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Analysis of Effect by Probabilistic Soil-structure Interaction on Seismic Fragility of Nuclear Power Plants Equipment

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1. Introduction

In order to assess the earthquake safety of nuclear power plants, a seismic hazard assessment that determines the seismic load on the site, a seismic fragility assessment that assesses the probability of damage to structures and equipment to an earthquake, and a seismic quantification process that calculates the frequency of core damage to an earthquake by considering the nuclear power plant system are necessary. This series of processes is called seismic probabilistic safety assessment (seismic PSA) [1-2]. Among them, seismic fragility assessment is the process of evaluating the safety margin of structures and equipment by comparing the performance of structures and equipment with their seismic responses.

The response of structures and equipment to an earthquake is determined by various factors, and soil-structure interaction is also one of the important factors. Soil-structure interaction refers to a phenomenon in which the upper structure and the lower ground interact with each other during an earthquake and affects the structure behavior during an earthquake due to an increase in the period of the soil-structure system and the damping ratio.

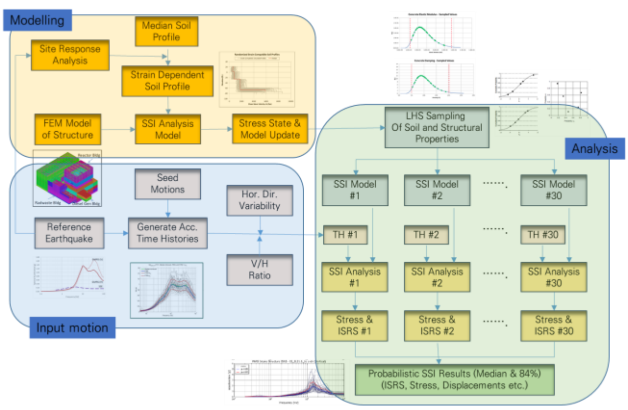

Fig. 1. Overview of probabilistic soil-structure interaction analysis procedure

Soil-structure interaction has inherent uncertainties related to seismic load, stiffness and damping of the soil, and stiffness and damping of the structure. The uncertainty of these input variables was mainly considered through deterministic approaches in the past, but deterministic approaches tend to be difficult to directly reflect the uncertainty of the response, and evaluate the response conservatively overall. Accordingly, a probabilistic approach has recently emerged to estimate the distribution of each input variable as a probability distribution, and sample and apply variables based on this. It is known that the probabilistic method can reduce the uncertainty of the response overall by directly calculating the probability distribution of the response [2].

In this study, probabilistic soil-structure interaction (PSSI) analysis is applied to derive structural responses for representative domestic nuclear power plant structures and to analyze the effect of PSSI on seismic fragility of major equipment.

2. Methods and Results

This section describes the probabilistic soil-structure response analysis procedure and seismic fragility assessment, and discusses the evaluation of the variability of structural response using PSSI and its impact on seismic performance.

2.1 Probabilistic Soil-structure Interaction Analysis

Probabilistic seismic response analysis is a method to derive the median response and distribution of major structures and equipment by performing multiple seismic response analyses. The variability included in the probabilistic SSI analysis is the variability of ground motion, the variability of soil properties (stiffness and damping), the variability of structure properties (stiffness and damping), and the time history phase. Latin hypercube sampling (LHS) can be used as an efficient method to determine the combination of parameters, and ASCE 4-16 recommends using at least 30 samples. The probability distribution of soil properties is developed based on statistical data of the plant site, and the general coefficients of variation of the structural stiffness and damping can be 0.30 and 0.35, respectively. Examples of the internal structural response spectrum (ISRS) and its variability, which are the results that can be derived from PSSI, are shown in the following figures.

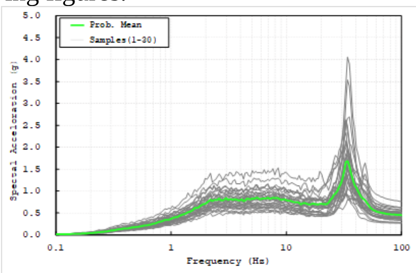

Fig. 2. Example of in-structure response spectrum (ISRS) by probabilistic soil-structure interaction (PSSI) analysis

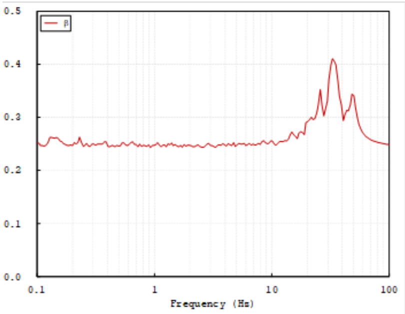

Fig. 3. Variability of in-structure response spectrum (ISRS) by probabilistic soil-structure interaction (PSSI) analysis

2.2 Seismic Fragility by Separation of Variable (SOV)

The separation of variable (SOV) method is a representative method for developing a fragility curve in seismic PSA [3]. In the case of equipment seismic fragility, the median performance (A_m) can be determined using the following equation, and the fragility curve can be derived as a double lognormal distribution function by evaluating the randomness (β_r) and uncertainty (β_u) of each variable.

$$A_m = F_c F_{er} F_{rs} PGA_{RE} \tag{1}$$

where, F_c is the capacity factor, F_{ER}, F_{RS} are the equipment and structure response factor, and PGA_{RE} is the PGA of the reference earthquake.

2.3 Seismic Fragility Assessment by PSSI

In this section, the seismic fragility of NPP equipment is reevaluated by performing probabilistic SSI using a 3D structural model. The target equipment is selected as a heat exchanger, which was found to be relatively vulnerable in the previous fragility assessment results. The PGA level of the reference earthquake is set to 0.5g, and the PSSI analyses are performed by applying the NUREG/CR-0098 spectrum to the input ground motion. Since it is difficult to perform PSSI analysis every time by considering the fragility variables of individual equipment, generic values of variability that can be used conservatively are applied.

Table I: Seismic fragility assessment for heat exchanger by PSSI

	Existing fragility assessment	Fragility assessment by PSSI
Am (g)	0.88	1.43
β_r	0.25	0.31
β_u	0.43	0.38
HCLPF (g)	0.29	0.46

Table I shows the results of the seismic fragility assessment of the modified heat exchanger by applying the PSSI results. Although the parameter variability applied in the PSSI analysis used very conservative values compared to those used in the existing fragility assessment, the response variability is evaluated to be slightly smaller than the variability by the existing fragility assessment results. The median performance (Am) is significantly improved compared to the existing fragility assessment, and this is because the conservatism of the design FRS used to derive the existing performance coefficient is removed through the reanalysis.

3. Conclusions

In this study, the fragility of nuclear power plant equipment is reevaluated by applying PSSI analysis. The analysis is performed considering the variability of soil and structure properties, and the input ground motions. Although the PSSI analysis is performed by applying conservative parameter variability, the response variability is slightly smaller than that derived from the existing seismic fragility assessment, and the seismic performance can be significantly improved by using the realistic response through the seismic re-analysis using the 3D model. If the PSSI analysis is performed using more realistic parameter variability suitable for the equipment, additional seismic performance improvement can be expected.

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