

Seismic Analysis of Control Building for the Innovative Small Modular Reactor (i-SMR)

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1. Introduction and Backgrounds

As the AI industry grows and the need for clean energy increases, more nuclear power plants are being built. Small Modular Reactors (SMRs) are becoming more popular because they can be made in a factory and assembled quickly, reducing construction time and costs.

In Korea, a project is currently in progress to establish a standard design for the Innovative Small Modular Reactor (i-SMR). The i-SMR is composed of four main buildings: the reactor protection building, the control building, the compound building, and the turbine generator building. The control building, in particular, includes the integrated control room, non-safety electrical equipment, and HVAC equipment.

Currently, seismic analysis and design of the control building for the i-SMR are being performed in accordance with the General Arrangement (GA). The seismic analysis of the control building is conducted with a maximum ground acceleration of 0.5g for the Safe Shutdown Earthquake (SSE) when the site-specific response spectrum is applied. However, when the standard design response spectrum based on the USNRC Regulatory Guide 1.60 is used, the maximum ground acceleration is 0.3g. Therefore, for the standard design of the i-SMR, a standard design response spectrum with a seismic level of 0.3g was used, and seismic analysis of the control building was performed to reflect the seismic input and seismic design variables that meet the requirements of the USNRC Standard Review Plan (SRP).

2. Seismic Analysis

2.1 Soil-Structure Interaction Analysis in Frequency Domain

When designing a nuclear power plant, seismic design is essential, and Soil-Structure Interaction (SSI) analysis must be considered. SSI analysis should take into account the half space of the soil, its complexity, and nonlinearity. However, due to the variability of structural properties and the complexity of analysis methods, it is challenging to create an accurate analysis model. To address this, various SSI analysis methods have been proposed, with the direct method and substructure method being widely used. For the seismic analysis of the i-SMR structure, the KIESSI-3D

program was used, which solves the problem in the frequency domain using the direct method [1,2]. KIESSI-3D is an SSI analysis program developed by a domestic research team, which uses finite elements for the near-field soil and dynamic infinite elements (IE) for the far-field layered soil.

2.2 Seismic Design Parameters

The design variables for the seismic analysis of the control building include seismic input, three-directional simultaneous excitation, control points, site conditions, damping ratio, nonlinear soil properties, crack/non-crack, and potential separation of the side walls. These variables satisfy the design requirements of USNRC SRP 3.7.2, ACI 350, ASCE 4, and KEPIC STB [3,4,5,6].

The seismic input consists of 7 sets of 3-directional seismic waves, including 2 horizontal and 1 vertical direction. An artificial seismic wave was generated based on the design response spectrum, using a recorded seismic wave as a seed motion, with a time interval of 0.005 seconds and a total duration of 20.48 seconds. During the seismic analysis, the 3-directional seismic input was applied simultaneously for each set. The control point was set at a location with a shear wave velocity of 3500 ft/sec or higher, and the site conditions were selected as 4 vertical soil conditions with shear wave velocities of 1000, 3500, 5000, and 8000 ft/sec. To reflect the nonlinearity of the soil, a 1D wave propagation analysis, SHAKE analysis, was performed for these soil conditions, and equivalent linear soil properties were calculated [7,8].

The control building is a reinforced concrete structure, and two types of analyses were performed: one considering the potential cracking of concrete by reducing the stiffness of the concrete elements by half, and the other without considering potential cracking. Additionally, two types of analyses were performed: one considering the potential separation of the side walls and the other without considering potential separation. The analysis cases considering these design variables are shown in Table I.

2.3 SSI Analysis Model

To perform the SSI analysis of the control building reflecting various design variables, a 3D finite element analysis model was created as shown in Figure 1. The control building consists of reinforced concrete walls,

slabs, basemat, and columns. The walls, slabs, and basemat were modeled using 4-node shell elements, and the columns were modeled using beam elements.

To perform the SSI analysis using KIESSI-3D, a finite element model of the near-field soil was created as shown in Figure 2. The finite element mesh size of the SSI analysis model varies depending on the shear wave velocity according to the site conditions. The infinite elements of the far-field soil are automatically generated within the program and calculate the absorption and scattering of waves at the boundary of the far-field soil region. Additionally, the potential separation between the structure and the near-field soil boundary was considered, and the backfill behind the structure was reflected with a 1:1 ratio with depth. As a result, more than 30 seismic responses were calculated at each slab floor of the structure, and the In-Structure Response Spectra (ISRS) was derived to encompass the maximum response of the seismic analysis considering all design variables. Figure 3 shows the response at the basemat and the ground surface.

Table I: SSI Analysis Case

	Operating Basis Earthquake	Safe Shutdown Earthquake
Seismic input	7	7
Soil type	4	4
Separation of sidewall	2	2
Total number of analysis cases	112	

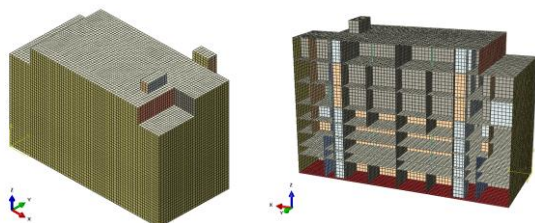


Fig. 1. Seismic analysis model of CB structure

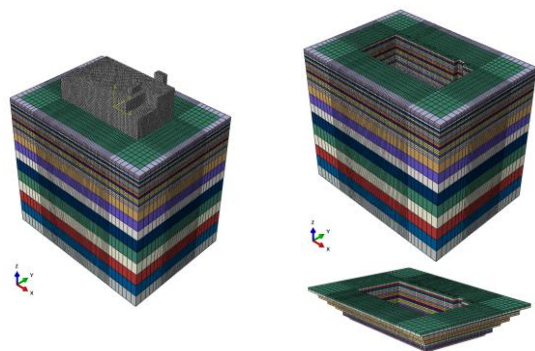


Fig. 2. SSI analysis model of CB, near-field soil model and backfill model

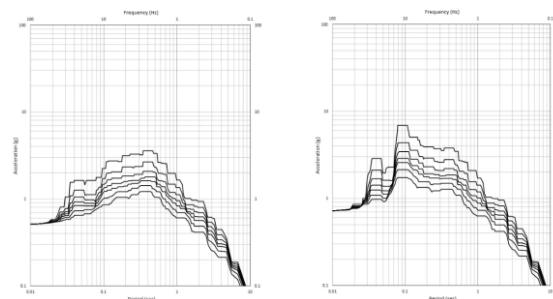


Fig. 3. Illustrative examples of ISRS in CB structure

3. Conclusions

A seismic analysis was performed on the control building of the i-SMR, taking into account various seismic design variables. Through the analysis, the ISRS was derived for all slab floors of the control building, which was then provided to the structural and system fields. Future plans include conducting a Structure-Soil-Structure Interaction (SSSI) analysis on the reactor protection building, the control building, the compound building, and the turbine generator building of the i-SMR to assess their seismic responses.

REFERENCES

- [1] CG. Seo, JM. Kim, "KIESSI Program for 3-D Soil-Structure Interaction Analysis", Computational Structural Engineering Institute of Korea, 25(3), pp.77-83, 2012.
- [2] CG. Seo, JS. Kwon, BC. Park, GS. Woo, and YS. Lee, "Auto-Generation Technique of Numerical Elements for Near-Far Field Soil in Three-Dimensional Soil-Structure Interaction System", Transactions of the Korean Nuclear Society Spring Meeting, Jeju, Korea, May 19-20, 2022.
- [3] US NRC, Standard Review Plan 3.7.2 Seismic System Analysis, Rev. 4, US Nuclear Regulatory Commission, 2013.
- [4] ACI Committee 350, Code Requirements for Environmental Engineering Concrete Structures and Commentary (ACI 350-20), American Concrete Institute, Farmington Hills, MI, 2021.
- [5] ASCE 4, Seismic Analysis of Safety-Related Nuclear Structures, American Society of Civil Engineers, Reston, VA, 2016.
- [6] KEPIC STB, Seismic Analysis and Seismic Capacity Evaluation for Nuclear Facilities, Korea, 2020.
- [7] P. B. Schnabel, J. Lysmer, and H. B. Seed, "SHAKE: A Computer Program for Earthquake Response Analysis of Horizontally Layered Sites", Report No. UCB/EERC-72/12, Earthquake Engineering Center, University of California, Berkeley, December, pp.102, 1972.
- [8] CG. Sun, JT. Han, JI. Choi, KS. Kim, and MM. Kim, "Investigation into the Input Earthquake Motions and Properties for Round Robin Test on Ground Response Analysis", KGS Fall National Conference, September 14-15, Busan, Korea, 2007.