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# Effect of second hardening on floor response spectrum of a base-isolated nuclear power plant

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## HIGHLIGHTS

- The effect of variability in the isolation device and earthquake is evaluated.
- The variability in earthquake characteristics dominates the floor response spectrum.
- Bouc-Wen model is employed to consider the second hardening behavior of isolator.
- The second hardening behavior is evaluated at various PGA levels.

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## ABSTRACT

The floor response spectra are calculated by constructing a numerical model (APR1400) equipped with base isolators of a bilinear material and a Bouc-Wen material, respectively, in order to investigate the effect of the second hardening. The variations of the earthquakes are incorporated to the loads, and two different properties of the isolator materials are modeled. The second hardening behavior increases the stiffness of the isolator in the high strain regime and suppresses the displacement of the isolator. Therefore, the role of the base isolation device isolating the superstructure from the ground motion does not perform properly, which causes amplification of the floor response of the superstructure. In practice, the second hardening of the isolator material might need to be taken into account for designing the base isolation system.

## 1. Introduction

Nuclear accidents can cause serious casualties, property damage, and devastating environmental hazards, as compared with other common accidents, due to the radioactive materials contained within the reactor. There is no doubt that the stability of nuclear power plant is significantly more important than other general structures. Especially, seismic load is one of the most important factors in the design of nuclear power plants, and its analysis and design process are relatively difficult and complex. Most nuclear structures have a thick concrete shear wall structure for radiation shielding. As a result, the dynamic characteristics of nuclear structures are matched with the main frequency range of the earthquake, which further increases the importance of the seismic design of nuclear structures (Joe, 1993).

In order to reduce the influence of the seismic loads, a method of applying a seismic isolator to a nuclear power plant has been introduced. This device separates the superstructure from the underlying substructure which is subjected to ground motion. As a result, responses due to the earthquake load are substantially reduced. Although there is no precedent of seismic isolation used to onsite nuclear power plants in South Korea yet, but various studies have been actively carried out to enhance the seismic safety to the nuclear power plants that will be exported to countries that might have strong earthquakes. Also, for critical structures other than nuclear power plants, seismic isolation devices have already been applied to various structures such as high-rise residential buildings, LNG storage tanks, and bridges. Seismic isolators (e.g., lead rubber bearings) are generally known to have a hardening phenomenon. Hardening properties increase the shear stiffness of the isolator at large strain ranges (Aiken, 1997; Kikuchi et al., 2010). It is therefore important to evaluate the structural stability of isolated structures affected by the nonlinearity of the isolator (Alhan and Gavin, 2004). Considering this nonlinearity,

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it is necessary to discuss whether the response of the superstructure increases as compared with the case without hardening. However, in the nonlinear region, it is still difficult to model the restoring force characteristics of the isolator, including the hardening effect. Therefore, a more detailed examination of the simplified analytical model of the isolator is required for response analysis (Fujita et al., 2016).

The study of internal equipment response was mainly concerned with the seismic safety of nuclear power plants (Biggs and Roesset, 1970; Villaverde, 1997). Nuclear power plants are equipped with numerous steel cabinets that accommodate electrical or control instrumentation. Most of them are important for safe operation and stopping of the power plant. In addition to maintaining structural integrity even in the case of strong earthquake such as design earthquake, the essential functions assigned to each equipment should be performed normally without any problems. For this purpose, the seismic safety of the structures should be ensured at the time of the construction of the power plant (Koo et al., 2008).

To quantify the earthquake risk of the internal equipment, several studies have been performed to estimate the maximum acceleration (Miranda and Taghavi, 2005; Rodriguez et al., 2002; Taghavi and Miranda, 2005). Particularly, the floor response spectrum (FRS) represents the peak response demand of non-structural components (e.g., internal devices) on each floor (Kanee et al., 2013). These data are commonly used in the seismic design of mechanical and electrical equipment (Suarez and Singh, 1987). The Nuclear Regulatory Commission's Regulatory Guide 1.122 (Nuclear Regulatory Commission, 1978) provides a methodology for smoothing a FRS by broadening peaks to accommodate the uncertainties in the structural frequencies.

Several studies have been carried out on the effects of the variability of seismic isolation devices. The effect of the arrangement and variability of the seismic isolator on the response of the isolated structure was investigated by Shenton and Holloway (Shenton and Holloway, 2000), and the effect of various types of isolators and earthquakes on the response of the seismic isolator was studied by Huang et al. (Huang et al., 2006). In this study, we investigated the influence of the variability of the seismic isolator and the variation of seismic load on the floor response, and the effect of second hardening on the floor response of the base-isolated nuclear power plant. Two types of software are used for efficient simulation. The one is a structural analysis program SAP2000 which performs a fast nonlinear analysis (FNA) for time-history analysis (Ibrahimbegovic and Wilson, 1989; Wilson, 1993). The FNA method which is one of the modal analyses is an extremely efficient method (Wilson and Habibullah, 1998) and is useful for performing a large number of simulations. Specifically, SAP2000 provides link elements for isolators, and the behavior of link elements is governed by a bilinear model. Therefore, SAP2000 is useful for performing a large number of simulations to evaluate the effect of variability (e.g., earthquake and isolator parameters) on the floor response spectrum. However, the bilinear model has a limitation in describing the second hardening behavior that occurs at high strain range of isolator. Therefore, an open-source earthquake engineering simulation code OpenSees is utilized to perform the earthquake analyses for the extended design basis (EDB) considering the second hardening behavior of isolator. OpenSees performs the time-history analysis using the direct integration method and provides various material models for describing the behavior of the isolator in addition to the bilinear material model. In particular, the behavior of seismic isolator is simulated using the Bouc-Wen material model, which is widely used for structural control, base-isolation devices for building, and other types of damping devices. The Bouc-Wen model has been applied and studied in various fields. Domaneschi investigated how to control the hysteresis components of a semi-active control system in real time through emulation using the Bouc-Wen model (Domaneschi, 2012). Ikhouane et al. studied the input-boundded output stability property of various classes of Bouc-Wen models (Ikhouane et al., 2007), and the ability to reproduce the physical characteristics inherent in the system. Sireteanu et al. also proposed an extended Bouc-Wen model to improve the ability to approximate the experimental symmetric hysteresis loop (Sireteanu et al., 2010). In this study, the second hardening behavior of the isolator is described using the Bouc-Wen material model and the results are compared with the numerical results calculated using the bilinear model. Finally, the effects of the characteristics of the seismic isolator on the floor response spectrum are evaluated, and the influence of the second hardening of the seismic isolator on the floor response spectrum is investigated.

## 2. Numerical model for nuclear power plant

### 2.1. APR1400 ANT model

To simulate the earthquake response, we numerically model the APR1400 (Advanced Power Reactor 1400), which is known as the Korean next generation reactor (KNGR) (Goldberg and Rosner, 2012). The numerical model was originally developed by KEPCO E&C (KEPCO Engineering & Construction Company, Inc.) using SAP2000. We converted the SAP2000 model to an OpenSees model in order to use the material models available in OpenSees software.

Fast Nonlinear Analysis (FNA), used in SAP2000, is a modal analysis method useful for static or dynamic evaluation of linear or nonlinear structural systems. Because FNA is computationally efficient, it is suitable for time history analysis and can perform computations more efficiently than direct integration method. However, there are limitations in clearly expressing the nonlinear behavior of various materials and analyzing its effects in the numerical analysis using the FNA method. Therefore, the Bouc-Wen model is applied to represent the nonlinear behavior in the high strain region of the isolator and the analysis is performed using OpenSees. One of the direct integration methods, Newmark method, is used for the analysis. As a result, analyses are performed using SAP2000 when performing various analyses considering the variability of parameters in the low strain area where secondary hardening did not occur. In order to analyze the effect of secondary hardening in high strain region, analyses are performed using OpenSees. For the analysis using SAP2000, the 5% damping is imposed by modal damping while 5% Rayleigh damping is used for OpenSees simulations. Dynamic response in OpenSees is carried out by direct integration, and the Rayleigh damping is determined by selecting two distinct modal frequencies. Because the first and second modal frequencies are very close to each other, we select the first and third frequencies to calculate the damping.

The superstructure and the nuclear island (NI) of the model are composed of beam–stick elements with lumped masses and three-dimensional solid elements, as shown in Fig. 1. The isolators are modeled using bearing elements, and 486 bearing elements are attached at the bottom of the nuclear island. The reactor containment building (RCB) and the auxiliary building (Aux. building) are located at the center of the model.

Modal analysis results of the numerical model are summarized in Table 1. In the base-fixed model, the 1st and 2nd modes are translational modes of the RCB, and the 3rd and 4th modes are the translational modes of the auxiliary building. In the model with seismic isolation devices, modes of the seismic isolation devices are added. The 1st and 2nd mode are translational modes of the isolation system, and the 3rd mode is the rotational mode. The 4th and 5th modes are the translational modes of the RCB, and