Post-processing technique for probabilistic seismic responses of nuclear power plant under performance-based seismic design

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1. Introduction

The seismic design of domestic nuclear power plant(NPP) structures and equipment has applied a deterministic seismic design while the performance-based seismic design has not yet been applied. Recently, research is being performed to apply a performance-based seismic design to nuclear power plants in Korea, but further research may be needed and understanding of structural engineers are required.

In this paper, we introduce the concept of the performance-based seismic design of the nuclear power plant structure, the probabilistic post-processing procedure for the probabilistic seismic analysis and the results, and the developed program.

2. Performance based seismic design

Structural designers in the field of NPPs have used deterministic seismic design for a long time because the procedure is simple and sequential, and it is possible to obtain conservative results without considering various random variables for design. In the deterministic seismic design of domestic NPPs, the design ground motion has the maximum ground acceleration with 1×10^{-4} level and the NRC regulation guide(NRC RG). It can be determined by one set of seismic motions that envelopes to the standard design response spectrum of NRC RG 1.60, and the seismic analysis of the structure is basically performed in the linear domain. The estimation of structural seismic performance is also quantified based on the design margin of structures or the results of seismic verification tests of equipment using floor response spectra(FRS).

The reason why the performance-based seismic design is interested in a design field is to consider the uncertainty of the real world (site response system). Performing probabilistic seismic analysis reflecting all random variables that can be estimated is not effective and is out of the engineering scope. Therefore, it is the performance-based seismic design that finds a realistic method between the probabilistic seismic phenomenon and the structural design. In addition, probabilistic seismic hazard analysis for beyond design based earthquake(BDBE), property evaluation of construction sites considering various parameters, site-specific uniform hazard response spectrum(UHRS) from site response analysis considering random variables. This includes the ground motion response spectrum(GMRS), probabilistic extraction of the superstructure stiffness and damping ratio, and nonlinear analysis. Figure 1 shows the performance-based seismic design procedure. It can be seen that it follows a complicated probabilistic analysis procedure compared to a deterministic seismic design. In addition, in order to evaluate the seismic performance of structures and equipment, the probability of failure for the BDBE, that is, it must be expressed as a quantitative performance target (P_f).

The criteria for the performance-based seismic design of NPPs are as follows. ASCE/SEI 43-05 issued in 2005 specifies performance targets for nuclear facilities at 1×10^{-5} levels, and provides probabilistic seismic analysis and performance standards for safety-related structures, safety systems, and equipment. Subsequently, ASCE/SEI 4-16 published in 2017 defines performance targets with probability of failure based on probabilistic methods for BDBE, one applies multi-set control motions, probabilistic site response analysis, and probabilistic seismic analysis. Recently issued in Korea, KEPIC-STC is a design technology standard for base-isolated nuclear structures. For the isolation design of NPP, refer to ASCE/SEI 4-16. However, the seismic analysis/design of a base-isolated NPPs developed by domestic researchers and the test/quality management of an isolator are partially included.

3. Probabilistic seismic analysis

The seismic analysis method presented in the latest technical standards has several characteristics different from the past. First, it is recommended to model the analytical model as 3D finite elements. The goal is to move away from the beam stick model and change more precise numerical discretization with the high performance of the computer. The second is a nonlinear analysis considering the elastoplastic properties of the material. This means to consider the application of an isolator or the material nonlinearity of the site or structure. The third is the simultaneity to excite one set of control motions together in three directions. This is because the linearity due to the response overlap in each direction disappears in the nonlinear analysis. The last is the introduction of probabilistic seismic analysis according to the performance-based design concept mentioned previously.

As shown in Figure 1, a probabilistic pre-analysis step is required to reach the probabilistic seismic analysis step. Characterization of construction sites and probabilistic seismic hazard analysis are performed, where multiple control motions based on UHRS of at the bedrock level are input to the probabilistic site response analysis. There are two main factors to obtain at the site response analysis stage. One is to calculate the undifferentiated GMRS using the UHRS on surface and the other is to extract the set of *N*-equivalent ground properties extracted from the probabilistic technique and the corresponding set of *N*-outcrop motions. These *N*-data sets are applied to seismic analysis considering subsequent soil-structure interaction(SSI), each of which is a case of probabilistic seismic analysis.

Basically, seismic analysis method considering SSI effect is divided into linear frequency domain analysis and nonlinear time domain analysis. The linear or nonlinear analysis is determined by how the stress field of the seismic dynamic system including the structure defines the stress-strain or force-displacement relation function of the material. There are many in-house or commercial packages that can perform SSI analysis and the processing methods such as the finite element modeling method of the near field and the numerical simulation method of the far field are different depending on the analysis region or the program.

4. Probabilistic post-processing

Figure 2 shows the probabilistic seismic response post-processing procedure presented in this study. It shows the procedure of obtaining FRS and seismic anchor motion(SAM) from a random layer(*f*) and a node of interest(*i*) of the layer and probabilistic combination so that it can be applied to nuclear power plant design and piping design. This procedure is much more complicated than processing the results of a deterministic seismic analysis inputting a single set of control motions. This is because it is necessary to repeatedly process the results of stochastic seismic analysis applying *N*-control motions and a set of ground properties, and stochastically extract the final results. Performing stochastic post-processing with designer's iterative work is likely to make errors and it is inefficient in time.

Therefore, in this study, ALLGEN, a program that can automatically perform this process, was developed. When the stochastic seismic analysis phase is over, ALLGEN automatically post-processes the large-scale analysis results according to the procedure in Figure 2. For the design reference earthquake, FRS and SAM are calculated as the 80th percentile design response and the 99th percentile value is extracted as a performance target. In addition, for the excess design reference earthquake defined as 150% of the design reference earthquake, the 90th percentile value of the response is extracted as a performance target.

5. Conclusion

In this paper, the concept of performance-based seismic design and probabilistic seismic analysis of nuclear power plants currently being studied in Korea are outlined and probabilistic post-processing procedures and automated programs are introduced. In the future, we will present probabilistic seismic analysis and post-processing examples for nuclear power plants.

REFERENCES

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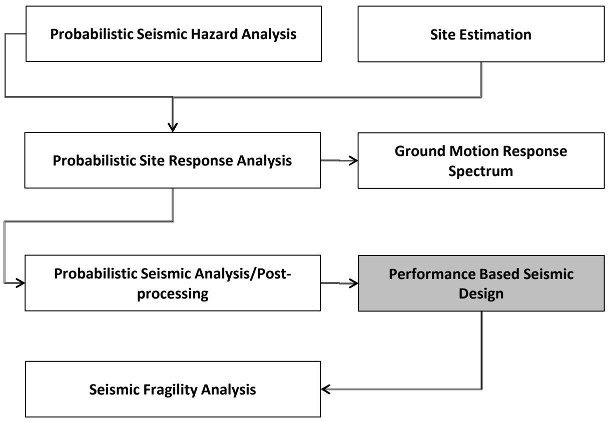

Fig. 1. Procedure of probabilistic seismic design

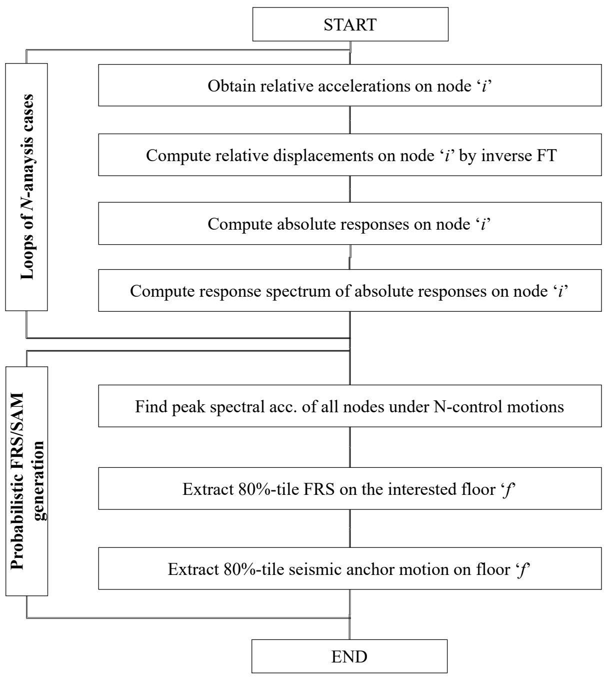

Fig. 2. Probabilistic post-processing