

Innovative Small Modular Reactor (i-SMR) Seismic Design for Reactor Protection Building

Jae-Sung Lim^a, Sung-Min Lee^a, Seung-Ryong Han^a, Choon-Gyo Seo^{a*}
^a KEPCO Engineering & Construction, 269 Hyeoksin-ro, Gimcheon-si, S. Korea
^{*}Corresponding author: seosck@kepc-enc.com

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1. Introduction

The global increase in data centers and AI adoption is driving a sharp rise in electricity demand. As a result, the construction of new nuclear power plants is becoming more prevalent to secure a reliable power supply. Additionally, nuclear power plants are a necessity to reduce carbon emissions and generate eco-friendly energy. In recent years, the small modular reactor (SMR) market has been rapidly emerging, offering improved safety and constructability through modular design. Globally, more than 80 new SMR designs are being developed, with some already under construction. In Korea, SMART100(System-integrated Modular Advanced Reactor) development began in 1997, and the standard design has recently been approved. The development of the marine SMR system(BANDI) is also gaining momentum. A two-stage project to develop the i-SMR has been ongoing since 2024, with multiple institutions participating in the government-led initiative.

This study conducted seismic analysis and design on the RPB where the i-SMR reactor is installed, taking into account the SSI effect. The building's seismic level is based on the top-tier requirement, with a peak ground acceleration(PGA) of 0.5g. However, when performing seismic design that incorporates site-specific ground motion response spectrum(GMRS), PGA 0.5g must be satisfied, but in the standard design stage, design response spectra(DRS) are used, so the design was performed at a seismic level of PGA 0.3g. As a result, seismic analysis was performed by incorporating seismic input motion and seismic design parameter that meet USNRC SRP requirements and have a seismic level of 0.3g.

2. Analysis Methods and Parameters

2.1 Frequency Domain Soil-Structure Analysis

Seismic analysis of nuclear power plant structures requires a precise analysis that takes into account the SSI effect. SSI analysis must simultaneously consider the linear horizontally layered half-space of the soil, soil complexity, and non-linear behavior. Furthermore, changes in structural material properties and the complexity of the analysis method make it challenging to develop an accurate analysis model. To overcome

this, various SSI analysis methods have been proposed, with the direct method and substructure method being commonly used. To perform seismic analysis of the i-SMR, the KIESSI-3D program was used, which employs the direct method to solve the problem in the frequency domain [1]. This program is a dedicated SSI program developed in Korea over many years, which models the near-field soil region using finite elements and uses dynamic infinite elements (IE) to represent the far-field soil region, enabling seismic analysis.

2.2 Seismic Design Parameter

The design parameters for RPB seismic analysis include seismic input motion, three-directional simultaneous seismic loading, control point, site soil condition, damping ratio, soil non-linearity, hydrodynamic model, steel-plate concrete, cracked/uncracked condition, and potential side-wall separation. These were developed to satisfy various requirements, including USNRC SRP 3.7.2, ACI 350, ASCE 4, and KEPIC STB [2,3,4,5]

Seismic input motion was generated in three directions, with two horizontal and one vertical component, and seven sets of artificial seismic waves were created. Real earthquake records were used as seed motions and modified to match the DRS with a total duration of 20.48 seconds and a time step of 0.005 seconds. During seismic analysis, three-directional seismic motions were applied simultaneously for each set. The control point was located at a point with a shear wave velocity of 3500 ft/sec or higher, where time-history seismic motion was input. The site soil conditions were classified into four categories, with shear wave velocities of 1000, 3500, 5000, and 8000 ft/sec, representing vertical soil profiles. To account for the non-linear characteristics of the soil, a one-dimensional wave propagation analysis, SHAKE analysis, was performed, and equivalent linear soil properties were obtained [6,7].

A hydrodynamic model was used to simulate the behavior of the water tanks inside the RPB, and steel-plate concrete was applied to the tank walls and specific areas within the building, while the remaining structures were modeled as reinforced concrete [8]. To account for the potential impact of cracking on the reinforced concrete, analyses were performed with the stiffness of all concrete elements reduced by 50%, as well as analyses that assumed no cracking. Furthermore,

analyses were performed with and without considering the potential separation of the side-walls. Taking into account all seismic variables, the cases of analyses were selected as shown in Table 1.

2.3 Analysis Model

A 3D finite element analysis model of the RPB was created, as shown in Figure 1, to perform SSI analysis that takes into account various seismic parameters. The RPB is composed of a reinforced concrete wall and slab system that provides horizontal load resistance, and a frame that supports vertical loads. The walls and slabs were modeled using 4-node shell elements, while the frames and foundations were modeled using beam elements and 8-node solid elements, respectively. A hydrodynamic model was applied to the water tanks inside the RPB, including the ECT, RWT, SFP, and refueling canal, by modeling the convective component with spring elements and the impulsive component with massless rigid elements.

For SSI analysis using KIESSI-3D, a finite element model of the near-field soil is necessary, as shown in Figure 2. The finite element mesh size for each analysis model differs depending on the site soil conditions. The program automatically assigns IE for the far-field soil, enabling the calculation of wave absorption and scattering at the far-field soil boundary. Furthermore, potential separation was considered at the interface between the structure and the near-field soil, and the backfill behind the structure was modeled at a 1:1 ratio with depth. Seismic analysis was performed to calculate over 30 seismic responses at all slab levels, and the in-structure response spectra that envelop the maximum response for all seismic analysis case was obtained. Figure 3 illustrates the response at the foundation slab and the ground surface.

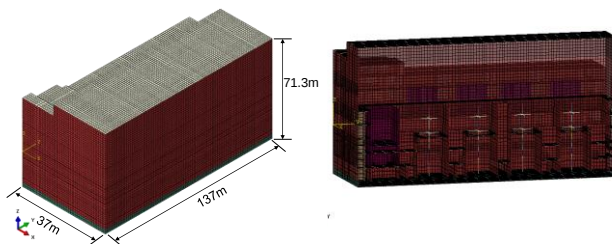


Fig. 1. Seismic analysis model of RPB structure

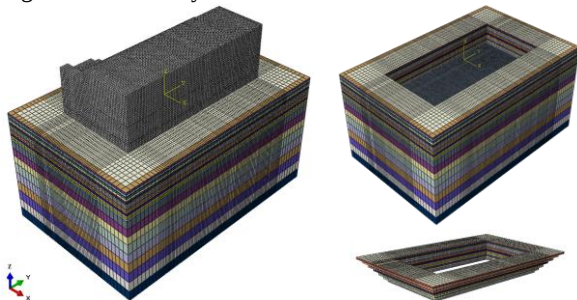
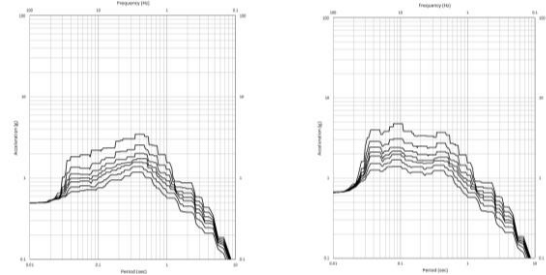


Fig. 2. SSI analysis model of RPB, near-field soil model and backfill model

Table I. SSI analysis case

	OBE	SSE
Input motion	7	7
Soil condition	4	4
Crack/uncrack	2	2
Separation of side-wall	2	2
Total number of analysis cases	224	



(a) Foundation (EW) (b) Ground surface (EW)
Fig. 3. In-structure response spectra (ISRS) of RPB structure

3. Conclusions

Seismic analysis was performed on the RPB with the i-SMR, reflecting various seismic parameters. As a result of the analysis, the ISRS was derived at all slab locations of the RPB. This result was provided as input data for various system fields. In the future, Structure-soil-structure interaction (SSSI) analysis will be performed on the RPB, control building, turbine generator building, and compound building to evaluate their responses.

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