Seismic Risk Analysis of Nuclear Power Plants

Seismic Risk Analysis of Nuclear Power Plants addresses the needs of graduate students in engineering, practicing engineers in industry, and regulators in government agencies, presenting the entire process of seismic risk analysis in a clear, logical, and concise manner. It offers a systematic and comprehensive introduction to seismic risk analysis of critical engineering structures focusing on nuclear power plants, with a balance between theory and applications, and includes the latest advances in research. It is suitable as a graduate-level textbook, for self-study, or as a reference book. Various aspects of seismic risk analysis, from seismic hazard, demand, and fragility analyses to seismic risk quantification, are discussed, with detailed step-by-step analysis of specific engineering examples. It presents a wide range of topics essential for understanding and performing seismic risk analysis, including engineering seismology, probability theory and random processes, digital signal processing, structural dynamics, random vibration, and engineering risk and reliability.

Seismic Risk Analysis of Nuclear Power Plants

WEI-CHAU XIE
University of Waterloo

SHUN-HAO NI
Candu Energy Inc.

WEI LIU
Candu Energy Inc.

WEI JIANG
Candu Energy Inc.

CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE
UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom

One Liberty Plaza, 20th Floor, New York, NY 10006, USA

477 Williamstown Road, Port Melbourne, VIC 3207, Australia

314–321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre, New Delhi – 110025, India

79 Anson Road, #06–04/06, Singapore 079906

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of education, learning, and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/9781107040465
DOI: 10.1017/9781139629010

First published 2019

Printed in the United Kingdom by T.J. International Ltd, Padstow, Cornwall

A catalogue record for this publication is available from the British Library.

Library of Congress Cataloging-in-Publication Data

Names: Xie, Wei-Chau, 1964– author.
Title: Seismic risk analysis of nuclear power plants / Wei-Chau Xie (University of Waterloo) [and three others].
Description: Cambridge ; New York, NY : Cambridge University Press, 2018. | Includes bibliographical references and index.
Identifiers: LCCN 2018026579| ISBN 9781107040465 (hardback : alk. paper) | ISBN 9781139629010 (alk. paper)
Subjects: LCSH: Nuclear power plants–Earthquake effects. | Nuclear power plants–Risk assessment. | Nuclear power plants–Safety measures. | Earthquake hazard analysis.
Classification: LCC TK1078 .S36275 2018 | DDC 621.48/35–dc23
LC record available at https://lccn.loc.gov/2018026579

ISBN 978-1-107-04046-5 Hardback

Cambridge University Press
978-1-107-04046-5 — Seismic Risk Analysis of Nuclear Power Plants
Wei-Chau Xie , Shun-Hao Ni , Wei Liu , Wei Jiang
Frontmatter
More Information

Contents

Preface

Background

Earthquakes are among the most destructive natural disasters. The Great East Japan earthquake, measuring 9.0 on the moment magnitude scale, hit Japan on March 11, 2011; the earthquake and the subsequent tsunami caused severe damage to a large number of critical engineering structures. For example, twenty-six Shinkansen bridges were damaged in the earthquake, resulting in major transportation system disruption in Japan for weeks. A total of eleven nuclear reactors shut down automatically following the earthquake. Although seismic forces did not cause any structural failure at the Fukushima Nuclear Power Plant (NPP), the flood caused by the ensuing tsunami led to a series of equipment failures, nuclear meltdowns, and releases of radioactive materials at the Fukushima Daiichi NPP. It was the largest nuclear disaster since the Chernobyl disaster of 1986 and only the second disaster to measure Level 7 on the International Nuclear Event Scale. On the other hand, the Onagawa NPP, which is the closest NPP to the epicentre, rode out the monster earthquake unscathed, demonstrating that the existing seismic design approaches have been tested by a real case of beyond design basis earthquake.

In response to the several destructive earthquakes that have occurred in recent decades, seismic risk analysis for critical engineering structures has become one of the most important and popular topics in earthquake engineering. Nuclear energy industries worldwide have launched an unprecedented and extensive re-evaluation of seismic hazards and risk to NPP systems. Furthermore, nuclear energy regulators and utilities are taking a critical look at the existing methods of estimating the seismic risk of NPPs. A number of deficiencies have been recognized in the existing methodologies of seismic risk analysis and design, which need improvements to enhance their reliability and effectiveness.

Seismic risk analysis involves a wide range of disciplines and topics, including engineering seismology, probability theory, seismic hazard analysis, seismic design earthquakes, random processes and digital signal processing, structural dynamics and random vibration, seismic fragility analysis, system reliability analysis, and seismic risk assessment. However, there is currently no book that presents a systematic introduction to and discussion on various aspects of seismic risk analysis for engineering structures, in particular NPPs, to graduate students and practicing engineers.

Objectives

This book addresses the needs of graduate students in engineering, practicing engineers in industry, and regulators in government agencies and aims to achieve the following objectives:

- **To present the entire process of seismic risk analysis in a clear, logical, and concise manner**
  Seismic risk analysis is an integral and systematic framework, in which all individual components (e.g., seismic hazard analysis, seismic demand analysis, and seismic fragility analysis) not only play their own roles but also interrelate with each other. This book is suitable not only as a textbook for graduate students in civil engineering, mechanical engineering, and other relevant programs but also as a reference book for practicing engineers and government regulators.
- **To have a balance between theory and applications**
  The book can be used as a reference for engineering graduate students, practicing engineers, and government regulators. As a reference, it has to be reasonably comprehensive and complete. Detailed step-by-step analysis for each topic of seismic risk analysis is presented with engineering examples.
- **To include the latest research advances and applications**
  Significant progress has been made on most of the topics in seismic risk analysis in the past decades. The latest research advances in improving the existing seismic risk analysis methods, including many contributions from our research team, are presented in the book.

Scope and Organization

In Chapter 1, various types of NPPs, important structures, systems, and components (SSCs) in NPPs, general seismic design philosophy, and seismic requirements for NPPs are briefly introduced. In Section 1.4, the procedure of seismic risk analysis of an NPP is outlined, which includes seismic hazard analysis, seismic demand analysis, seismic fragility analysis, system analysis, and seismic risk quantification.

In Chapter 2, fundamental principles, definitions, and terminologies in engineering seismology that are essential to the seismic risk analysis of NPPs are presented.

In Chapter 3, basic theory of random processes, structural dynamics, and random vibration is presented, which is essential background knowledge to engineering analysts in earthquake engineering.

The organization of the remainder of the book follows the general procedure of seismic risk analysis of NPPs as presented in Section 1.4.

Chapters 4–6 are on seismic hazard analysis to provide response spectra and spectra-compatible ground-motion time-histories for seismic demand. Chapter 4 introduces seismic response spectra, including ground response spectra and t-response spectra, which are used in the direct method for generating floor response spectra (FRS) in Chapter 8. Chapter 5 presents seismic hazard analysis, including probabilistic seismic hazard analysis (PSHA), seismic hazard deaggregation (SHD), and site response analysis. Chapter 6 introduces various methods for generating spectrum-compatible time-histories, such as Fourier-based, wavelet-based, and Hilbert–Huang transform-based spectral matching algorithms. A new method using eigenfunctions for generating consistent, drift-free, and spectrum-compatible time-histories is also presented.

Chapters 7 and 8 are on seismic demand analysis. In Chapter 7, general principles and approaches for modelling a structure into a dynamic 3D finite element model or stick model are presented. Chapter 8 presents methods for generating FRS, which are the seismic input to SSCs in an NPP. The methods presented include time-history method, direct spectra-to-spectra method for fixed-based models and considering soil–structure interaction, and the scaling method.

Chapter 9 introduces the general methods for seismic fragility analysis of SSCs, including the method of fragility analysis, high confidence and low probability of failure (HCLPF) values, and conservative deterministic failure margin (CDFM) method for determining HCLPF values. To illustrate the general approach of fragility analysis, two detailed examples on horizontal heat exchanger and masonry block wall are worked using both the fragility method and the CDFM method.

In Chapter 10, basic principles and methods of system analysis are introduced first. Two methods of seismic risk quantification, i.e., seismic margin assessment (SMA) and seismic probabilistic safety assessment (seismic PSA), are presented.

Appendix A reviews important properties and results of normal distribution and lognormal distribution.

In Appendix B, some relevant topics in digital signal processing are presented, including sampling, Fourier transforms, digital filter, and resampling a signal at a different rate, which are important in processing real earthquake records and generating spectra-compatible artificial ground-motion time-histories.

Acknowledgements

First and foremost, our sincere appreciation goes to Candu Energy Inc. (formerly Atomic Energy of Canada Limited), in particular Han Ming, who has always supported the training and growth of students and graduates from the University of Waterloo. We are very grateful to Dr. Binh-Le Ly, who has offered many insights and directions on seismic analysis and design. We appreciate the support and collaborations of our colleagues at Candu Energy Inc. We are grateful to the members of CSA N289 Technical Committee on Seismic Design for their encouragement and feedback on our research progress.

The Collaborative R&D grants from the University Network of Excellence in Nuclear Engineering (UNENE) and Natural Sciences and Engineering Research Council

(NSERC) in Seismic Risk Analysis of Nuclear Power Plants are greatly appreciated. These grants helped support collaborative research between the University of Waterloo and Candu Energy Inc. and training of PhD students at the University of Waterloo.

Dr. Zhen Cai has carefully read the book and made many helpful and critical suggestions. A number of graduate students at the University of Waterloo have reviewed and commented on portions of various drafts of this book.

Our sincere appreciation goes to Peter Gordon, former Senior Editor, and Steven Elliot, Senior Editor, Engineering, Cambridge University Press, for their trust, encouragement, and hard work to publish this book.

Wei-Chau Xie: I am grateful to my former graduate students, collaborators, co-authors, and friends, Wei Liu, Shun-Hao Ni, and Wei Jiang for their hard work during this long process and for contributing their expertise in various areas of seismic risk analysis to make this book possible.

This book is dedicated in the loving memory of my beloved mother, who passed away on Good Friday of 2016. She had always unconditionally loved and supported me. I thank my wife Cong-Rong for her love, encouragement, and support. I am very grateful to my lovely daughters, Victoria and Tiffany, for their love and encouragement. I am thrilled that we have a positive influence on their value system; they have developed great work ethics and, through hard work, have achieved great success in their academic and professional careers.

Shun-Hao Ni: I would especially like to express my sincere appreciation to Dr. Wei-Chau Xie, my professor and the leading author of this book, who has led me into the world of seismic-related research of nuclear power plants. His encouragement, guidance, and support not only enabled me to develop an understanding of the subject, but also brought us together to initiate a plan for writing this book.

Many thanks to all who have inspired, supported, and helped me during the course of writing this book. I would like to extend my gratitude to many people who have supported and helped me in various ways in my professional career, including my graduate co-supervisor, Professor Mahesh D. Pandey of the University of Waterloo.

I would like to acknowledge with gratitude, the unflagging love, support, and encouragement from my family, especially my mother, my wife, Qi Sun, and my lovely son, Kai.

Wei Liu: First and foremost, I would like to thank my mentor, Professor Xie, for his inspiration and motivation in my life and career development. Special thanks to my family, especially my two daughters, Catherine and Helen, for always cheering me up and keeping me going. I hope that one day they can read this book and understand the seismic issues that I have been working on.

Wei Jiang: I would like to express my deepest gratitude to Professor Wei-Chau Xie, who is the supervisor for my PhD study, for enabling me to be a part of this book. I would like to thank him for inspiring me and for allowing me to grow in all aspects of life. His guidance on both research and my life have been invaluable.

I am also truly grateful to my friends and colleagues at University of Waterloo and Candu Energy Inc. for their continuous help and valuable suggestions on my career.

I want to thank my wife, Bingqian Zhou, who understood, supported, and encouraged me despite all the time it took me away from her. It was a long and difficult journey for her.

I thank my parents, my parents-in-law, and my family. This chapter of my life would be less fulfilling without their unflagging love and unconditional support throughout these years.

We appreciate hearing your comments via email (xie@uwaterloo.ca).

Nomenclature

ACI	American Concrete Institute
AEP	annual exceedance probability
AFE	annual frequency of exceedance
ARS	acceleration response spectrum/spectra
ASCE	American Society of Civil Engineers
BH	borehole
BNSP	balance of nuclear steam plant
BOP	balance of plant
BWR	boiling water reactor
CD	core damage
CDF	core damage frequency
	cumulative distribution function
CDFM	conservative deterministic failure margin
CENA	Central and Eastern North America
CI	conventional island
CLCS	consequence limiting control system
CMS	conditional mean spectrum/spectra
CoV	coefficient of variation, equals mean value divided by standard deviation
Cov(X, Y)	covariance of random variables X and Y
CQC	complete quadratic combination
CRDM	control rod drive mechanism
CSA	Canadian Standard Association
CSIS	containment spray injection system
DBE	design basis earthquake
DFT	discrete Fourier transform
DMF	dynamic magnification factor
DOF	degrees-of-freedom
DRS	design response spectrum/spectra
DS	damage state

DSHA	deterministic seismic hazard analysis
DTFT	discrete-time Fourier transform
ECC	emergency core cooling
ECI	emergency coolant injection
EMD	empirical mode decomposition
ENA	Eastern North America
EPRI	Electric Power Research Institute
ESD	energy spectral density
EWS	emergency water supply
FA	fragility analysis
FAS	Fourier amplitude spectrum/spectra
FE	finite element
FEM	finite element method
FIR	finite impulse response
FIRS	foundation input response spectrum/spectra
FLIRS	foundation level input response spectrum/spectra
FRS	floor response spectrum/spectra
FT	Fourier transform
GMP	ground-motion parameter
GMPE	ground-motion prediction equation
GMRS	ground-motion response spectrum/spectra
GRS	ground response spectrum/spectra
GWN	Gaussian white noise
HAS	Hilbert amplitude spectrum
HCLPF	high confidence and low probability of failure
HCSCP	hazard-consistent, strain-compatible properties
HES	Hilbert energy spectrum
HSA	Hilbert spectral analysis
HTS	heat transport system
IDFT	inverse discrete Fourier transform
IDTFT	inverse discrete-time Fourier transform
IFT	inverse Fourier transform
IMF	intrinsic mode functions
IRVT	inverse random vibration theory

LERF	large early release frequency
LLOCA	large loss of coolant accident
LOCA	loss of coolant accident
LOOP	loss of offsite power
MCR	main control room
MDOF	multiple degrees-of-freedom
MMI	modified Mercalli intensity
NBCC	National Building Code of Canada
NEP	nonexceedance probability
NGA	next generation attenuation
NI	nuclear island
NPPs	nuclear power plants
NPS	nuclear power stations
NRCAN	Natural Resources Canada
NSP	nuclear steam plant
NUREG	Nuclear Regulatory (U.S. Nuclear Regulatory Commission)
PDF	probability density function
PEER	Pacific Earthquake Engineering Research
PGA	peak ground acceleration
PGD	peak ground displacement
PGV	peak ground velocity
PHWR	pressurized heavy water reactor
PMF	probability mass function
PSA	probabilistic safety assessment
PSD	power spectral density
PSHA	probabilistic seismic hazard analysis
PWR	pressurized water reactor
RB	reactor building
RBD	reliability block diagram
RE	reference earthquake
RLE	review level earthquake
RS	response spectrum/spectra
RVT	random vibration theory
RWST	refueling water storage tank

SA	spectral acceleration
SAM	seismic anchor movements
SB	service building
SCA	secondary control area
SD	standard deviation
SDE	site design earthquake
SDOF	single degree-of-freedom
SHD	seismic hazard deaggregation
SIS	safety injection system
SMA	seismic margin assessment
SME	seismic margin earthquake
SPRA	seismic probabilistic risk assessment
SPT	standard penetration test
SRHA	seismic response history analysis
SRSA	seismic response spectrum analysis
SRSS	square root of sum of squares
SSCs	structures, systems, and components
SSE	safe shutdown earthquake
SSEL	safe shutdown equipment list
SSI	soil–structure interaction
TP	test pit
tRS	t-response spectrum/spectra
TSCR	truncated soil column response
UHS	uniform hazard spectrum/spectra
USNRC	U.S. Nuclear Regulatory Commission
VPSHA	vector-valued probabilistic seismic hazard analysis
WNA	Western North America
ZPA	zero period acceleration