

## *University of Waterloo – Wei-Chau Xie CRD*

### *CRD Title: Seismic Risk Analysis of Nuclear Plants*

#### Overview

The objective of this research project is to develop a probabilistic framework of analysis, in terms of risk and reliability, for seismic risk analysis of NPPs. More specifically, the project will provide methodologies for Seismic Response History Analysis (SRHA) and Seismic Response Spectral Analysis (SRSA) consistent with Probabilistic Seismic Hazard Analysis (PSHA).



#### Research Team

Two PhD students have graduated since this CRD project started in January 2011 (Shun-Hao Ni in September 2012, De-Yi Zhang in November 2013). Five PhD students (Zhao-Liang Wang, Bo Li, Wei Jiang, Zhen Cai, and Sen Long) are currently working in the project. Zhen Cai and Sen Long are the two new students who joined the project team in January 2013.

#### Progress

Some significant progresses in 2013 are highlighted in the following.

##### *A Direct Method for the Generation of Floor Response Spectra*

A more efficient, convenient, and reliable method for generating floor response spectra (FRS) is being developed. Compared to the time history method, the proposed method has some advantages. Ground response spectra are used as seismic input directly. No spectrum-compatible time histories have to be produced and no time history analysis needs to be performed. Only basic modal information of primary structures and simple dynamic characteristics (modal frequencies and damping ratios) of SSCs are need to calculate FRS, so that it is convenient to use in preliminary design. A probabilistic concept is implicitly incorporated in this method: FRS with specified probabilities of exceedance can be given.

The successful implementation of this project will significant reduce the time and effort required to generate accurate FRS, compared with the time history method using a large number of time histories. It will also provide a complete probabilistic description of the FRS required for seismic analysis and design.

##### *Statistical Relationship between t-response Spectrum and Response Spectrum*

This project is conduct to support the direct method for the generation of FRS.

The notion of t-response spectrum is proposed in this study. The t-response spectrum represents the floor response spectrum in the resonant case (the secondary single degree-of-freedom SSC and the primary single degree-of-freedom supporting structure having the same

natural frequency and damping ratio). The statistical relationships between t-response spectrum and response spectrum, which are necessary for generating floor response spectra by our new direct method, are constructed using different suites of ground motion records.

The statistical relationships between t-response spectrum and response spectrum are constructed based on five different suites of ground motions. The five suites of ground motions are the 28 ground motions used by Newmark to construct design spectra in U.S. Nuclear Regulatory Commission NUREG/CR-0098, the 31 ground motions used to construct design spectra in U.S. Atomic Energy Commission Regulatory Guide 1.60 (1973), the 38 ground motions recorded at B sites, the 172 ground motions recorded at C sites, and the 210 ground motions recorded at D sites.

It is found that site conditions affect statistical relationship between t-response spectrum and response spectrum; the statistical relationship could be categorized by soil sites and rock sites. For generating FRS for seismic analysis and design, the statistical relationships for soil sites and rock sites are recommended.

#### *Vector-Valued Seismic Fragility Analysis and Risk Analysis*

Research work on vector-values seismic fragility analysis and risk analysis was initiated in 2013. In vector-value seismic fragility analysis, multiple seismic intensity measures are considered to remove the influence of the spectral shapes of the design response spectrum and review level earthquake response spectrum. This approach will release the redundant seismic margin and reduce the conservatism in the current seismic design.

#### Interaction with Industry

Our research team has been working very closely with the Department of Engineering Analysis, Candu Energy Inc. by working on projects of their immediate interest and providing training.

#### Publications 2012/2013

##### *Journal Papers*

1. De-Yi Zhang, Hong-Yu Jia, Shi-Xiong Zheng, Wei-Chau Xie, and Mahesh D. Pandey, "A Highly Efficient and Accurate Stochastic Seismic Analysis Approach for Structures under Tridirectional Nonstationary Multiple Excitations," *Computer and Structures*.
2. Xi Li, De-Yi Zhang, Wei-Ming Yan, Wei-Chau Xie, and Mahesh D. Pandey, 2013, "Effects of Model Updating on Stochastic Seismic Response of a Concrete-Filled Steel Tubular (CFST) Arch Bridge," *Structure and Infrastructure Engineering*, DOI:10.1080/15732479.2013.837079.
3. De-Yi Zhang, Xi Li, Wei-Ming Yan, Wei-Chau Xie, and Mahesh D. Pandey, 2013, "Stochastic Seismic Analysis of a Concrete-Filled Steel Tubular (CFST) Arch Bridge under Tridirectional Multiple Excitations," *Engineering Structures*, **52**, 355–371.
4. De-Yi Zhang, Wei Liu, Wei-Chau Xie, Mahesh D. Pandey, 2013, "Modeling of Spatially Correlated, Site-Reflected, and Nonstationary Ground Motions Compatible with the Response Spectrum," *Soil Dynamics and Earthquake Engineering*, **55**, 21–32.

5. Hong-Yu Jia, De-Yi Zhang, Shi-Xiong Zheng, Wei-Chau Xie, and Mahesh D. Pandey, 2013, "Local Site Effects on a High-Pier Railway Bridge under Tridirectional Spatial Excitations: Nonstationary Stochastic Analysis", *Soil Dynamics and Earthquake Engineering*, **52**, 55–69.
6. Shun-Hao Ni, Wei-Chau Xie, and Mahesh Pandey, 2013, "Generation of Spectrum-Compatible Earthquake Ground Motions Considering Intrinsic Spectral Variability Using Hilbert-Huang Transform," *Journal of Structural Safety*, **42**, 45–53.
7. De-Yi Zhang, Wei-Chau Xie, and Mahesh D. Pandey, 2013, "A Meshfree-Galerkin Method in Modeling and Synthesis of Spatially Varying Soil Properties," *Probabilistic Engineering Mechanics*, **31**, 52-64.
8. De-Yi Zhang, Wei-Chau Xie, and Mahesh Pandey, 2012, "Synthesis of Spatially Correlated Ground Motions at Varying Sites Based on Vector-Valued Seismic Hazard Deaggregation," *Soil Dynamics and Earthquake Engineering*, **41**, 1–13.
9. Shun-Hao Ni, De-Yi Zhang, Wei-Chau Xie, and Mahesh Pandey, 2012, "Vector-Valued Uniform Hazard Spectra," *Earthquake Spectra*, **28**(4), 1549–1568.

#### *Conference Publications*

1. Shun-Hao Ni, Wei-Chau Xie, Mahesh D. Pandey, and Wei Liu, 2013, "Seismic Design Spectra for Nuclear Power Plants Based on Probabilistic Seismic Hazard Analysis," *Proceeding the 22nd International Conference on Structural Mechanics in Reactor Technology (SMiRT-22)*, August 18-23, 2013, San Francisco, California, USA.
2. Bo Li, Shun-Hao Ni, Wei-Chau Xie, and Mahesh D. Pandey, 2013, "Probabilistic Seismic Hazard Analysis Considering Nonlinear Soil Effects and Variability of Soil Parameters," *Proceeding the 22nd International Conference on Structural Mechanics in Reactor Technology (SMiRT-22)*, August 18-23, 2013, San Francisco, California, USA.
3. Shun-Hao Ni, Wei-Chau Xie, Mahesh Pandey, and Wei Liu, 2013, "Generation of Earthquake Ground Motions Preserving Non-stationary Characteristic for Nuclear Power Plants," *Proceedings of the 34th CNS Annual Conference*, June 9-12, 2013, Toronto, Ontario, Canada.
4. Zhao-Liang Wang, Mahesh D. Pandey, and Wei-Chau Xie, 2013, "A Bayesian Formulation of Seismic Fragility Analysis of Safety Related Equipment," *Proceedings of the 34th CNS Annual Conference*, June 9-12, 2013, Toronto, Ontario, Canada.
5. De-Yi Zhang, Wei-Chau Xie, and Mahesh D. Pandey, 2013, "A Meshfree-Galerkin Method in Modeling and Synthesis of Spatially Varying Soil Properties," *Proceedings of the 11th International Conference on Structural Safety & Reliability*, June 16-20, 2013, Columbia University, New York, NY, USA.
6. Zhao-Liang Wang, Shun-Hao Ni, Wei-Chau Xie, and Mahesh D. Pandey, 2013, "Computationally Efficient Seismic Risk Analysis for Engineering Structures Using Seismic Hazard deaggregation," *Proceedings of the 11th International Conference on Structural Safety & Reliability*, June 16-20, 2013, Columbia University, New York, NY, USA.
7. De-Yi Zhang, Wei-Chau Xie, and Mahesh D. Pandey, 2012, "Modeling and Synthesis of Spatially Correlated, Site-Reflected, and Non-Stationary Ground Motions Compatible with Vector-Valued Uniform Hazard Spectra," *Proceedings of the 20th International Conference on Nuclear Engineering and the ASME 2012 Power Conference (ICONE20-POWER2012)*, July 30-August 3, 2012, Anaheim, California, USA.

8. De-Yi Zhang, Wei-Chau Xie, and Mahesh D. Pandey, 2012, "Synthesis of Spatially Correlated Ground Motions Considering Different Site-Response Effects," *Proceedings of the 3rd International Structural Specialty Conference*, June 6-9, 2012, Edmonton, Alberta, Canada.

#### *Conference Posters*

1. Sen Long, Wei-Chau Xie, and Mahesh D. Pandey, 2013, "Seismic Risk Quantification for Nuclear Power Plants," *University Network of Excellence in Nuclear Engineering (UNENE) R&D Workshop*, December 10-11, 2013, Toronto, Ontario, Canada.
2. Zhen Cai, W.-C. Xie, and Mahesh D. Pandey, 2013, "Seismic Probabilistic Risk Assessment Considering Multiple Intensity Measures," *University Network of Excellence in Nuclear Engineering (UNENE) R&D Workshop*, December 10-11, 2013, Toronto, Ontario, Canada.
3. Wei Jiang, Bo Li, Wei-Chau Xie, and Mahesh D. Pandey, 2013, "A Direct Method for Generation of Floor Response Spectra," *University Network of Excellence in Nuclear Engineering (UNENE) R&D Workshop*, December 10-11, 2013, Toronto, Ontario, Canada.
4. Bo Li, Wei Jiang, Wei-Chau Xie, and Mahesh D. Pandey, 2013, "Study of Amplification Factors for Design Earthquakes of Nuclear Power Plants and t-Response Spectra," *University Network of Excellence in Nuclear Engineering (UNENE) R&D Workshop*, December 10-11, 2013, Toronto, Ontario, Canada.
5. Bo Li, W.-C. Xie, and M. D. Pandey, 2013, "Influences of Soil Parameter Variability and Site Depths on Seismic Responses of Nuclear Power Plant Sites," *University Network of Excellence in Nuclear Engineering (UNENE) R&D Workshop*, December 10-11, 2013, Toronto, Ontario, Canada.
6. Bo Li, Shun-Hao Ni, Wei-Chau Xie, and M. D. Pandey, 2012, "Design Earthquake for Nuclear Power Plants Considering Nonlinear Site Effects," *University Network of Excellence in Nuclear Engineering (UNENE) R&D Workshop*, December 11-12, 2012, Toronto, Ontario, Canada.
7. Zhao-Liang Wang, Wei-Chau Xie, and M. D. Pandey, 2012, "Computationally Efficient Seismic Risk Analysis for Nuclear Energy Facilities," *University Network of Excellence in Nuclear Engineering (UNENE) R&D Workshop*, December 11-12, 2012, Toronto, Ontario, Canada.