Methodology for Probabilistic Soil-Structure Interaction Analysis of NPP Structures

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1. Introduction

All safety-related nuclear power plant (NPP) structures should consider the effects of soil-structure interaction (SSI), except for fixed-base soil conditions following regulations. SSI effects change the soil's geometry and dynamic characteristics of the NPP structure due to the properties of the near-field soil and the input motions. Typically, SSI effects are known to reduce the structure's accelerations and inertial forces, while increasing foundation deformation.

Seismic performance evaluations of NPP structures using SSI analysis have been performed generally with a deterministic method in Korea. However, this method is not able to represent the uncertainties of seismic input motion, soil properties, and structural behavior. On the other hand, probabilistic soil-structure interaction analysis (PSSIA) provides a much more detail understanding of these uncertainties. PSSIA has been introduced in practice for seismic design based on performance-based design in the U.S., and is being included and recommended for seismic analysis.

This paper reviewed a methodology for applying PSSIA in NPP structures design and evaluation based on the standards and guidance.

2. Method

This section describes some of the parameters used for PSSIA: simulation methods, input motion, variability of soil properties, and variability of structural stiffness and damping. PSSIA guideline is provided in the ASCE 04-16 [1] standard and USNRC RG 1.208 [2].

2.1 Probabilistic simulation methods

A probabilistic simulation method can apply Monte Carlo simulation (MCS) or equivalent procedures such as Latin hypercube simulation (LHS). In the standard, LHS is recommended which is a more efficient stratified sampling approach. In the standard or guidance, there is requirement of a minimum number of randomized simulations (a minimum of 30 simulations for PSSIA, and a minimum of 60 simulations for probabilistic seismic response analysis (PSRA)).

2.2 Input motion variations

The seismic input motion shall be composed of an ensemble of input motion sets and the *N*-simulated set of input motion shall consist of two horizontal components and one vertical component (X, Y, and Z).

The standard includes two probabilistic simulation methods for generating input acceleration time histories that are recommended as follows.

- Method 1 generates spectra with a similar shape to match closely the target control motion (foundation input response spectra or free surface motion) [3]. This method is that the frequency content of the spectrum and the general shape of the input motions remains unchanged and only the seismic hazard levels vary, because the unchanged things is already considered in the development of the seismic hazard. (Figure 1)

- Method 2 generates spectra with a random shape that have random amplitudes at different frequencies. This method is that is based on the idealization of the probabilistic input response spectrum by an ensemble of randomized variable shape spectrum realizations [4]. This method considers the statistical correlations between the ground response spectrum (GRS) random amplitudes at different frequencies using a constant correlation length, a correlation length vector, or a correlation matrix. This method is generated seismic inputs have large variations in the frequency content, while their mean spectrum shows compliance with the initial spectrum. (Figure 2)

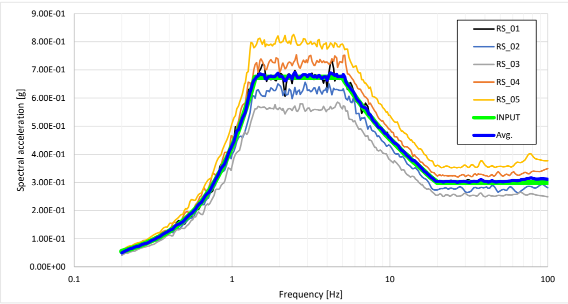


Fig. 1. Probabilistic GRS samples using Method 1

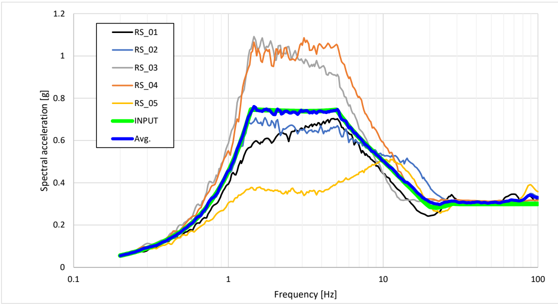


Fig. 2. Probabilistic GRS samples using Method 2

2.3 Variability of soil properties

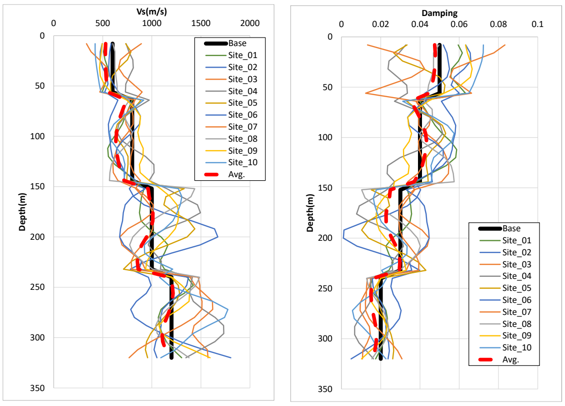
A variability of soil properties is considered in two parts. The first part is dynamic characteristics of soil, which are shear wave velocity (Vs) and damping (ξ). The Vs and ξ per soil layer are assumed to be a pair of statistically dependent lognormal random variables. The second part is PSRA which is the strain-iterated profiles developed in accordance with ASCE 04-16 Chap 2. The N-simulated soil profiles used for PSSIA shall be randomly sampled from the strain-compatible soil profiles developed in the probabilistic site response analysis performed in accordance with ASCE 04-16 Section 2.3.

The PSRA can analyze using ACS-SASSI Option PRO software which is developed for performing the probabilistic site response [5]. The ACS-SASSI provides two Soil Profile Stochastic Simulation Models.

- Model 1 option produces assumes a single-component stochastic field model.

- Model 2 option assumes a two-component composite stochastic field model since it contains two sources of the random variations, one including a slow-amplitude or long-wavelength variation and another a rapid-amplitude or short-wavelength variation.

The software describes that the selection of the soil profile model should be made based on the field measurements on the site.



(a) Shear wave velocity (b) Damping

Fig. 3. Simulated samples using Model 1

2.4 Variability of Structural Stiffness and Damping.

Stiffness and damping properties of the structure are recommended for lognormal probability distribution. The cumulative distribution function of structural stiffness and damping shall be based on coefficient of variation or the best-estimate. Recommended coefficients of variation (C_V) of structural stiffness and damping are 0.30 and 0.35, respectively in ASCE/SEI 04-16. A NPP structure's models can consist of a pair of dependent random variables for each structural element group and for each material type.

3. Conclusions

This paper discussed PSSIA methodology based on standards and guidelines for nuclear power plant structures. A deterministic approach may be overestimated or underestimated due to the safety factors used for uncertainty in the SSI analysis and is unlikely to appropriate uncertainty, a probabilistic approach is considered appropriate for future SSI analyses.

Especially, for the exact analysis by PSSIA, it is necessary to use the parameters for variabilities used in PSSIA mentioned in this paper appropriately. In the future, the following points should be considered for the probabilistic approaches in the performance-based seismic evaluation of NPP structures.

(1) There are two main methods of input motion proposed by the regulation. Although method 2 seems to be a more stochastic seismic wave generation due to its various frequency contents, Method 1 is considered appropriate Method 1 is considered appropriate if the seismic hazard is already considered by probabilistic seismic hazard analysis.

(2) In the case of Variability of Soil Properties, more general and realistic soil profiles can be simulated using Model 2. But the selection of the soil profile model should be made based on the Vs field measurements on the site. In addition, it is necessary to properly consider the correlation between Vs and D in PSSIA and perform the analysis to avoid using excessive sampling parameters.

(3) Recommended C_V of structural stiffness and damping are represented in the regulation. The effective stiffness reduction factor and damping values should reflect the concrete cracking pattern that occurs for each SSI analysis input sample. Therefore, C_V will check the sensitivity before applying analysis models.

ACKNOWLEDGEMENT

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