University of Waterloo – Wei-Chau Xie CRD

CRD Title: Seismic Risk Analysis of Nuclear Plants

Overview

The objectives of this research are

- to develop comprehensive methodologies for the accurate determination of floor response spectra (FRS);
- to develop methods for accurate estimates of seismic fragility of systems, structures, and components (SSCs) by considering multiple ground motion parameters (GMPs) to ensure that SSCs in nuclear power plants (NPPs) are seismically qualified in a cost-effective way; and
- to generate drift-free, consistent, and spectrum-compatible ground motion time histories for various dynamic analyses of NPP structures.

The outcomes are critical for Seismic Margin Assessment (SMA) and Seismic Probabilistic Risk Assessment (SPRA) of nuclear power plants.

Research Team

In 2016, two Ph.D. students (Wei Jiang, Zhen Cai) graduated. Both Dr. Jiang and Dr. Cai worked as a postdoctoral fellow for a short period of time after graduation. Dr. Wei Jiang is working at Candu Energy Inc. and Dr. Zhen Cai is working at National Research Council of Canada. One Ph.D. student (Yang Zhou) continued to work on the project under this CRD.

Progress

Some significant progresses in 2016-2017 are highlighted in the following.

A Direct Method for Generating FRS Considering Soil-Structure Interaction

A methodology is developed for generating FRS considering the effect of dynamic soil-structure interaction based on the substructure technique and the direct spectra-to-spectra method developed in this CRD. Dynamic stiffness matrix of a three-dimensional structure with a rigid foundation subject to three translational and three rotational base excitations is derived, and is expressed in terms of the modal information of the structure. A transfer matrix which is dependent on the dynamic stiffness matrix of the structure-foundation system and that of generalized soil springs is developed to modify the tri-directional response spectra at the foundation level of free field (FIRS) in soil medium. The modified response spectra, called foundation level input response spectra (FLIRS), are then used as the input to the fixed-base structure to generate FRS using the direct spectra-to-spectra method. Numerical examples of a reactor building and a service building in nuclear power plants demonstrate the accuracy and efficiency of the proposed method. FRS with 50% and 84% Non-Exceedance Probability (NEP) given by the method agree extremely well with the FRS obtained from a large number of time history analyses.

Seismic Fragilities Analysis Using Multiple Ground Motion Parameter
Seismic fragility analysis (FA) has been widely used to evaluate seismic capacities of SSCs in NPPs. In seismic FA, a single GMP, such as peak ground acceleration, is used to represent the seismic capacities and fragilities of SSCs. However, a number of problems of seismic FA, due to the use of a single GMP, are recognized in practice.

An improved seismic FA method, which overcomes the problems in traditional seismic FA by using multiple GMPs, was proposed. It gives more realistic seismic capacity and fragility estimates of SSCs. By incorporating vector-valued probabilistic seismic hazard analysis, weighted seismic capacities and fragilities are represented by a selected GMP, which can be readily applied in traditional SMA and seismic PSA.

As an example, seismic fragility curves and High Confidence and Low Probability of Failure (HCLPF) seismic capacity of a heat exchanger are calculated by the traditional and improved FA methods. By using two GMPs, i.e. spectral acceleration at the longitudinal direction of the heat exchanger and peak ground acceleration, the weighted median seismic capacity of the heat exchanger has a remarkable 53.9% increase, and the weighted HCLPF seismic capacity is increased by 26.1%. Both results indicate that, by using multiple GMPs, the improved FA methodology could uncover the excessive conservatism in the traditional method, resulting in more accurate estimates of seismic capacity and fragility of SSCs and more accurate assessment of seismic risk in NPPs.

Generating Spectrum-Compatible Time Histories In many earthquake engineering applications, such as evaluation of dynamic response analysis of inelastic structures, sloshing analysis, or analysis of multi-supported systems (e.g. piping), time history analysis may be required, with ground motions being the input. Over the past decades, considerable efforts have been made to develop algorithms for generating spectrum-compatible time histories. In earlier work by my research team, Hilbert-Huang Transform technique is used to analyze frequency contents and amplitudes of seed motions. Through adjusting the frequency contents and amplitudes of seed motions, spectrum-compatible time histories are obtained.

Before and after an earthquake, the ground is at rest. Naturally, acceleration, velocity, and displacement time histories should be zero at both ends as well if there is no permanent ground displacement. However, there are drifts in the generated velocity and displacement time histories caused by the integration of an accelerogram, in which the time histories are not at rest at one or both ends. This phenomenon was first reported by Housner but gave no remedy. Newmark standardized baseline correction by using a polynomial. The baseline correction approach using the Butterworth filter has been implemented by USGS to process recorded ground motions.

Baseline correction, although endorsed by codes and standards, is not a suitable remedial measure because it introduces a large low-frequency component and renders the corrected time histories no longer mutually consistent, in which integration (or differentiation) of one process is not equal to the supposedly related process. In spite of practical implications, drift and inconsistency have not been resolved satisfactorily for decades.

Our research team discovered that, in addition to numerical errors, drift is caused by overdeterminacy in the constants of integration. To solve the problem of drift in time histories, the eigenfunctions from an eigenvalue problem, which is described by a sixth-order ordinary differential equation satisfying the six initial and terminal at-rest conditions, are derived as a basis of expansion. The eigenfunctions are used to expand an accelerogram. A method using the Hilbert-Huang transform and optimization was developed to modify a real recorded accelerogram using the eigenfunctions to generate time histories compatible with the target response spectra without drift. Drift-free consistent velocity and displacement time histories are then obtained, also in terms of the eigenfunctions, without direct integration and baseline correction. Furthermore, a method of optimization was also proposed to modify a set of tri-directional real recorded accelerograms using the eigenfunctions to generate consistent tri-directional time histories compatible with the target response spectra without drift.

Realistic ground motion time histories that are drift-free and consistent are critical for the results of time history analyses to be acceptable in practice. By using eigenfunctions expansions, we are able to generate drift-free and consistent time histories rigorously, without resorting to baseline correction, a challenge that has long been conceded to be unattainable.

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 through providing training.

Publications

Journal Papers

1. Wei Jiang, Yang Zhou, Wei-Chau Xie, Mahesh Pandey, "Direct Method for Generating Floor Response Spectra Considering Soil-Structure Interaction," *Soil Dynamics and Earthquake Engineering*, (in revision).
2. Zhen Cai, Wei-Chau Xie, Mahesh D. Pandey, Shun-Hao Ni, 2018, "Determining Seismic Fragility of Structures and Components in Nuclear Power Plants Using Multiple Ground Motion Parameters – Part I: Methodology," *Nuclear Engineering and Design*, **335**, 195–201, doi.org/10.1016/j.nucengdes.2018.05.013.
3. Zhen Cai, Wei-Chau Xie, Mahesh D. Pandey, Shun-Hao Ni, 2018, "Determining Seismic Fragility of Structures and Components in Nuclear Power Plants Using Multiple Ground Motion Parameters – Part II: Application," *Nuclear Engineering and Design*, **335**, 186–194, doi.org/10.1016/j.nucengdes.2018.05.016.
4. Bo Li, Zhen Cai, Wei-Chau Xie, Mahesh Pandey, 2018, "Probabilistic Seismic Hazard Analysis Considering Site-Specific Effects," *Soil Dynamics and Earthquake Engineering*, **105**, 103-113, doi.org/10.1016/j.soildyn.2017.11.029.
5. Wei Jiang, Wei Liu, Wei-Chau Xie, Mahesh D. Pandey, 2017, "A Scaling Method for Generating Floor Response Spectra," *Annals of Nuclear Energy*, **110**, 613–632.
6. Bo Li, Binh-Le Ly, Wei-Chau Xie, Mahesh D. Pandey, 2017, "Generating Spectrum-Compatible Time Histories Using Eigenfunctions," *Bulletin of the Seismological Society of America*, **107**(3) 1512–1525, DOI: 10.1785/0120160206.
7. Zhaoliang Wang, Wei-Chau Xie, and Mahesh Pandey, 2016, "Computationally Efficient Vector-valued Seismic Risk Analysis of Engineering Structures," *ASCE's Journal of Structural Engineering,* **142**(9), doi: 10.1061/(ASCE)ST.1943-541X.0001504.

8. Bo Li, Wei-Chau Xie, Mahesh D. Pandey, 2016, “Newmark Design Spectra Considering Earthquake Magnitudes and Site Categories,” *Earthquake Engineering and Engineering Vibration*, **15**(3), 519–535, doi:10.1007/s11803-016-0341-1.

9. Bo Li, Wei-Chau Xie, Mahesh D. Pandey, 2016, “Generate Tri-Directional Spectra-Compatible Time Histories Using HHT Method,” *Nuclear Engineering and Design*, **308**, 73–85, doi:10.1016/j.nucengdes.2016.08.009.