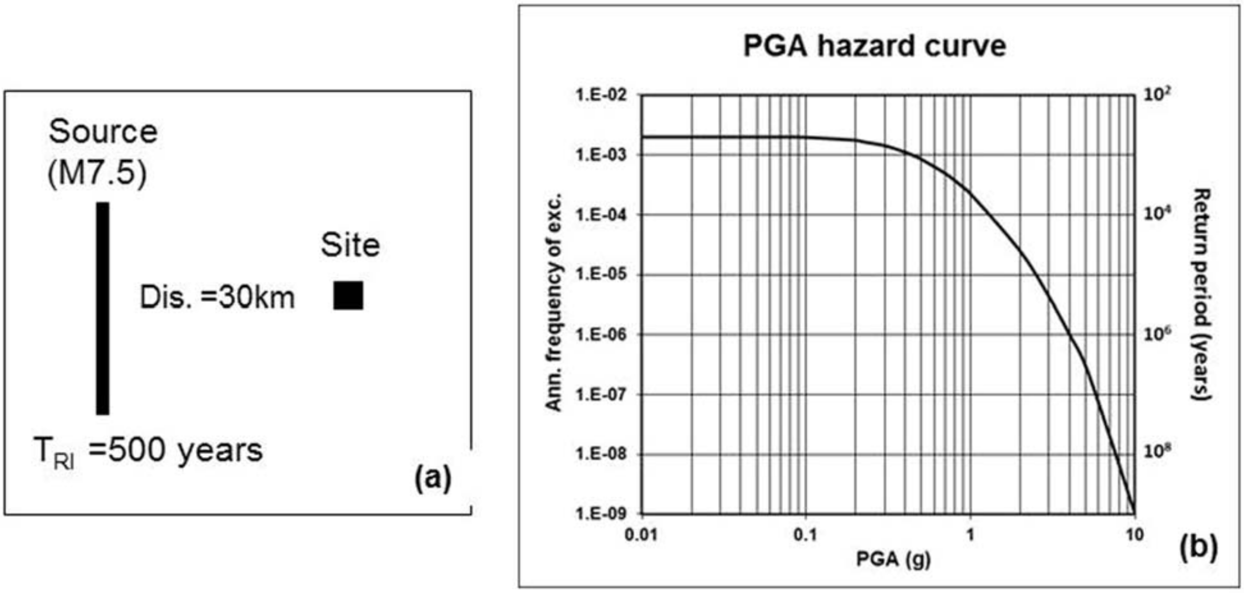


Figure 9-5. A hypothetical characteristic seismic source (a) and mean PGA hazard curve (b) at a site 30 km from the source. A median PGA of 0.44 g and standard deviation of 0.67 (in ln) were assumed at the site for an M7.5 earthquake

This can be demonstrated in a simple case: probabilistic ground-motion hazard at a site that is subject to a single characteristic earthquake (Fig. 9-5a). As shown in Figure 9-5b, PSHA produces many ground motions with return periods ranging from 500 to a billion years at the site from the single characteristic earthquake. But one earthquake can generate only one ground motion at a site. For example, the August 23, 2011, Virginia earthquake (M5.8) generated a strong ground motion that shook Washington, D.C., and damaged the Washington Monument (Earthquake Engineering Research Institute, 2011). If the average recurrence interval of the Virginia earthquake (M5.8) is 3,000 years, the return period (i.e., the average time between occurrences) of the ground motion generated by the earthquake at the Washington Monument must also be 3,000 years. From this perspective, the outputs (many ground motions) from a single characteristic earthquake by PSHA can be viewed as artifacts. The extremely high ground-motions derived from PSHA at the Yucca Mountain nuclear waste repository, 11 g PGA and 13 m/s peak ground velocity at the rate of 10^{-8} per year or a return period of 100 million years (Stepp and others, 2001), are artifact and cannot be verified by observations (Hanks, 2011).

Thus, PSHA has no earth science basis, and its results are artifacts.

Deterministic or Scenario Seismic Hazard Analysis

Deterministic seismic hazard analysis (DSHA) has been widely used in seismic-hazard assessment. DSHA develops a particular scenario earthquake (e.g., maximum credible earthquake or maximum considered earthquake) upon which a ground-motion hazard evaluation is based. The scenario consists of the postulated occurrence of an earthquake of a specified size at a specified location. DSHA uses four basic elements (Reiter, 1990; Krinitzsky, 1995, 2002):

(1) Determination of earthquake sources

(2) Determination of earthquake occurrence frequencies – selecting controlling earthquake(s): the maximum magnitude, maximum credible, or maximum considered earthquake

(3) Determination of ground-motion attenuation relationships

(4) Determination of seismic hazard from a particular scenario earthquake.

For example, the ground motion specified for bridge design in California is partly determined by the deterministic ground motion from the maximum credible earthquake (Mualchin, 2011). The ground motion for building seismic design in coastal California is capped by a deterministic ground motion close to major fault sources (BSSC, 1995, 1998, 2009). DSHA has also been widely used in the New Madrid region for a variety of purposes. Street and others (1996) and Wang and others (2007) used DSHA to develop ground-motion hazard maps for bridge and highway seismic design in Kentucky. Haase and Nowack (2011) developed scenario ground-motion hazard maps for Evansville, Ind.

DSHA determines the ground motion from a single or several scenario earthquakes that have maximum impact. It addresses the ground motion from individual (i.e., maximum magnitude, maximum probable, or maximum credible) earthquakes. Seismic hazard derived from DSHA has a clear physical and statistical meaning. Recent efforts in DSHA have focused on computer simulation for ground-motion hazard quantification (Wang and others, 2007; Irikura and Miyake, 2011) or the so-called neo-DSHA (Zuccolo and others, 2011; Peresan and Panza, 2012). DSHA or neo-DSHA has several advantages:

(1) Ground motion derived has an easily understood physical and statistical meaning

(2) The results are easily understood by earth scientists, engineers, and others

(3) It utilizes ground-motion simulation.

The biggest criticism of DSHA is that it "does not take into account the inherent uncertainty in seismic hazard estimation" (Reiter, 1990, p. 225), but actually DSHA does account for all the inherent uncertainty explicitly for each scenario earthquake. For example, the maximum credible earthquake ground motion is usually defined as a mean + 1 standard deviation (i.e., 84th percentile) in the scatter of recorded earthquake ground motions (Krinitzsky, 1995, 2002; Silva and Darragh, 2011; BSSC, 2009). Another perceived weakness of DSHA is that "frequency of occurrence is not explicitly taken into account" (Reiter, 1990, p. 225). The temporal characteristic of earthquakes (i.e., recurrence interval or frequency and its associated uncertainty) is not addressed in traditional DSHA. The temporal characteristic of earthquakes and resulting ground motions at a site is an integral part of seismic hazard and must be considered in engineering design and other policy considerations. As pointed out by Wang and others (2004), a scenario earthquake can always be associated with a recurrence interval and its uncertainty. For example, the average recurrence interval of the New Madrid scenario earthquake is about 500 to 1,000 years (Haase and Nowack, 2011). This recurrence interval can be used to estimate seismic risk with equations (9-2) or (9-3). Thus, DSHA includes elements of uncertainty (probability). This can be demonstrated in the simple case: scenario ground-motion hazard at a site that is subject to a single characteristic earthquake (Fig. 9-3a). DSHA gives median PGA of 0.44 g or median + one standard deviation PGA of 0.86 g at the site. The return period of the PGA's is the same as the recurrence interval of the characteristic earthquake, 500 years.

NEHRP DESIGN GROUND MOTION

As shown in Figure 9-1, the NEHRP design ground motion maps were developed by the Building Seismic Safety Council from the USGS national seismic hazard maps (Algermissen and Perkins, 1976; Frankel and others, 1996; Petersen and others, 2008), based on a set of rules and policy decisions (1995, 1998, 2009). NEHRP provisions have evolved greatly over time and can be separated into three periods, pre-1997, 1997–2006, and 2009. The rules and policy decisions are different in each period, and so are the resulting design ground-motion maps.

Pre-1997 NEHRP Design Maps

The rules and policy decisions that were made for the pre-1997 NEHRP design ground-motion maps (BSSC, 1995, p. 277–278) are:

1. "The distance from anticipated earthquake sources should be taken into account."
2. "The probability of exceeding the design ground-shaking should be roughly the same in all parts of the country – 10 percent probability of the ground motion being exceeded in 50 years."
3. "The regionalization maps should not attempt to microzone (i.e., there was to be no attempt to locate actual faults on the regionalization maps, and variations of ground-shaking over short distance – on a scale of about 10 miles or less – were not to be considered)."

The ground-motion parameters chosen for seismic design are the effective peak acceleration, A_a, and the effective peak velocity, A_v. The EPA map was developed from the contour map of the peak ground acceleration on rock with 10 percent probability of exceedance in 50 years, produced by the USGS (Algermissen and Perkins, 1976) (Fig. 9-6a). Figure 9-6b shows the resulting effective peak acceleration coefficient, A_a (BSSC, 1995). As shown in Figure 9-6, the EPA was capped at 0.4 g in the area of highest seismicity in California, and the EPA in western Kentucky was 0.1 to 0.2 g. The highest EPA is about 0.2 g in the New Madrid area.

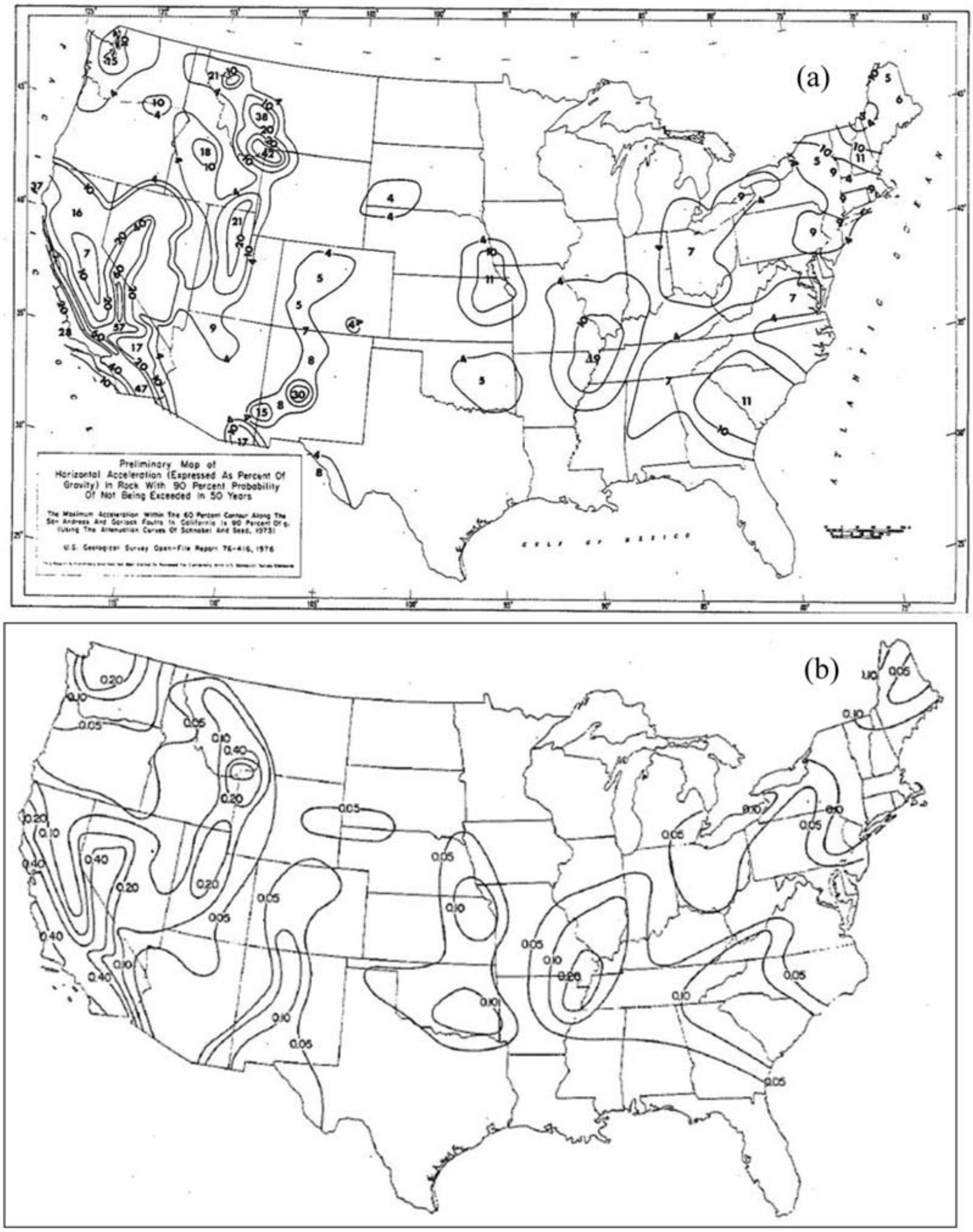


Figure 9-6. (a) Contour map of the peak ground acceleration on rock with 10 percent probability of exceedance in 50 years, produced by the USGS (Algermissen and Perkins, 1976). (b) Contour map of the effective peak acceleration coefficient, A_a (BSSC, 1995)

1997–2006 NEHRP Design Maps

Significant changes occurred in the 1997 edition of the NEHRP design ground-motion maps. This is reflected in the rules and policy decisions that were made for the 1997 edition (BSSC, 1998, p. 288):

1. "The maps define the maximum considered earthquake ground motion (MCE) for use in design procedure."

2. "The use of the maps for design provide an approximately uniform margin against collapse for ground motions in excess of the design levels in all areas."
3. "The maps are based on both probabilistic and determinstic seismic hazard maps" – deterministic ground motions (1.5 median) from the maximum considered earthquake in coastal California and probabilistic ground motions with 2 percent probability of exceedance in 50 years.
4. "The maps are response spectra ordinate maps and reflect the differences in the short-period range of the response spectra for the areas of the United States and its territories with different ground motion attenuation characteristics and different recurrence times."

The probabilistic ground motions for 0.2 s spectral response acceleration (5 percent of critical damping) with 2 percent probability of exceedance in 50 years were produced by the USGS (Frankel and others, 1996) (Fig. 9-7a). Figure 9-7b shows the resulting maximum considered earthquake ground motion for 0.2 s spectral response acceleration (5 percent of critical damping), site class B (BSSC, 1998). The short-period (0.2 s) design response acceleration is 1.0 g (1.5 g/1.5) for San Francisco, and about 1.33 g (2.0 g/1.5) for Paducah, Ky., respectively. The equivalent EPA is 0.4 g (1.0 g/2.5) for San Francisco and 0.53 g for Paducah. The highest short-period design response acceleration is 1.6 g (2.4 g/1.5) for coastal California, whereas it is 2.47 g (3.7 g/1.5) for the New Madrid area.

2009 NEHRP Design Maps

Some changes were introduced in the 2009 edition of the NEHRP provisions. The most significant changes were (1) the adoption by reference of the national consensus design loads standard – ASCE/SEI 7-05, *Minimum Design Loads for Buildings and Other Structures* – and (2) risk-targeted ground motions (BSSC, 2009). The rules and policy decisions for the 2009 NEHRP design ground-motion maps (BSSC, 2009) include:

1. The maps define the risk-targeted maximum considered earthquake (MCE_R) ground motion.
2. The use of the maps for design provide an approximate collapse probability (i.e., collapse risk objective of 1 percent in 50 years) for ground motions in excess of the design levels in all areas.
3. The maps are based on both probabilistic and determinstic seismic hazard maps – deterministic ground motions (84^{th} percentile) from the maximum considered earthquake in coastal California and some other regions and risk-targeted probabilistic ground motions with 2 percent probability of exceedance in 50 years.
4. The maps are response spectra ordinate maps.
5. The maps are the maximum directional ground motion.

The probabilistic ground motions for 0.2 s spectral response acceleration (5 percent of critical damping) with 2 percent probability of exceedance in 50 years were produced by the USGS (Petersen and others, 2008) (Fig. 9-8a). Figure 9-8b shows the resulting

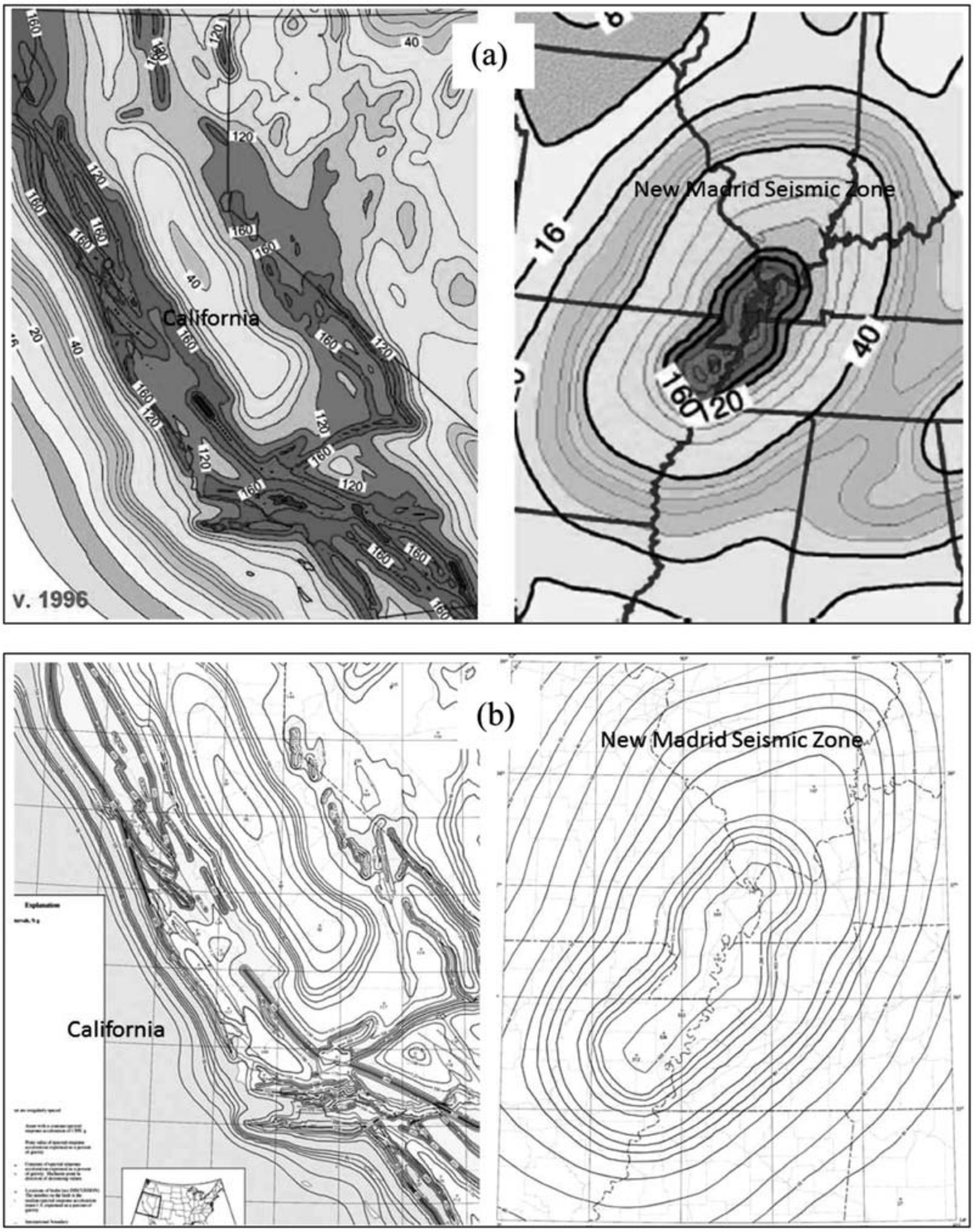


Figure 9-7. (a) The 0.2-second spectral response acceleration (5 percent of critical damping) with 2 percent PE in 50 years, site class B (Frankel and others, 1996). (b) Maximum considered earthquake ground motion for 0.2 s spectral response acceleration (5 percent of critical damping), site class B (BSSC, 1998)

risk-targeted maximum considered earthquake (MCE_R) ground motion for 0.2 s spectral response acceleration (5 percent of critical damping), site class B (BSSC, 2009). The short-period (0.2 s) design response acceleration is 1.0 g (1.5 g/1.5) for San Francisco and about 1.0 g (1.5 g/1.5) for Paducah, Ky.. The highest short-period design response acceleration is 1.33 g (2.0 g/1.5) for coastal California, whereas it is 2.04 g (3.06 g/1.5) for the New Madrid area.

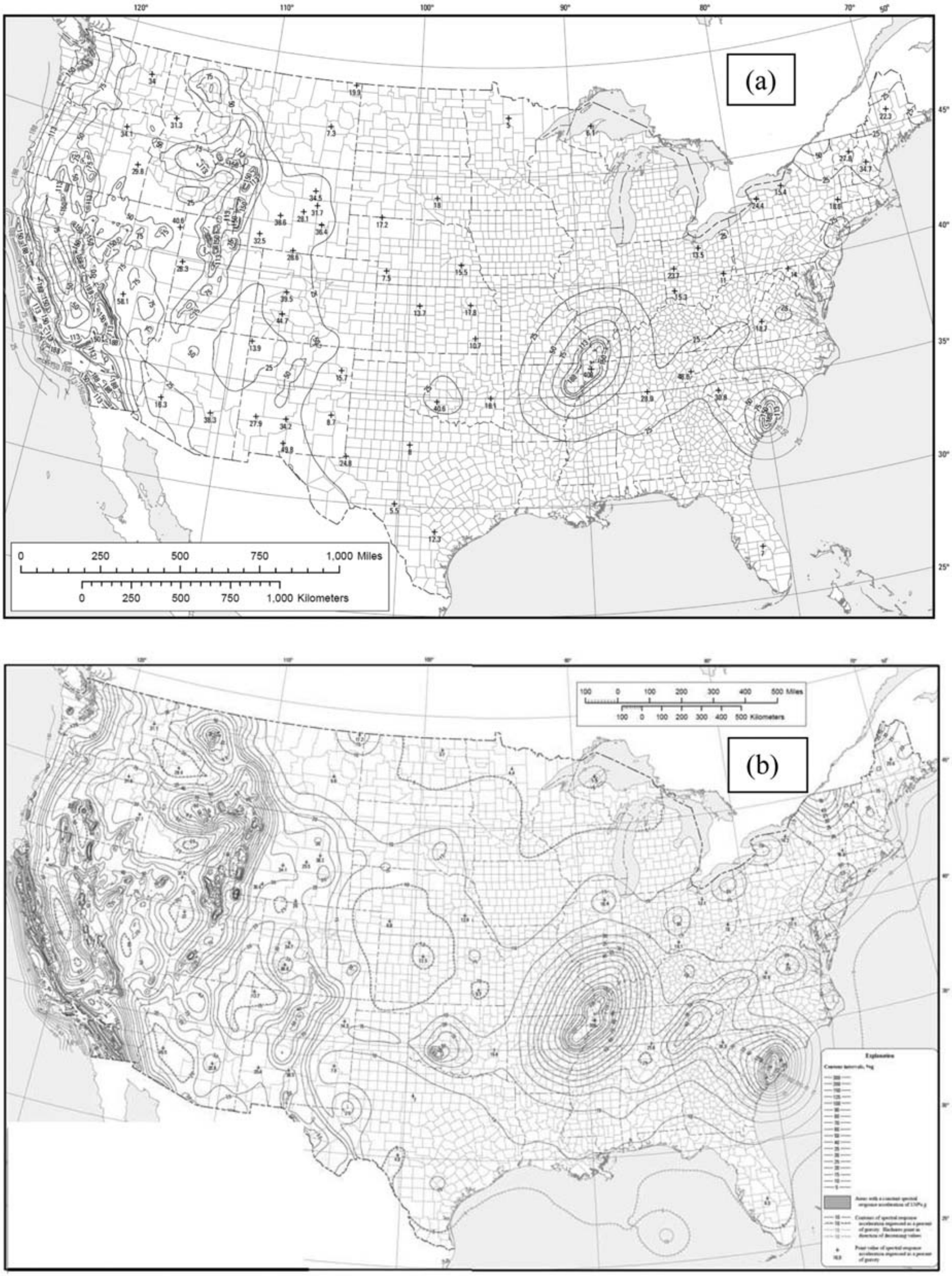


Figure 9-8. (a) The national ground motion hazard (2 percent PE in 50 years) of 0.2-second spectral response acceleration (5 percent of critical damping), site class B (Petersen and others, 2008). (b) Ss risk-targeted maximum considered earthquake (MCE_R) ground motion for the conterminous United States for 0.2 s spectral response acceleration (5 percent of critical damping), site class B (ASCE, 2010)

As shown in Figures 9-6 through 9-8, the design ground motions have been changed significantly in the New Madrid region from one edition to the others of the NEHRP provisions. For example, in Paducah, design PGA has been changed from about 0.2 g in the 1994 edition, to about 0.53 g in the 1997 edition, and about 0.4 g in the 2009 edition. However, the design ground motions have not been changed significantly in the coastal California. For example, in San Francisco, design PGA was about the same, 0.4 g, in the 1994 edition, the 1997 edition, and the 2009 edition, respectively.

DISCUSSION AND RECOMMENDATION

Although the rules and policy decisions made for the NEHRP provisions have changed greatly, along with the advances of science and engineering (BSSC, 1995, 1998, 2009), the design ground motion for coastal California has not been changed significantly: the same short-period response acceleration of about 1.0 g in San Francisco. This stable design ground motion resulted from the use of DSHA. As shown in Figure 9-6, the design EPA was capped at 0.4 g in coastal California, "based in part on scientific knowledge and in part on judgment and compromise" (BSSC, 1995, p. 283). As determined by BSSC in 1998, the design ground motions for coastal California were the deterministic ground motions from maximum magnitude earthquakes. Similarly, the design ground motions for coastal California were the deterministic ground motions from maximum considered earthquakes for the 2009 NEHRP provisions (BSSC, 2009). Thus, DSHA, not PSHA, was used to derive the design ground motions for the NEHRP provisions and the resulting building codes and other regulations for coastal California. In other words, the ground motion hazard maps produced from PSHA have never been used to develop the design ground motion for coastal California. The actual earthquake experience in coastal California provides increased confidence in the seismic margins contained in the NEHRP provisions (BSSC, 1998). The California experience is based on DSHA, not PSHA. Thus, the ground motions produced from PSHA, the national seismic hazard maps in particular, are not appropriate for development of design ground motion for NEHRP provisions.

National Seismic Hazard Curves and Maps

The national seismic hazard maps were produced by the U.S. Geological Survey using PSHA (Algermissen and Perkins, 1976; Frankel and others, 1996; Petersen and others, 2008). As shown by Petersen and others (2008), a very comprehensive consensus process, involving many geologists, seismologists, engineers, and others, was carried out to build a scientific database (Fig. 9-9). The database was then used to produce the seismic hazard curves calculated on a grid showing sites across the United States that describe the frequency of exceeding a set of ground motions from PSHA (Petersen and others, 2008). Figure 9-10 shows 0.2 s response acceleration hazard curves for Memphis, New Madrid, Paducah, and San Francisco from the 2008 national hazard mapping (Petersen and others, 2008). These curves provide a range of ground motion, from 0.001 to 5.0 g 0.2 s pseudo-response accelerations, versus a range of annual frequencies of exceedance, from 1.0 to

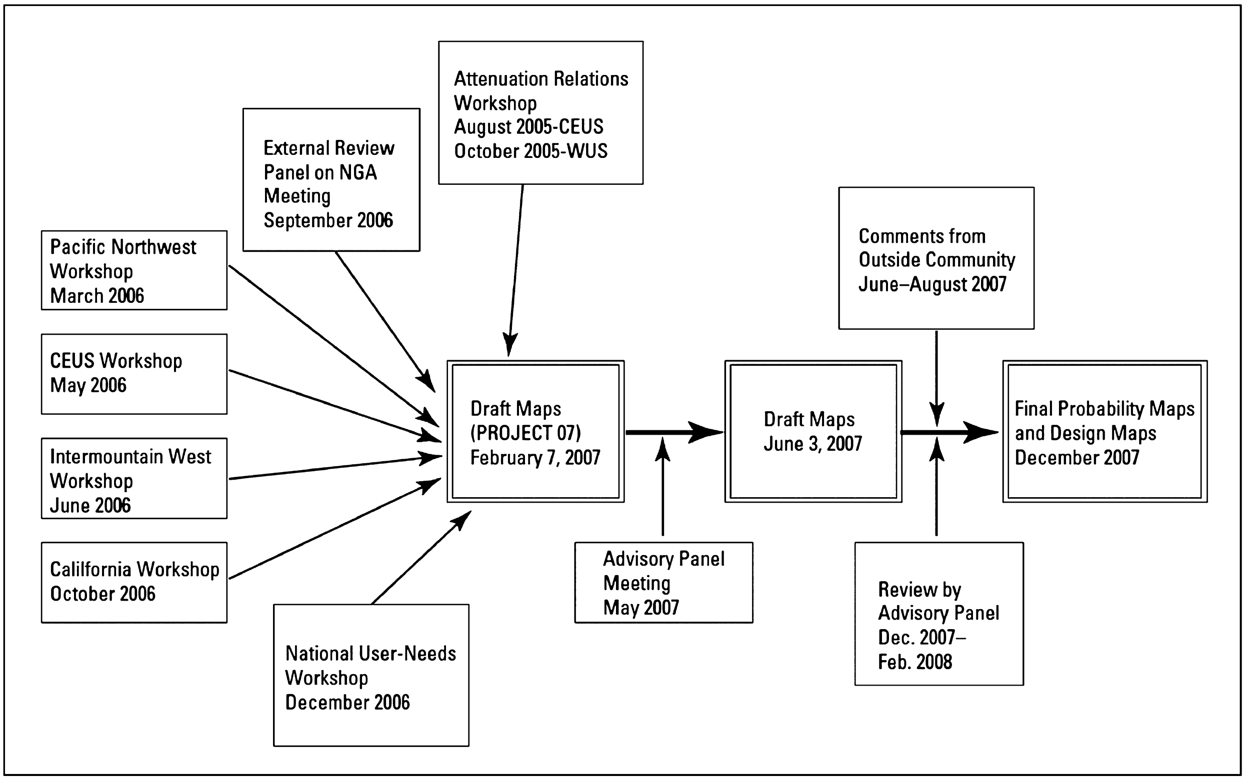


Figure 9-9. Process for developing the 2008 USGS national seismic hazard maps
SOURCE: Petersen and others, 2008

0.00001 (1/yr). Three points on the curves corresponding to annual frequencies of exceedance of 0.002, 0.001, and 0.0004 (1/yr) were picked to produce the national seismic hazard maps (Petersen and others, 2008). The reciprocals of the annual frequencies of exceedance of 0.002, 0.001, and 0.0004 (1/yr), the return periods of 500, 1,000, and 2,500 years, were used to calculate the probabilities of exceedance of 10, 5, and 2 percent for buildings with an average life of 50 years, using equation (9-3) (Algermissen and Perkins, 1976; BSSC, 1995, 1998, 2009; Frankel and others, 1996; Petersen and others, 2008).

As discussed earlier, PSHA determines the annual probability of exceedance for a given ground motion at a site, not the annual frequency (per year). It is mathematically incorrect to interpret or use the annual probability of exceedance as the annual frequency or rate of exceedance. It is also mathematically inappropriate to interpret or use the reciprocal of the annual probability of exceedance as the average time between occurrences of a given ground motion. Thus, the hazard curves and maps produced from the national seismic hazard mapping project (Algermissen and Perkins, 1976; Frankel, 1996; Petersen and others, 2008) are artifacts, even though the input database is scientifically sound. The national seismic hazard maps have not been understood and used correctly. This can be seen in the development of the risk-targeted earthquake ground motion (Luco and others, 2007).

The risk-targeted maximum considered earthquake ground motion was derived from a risk analysis based on the seismic hazard curves of the national seismic hazard mapping

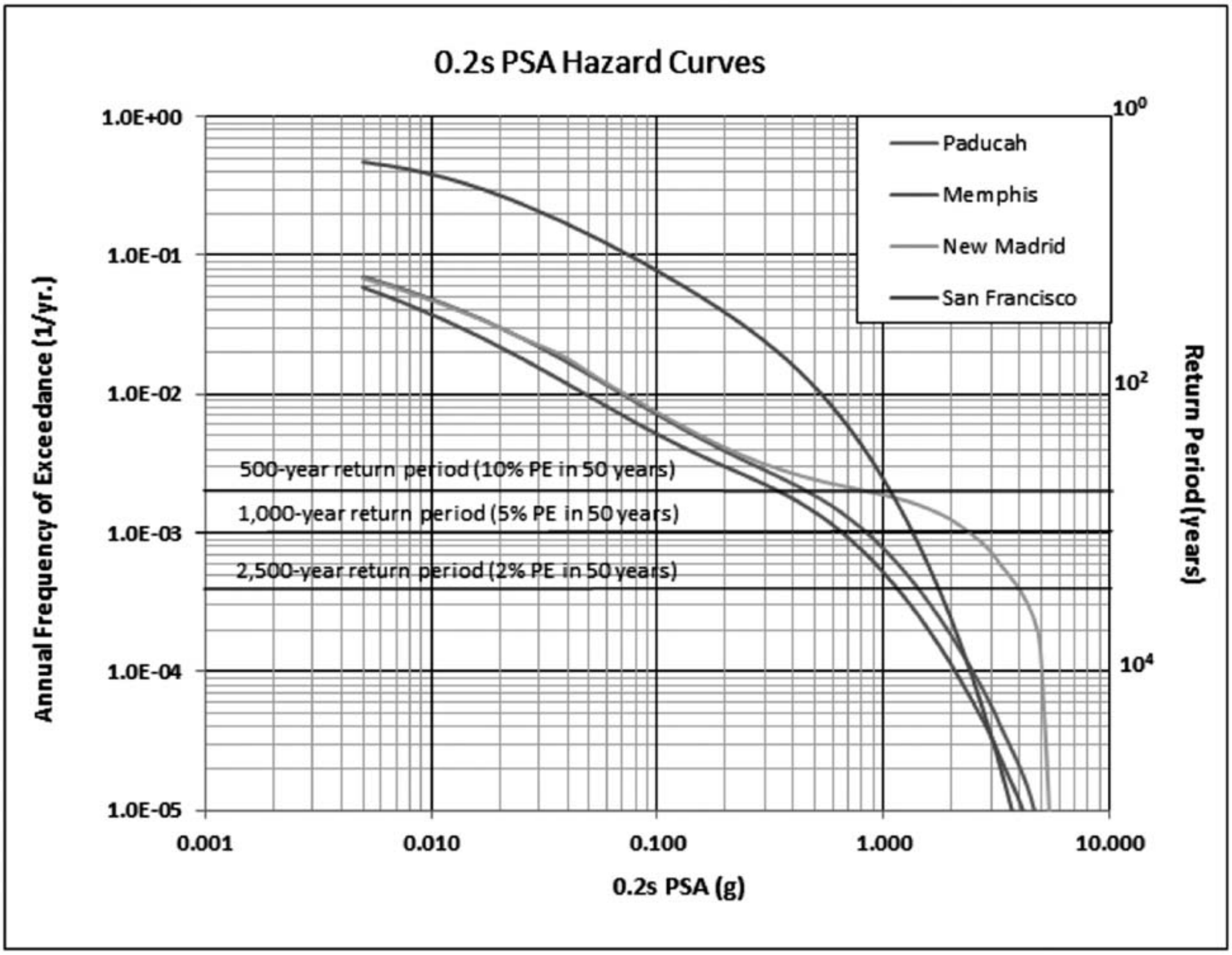


Figure 9-10. The 0.2 s response acceleration hazard curves for Memphis (N35.15°/W90.05°), New Madrid (N36.25°/W89.50°), Paducah (N37.10°/W88.60°), and San Francisco (N37.80°/W122.40°) from the 2008 national seismic hazard maps
SOURCE: Petersen and others, 2008

and a generic collapse fragility (10 percent collapse probability given MCE ground motions) (Luco and others, 2007). Luco and others (2007) estimated the annual collapse probability, *P[collapse]*, as

$$P[collapse] = \int_0^\infty P[SA > c] f_{capacity}(c) dc, \qquad \text{Eq. 9-16}$$

where *P[SA>c]* is the annual probability that the spectral acceleration exceeds the capacity value (i.e., the seismic hazard curve from the national seismic hazard mapping), and $f_{capacity}$(c) is the probability density function for the collapse capacity. Then Luco and others (2007) used the annual collapse probability to calculate the probability of collapse in Y years with equation (9-3):

$$P[collapse\ in\ Y\ years] = 1 - (1 - P[collapse])^Y. \qquad \text{Eq. 9-17}$$

As shown in equation (9-3), *P[collapse]* should be a dimensional quantity with the unit of per year. This implies that *P[SA>c]* in equation (9-16) is also a dimensional quantity with the unit of per year. Thus, the annual probability of exceedance, *P[SA>c]*, was used as a dimensional quantity with the unit of per year in the risk analysis (Luco and others, 2007). In other words, the dimensionless quantity (i.e., the *annual probability of exceedance* – probability of exceedance in 1 year) had been incorrectly used as a dimensional quantity with the unit of per year (i.e., the annual frequency) in building collapse risk calculation (Luco and others, 2007). Thus, the resulting building collapse risk calculations are artifacts, and the use of the NEHRP design ground motion maps will not result in an approximate collapse probability (i.e., collapse risk objective of 1 percent in 50 years) for ground motions in excess of the design levels in all areas. This can be demonstrated by seismic risk comparison between two identical buildings with a normal life of 50 years, one in San Francisco and one in Paducah (Fig. 9-11).

As shown in Figure 9-11, the building in San Francisco is in an MMI VIII or larger zone, and the one in Paducah is in a similar zone. The impact area is much larger for the central United States than for the similar-magnitude event in California for a similar magnitude earthquake (M7.8) because ground motion attenuates much more slowly in the older and harder rocks in the central United States. This does not mean that the central United States has higher seismic hazard, however, because the earthquake occurrence frequencies are different. The recurrence interval of the M7.8 earthquake along the San Andreas Fault is about 200 years, and recurrence interval of the M7.7 earthquake along the New Madrid Fault is about 500 to 1,000 years (Petersen and others, 2008). If earthquake occurrence follows a Poisson distribution, equation (9-2) or (9-3) can be used to estimate the probability that the buildings could experience intensity of MMI VIII or greater during their lives (i.e., 50 years). The resulting probabilities are about 22 percent in 50 years for the building in San Francisco and about 5 to 10 percent for the building in Paducah. If the buildings have the same fragility (50 percent probability of collapse when

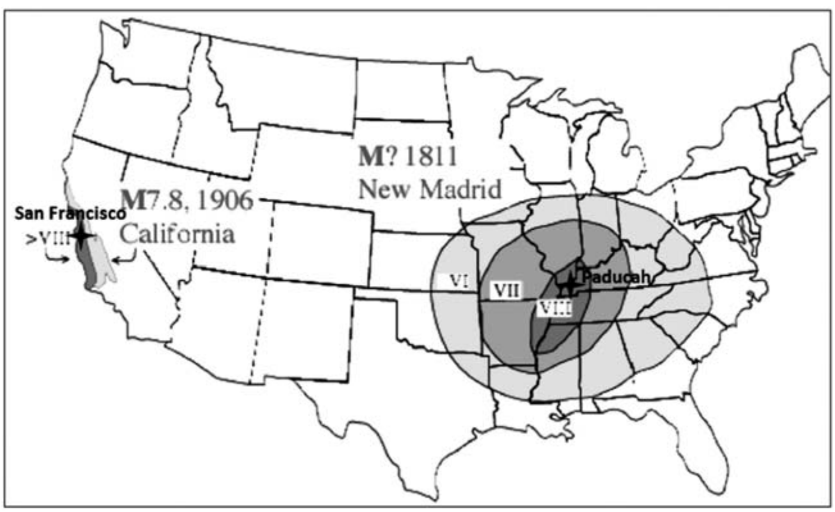


Figure 9-11. Seismic hazard and risk comparison between the New Madrid region and the San Francisco Bay Area

MMI VIII or greater occurs), then from equation (9-4), the resulting collapse probabilities are 11 percent in 50 years for the building in San Francisco and 2.5 to 5 percent in 50 years for the one in Paducah. This comparison shows that the collapse risks for the buildings are different for the same design intensity of MMI VIII. Thus, the same design ground motions, about 1.0 g PSA in San Francisco and Paducah, don't result in a similar collapse risk.

Alternative Seismic Hazard Maps

As stated in the 2009 edition of the NEHRP provisions, "one of the goals 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." Thus, seismic risk estimates are essential for formulating mitigation policies to reduce damage and injury due to earthquakes in the United States. As shown in Figure 9-11, a simple comparison shows that the collapse risk for a single building is 2 to 5 times higher in San Francisco than in Paducah. Similarly, as shown in Figure 9-12, the regional (aggregated) risk in terms of damage and injury will be much higher in the San Francisco Bay area if an M7.8 earthquake occurs along the San Andreas Fault than in the New Madrid area if a similar earthquake occurs along the central New Madrid Fault because the exposures are much higher in the San Francisco Bay area. These simple individual and aggregated risk comparisons between San Francisco Bay area and the New Madrid area suggest that a similar even higher design ground motion in the New Madrid area is not a good policy. As shown on the risk-targeted earthquake ground motion (Fig. 9-8b), the higher MCE_R in the New Madrid area than the San Francisco Bay area is not consistent with basic earthquake science and resulted from the incorrect use of the hazard curves of the national seismic hazard mapping.

The New Madrid region also faces other natural hazards, particularly weather related hazards such as tornados, floods, and ice storms. For example, on February 5–6, 2008, tornados killed 57 people and caused more than $400 million in property damage in Arkansas, Tennessee, and Kentucky, all part of the New Madrid region. A massive ice storm struck several states in the New Madrid region on January 26–29, 2009 and caused 36 fatalities and more than $0.5 billion in damage in Kentucky alone. Between April 25 and 28, 2011, tornados killed 236 people and caused more than $3 billion in damage in Alabama. On May 22, 2011, a deadly tornado killed 141 people and caused more than $3 billion in damage in Joplin, Mo. And in May 2011, a historic flood inundated many areas from southern Illinois all the way down to Louisiana and caused more than $1 billion in damage. We suggest that tornados, floods, ice storms, and other weather-related hazards pose an even higher risk in the New Madrid region than earthquakes do. Therefore, a comprehensive mitigation policy that addresses all natural hazards – tornados, floods, ice storms, and earthquakes in particular – is needed for the New Madrid region.

The lack of a comprehensive assessment of all risks posted by the natural hazards makes it difficult to develop and implement a sound mitigation policy for earthquakes in the central United States, although it is certain that the region is facing seismic hazards

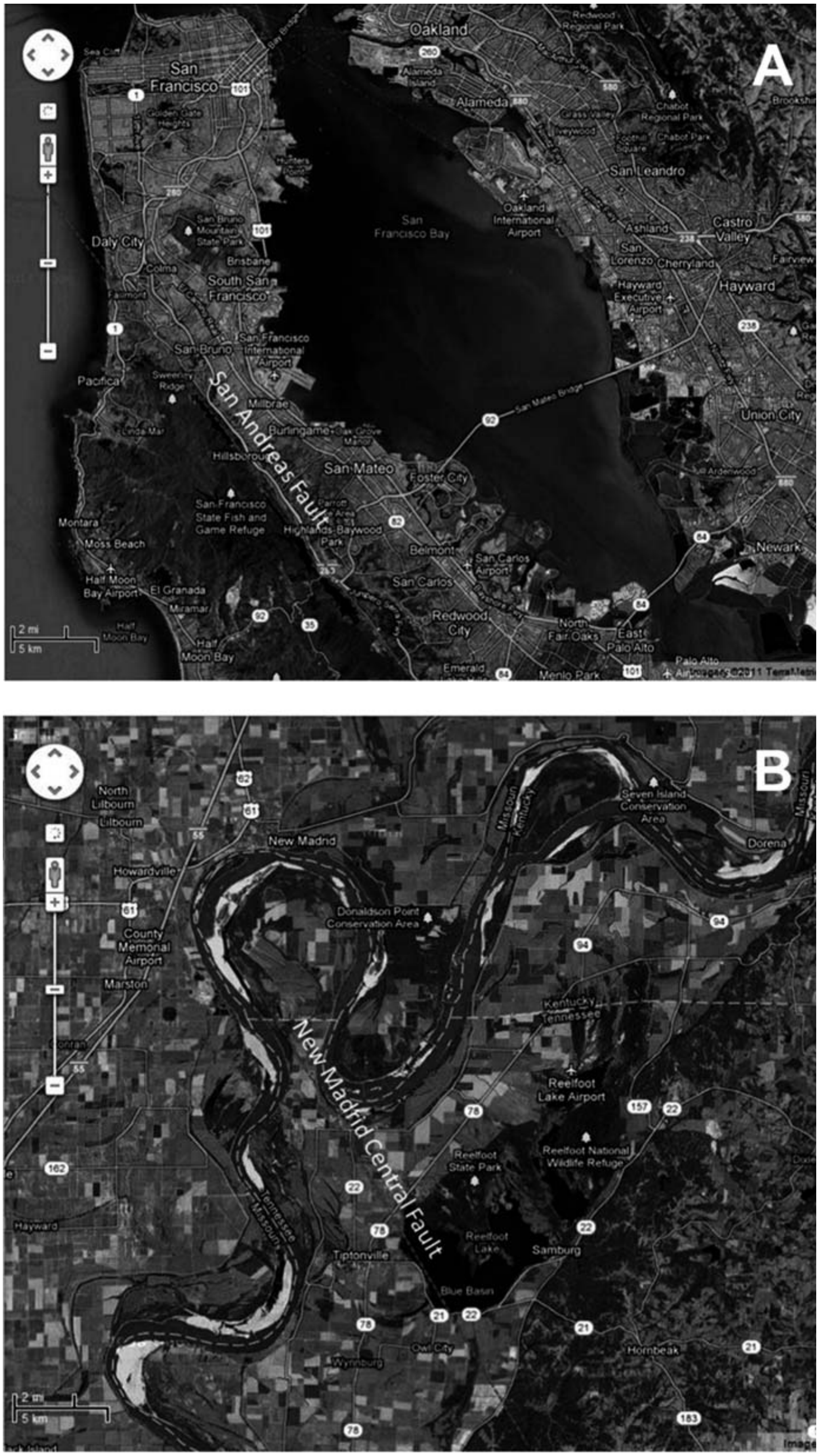


Figure 9-12. Exposure comparisons on Google map bewteen the San Francisco Bay area (A) and the central New Madrid area (B). The red dash line shows the location of the San Andreas Fault and the central New Madrid Fault

and risk. As shown in Figure 9-1, the development of a seismic mitigation policy starts with seismic hazard assessment. As discussed earlier, PSHA is scientifically flawed and the uses of PSHA have caused problems in seismic hazard assessment and resulting risk assessment and mitigation policies. The key question is which method should be used for seismic hazard assessment that would be appropriate for risk assessment and mitigation policy development.

As shown in the NEHRP provisions (BSSC, 1995, 1998, 2009), the design ground motion is capped deterministically in the coastal California (Figs. 9-6–9-8). In other words, the California's experience shows that seismic hazard maps derived from DSHA are appropriate for the NEHRP provisions. As shown by Street and others (1996), Wang and others (2007), and Beavers (2010), DSHA is also more appropriate for developing the ground motions for engineering seismic design considerations. As shown by Beavers (2010), A PGA of 0.36 g at bedrock, derived from a DSHA using the same database as the 2008 national seismic hazard mapping project, is appropriate for engineering design consideration of a landfill at the Paducah Gaseous Diffussion Plant. The resulting design PGA for the landfill was 0.33 g when considering the site response with the input bedrock PGA of 0.36 g. Figure 9-13 shows the deterministic/scenario peak ground acceleration from maximum credible earthquakes for Kentucky (Wang, 2010). The deterministic/scenario ground motion hazard maps (Wang and others, 2007; Wang, 2010) have been used in enginering designs for residential buildings and highway bridges. Thus, the ground-motion hazard maps derived from DSHA would be recommended for the consideration of design ground motion development for the NEHRP provisions.

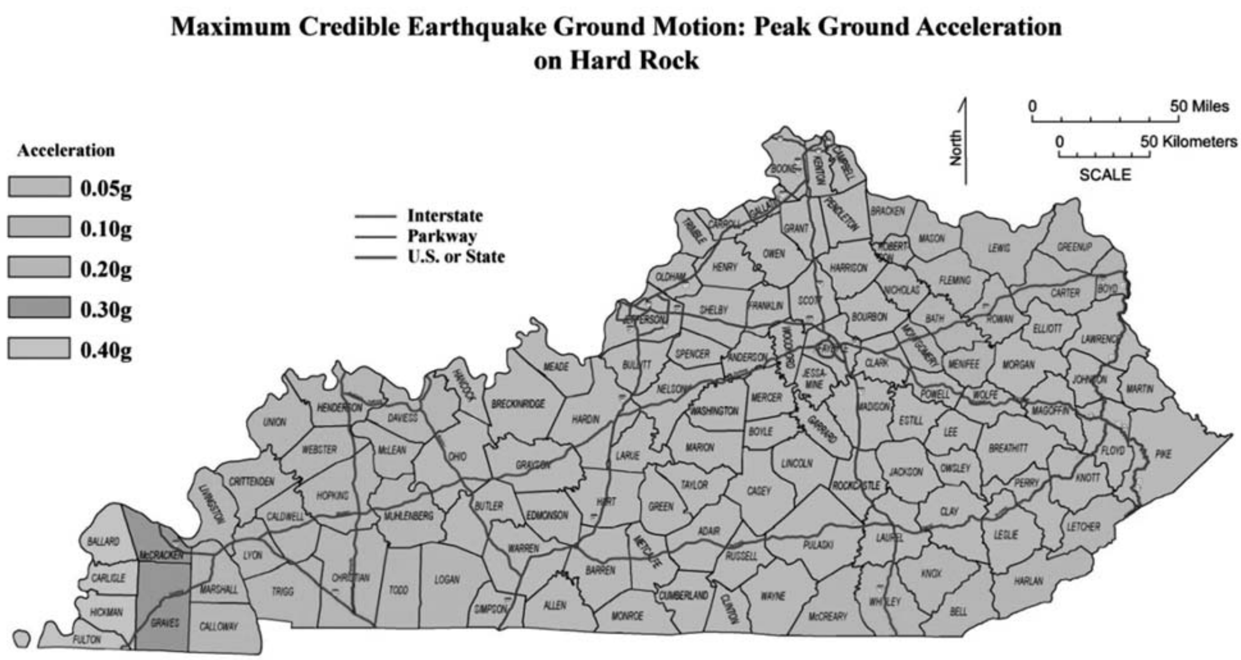


Figure 9-13. Deterministic peak ground acceleration from maximum credible earthquakes for Kentucky (Wang, 2010)

SUMMARY

The understanding of earthquakes in the New Madrid Seismic Zone has advanced greatly through scientific studies supported by the NEHRP program. These advances have resulted in neither a better assessment of seismic hazard and risk, nor a better mitigation policy in the New Madrid region. The main reason for this is the use of PSHA for producing the national seismic hazard maps. PSHA is scientifically flawed, particularly because it contains a mathematical error: equating a dimensionless quantity (i.e., the *annual probability of exceedance* – probability of exceedance in *1* year) to a dimensional quantity with the unit of per year (i.e., the *annual frequency of exceedance*). In other words, the dimensionless quantity (i.e., the annual probability of exceedance – probability of exceedance in 1 year) and dimensional quantity with the unit of per year (i.e., the annual frequency) have been used interchangeably in PSHA. Even though the numbers are equivalent, 1 percent (0.01) = 1 percent (0.01), 1 percent (0.01) in 1 year is not equal to 1 percent (0.01) per year because the dimensions are not equal. The reciprocal of 1 percent (0.01) is 100 and means that the chance of occurrence is 1 in 100, but it is not the average recurrence time in years. Thus, the hazard curves and maps produced from a PSHA are artifacts. In other words, the hazard curves and maps produced from the national seismic hazard mapping project, as well as the resulting risk estimates, are all artifacts.

Although seismic hazard and seismic risk have often been used interchangeably, they are two fundamentally different concepts. Seismic hazard describes the *natural phenomenon* or *property* of an earthquake, whereas seismic risk describes the *probability* of loss or damage that could be caused by a seismic hazard. In other words, seismic hazard emphasizes the physical property of an earthquake, whereas seismic risk emphasizes the probability of adverse consequence that could an earthquake could cause to society. Seismic hazard and seismic risk play different roles in engineering design and other policy considerations. Furthermore, measures for seismic hazard mitigation are different from those for seismic risk reduction. The difficulties in the development of design ground motion for NEHRP provisions are caused by the use of the national seismic hazard maps, because they are artifacts – neither seismic hazard nor seismic risk. The resulting design ground motions for building codes and other policy considerations are problematic.

The actual earthquake experience in coastal California is the basis for the development of the NEHRP provisions and other policies. Although the rules and policy decisions made for the NEHRP provisions have changed greatly along with the advances of science and engineering, the design ground motion for coastal California has not been changed: the same short-period response acceleration of about 1.0 g for San Francisco. This stable design ground motion resulted from the use of DSHA. In other words, DSHA, not PSHA, is the method being used to derive the design ground motions for coastal California. The ground motion hazard maps produced from PSHA have never been used to develop the design ground motion in coastal California. Thus, the ground motions produced from PSHA are not appropriate for development of design ground motion for NEHRP provisions. DSHA is a more appropriate approach for seismic hazard assessment, seismic

risk assessment, as well as engineering design and other policy development in the New Madrid region, as well as other regions.

ACKNOWLEDGMENTS

I thank Meg Smath of the Kentucky Geological Survey for editorial help. I appreciated the great effort by James Beavers for organizing the workshop and putting together this monograph.

References

Advisory Committee on Earthquake Hazards Reduction (ACEHR), 2011, National Earthquake Hazards Reduction Program (NEHRP) bicentennial statement, February 11, 2011.

Algermissen, S.T., and Perkins, D.M., 1976, A probabilistic estimate of the maximum acceleration in rock in the contiguous United States: U.S. Geological Survey Open-File Report 76-416, 45 p.

American Society of Civil Engineers (ASCE), 2010, Minimum design loads for buildings and other structures: ASCE/SEI 7-10, 608 p.

Anderson, G.A., and Brune, J.N., 1999, Probabilistic seismic hazard analysis without the ergodic assumption: Seismological Research Letters, v. 70, p. 19–28.

Atkinson, G.M., and Boore, D.M., 2006, Earthquake ground-motion predictions for eastern North America: Bulletin of the Seismological Society of America, v. 96, p. 2181–2205.

Beavers, J.E., 2010, Seismic hazard reevaluation for the C-746-U contained landfill: A deterministic approach: James E. Beavers Consultants, November 1, 2010, 10 p.

Beavers, J.E., Hall, W.E. and Hunt, R.J., 2013, "Introduction To The 2012 Seismic Hazard Workshop," Seismic Hazard Workshop, Council on Disaster Risk Management, American Society of Civil Engineers, Monograph No. 6, 1801 Alexander Bell Drive, Reston, Virginia.

Building Seismic Safety Council (BSSC), 1995, NEHRP recommended provisions for seismic regulations for new buildings [1994 ed.]: Federal Emergency Management Agency, FEMA 222, 290 p.

Building Seismic Safety Council (BSSC), 1998, NEHRP recommended provisions for seismic regulations for new buildings [1997 ed.]: Federal Emergency Management Agency, FEMA 302, 337 p.

Building Seismic Safety Council (BSSC), 2009, NEHRP recommended provisions for seismic regulations for new buildings [2009 ed.]: Federal Emergency Management Agency, FEMA P-750, 372 p.

Cornell, C.A., 1968, Engineering seismic risk analysis: Bulletin of the Seismological Society of America, v. 58, p. 1583–1606.

Earthquake Engineering Research Institute (EERI), 2011, The M_w 5.8 Virginia earthquake of August 23, 2011: EERI Special Earthquake Report, 13 p.

Frankel, A., 2003, Comments on an article, "Should Memphis Build for California's Earthquakes?": Eos, v. 84, p. 271–273.

Frankel, A., 2004, How can seismic hazard around the New Madrid Seismic Zone be similar to that in California?: Seismological Research Letters, v. 75, p. 575–586.

Frankel, A., 2005, Reply to "Comment on 'How Can Seismic Hazard Around the New Madrid Seismic Zone Be Similar to that in California?' by Arthur Frankel," by Zhenming Wang, Baoping Shi, and John D. Kiefer: Seismological Research Letters, v. 76, p. 472–475.

Frankel, A., Mueller, C., Barnhard, T., Perkins, D., Leyendecker, E., Dickman, N., Hanson, S., and Hopper, M., 1996, National seismic hazard maps: Documentation June 1996: U.S. Geological Survey Open-File Report 96-532, 110 p.

Gupta, R.S., 1989, Hydrology and hydraulic systems: Englewood Cliffs, N.J., Prentice Hall, 739 p.
Haase, J.S., and Nowack, R.L., 2011, Earthquake scenario ground motions for the urban area of Evansville, Indiana: Seismological Research Letters, v. 82, p. 177–187.
Hanks, T.C., 2011, Extreme ground motions: Seismological Society of America annual meeting, Joyner Lecture, Memphis, Tenn., April 13–15, 2011.
Independent Expert Panel on New Madrid Seismic Zone Earthquake Hazards, 2011, Report: 26 p.
International Building Code Council (IBCC), 2012, International building code: 678 p.
Irikura, K., and Miyake, H., 2011, Recipe for predicting strong ground motion from crustal earthquake scenarios: Pure and Applied Geophysics, v. 168, p. 85–104.
Kircher, C.A., Nassar, A.A., Kustu, O., and Holmes, W.T., 1997, Development of building damage functions for earthquake loss estimation: Earthquake Spectra, v. 13, p. 663–682.
Krinitzsky, E.L., 1995, Deterministic versus probabilistic seismic hazard analysis for critical structures: Engineering Geology, v. 40, p. 1–7.
Krinitzsky, E.L., 2002, How to obtain earthquake ground motions for engineering design: Engineering Geology, v. 65, p. 1–16.
Luco, N., Ellingwood, B.R., Hamburger, R.O., Hooper, J.D., Kimball, J.K., and Kircher, C.A., 2007, Risk-targeted versus current seismic design maps for the conterminous United States: Structural Engineers Association of Kentucky 2007 Convention Proceedings, p. 163–171.
Malhotra, P.K., 2008, Seismic design loads from site-specific and aggregate hazard analyses: Bulletin of the Seismological Society of America, v. 98, p. 1849–1862.
McGuire, R.K., 1976, FORTRAN computer program for seismic risk analysis: U.S. Geological Survey Open-File Report 76-67.
McGuire, R.K., 2004, Seismic hazard and risk analysis: Earthquake Engineering Research Institute, MNO-10, 240 p.
McGuire, R.K., 2008, Probabilistic seismic hazard analysis: Early history: Earthquake Engineering and Structural Dynamics, v. 37, p. 329–338.
Milne, W.G., and Davenport, A.G., 1969, Distribution of earthquake risk in Canada: Bulletin of the Seismological Society of America, v. 59, p. 729–754.
Mualchin, L., 2011, History of modern earthquake hazard mapping and assessment in California using a deterministic or scenario approach: Pure and Applied Geophysics, v. 168, p. 383–407.
Musson, R.M.W., 2012a, PSHA validated by quasi observational means: Seismological Research Letters, v. 83, p. 130–134.
Musson, R.M.W., 2012b, Probability in PSHA: Reply to "Comment on 'PSHA Validated by Quasi-Observational Means' " by Z. Wang: Seismological Research Letters, v. 83, p. 717–719.
Peresan, A. Panza, G.F., 2012, Improving earthquake hazard assessments in Italy: An alternative to "Texas Sharpshooting", Eos, v. 93, p. 538.
Petersen, M.D., Frankel, A.D., Harmsen, S.C., Mueller, C.S., Haller, K.M., Wheeler, R.L., Wesson, R.L., Zeng, Y., Boyd, O.S., Perkins, D.M., Luco, N., Field, E.H., Wills, C.J., and Rukstales, K.S., 2008, Documentation for the 2008 update of the United States national seismic hazard maps: U.S. Geological Survey Open-File Report 08-1128, 60 p.
Pezeshk, S., Zandieh, A., and Tavakoli, B., 2011, Hybrid empirical ground-motion prediction equations for eastern North America using NGA models and updated seismological parameters, Bulletin of the Seismological Society of America, v. 101, p. 1859–1870.
Reiter, L., 1990, Earthquake hazard analysis: New York, Columbia University Press, 254 p.
Sachs, P., 1978, Wind forces in engineering [2nd ed.]: Elmsford, N.Y., Pergamon Press Inc., 400 p.
Scherbaum, F. and Kuehn, N, 2011, Logic tree branch weights and probabilities: Summing up to one is not enough: Earthquake Spectra, v. 27, p.1237–1251.

Scherbaum, F. and Kuehn, N, 2012, Capturing epistemic uncertainties in PSHA within a logic tree framework (abstract): the 2012 Seismological Society of America Annual Meeting, April 17-19, 2012, San Diego, CA.

Silva, W.J., and Darragh, B., 2011, Development of design ground motions for the Ohio County contained landfill: Final report: Pacific Engineering & Analysis**,** June 7, 2011, 65 p.

Stein, S., 2010, Disaster deferred: New York, Columbia University Press, 282 p.

Stein, S., Tomasello, J., and Newman, A., 2003a, Should Memphis build for California's earthquakes?: Eos, v. 84, p. 177, 184–185.

Stein, S., Tomasello, J., and Newman, A., 2003b, Should Memphis build for California's earthquakes? Eos, v. 84, 273 p.

Stepp, J.C., Wong, I., Whitney, J., Quittmeyer, R., Abrahamson, N., Toro, G., Youngs, R., Coppersmith, K., Savy, J., Sullivan, T., and Yucca Mountain PSHA project members, 2001, Probabilistic seismic hazard analysis for ground motions and fault displacements at Yucca Mountain, Nevada: Earthquake Spectra, v. 17, p. 113–151.

Street, R., Wang, Z., Harik, I., and Allen, D., 1996, Source zones, recurrence rates, and time histories for earthquakes affecting Kentucky: University of Kentucky, Kentucky Transportation Center, Research Report KCT-96-4, 187 p.

Wang, Z., 2003, Summary for the NEHRP seismic design maps, *in* Wang, Z., comp., The Kentucky NEHRP Seismic Hazard and Design Maps Workshop: Kentucky Geological Survey, ser. 12, Special Publication 5, p. 32–33.

Wang, Z., 2005, Better understanding and communication of the national seismic hazard maps: Summary of USGS-KGS meeting on seismic hazard assessment in western Kentucky: Kentucky Geological Survey, ser. 12, Special Publication 7, 47 p.

Wang, Z., 2006, Understanding Seismic Hazard and Risk Assessments: An Example in the New Madrid Seismic Zone of the Central United States, Proceedings of the 8th National Conference on Earthquake Engineering, April 18–22, 2006, San Francisco, CA, Paper no. 416., Earthquake Engineering Research Institute, Oakland, CA.

Wang, Z., 2007, Seismic hazard and risk assessment in the intraplate environment: The New Madrid Seismic Zone of the central United States, *in* Stein, S., and Mazzotti, S., ed., Continental intraplate earthquakes: Science, hazard, and policy issues: Geological Society of America Special Paper 425, p. 363–373.

Wang, Z., 2009, Seismic hazard vs. seismic risk: Seismological Research Letters, v. 80, p. 673–674.

Wang, Z., 2010, Ground motion for the maximum credible earthquake in Kentucky, Kentucky Geological Survey, ser. 12, Report of Investigations 22, 9 p.

Wang, Z., 2011a, Seismic Risk Assessment and Application in the Central United States, Proceedings of the GeoRisk 2011 Conference, June 26 – 28, 2011, Atlanta, GA, p. 1020–1027.

Wang, Z., 2011b, Seismic hazard assessment: Issues and alternatives: Pure and Applied Geophysics, v. 168, p. 11–25.

Wang, Z., 2012, Comment on "PSHA Validated by Quasi Observational Means" by R.M.W. Musson, Seismological Research Letters, v. 83, p. 714–716.

Wang, Z., and Cobb, J.C., 2012, A critique of probabilistic versus deterministic seismic hazard analysis with special reference to the New Madrid seismic zone, in Cox, R.T., Tuttle, M.P., Boyd, O.S., and Locat, J., eds., Recent Advances in North American Paleoseismology and Neotectonics East of the Rockies: Geological Society of America Special Paper 493, p. 259–275, doi:10.1130/2012.2493(13)

Wang, Z., and Lu, M., 2011, A Short Note on Ground-Motion Recordings from the M7.9 Wenchuan, China, Earthquake and Ground-Motion Prediction Equations in the Central and Eastern United States, Seismological Research Letters, v. 82, p. 731–733.

Wang, Z., Woolery, E.W., Shi, B., and Harik, I.E., 2007, Seismic hazard maps and time histories from earthquakes affecting Kentucky: University of Kentucky, Kentucky Transportation Center, Research Report KTC-07-06/SPR246-02-6F, 96 p.

Wang, Z., Woolery, E.W., Shi, B., and Kiefer, J.D., 2003, Communicating with uncertainty: A critical issue with probabilistic seismic hazard analysis: Eos, v. 84, p. 501, 506, 508.

Wang, Z., Woolery, E.W., Shi, B., and Kiefer, J.D., 2004, Reply to comment on "Communicating with Uncertainty: A Critical Issue with Probabilistic Seismic Hazard Analysis" by C.H. Cramer: Eos, v. 85, p. 283, 286.

Wang, Z., Woolery, E.W., Shi, B., and Kiefer, J.D., 2005, Comment on "How Can Seismic Hazard Around the New Madrid Seismic Zone Be Similar to that in California?" by Arthur Frankel: Seismological Research Letters, v. 76, p. 466–471.

Wang, Z., and Zhou, M., 2007, Comment on "Why Do Modern Probabilistic Seismic-Hazard Analyses Often Lead to Increased Hazard Estimates?" by Julian J. Bommer and Norman A. Abrahamson: Bulletin of the Seismological Society of America, v. 97, p. 2212–2214.

Wheeler, R.L., 2011, Reassessment of Stable Continental Regions of Southeast Asia, Seismological Research Letters, v. 82, p. 971–983.

Zuccolo, E., Vaccari, A., Peresan, A., and Panza, G.F., 2011, Neo-deterministic and probabilistic seismic hazard assessments: A comparison over the Italian territory: Pure and Applied Geophysics, v. 168, p. 69–84.

CHAPTER 10

Developing Resiliency Measures to Reduce Seismic Hazard Impact in the Central United States

Vilas Mujumdar, P.E., S.E.*

INTRODUCTION

When a damaging seismic event occurs in an area, fatalities and injuries happen; damage to building structures and infrastructure systems occurs resulting in short-term and long-term economic losses and disruptions to societal systems. Given a particular damaging seismic event, the consequences of the event on a community depend on several factors: primary among them are the vulnerabilities of physical and socio-economic systems, and exposure to the damaging seismic event. The seismic risk to a community is a function of hazard, vulnerability, and consequences. The impact on the community due to a damaging seismic event is shown in Figure 10-1. The author is of the opinion that the total seismic risk comprises of *technical, economic and societal components*. Thus, the seismic hazard impact reduction needs a community systems-level approach that necessarily includes interaction of technical systems, economic systems, and societal systems within the constraints of existing organizational systems.

In the central US, the most significant area of concern is the New Madrid Seismic Zone (TMSZ) which directly impacts eight adjoining states. However, the area in the Central US which could be impacted due to a major earthquake is much broader (Figure 10-5). Another important factor to consider is that the impact of an earthquake in NMSZ is different than that in the Western US due to significant differences in geology of the two areas.

To minimize the impact of a damaging earthquake, community resiliency must be developed. While some measures of resiliency in physical systems can be quantified, resiliency measures for socio-economic systems are difficult to quantify. Qualitative measures are most appropriate to describe the overall community resiliency. Overall community resiliency can be compared across various regions to deploy resources effectively. This paper provides conceptual framework for developing resiliency measures.

*Consulting Engineer Vienna, VA.

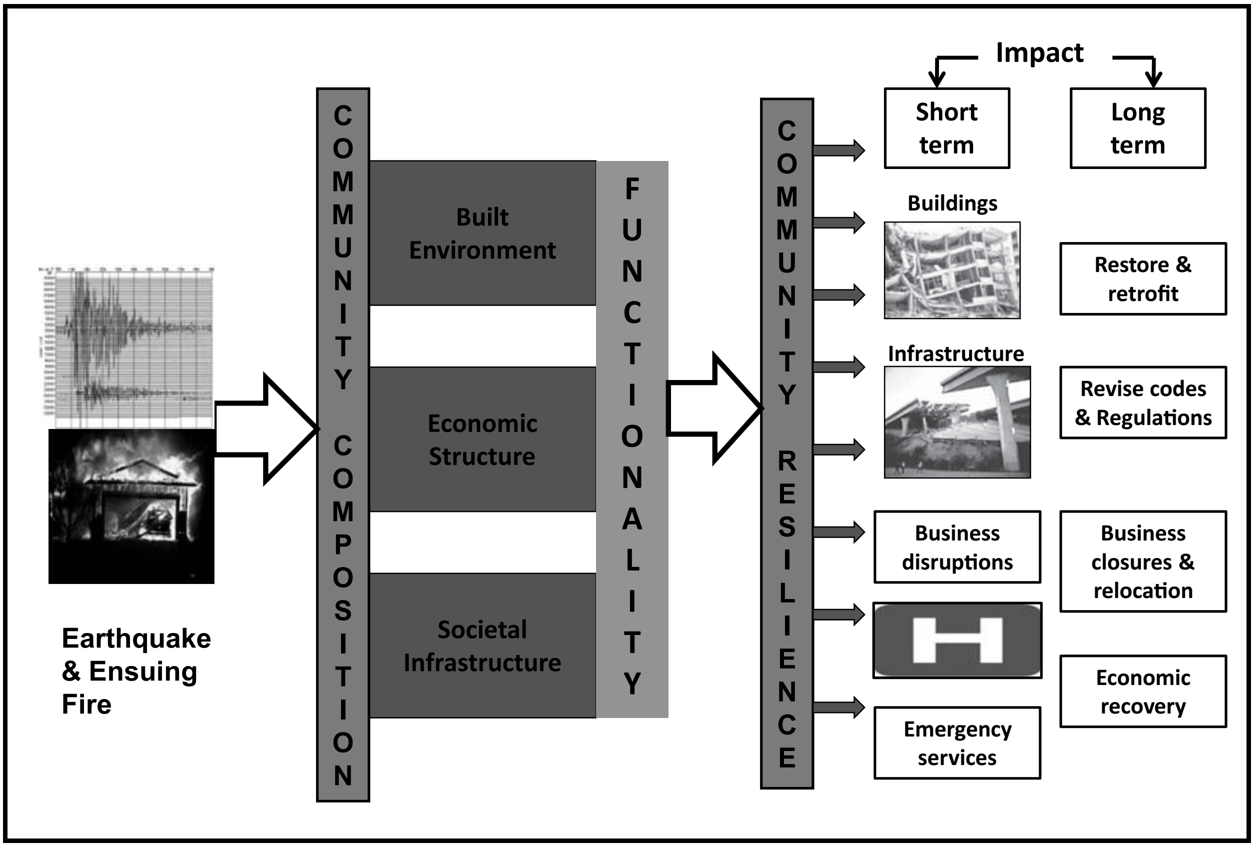


Figure 10-1. Earthquake Impact on Community

COMMUNITY AS A COMPLEX SYSTEM

Technical disciplines, and specifically engineering disciplines concentrate on the design and construction of physical infrastructure systems as that is their professional expertise. It is important to develop latest codes of practice based on research and experience in seismic events, and construct facilities that conform to design and specifications. The assumption inherent in a design is that all sub-systems within the built structure will function properly. The interdependency of systems is ignored as that is nearly impossible to codify; e.g. water and waste-water systems depend on pumping stations which depend on electrical power to operate. In a damaging earthquake event, when electrical power is affected, pumps may not work impacting the water systems and thus the societal daily need. Damage to water system also impacts fire districts compromising their capacity to fight fires following an earthquake, which potentially may ensue. All utility and infrastructure systems require human operations. Human interaction with physical systems creates uncertainty that is not accounted for in calculating risk. Such interdependencies among engineering systems and socio-economic can only be addressed by a total community complex systems approach.

As can be seen from Figure 10-2, technical systems comprise only a part of the total complex community system. To make decisions for resource allocations for mitigation,

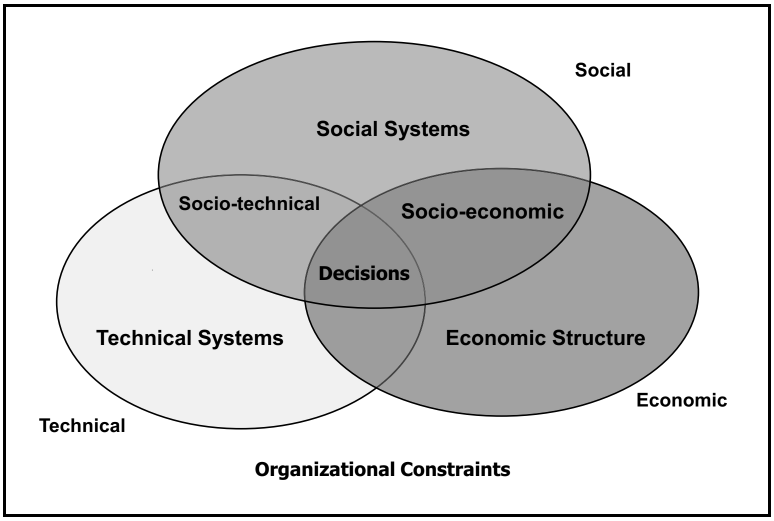


Figure 10-2. Societal Decision-making Model

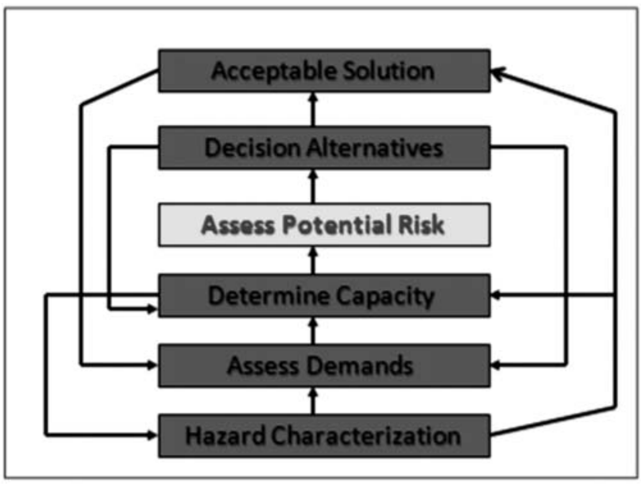


Figure 10-3. Systems Level Approach to Hazard-Response

response and recovery and to build resiliency in a community, various stakeholders are involved and their input is required. A decision-making diagram for a community with various disciplines is illustrated in Figure 10-2.

A total systems-level approach to a natural hazard response is shown in Figure 10-3. This approach is well suited for seismic hazard as well. Although the approach starts with the characterization of the hazard and progresses towards acceptable solution through what appears to be a hierarchy, the progression is neither linear nor simple. Various steps are interconnected and decisions at different steps are interdependent, e.g. available capacity of the system has an influence on potential risk and decision alternatives. Similarly, acceptable solutions may also impact the hazard characterization. This approach is applicable to not only the engineering systems but also to socio-economic systems.

Figure 10-4. Central US and New Madrid Seismic Zone
SOURCE: MAE Center

CENTRAL US – POTENTIAL DAMAGE SCENARIO

The central US, for the purposes of earthquake impact, comprises of eight adjoining states as shown in Figure 10-4, with the highlighted areas denoting the New Madrid Seismic Zone (NMSZ). NMSZ is made up of several thrust faults that stretch from Marked Tree, Arkansas to Cairo, Illinois. The highlighted area denotes the area that could be impacted under an Mw 7.7 magnitude earthquake, according to Mid-America Earthquake (MAE) Center, University of Illinois, Urbana-Champaign, study. USGS, in their study of the area has stated that there is a 25 percent to 40 percent chance of a magnitude Mw 6.0 or greater earthquake in the next 50 years for the central United States. The area of the central US that could be impacted by such an earthquake is shown in Figure 10-5. The impacted area is much larger than in the western US due to differences in geology east and west of the Rocky Mountains. The contrast in impact is exemplified by the historical account of the two earthquakes; the San Francisco, CA, earthquake of 1906 (magnitude Mw 7.8) was felt 350 miles away in the middle of Nevada, whereas the New Madrid earthquake of December 1811 (magnitude Mw 7.7) rang church bells in Boston, Mass. 1,000 miles away.

The eight-state region shown in Figure 10-4 has a population of nearly 47M with a regional gross product of $1.8 T (Bureau of Economic Analysis, US Dept. Commerce,

Figure 10-5. Affected area due to Mw 6.0 Earthquake
SOURCE: USGS

2011). Under a study by MAE Center (2008), a scenario earthquake of Mw 7.7 (the same magnitude that of 1811 earthquake) could potentially have the following impact on the eight-state region:

- 3500 fatalities, 82,500 injured (20,000 requiring hospitalization)
- A total of 2.6 million households without power immediately after the event
- A total of 1.1 million households without water
- The outages may last several weeks or months depending upon the extent of damage to infrastructure
- 60% of Unreinforced Masonry Buildings (URM) and wood-frame buildings damaged (96% of all low-rise buildings are URM and Wood-frame)
- 800 essential service facilities completely damaged
- 1225 bridges completely damaged
- Direct economic loss ~ $300B (nearly 16% of Regional Gross Product)

These are dire scenario projections, and do not even take into account the consequent impact on rest of the country because central US is the transportation hub for the country and many goods are warehoused and shipped from central US to the rest of the country. In a globally connected economy, the impact goes beyond the US border and may be felt globally.

INTERDEPENDENCY OF SYSTEMS

A *system* can be defined as a group of independent elements or subsystems linked together that interact coherently and synergistically forming a unified whole to achieve a beneficial purpose. Linkages among various elements of the system are extremely important. For the system to be responsive, it is necessary to have feedback loops as their input along with the types of linkages determine and modify the behavior of the entire system. Civil physical infrastructure systems are static and do not have feedback loops for behavior modification. Socio-economic systems though, are dynamic and may modify the behavior of the system based on the feedback. It can be concluded that the total community system is comprised of static and dynamic components. The types of linkages among various sub-systems are shown in Figure 10-6.

Interdependency in physical systems causes cascading effects and impacts the functioning of a community beyond the physical locations of damage. Thus, modeling interdependency among various infrastructure systems is critical to understanding the behavior of the total engineering system.

Interdependencies can be grouped in four categories (Rinaldi, 2001): *physical, geographic, cyber, and logical.* Although these categories are helpful in understanding interdependencies, this author proposes a specific categorization of interdependencies based on their influence, for physical civil infrastructure systems: *system engineering design basis; operational basis*. Following examples of interdependency are given for illustration purposes only:

(i) System engineering design basis

- Water system with electrical network
- Transportation network with electrical network

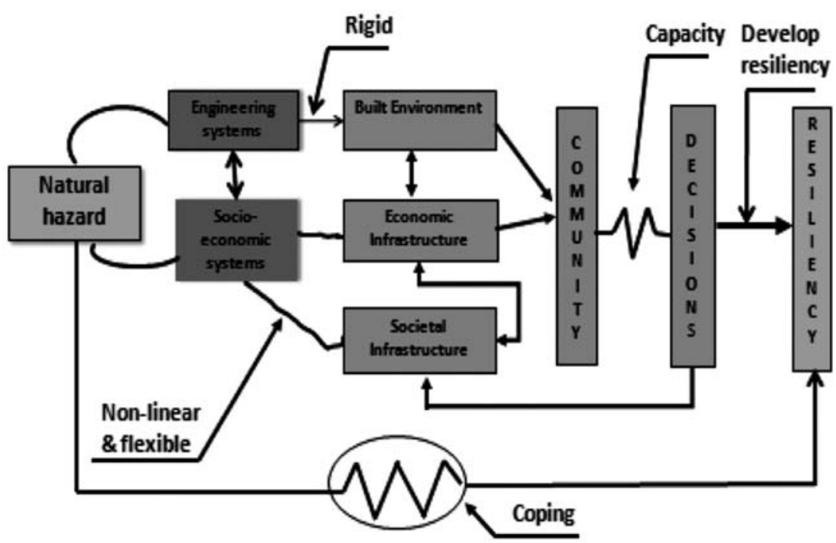


Figure 10-6. Linkages of Sub-systems

- Electrical network with communication systems
- Wastewater system with electrical network

(ii) Operational basis

- Hierarchical – within organizations
- Organizational – between organizations
- Socio-economic systems

When an earthquake damages the electrical network, water systems are impacted because the pumping stations may be affected. This consequence is in addition to the direct damage to the water system due the earthquake. Therefore, the water system is considered dependent on the electrical network. To determine the impact of damaged water system on customers, the dependence of the water system on the electrical system needs to be assessed and modeled. Similarly, electrical network affects transportation network as traffic signals depend on electrical power. To assess the combined effect requires deriving *joint fragilities* for interdependent systems. The extent of dependency of each system on one another needs to be determined. Degree of interdependency between systems depends on the different factors such as redundancy, existence of back-up system, design-basis, and operational-basis. Once assessed, dependency can be categorized, such as *high, medium, low, very low or none.* Numerical scores can be assigned to each category.

Operational dependency relationships require a different approach as many stakeholders are engaged and their specific decision-behavior has to be taken into account. A proposed methodology for determining operational-level interdependency is *agent-based* modeling. An example of water system dependency on various systems is shown in Figure 10-7. It considers both the system design-basis and operational-level interdependencies.

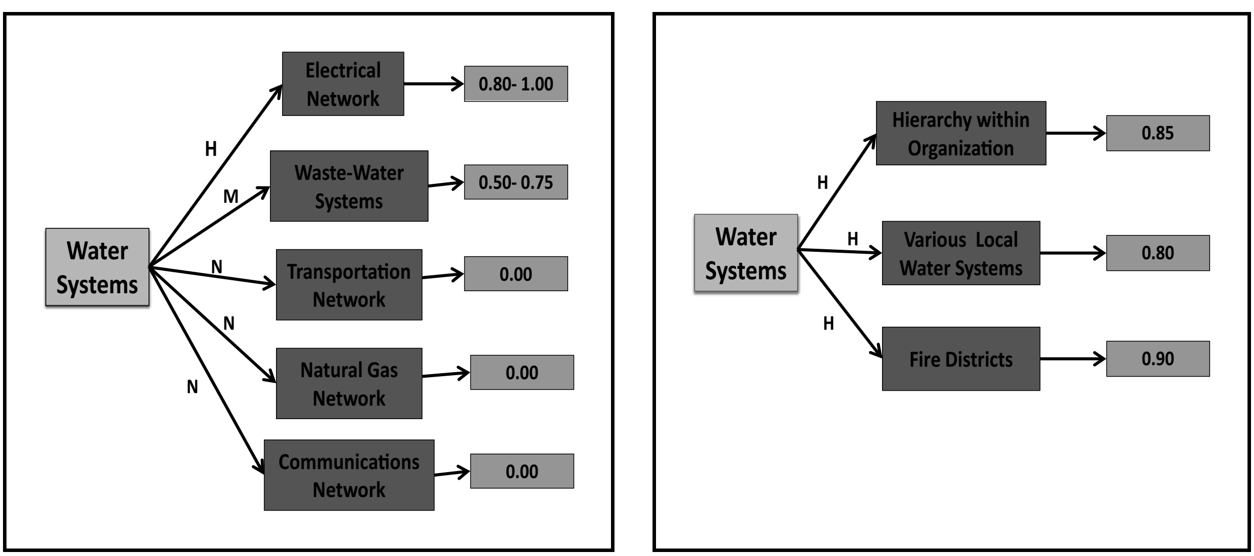


Figure 10-7. (a) System-design basis interdependency (b) Operational-level interdependency

Once the Interdependency relationships are defined, systems can be evaluated and actions can be taken for enhancing system-level resiliency to reduce hazard impacts.

RESILIENCY

The engineering definition of resiliency has its roots in elasticity of materials and their behavior under compressive loads. It is defined as *"the ability of a material to come back to its original shape after it is deformed particularly under compressive forces not exceeding the elastic limit"*. This definition is neither suitable for understanding resiliency of engineering systems nor for understanding the behavior of community complex system.

By its very concept community resiliency is multi-disciplinary. In this context the dictionary definition of resiliency, *"the human ability to recover quickly from disruptive change, or misfortune without being overwhelmed or acting in dysfunctional or harmful ways"* is more suitable for describing community resiliency and is used in this paper.

The overall goal of resiliency is to reduce the impact of the hazard on the community at–large and specifically in the central US as that is region of concern for this paper.

In general, resiliency can be assessed by the *time required* to restore:

- Built environment,
- Economic activity, and
- Societal services needed for normal functioning

To understand community resiliency better, this author has decomposed it in three components: *technical, economic and social*, as shown in Eq. 10-1. It is to be noted that although decomposed, these components are interdependent.

$$\mathbf{R_C} = \sum \mathbf{R_B}, \mathbf{R_E}, \mathbf{R_S} \,|\, \mathbf{F} \qquad \text{Eq. 10-1}$$

Where,

R_C = Total Community resiliency
R_B = Resiliency of Built Environment
R_E = Economic System resiliency
R_S = Societal System resiliency
F = Functionality

Although it is possible to quantify resiliency of built environment systems, quantifying overall Community Resiliency in numerical terms is difficult; therefore, qualitative descriptions such as ***very low, low, medium, high and very high*** are used. Functionality can be graded as ***poor, average, and good.***

(a) Resiliency Determinants

On a broad-basis, resiliency can be thought of as originating from two disparate areas: system design; operations.

System Design

Once a technical system, such as a utility network is designed and constructed, capacity of the system to respond to a demand is determined and cannot be easily changed. Thus, when subjected to seismic hazard, its overall response is predetermined to a large-degree although local damages to its components may alter the overall response. For example, when a water system is damaged in an earthquake, consumers are left without water. However, depending upon the damage to specific pipes, only a part of the water system may be affected thus modifying the resiliency of the overall system.

Operations

All engineering systems are operated by human beings and are subject to human response in an earthquake event. Depending on the demand from other interconnected systems, operation of a system can changed thus changing this resiliency component. For example, when certain pump stations in a water system network are damaged in an earthquake, the operator may call upon the electrical network operator to have power to those specific pump stations restored earlier than others, if it is possible in the inherent system design. Such an action would restore the water system quicker and enhance its resiliency.

As stated earlier in the paper, most of the buildings in the central US are of unreinforced masonry or wood frame. Their resilience to damaging earthquake event is low. Similarly, the utility systems are old and exact locations of underground utility pipes may not even be known, making them vulnerable to damage due to ground movement. Other infrastructure systems are also old and are in need of repair. All these existing conditions offer *low resilience* to a damaging seismic event in the central US.

(b) Resiliency Components

Each of the components, *Built Environment resiliency $R_{B,}$ Economic System resiliency R_E, and Social Systems resiliency $R_{S,}$* is discussed considering the two determinants: system design, and operations.

Built Environment Resiliency – R_B

The factors which make up this component are:

System design:

I. *Design codes and Regulations*: updated design codes and regulations based on experience in recent earthquake events, research, and advanced modeling techniques will enhance resiliency.

II. *Network Redundancy*: Previously, redundancy in structural systems was emphasized in resisting earthquake forces. However, there has been a noticeable trend towards designing structural systems with specific elements that are designed to fail in an earthquake thus dissipating energy and keeping the rest of the structural system relatively undamaged. In network systems, similar trend can be noticed. Due to lack of redundancy, resiliency is reduced. Alternate paths to dissipate energy always increase resiliency.

III. *Robustness of components and overall network*: A network is only as robust as its weakest component. Increasing robustness of components increases resiliency of the overall network.

IV. *Shock-absorbing design*: Shock absorbing elements play a significant part in the earthquake-resistant design. These may also include isolation techniques, damping techniques etc. With advances in modeling and composite materials, resiliency can be increased significantly in some facilities such as hospitals.

V. *Self–repairing capacity of components*: Advanced memory-alloys, when appropriately placed and used can increase resiliency as they are designed to self-repair without external help.

VI. *New Materials and Properties*: Material science advances have given us several composite materials from fiber-reinforce concrete to polymer-modified concrete, to just name a few. Properties of materials are also being looked anew considering nano-structures. All these developments modify resiliency. Some materials may not be suitable for earthquake resistant construction and may actually decrease resiliency.

VII. *Quality of construction*: One of the most significant aspects in built environment is the quality of construction. It is normally assumed that construction follows the design intent and specifications. However, as is evident from many failures in earthquake events around the world, that in spite of good building codes and regulations, construction quality is compromised and did not meet the design specifications. Such deviations from design intent cause resiliency to decrease significantly.

Operations:

a. *Enforcement of codes and regulations:* The codes and regulations may be advanced and updated regularly, but their enforcement is always left to the regulatory authorities. In many countries, such as Japan no special construction inspectors are employed. The practice is to trust the contractor to follow the design intent. In central and other parts of US except in California, regulatory authorities do not employ qualified professionals, thus compromising the enforcement of codes and regulations. This certainly impacts the resiliency.

b. *Maintenance of networks*: This has been a continuing problem in the US. Not sufficient resources are allocated to properly maintain the public infrastructure networks. Where the utilities are privately owned, maintenance is generally undertaken to assure that the system delivers its promised services. However, with the smallest incidence of overstress, system failures are known to happen, indicating that maintenance is barely adequate. This aspect is particularly critical in the central US as the networks are old and not designed to withstand a major earthquake shock.

c. *Review of age and condition of networks*: Every three years, ASCE undertakes a review of the nations' infrastructure and produces a report card. The current grade for the infrastructure is "D" indicating a serious need to upgrade the infrastructure. To provide adequate funding for upgrade is a resource allocation issue with political consequences.

d. *Retrofit requirements and incentives for retrofit*: Older structures, particularly where people gather daily, need upgrade. However, unless mandated through regulatory process, there is little incentive for the owners to do so. Creating regulations for retrofit is a complicated issue as many stakeholders influence the process. In the central US, where no earthquake events have occurred for decades, it is not on anyone's priority list.

Economic Resiliency – R_E

The factors which make up this component are:

System design:

I. *Economic structure of the community*: Better the economic structure of a community, greater the resiliency, as resources are available for preventive measures. Many parts of central US are economically poor not affording the necessary resources.

II. *Low-cost business insurance:* Experience in major earthquake events around the world and particularly in California, has demonstrated that many small businesses that were seriously impacted did not have the ability to restart their businesses. They did not carry the business insurance due to high premium costs and thus went out of business due to damage to their facilities affecting the economic environment of a community. Unless premiums are affordable, small businesses which are the prime drivers of economic activity in a community, would suffer the same fate in the central US impacting the economic resiliency adversely.

III. *Government policies to promote business environment*: This is a policy issue and local and state governments are responsible for creating a business friendly environment. Better the environment, greater the resiliency.

IV. *Infrastructure to conduct daily business*: In addition to creating business friendly policies, it is also necessary to create adequate economic and physical infrastructure to conduct business. Lack of adequate infrastructure results in negative impact on resiliency.

V. *Availability of needed workforce*: Depending on the nature of business, workforce availability for that type of business is a priority. If suitable workforce is not available, businesses will relocate to other areas impacting the economic mix of the community. It also important to educate and train the local workforce suitable for the business requirements.

Operations:

a. *Business association to address common issues*: If a credible association of businesses in the area exists, they can speak with one voice and also coordinate actions to mitigate earthquake hazard thus increasing resiliency.

b. *Emergency plan for workforce*: Most businesses in California have an emergency plan to evacuate employees in an earthquake. However, such a case may not be true in central US, where the frequency of earthquakes is very rare. Unless an emergency plan is in place, tremendous confusion in an actual event results, causing more casualties than necessary.

c. *Ability to quickly restart business*: To continue a business during an earthquake event or soon thereafter is beneficial to community, Ability to quickly restart a business increases resiliency by minimizing the time.

d. *Partnership with other businesses and various agencies*: Partnerships with other business entities and various governmental and non-governmental agencies creates a cohesive and coordinated action to prepare for and respond to an earthquake event.

Societal Resiliency – R_S

The factors which make up this component are:

System design:

I. *Established social institutions*: Stronger the social institutions with well established organizational structure and operational procedures, the greater the resiliency.

II. *Community volunteer groups*: Community volunteer groups serve a very useful need in an earthquake event; however, their actions must be coordinated and focused.

III. *Established lines of communications*: Experience shows that a lot of effort is wasted in responding to an earthquake event if communication hierarchy is not established prior to the event. This decreases resiliency. It is important that lines of communications be clearly known and identifiable.

IV. *Community facilities for temporary housing*: Temporary housing for displaced persons is required in an earthquake event. Usually, facilities such as public schools are used for this purpose. However, the school facilities must be functional. If they are also damaged, this important resource is no longer available. In the central US, unless, the schools are upgraded to meet the current seismic codes, this resource will not be available for temporary housing thus impacting the resilience negatively.

V. *Stock of basic supplies for 72 hours*: Since many businesses will be closed and transportation routes may not be available, and utilities may be damaged, it is important for community members to keep a supply of basic necessities that would last for at least 72 hours.

Operations:

a. *Regular evacuation drills*: Evacuation response can be efficient if it is practiced on a regular basis. While, such a practice exists in Japan, it is not yet a reality in the US. A regular evacuation drill will save many lives and increase resiliency.

Table 10-1. Resiliency Comparison

	Central US EQ (?)	*Chile EQ (2010)*	*New Zealand EQ (2010,2011)*
R_B	Low	Medium/High	High
R_E	High	Medium	High
R_S	Medium	Low/Medium	High/Very High
Functionality (F)	Average	Average	Average/Good
Overall Resiliency R_C	**Medium**	**Medium**	**High**

b. *Available evacuation routes*: It is to be recognized that some traffic routes will be closed during an earthquake event. It is important to identify the routes that will still be operable after an event.

c. *Community education in risk and risk management*: This aspect cannot be overemphasized. Very little education is given to community members in risk and risk management. A deliberate effort in this regard will go a long way in increasing community resiliency.

The author assessed resiliency in the Chile earthquake (2010) and New Zealand earthquakes (2010, 2011) and the results are shown in Table 10-1 with an assessment of resiliency for the central US region in a potentially damaging earthquake.

Functionality – F

Functionality of various systems refers to their actual operations. In spite having built the resiliency in the design, systems may not function adequately due to some other constraints which cannot be modeled. For example, government policies may prevent from taking certain actions, large corporations might want to protect their image by restricting certain information, etc. As these actions cannot be predicted or modeled, their impact can only be felt during response to an earthquake event. Functionality can be graded as *poor, average, and good*.

CONCLUSIONS

a. The impact of an earthquake event depends not only on its intensity and duration but also on the pre-existing conditions in a community

b. Pre-existing conditions can be assessed in three broad areas: *built environment, economic structure and social institutions.* These conditions decide the resiliency of each component

c. Functionality/operations of various systems play a critical role in determining resiliency of each component

d. Overall resiliency of a community comprises of resiliency *of built environment, resiliency of economic structure, and resiliency of social institutions*

e. A well defined organizational structure and clarity in hierarchical responsibilities and clear lines of communications are necessary

f. It is almost impossible to assign numerical score to each component of community resiliency. The overall community resiliency can best be described on a *five measure qualitative scale varying from very high to very low*

g. By comparing various communities, impacts can be compared and priorities for can deploying resources effectively can be generated for enhancing resiliency

h. Enhancing community resilience results in minimizing the impact of a an earthquake Hazard

References

1. American Lifelines Alliance Power Systems, Water, Transportation and Communications Lifeline Interdependencies March 2006 (DRAFT).
2. Bureau of Economic Analysis, US Dept. Commerce, 2011.
3. Department of Homeland Security, National Infrastructure Protection Plan 2006. Department of Homeland Security.
4. Mid-America Earthquake Center, Reports on "Impact of Earthquakes in the Central USA" (2008, 2010), University of Illinois, Urbana-Champaign, IL.
5. Mujumdar, V., "Multi-hazards, Vulnerability, Mitigation, and Decision-making in Public policy Context", Short invited Graduate Course, University of Illinois, Urbana-Champaign, IL, Feb.2009.
6. Rinaldi, S, Peerenboom, J, and Kelly, T. Identifying, Understanding and Analyzing Critical Infrastructure Interdependencies. IEEE Control System Magazine; 21:11–25.

Index

Page numbers followed by *e, f,* and *t* indicate equations, figures, and tables, respectively.