Direct Method of Generating Floor Response Spectra for Structures Considering Soil-Structure Interaction

by

Yue Li

A thesis
presented to the University of Waterloo
in fulfilment of the
thesis requirement for the degree of
Doctor of Philosophy
in
Civil Engineering

Waterloo, Ontario, Canada, 2024

© Yue Li 2024

Abstract

Floor Response Spectra (FRS) are crucial for the seismic design and safety assessment of structures, systems, and components (SSCs) in nuclear power facilities. Generating accurate FRS requires considering soil-structure interaction (SSI) effects, especially for structures with flexible foundations and spatially varying ground motions. This thesis presents a comprehensive approach to address these challenges in the context of nuclear power plant (NPP) structures, with a specific focus on the applicability of this method to Small Modular Reactors (SMRs). The main contributions are as follows:

(1). A novel direct spectra-to-spectra method is extended for efficient FRS generation in multi-supported structures, incorporating SSI effects through a substructure approach. This method converts Foundation Input Response Spectra (FIRS) into Foundation Level Input Response Spectra (FLIRS) using analytically derived transfer matrices based on soil stiffness and structural modal information. It accommodates both flexible and rigid foundations under varying seismic inputs, eliminating intermediate spectrum-compatible time history generations and full system reanalysis when properties change. (**Chapter 2**)

(2). A numerical example of a 3-DOF structure with two structural nodes and one foundation node supported by a generalized soil spring is presented to verify the proposed method. Both theoretical formulation and numerical simulation verified and solidified the equivalence of seismic responses between the coupled soil-structure system under FIRS excitations and the decoupled structure under FLIRS inputs. This validation confirms the theoretical rigor of replacing FIRS with FLIRS in the analysis. (**Chapter 3**)

(3). A comprehensive methodology for evaluating dynamic soil stiffness matrices is presented, utilizing the relationship between dynamic flexibility and stiffness matrices. The method applies sinusoidal excitations to calculate steady-state response amplitudes and phase lags, deriving real and imaginary parts of the dynamic response. A progressive validation strategy is employed, systematically validating the method from simple lumped-mass systems to continuous-mass systems, then to complex 3D half-space soil models, ensuring its reliability across various scenarios. This approach

provides a robust and versatile tool for characterizing dynamic soil stiffness properties across various structural complexities. The method can significantly reduces dependence on specialized software running in "blackbox", such as ACS SASSI, thus enhance the accessibility and efficiency of seismic analysis for nuclear facilities. (**Chapter 4**)

(4). The proposed direct method was applied to the multiple supported structure with SSI taken into account. The FRS from the proposed method shows excellent agreement with "benchmark" time history results, particularly in horizontal directions, with errors consistently below 5%. Two seismic input scenarios, fully correlated and fully independent excitations at multiple supports, are explored, showcasing the method's versatility. Some discrepancies in vertical direction are attributed to limitations in vertical tRS, indicating areas for future refinement including the need to refine tRS. (**Chapter 5**)

(5). Parametric studies investigate the influence of site conditions and internal-external structure coupling element stiffness on FRS. Evaluated across various site classes per ASCE 7-10 standard, the method demonstrates robust performance for most site types. The study reveals optimal stiffness ranges affecting FRS peaks. It also identifies energy transfer patterns between structural components as the stiffness in the connecting elements changes, offering insights for nuclear facility design. (**Chapter 5**)

The methodologies developed in this thesis advance the state-of-the-art in seismic analysis and design of nuclear structures, particularly SMRs. By addressing the complex challenges posed by multi-support excitations and SSI, this research provides a foundation for safer and more economical designs of nuclear facilities.