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FLOOR RESPONSE SPECTRUM ANALYSIS OF BASE ISOLATED NUCLEAR POWER PLANT AND SIMPLIFIED MODEL

Jae-Wook Jung[1], Heungwoon Jang[2], and Jung-Wuk Hong[3]

[1] Ph.D. Candidate, KAIST, Republic of Korea (jaewook1987@kaist.ac.kr)
[2] M.S. Student, KAIST, Republic of Korea
[3] Associate Professor, KAIST, Republic of Korea (j.hong@kaist.ac.kr)

ABSTRACT

Need for the safety of the nuclear power plant (NPP) is emerging due to the Fukushima nuclear accident that recently occurred in Japan. The nuclear accidents cause a large number of casualties and serious property damage more than any other common accidents. In particular, ongoing risks due to the radiation leakage can be a great threat to the society. The way to apply the seismic isolation device to a NPP is presented as a measure for ensuring the safety of NPP. By applying the isolation device to the structure, the natural period of the structure is longer, and the response of the structure can be reduced. Especially in the Fukushima nuclear accident, damage to the power supply and cooling system by flooding of the power plant caused the leakage of radioactive material and the explosion. Therefore, ensuring the safety of internal devices as well as NPP itself is essential. As a result, in order to evaluate the seismic safety of the base isolated NPP, it is necessary to create floor response spectrum (FRS) considering the base isolation system. To create FRS, a lot of simulations should be performed in order to consider the variation such as earthquake or the property of isolation device. It takes considerable time to create FRS through the simulation of a full-scale structure. In this research, the way to simulate base isolated NPP by using simplified model and the method to estimate the FRS of the whole structure are discussed.

INTRODUCTION

Requirement for the safety of the NPP is emerging since the Fukushima nuclear accident took place in Japan. Especially, the nuclear accident can cause numerous casualties and serious property damage. As a way of ensuring the safety of NPP, the approach to apply the isolation device to a NPP has been introduced. The base Isolation system is one of the most popular and useful devices to protect a structure against seismic loading (Datta (2010)). The device decouples a superstructure from its substructure that is subjected to the ground motion. As a result, the response of the structure due to the seismic loading can be substantially reduced. Although the advantages of the base isolation system are well known for the safety of NPP (Eidinger and Kelly (1985)), these advantages have not been quantified completely (Huang *et al.* (2010)).

Especially, ensuring the safety of the internal devices as well as NPP itself is essential. Floor response spectrum (FRS) is commonly used as an input data to conduct seismic design for the equipment located on the specific floor (Suarez and Singh (1987)). Also, in order to evaluate the safety of the base isolated NPP, it is required to create FRS considering the base isolation. FRS represents the peak response demand of non-structural components on the each floor (Kanee *et al.* (2013)). Several studies about the standard of design response spectrum have been conducted, and the representative one of them is Reg. Guide 1.122 (U.S. NRC (1978)), where the methodology of smoothing floor response spectra and broadening peaks is represented to account for uncertainties in the structural frequencies (U.S. NRC (1978)). However, the reliability of the existing methodology with regard to the base isolated NPP has not been sufficiently investigated yet.

In order to calculate FRS considering the uncertainties of material properties and earthquake, a large number of simulations are required to be performed, and it takes extensive time to perform the simulations for full-scale structures. In this research, the methodology to perform the analysis of base isolated NPP by using simplified model and the estimation of the FRS of full-scale structure is discussed.

SIMULATION MODEL

For the simulation of the nuclear power plant (NPP), the APR1400 (Advanced Power Reactor 1400) is numerically modeled, which is originally known as Korean Next Generation Reactor (KNGR) (Goldberg and Rosner (2012)). The superstructure and the nuclear island (NI) of the model are made up of the masses, beam stick elements and the 3D-solid elements, respectively. 454 base isolators are modelled at the bottom of the nuclear island using link elements. At the center of the model, the reactor containment building (RCB) is placed, and the auxiliary building (Aux. building) is located surrounding the model.

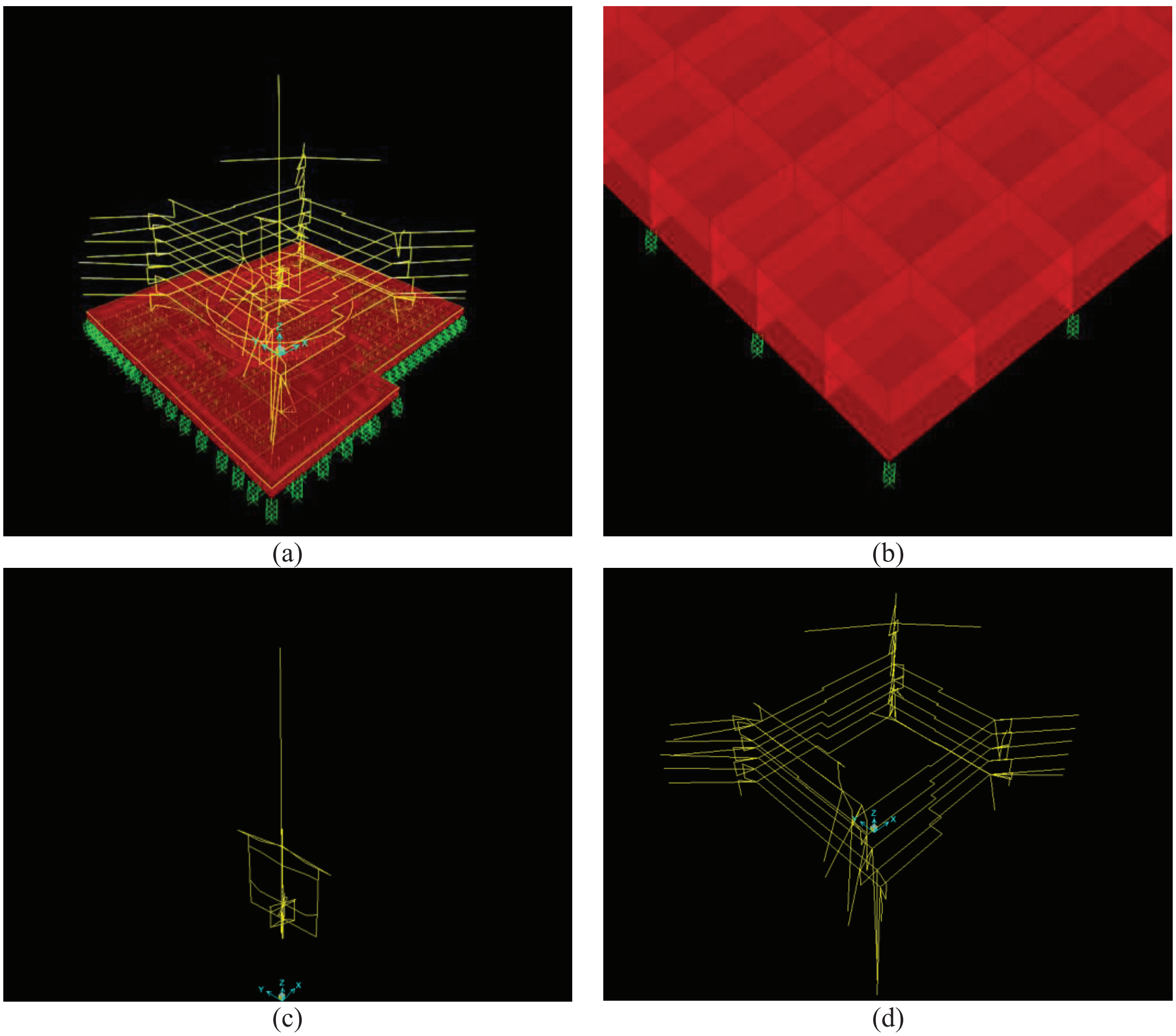


Figure 1. (a) APR1400 Full model, (b) solid and link elements, (c) RCB, and (d) Aux. building.

The behavior of the base isolator is assumed to be bi-linear, and the properties can be described using parameters such as the 1st stiffness (K_1), 2nd stiffness (K_2), and the characteristic stiffness (Q_d) as shown in Figure 2. The properties of the isolator are summarized in Table 1.

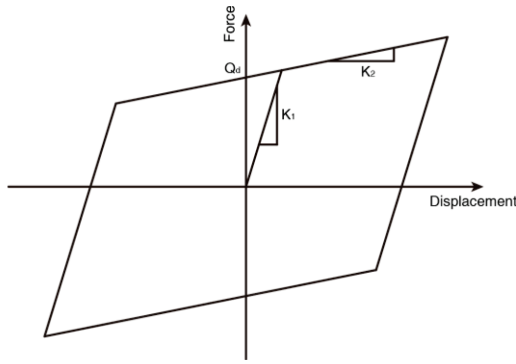


Figure 2. Bilinear response and coefficients of the isolator.

Table 1: Coefficients of the isolator of the full model.

Property	Isolator	Isolation system
K_1	81.41 MN/m	36.96 GN/m
K_2	6.27 MN/m	2.85 GN/m
Q_d	1.21 MN	549.33 MN

The simplified model is constructed by considering only RCB. The lumped masses of the RCB are allocated to the nodes of the three columns. The mass of the nuclear island is added at the nodes on the base.

(a) (b)

Figure 3. (a) APR1400 Simplified model and (b) link element.

The properties (K_1, K_2, and Q_d) of the isolator of the simplified model are determined such that the ratio of the total mass of the full model and the total mass of the simplified model satisfies the following relationships:

$$K_1^{Full} N_{Isolator}^{Full} : K_1^{Simplified} N_{Isolator}^{Simplified} = Total\ mass^{Full} : Total\ mass^{Simplified} \quad (1)$$

$$K_2^{Full} N_{Isolator}^{Full} : K_2^{Simplified} N_{Isolator}^{Simplified} = Total\ mass^{Full} : Total\ mass^{Simplified} \quad (2)$$

$$Q_d^{Full} N_{Isolator}^{Full} : Q_d^{Simplified} N_{Isolator}^{Simplified} = Total\ mass^{Full} : Total\ mass^{Simplified} \quad (3)$$

where K_1^{Full}, K_2^{Full}, and Q_d^{Full} are the properties of the isolator attached to the full model, $K_1^{Simplified}$, $K_2^{Simplified}$, and $Q_d^{Simplified}$ are the properties attached to the simplified model, $N_{Isolator}^{Full}$ is the number of isolators of the full model, and $N_{Isolator}^{Simplified}$ is the number of isolators of the simplified model.

In these models, the total number of isolators of the full model is 454 while 3 isolators are used for the simplified model. The total mass of the full model and the simplified model is 466,692 ton and 177,644 ton, respectively. Using Equations (1), (2), and (3), the coefficients of the isolator are calculated, and the coefficients are listed in Table 2.

Table 2: The properties of isolator and isolation system of the simplified model

Property	Isolator	Isolation system
K_1	3,105.65 MN/m	9.32 GN/m
K_2	239.13 MN/m	0.72 GN/m
Q_d	46.16 MN	138.48 MN

NUMERICAL CALCULATION

In order to perform the seismic analysis, an earthquake history is selected, and the history is modified to satisfy the 0.5g target spectrum described in the Reg. Guide 1.60 (U.S. NRC (1978)). The analyses are performed considering two loading cases. In the first comparison, the loading is in x-direction only, and in the second comparison, the loading is in x-, y-, z-directions. The time histories of the responses are given in Figures 4 to 7. In this comparison, it should be noted that the force histories of the simplified model are divided by the factor 38 because the properties of the isolator in the simplified model are about 38 times larger than those of the full model and the force of the isolator in the simplified model is 38 times larger than the force of the full model for a same displacement.

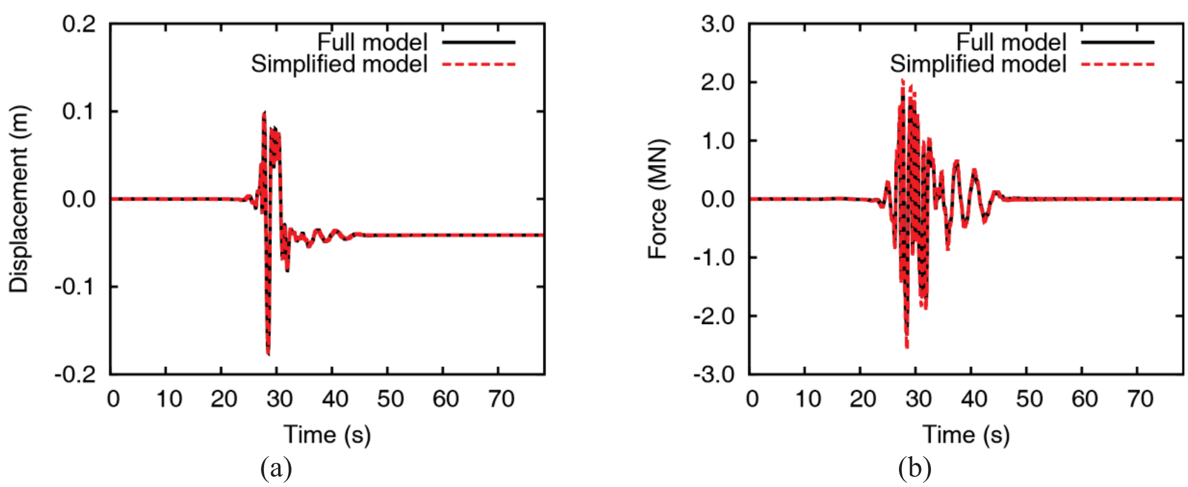


Figure 4. X-directional (a) displacements and (b) forces of the full model and the simplified model due to X-directional earthquake input.

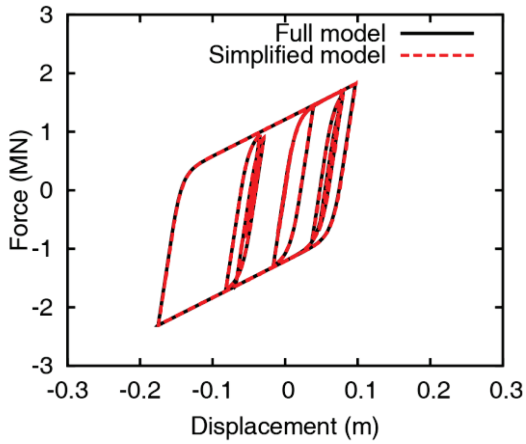
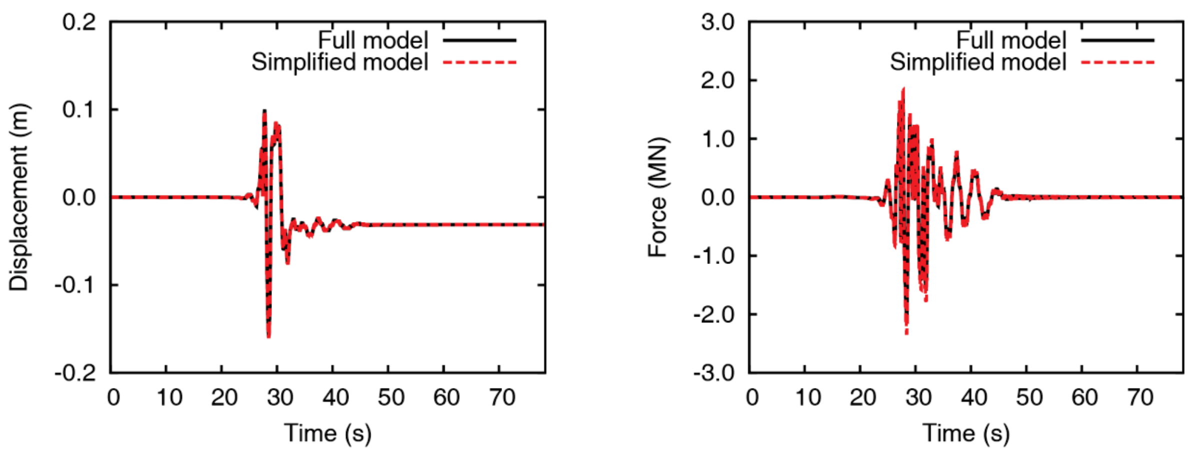


Figure 5. Force-displacement curves of the full model and the simplified model due to X-directional earthquake input



(a) (b)

Figure 6. X-directional (a) displacements and (b) forces of isolator in the full model and the simplified model due to X-, Y-, and Z-directional earthquake input.

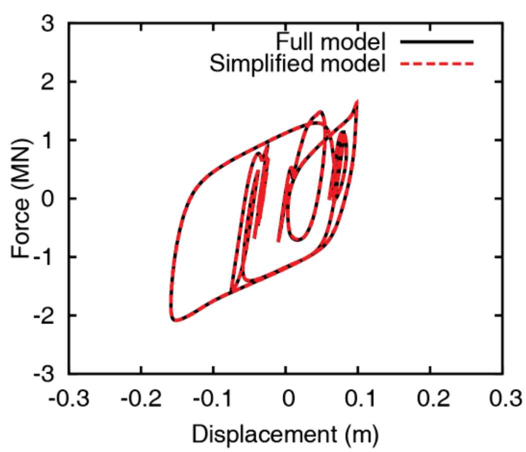


Figure 7. Force-displacement curves of the full model and the simplified model due to X-, Y-, and Z-directional earthquake input.

From Figures 4, 5, 6, and 7, it is observed that the responses of the simplified model show good agreement with the responses of the full model. However, the results by the X, Y, and Z-directional earthquake input are relatively smaller, compared to the result by X-direction earthquake input as shown in Figures 4-(b) and 6-(b). The reason is that the multi-axis input causes the smaller yield point due to the 2-axis interaction. This characteristic is also observed in the force-displacement curves in Figures 5 and 7.

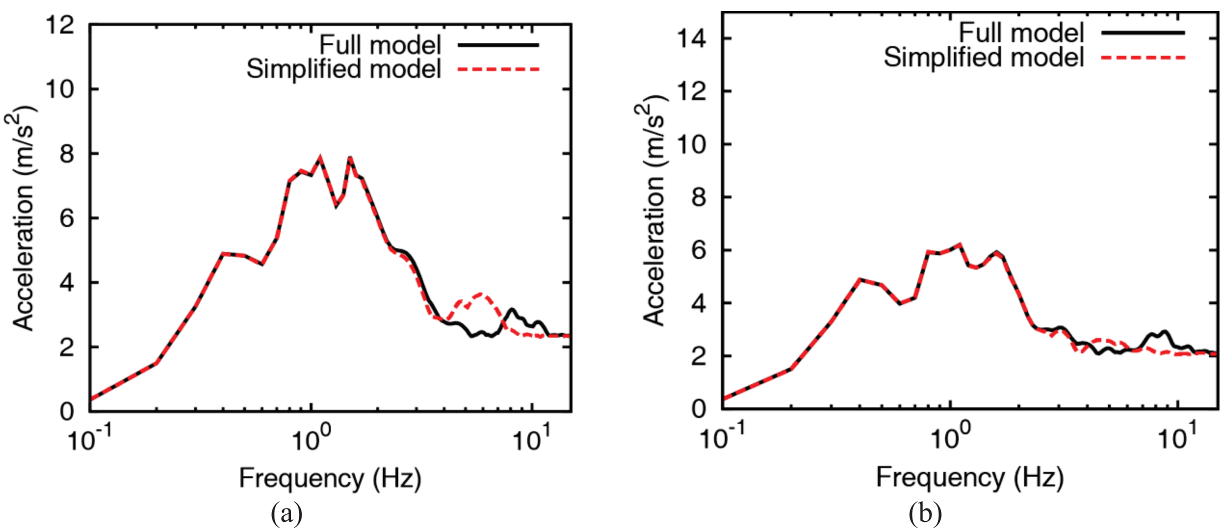


Figure 8. FRS at h=20.42 m due to (a) X-directional input and (b) X-, Y-, and Z-directional earthquake input.

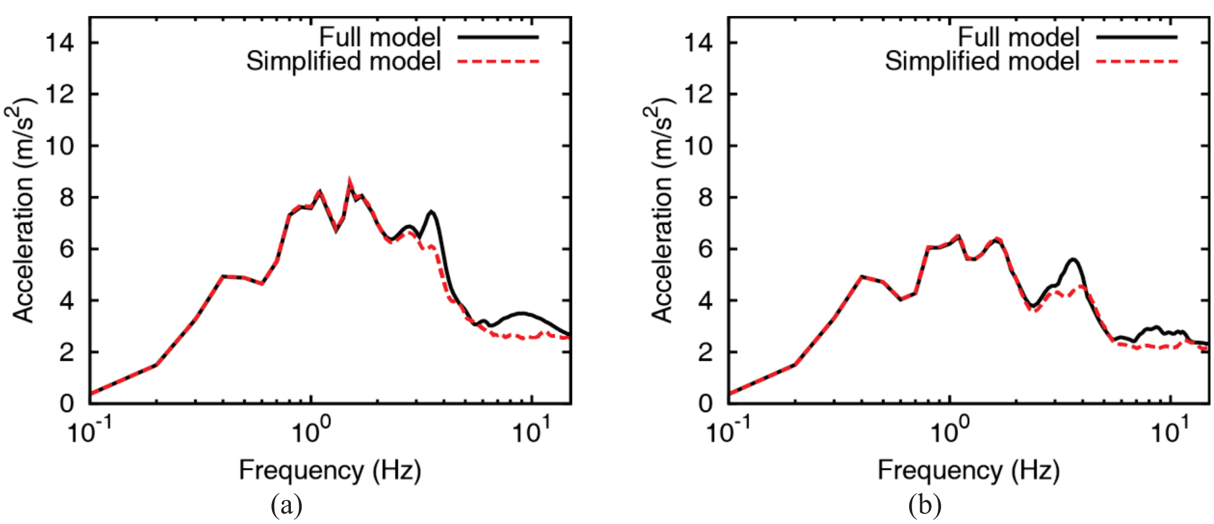


Figure 9. FRS at h=59.74 m due to (a) X-directional input and (b) X-, Y-, and Z-directional earthquake input.

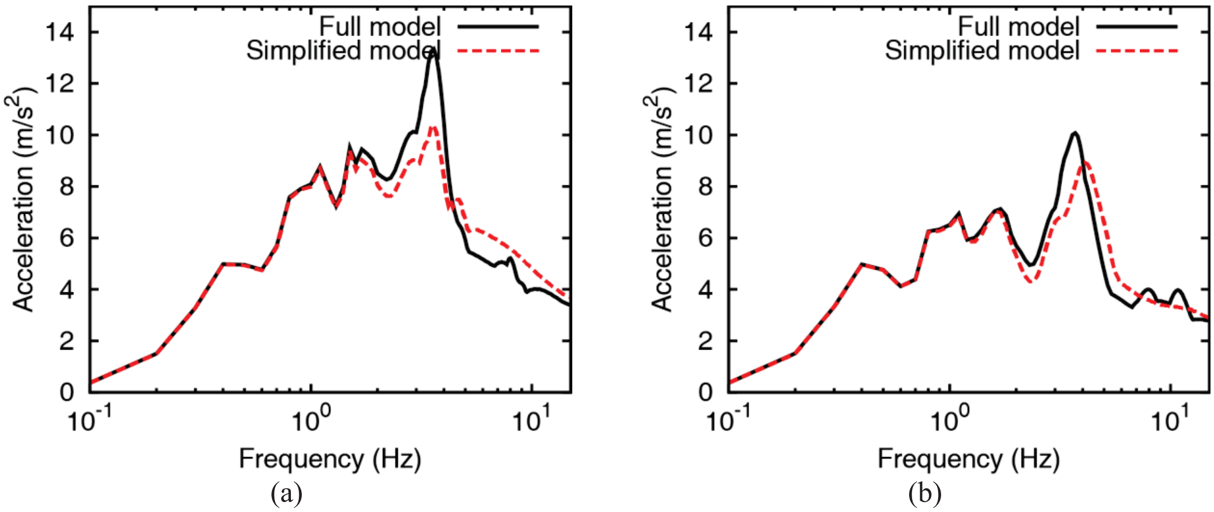


Figure 10. FRS at h=100.95 m due to (a) X-directional input and (b) X-, Y-, and Z-directional earthquake input.

In order to verify the simplified model for the evaluation of FRS, the calculated floor responses are compared at three different locations (h=24.42 m, 59.74 m, and 100.95 m), and the results are plotted in Figures 8 to 10. As the height increases, the response also increases in the specific frequency region (3~5 Hz), and this characteristic is observed in the both full and simplified model. As aforementioned, the floor responses due to X-, Y-, and Z-directional earthquake input are smaller than the responses by only X-directional earthquake input.

CONCLUSION

The calculation of the floor responses of the full model takes large amount of time. In order to alleviate the computational cost, a simplified model of NPP is developed to replace the use of the full model, and the applicability of the model is investigated. For the numerical study, APR1400 which is originally known as a Korean Next Generation Reactor is considered, and only the RCB is modeled. The properties of the simplified model's isolator are determined to match the scale law, and the responses are measured at three different locations. Overall, the responses of the simplified model show good agreement with those of the full model. Therefore the applicability of the simplified model of the APR1400 is verified.

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