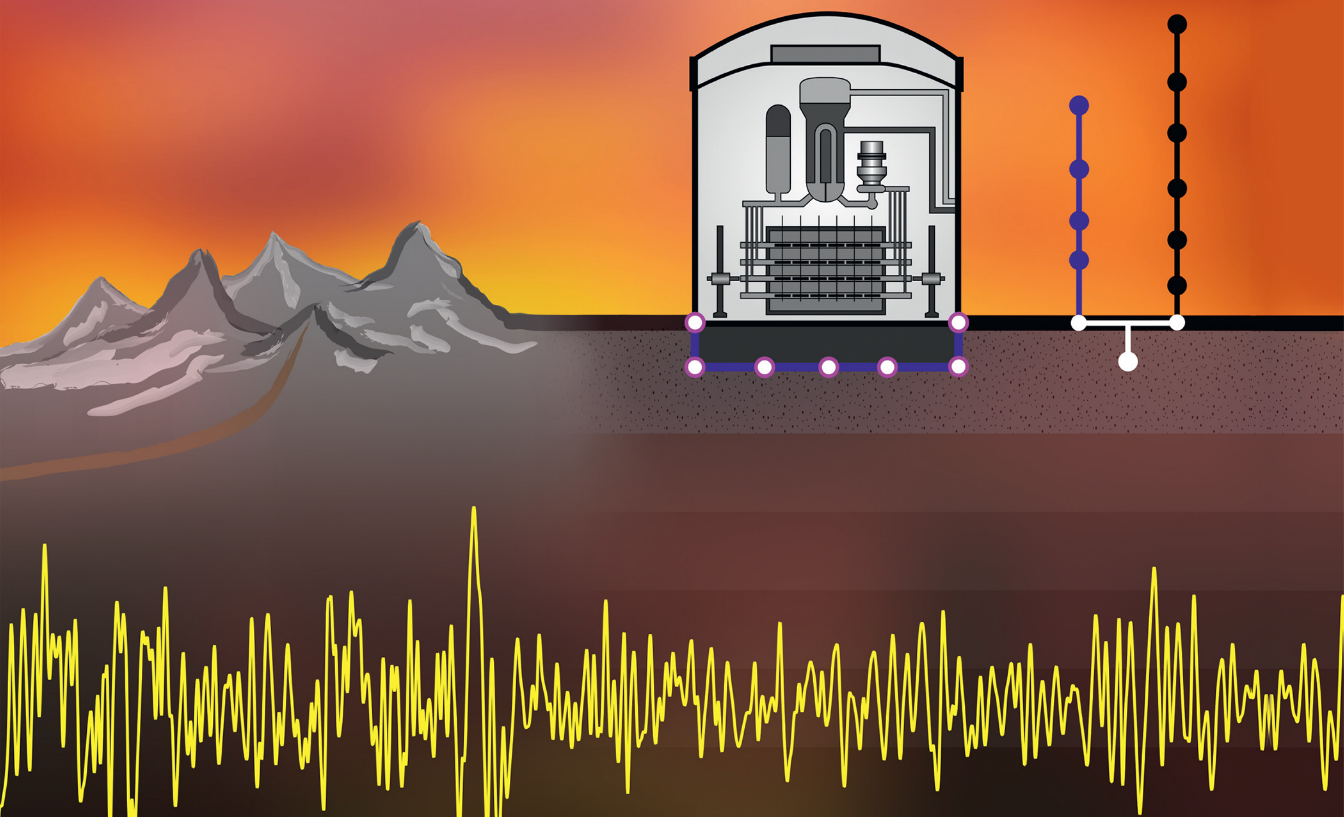
SEISMIC RISK ANALYSIS OF NUCLEAR POWER PLANTS



WEI-CHAU XIE, SHUN-HAO NI, WEI LIU, WEI JIANG

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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.

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

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