FLOOR RESPONSE SPECTRUM OF A BASE-ISOLATED NUCLEAR POWER PLANT CONSIDERING SECOND HARDENING OF THE ISOLATOR SYSTEM

Jae-Wook Jung[1], Sangmin Lee[2], and Jung-Wuk Hong*[3]

[1] *Department of Civil and Environmental Engineering, KAIST, 291 Deahak-ro, Yuseong-gu, Daejeon 34141, Republic of Korea (jaewook1987@kaist.ac.kr)*
[2] *Department of Civil and Environmental Engineering, KAIST, 291 Deahak-ro, Yuseong-gu, Daejeon 34141, Republic of Korea (lesami89@kaist.ac.kr)*
[3] *Department of Civil and Environmental Engineering, KAIST, 291 Deahak-ro, Yuseong-gu, Daejeon 34141, Republic of Korea (jwhong@alum.mit.edu; j.hong@kaist.ac.kr)*

In order to ensure the safe operation of nuclear power plants, it is essential to evaluate the reliabilities of internal devices as well as nuclear power plant itself. The floor response spectrum which represents peak response demand of non-structural components is utilized to predict the safety of the components. In this research, the influences of specific factors on the floor response spectrum are investigated for designing the standard response spectrum. A nuclear power plant including the base isolation system is numerically modeled, and floor response spectrum by earthquakes is evaluated at the selected locations. The behavior of the isolation device is generally assumed to be bi-linear. However, the lead rubber bearing isolator shows the second hardening behavior at high strain range. The Bouc-Wen model is employed in order to consider the second hardening responses. Numerous simulations are carried out to analyze the effect of variability of each factors. The variability of isolation parameters affects on the floor response spectrum, and effect of the second hardening of the isolation device is significant under strong earthquakes. The effect of the variability of given parameters such as earthquake inputs and properties of the isolation device is investigated, and the effects of those parameters are analyzed. The results might be used for improving the design guidelines of the standard response spectrum.

I. INTRODUCTION

It is essential to ensure the safety of the nuclear power plant (NPP) because the nuclear accident causes numerous casualties and serious property damage. An approach to apply the isolation device to the NPP has been introduced as a way of ensuring the safety of NPP against seismic loading. The isolation device is widely used and one of the popular and useful devices to protect structures against earthquakes [1]. By using the device with very soft lateral stiffness, it is possible to decouple a superstructure from the ground motion which is caused by earthquakes. Thus, the isolation device elongates the natural period of the superstructure and substantially reduces the response of the superstructure due to the seismic loading.

Also, it is essential to ensure the safety of the internal devices as well as NPP itself. In order to design the internal devices located on the specific floor, floor response spectrum (FRS) is the peak response demand of non-structural components on the each floor [2] and commonly used as an input data to conduct seismic design (Suarez and Singh (1987)). Therefore, it is required to generate FRS considering the base isolation devices for the safety assessment of base isolated NPP. A number of studies for the standard of design response spectrum have been carried out. One of representative studies is Reg. Guide 1.122 [3]. In the study, the methodologies of smoothing floor response spectra and broadening peaks are introduced to consider the uncertainties in the structure frequencies [3]. However, the additional investigation is required to determine if the existing methodology is applicable to the base isolated NPP.

The isolation device made by rubber-based material deforms bi-linearly in the range of 250% or less shear strain. However, in the range over 250% shear strain, the shear stiffness of the isolation device increases. This stiffness increase is called “Hardening Effect” [4]. This hardening effect which is so called “second hardening” restricts the role of the isolation devices and changes the response of the superstructure. Although the hardening effect occurs in high shear strain range, it is required to evaluate FRS considering the hardening effect in order to ensure the safety of base isolated NPP against strong earthquakes.

In this research, the advanced power reactor 1400 (APR1400) is taken into consideration as a numerical model for simulating seismic analysis. And then, the effect of uncertainties of earthquake and isolation devices on the FRS is evaluated, and the effect of hardening effect is investigated in the extended design basis (EDB).

II. NUMERICAL MODEL

II.A. Nuclear power plant

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). The numerical model is originally developed by KEPCO E&C (KEPCO Engineering & Construction Company, INC) using the structural analysis program, SAP2000. And, the model is converted to the numerical model for OpenSees by authors in order to consider the second hardening behavior of the isolation device.

The superstructure and the nuclear island (NI) of the model are made up of the beam-stick model with lumped masses and 3D-solid elements, respectively (Fig. 1). 486 isolation devices are modelled at the bottom of the nuclear island using elastomeric bearing elements. At the center of the model, the reactor containment building (RCB) and auxiliary building (aux. building) are located.

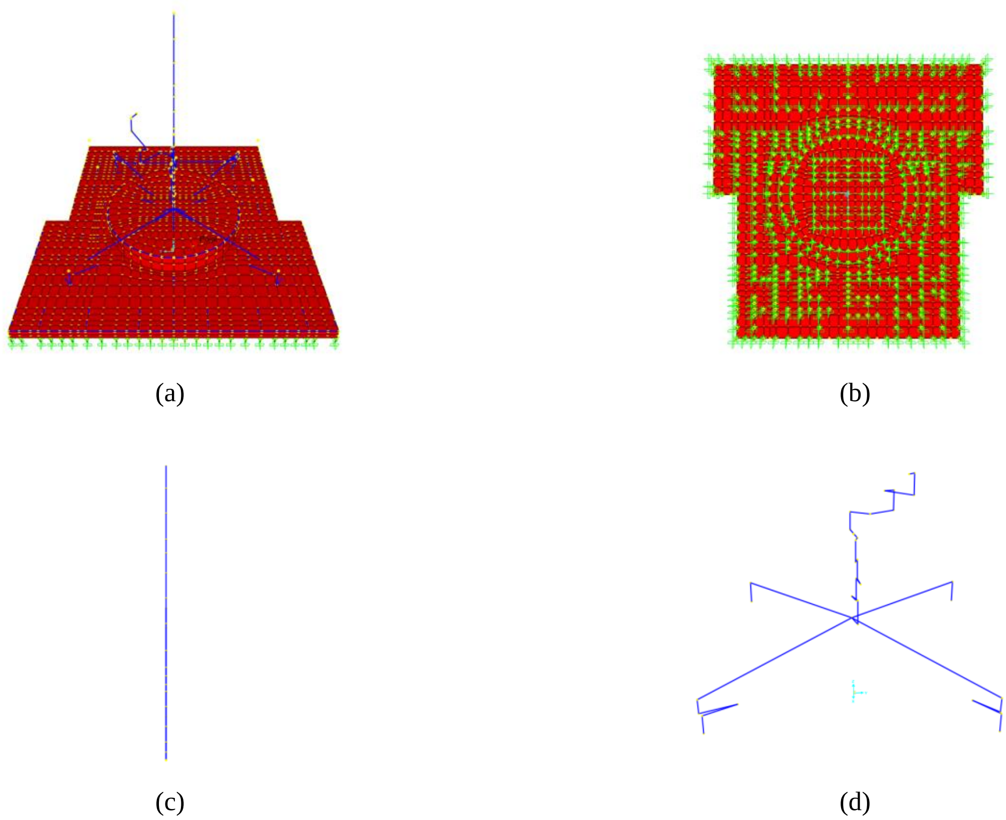


Fig. 1. (a) APR1400 Full model, (b) distribution of isolation devices, (c) RCB, and (d) aux. building..

II.B. Properties of isolation device

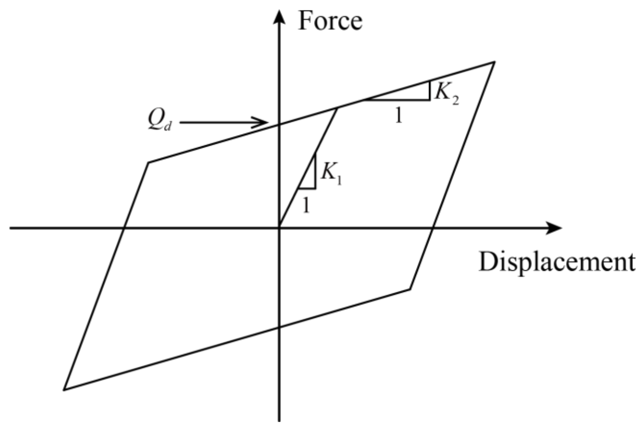


Fig. 2. Behavior properties of isolation device (bi-linear model).

The behavior of the isolation device is basically assumed to be bi-linear in SAP2000, 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 Fig. 2. The properties of the isolation device are summarized in TABLE II.

TABLE I. Selected input earthquake

Parameter	K_1 (MN/m)	K_2 (MN/m)	Q_d (MN)
Value	524.755	2.262	2.251

In order to consider the second hardening behavior of the isolation device, elastomeric bearing element with Bouc-Wen model is employed for the numerical model in OpenSees [5]. While the 2nd stiffness is defined as constant value in the bi-linear model, it is determined from the exponential function in Bouc-Wen model by Eq. (1).

$$K_2 = \alpha_1 K_1 + \alpha_2 K_1 \mu \left| d_y \right|^{\mu-1} \qquad (1)$$

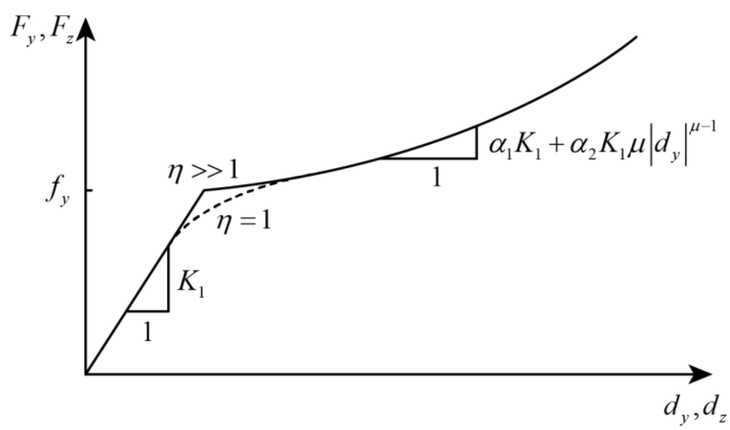


Fig. 3. Behavior properties of Bouc-Wen model.

where α_1 and α_2 are the post yield stiffness ratio of linear and non-linear hardening component, respectively, μ is the exponent of non-linear hardening component. The 2nd stiffness is composed of the linear hardening component ($\alpha_1 K_1$) and the non-linear hardening component ($\alpha_2 K_1 \mu \left| d_y \right|^{\mu-1}$). The linear hardening component is identical with the 2nd stiffness of the bi-linear model. And, the non-linear hardening component determines additional hardening behavior in the hardening range.

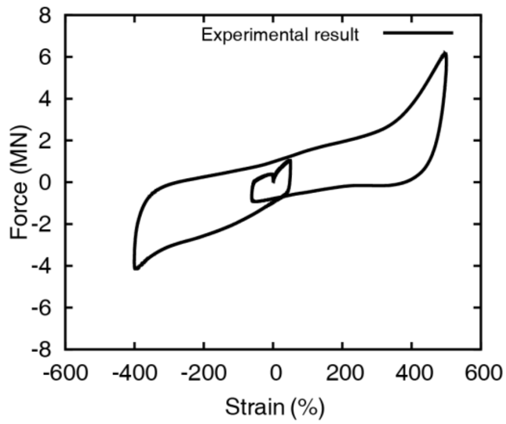


Fig. 4. Force-strain curves of isolation device from experiment (500% strain).

The second hardening behavior of isolator is described using non-linear hardening parameters such as α_2 and μ in Bouc-Wen model. Experimental works about the behavior of the isolation device against horizontal loading was carried out by Korea atomic energy research institute (KAERI). One of the experimental results is shown in Fig. 4, and the second hardening behavior is clearly confirmed in about over 300% strain range. The values of the α_2 and μ are determined based on the experimental result. In order to fit the behavior of the Bouc-Wen model to experimental result, Nelder-Mead method is employed. The Nelder-Mead method is a commonly applied numerical method used to find the minimum or maximum of an objective function in a multidimensional space [6]. After determining the values of 1st stiffness and linear-hardening parameters (α_1, K_1, and f_y) are determined from the parameters of bi-linear model (TABLE I), non-linear hardening parameters (α_2 and μ) are determined using the Nelder-Mead method (TABLE II).

TABLE II. Selected input earthquake

Parameter	a_2	μ
Value	0.00197	7.73372

II.C. Input earthquake

For the earthquake analyses, 30 sets of input earthquakes are selected, and the input earthquake histories are modified to satisfy the 0.5 g target spectrum described in the Reg. Guide 1.60 (U.S. NRC (1978). The selected earthquakes are summarized in TABLE III. The x, y, and z directional earthquake inputs are taken into consideration

TABLE III. Selected input earthquake

Earthquake	**Station**	**ATR/SCR**	**Rock/Soil**	M_w	**Distance (km)**
Miramich, Canada	IB2	SCR	Soil	5.7	5.10
Saguenay, Canada	DCKY	SCR		5.9	194.70
Parkfield	TMB	ATR	Rock	6.19	15.96
San Fernando	PUL	ATR	Rock	6.61	1.81
Gazli, USSR	GAZ	ATR	Rock	6.80	5.46
Imperial Valley	E05	ATR	Soil	6.53	3.95
Imperial Valley	SUP	ATR	Rock	6.53	24.61
Livermore-01	KOD	ATR	Soil	5.80	17.00
Victoria, Maxico	CPE	ATR	Rock	6.33	14.37
Morgan Hill	CLS	ATR	Rock	6.19	23.24

Morgan Hill	G06	ATR	Rock	6.19	9.86
Nahanni	S1	SCR	Rock	6.76	9.60
Nahanni	S3	SCR	Rock	6.76	5.32
Superstition Hills-02	ICC	ATR	Soil	6.54	18.20
Spitak, Armenia	GUK	SCR	Rock	6.77	36.00
Loma Prieta	BRN	ATR	Rock	6.93	10.72
Loma Prieta	CLS	ATR	Rock	6.93	3.85
Loma Prieta	LGPC	ATR	Rock	6.93	3.88
Erzican, Turkey	ERZ	ATR	Soil	6.69	4.38
Cape Mendocino	CPM	ATR	Rock	7.01	6.96
Northridge-01	CHL	ATR	Rock	6.69	20.45
Northridge	PAC	ATR	Rock	6.69	7.01
Northridge	PKC	ATR	Rock	6.69	7.26
Northridge-01	RRS	ATR	Soil	6.69	6.50
Kobe	KJMA	ATR	Rock	6.90	0.96
Kocaeli, Turkey	GYN	ATR	Rock	7.51	31.74
Kocaeli, Turkey	IZT	ATR	Rock	7.51	7.21
Chi-Chi, Taiwan	TCU072	ATR	Rock	7.62	7.03
ChiChi, Taiwan	TCU089	ATR	Rock	7.62	8.88
Duzce, Turkey	BOL	ATR	Rock	7.14	12.04

III. EVALUATION OF FLOOR RESPONSE SPECTRUM (FRS)

As a result of the earthquake analyses, FRS on the aux. building is evaluated, and two nodes located at different height (h = 23.77 and 47.55 m) are selected to generate FRS. The FRS investigated considering the uncertainties of earthquakes and isolation devices, and the effect of the hardening effect also investigated.

III.A. Effect of variability on the floor response spectrum

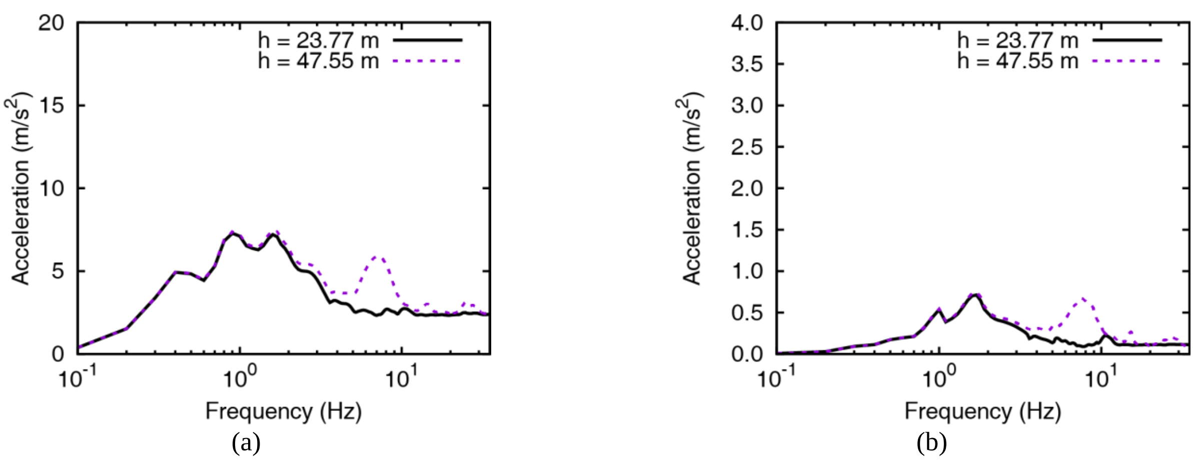
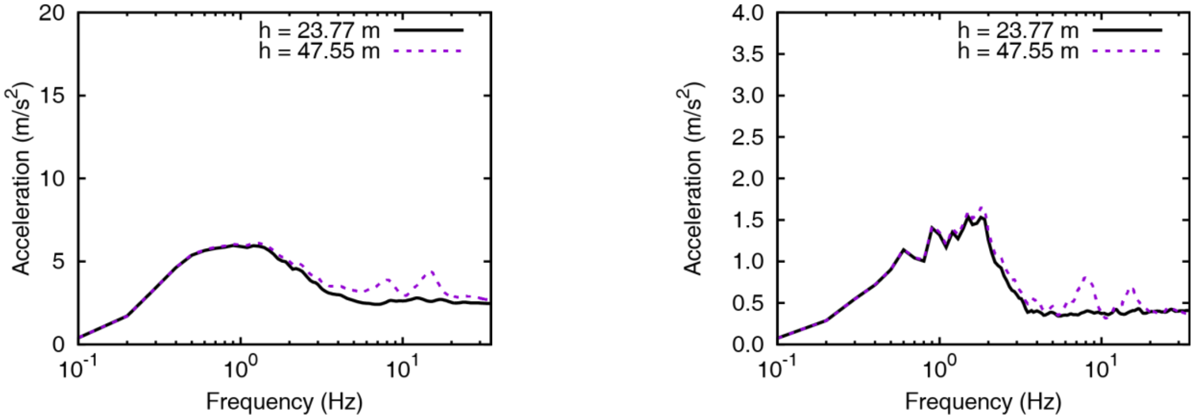


Fig. 5. (a) Mean value and (b) standard deviation of floor response spectrum considering variability of isolation device.

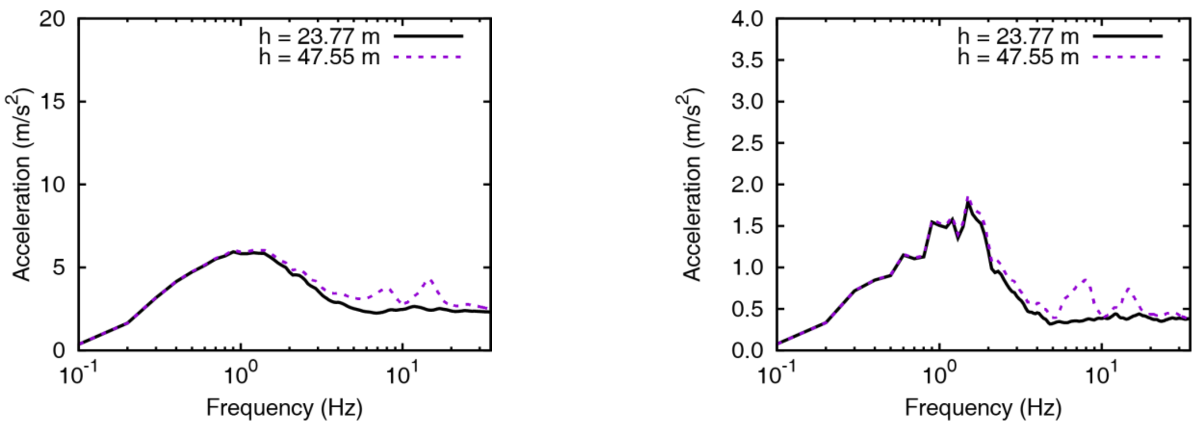
The variability of the isolation device is taken into consideration (Fig. 5). The distribution of the properties for the isolation device is generated using Latin hypercube Sampling (LHS). The distribution is assumed as the properties (K_1, K_2, and Q_d) have the 95% confidence interval in the range from -20% to +20%. The 30 sets of the isolator parameters are generated based on the distribution. And, 30 earthquake analyses are performed with 30 parameter sets of isolator and one of the input earthquake sets. Floor response spectrum is evaluated in terms of the mean value and standard deviation. Although the height is changed the responses remain almost same at the low frequency region (<2 Hz) while the response increases as the height increases in the frequency region of the superstructure.



(a) (b)

Fig. 6. (a) Mean value and (b) standard deviation of floor response spectrum considering variability of earthquake.

In order to perform the seismic analysis considering the variability of the earthquake, 30 sets of input earthquakes are used (TABLE III), and 30 earthquake analyses are carried out. Floor response spectrum is evaluated in terms of the mean value and standard deviation from the results of 30 earthquake analyses. It is confirmed that the tendency of the mean value is almost same with the result considering the variability of isolation devices while the standard deviation represents significantly larger value.



(a) (b)

Fig. 7. (a) Mean value and (b) standard deviation of floor response spectrum considering variability of earthquake and isolation device simultaneously.

To evaluate the effect of variability of earthquake and isolation device simultaneously, the 30 sets of input earthquake sets and the 30 sets of isolator parameter sets are taken into consideration at the same time. Therefore, 900 cases of numerical analyses are carried out. From the 900 analyses results, the mean value and standard deviation of the FRS is confirmed. The results are almost same compared with the result when we considering only the effect of the earthquake. It is considered that the variability of the earthquake governs the variability of the isolation parameters. Therefore, it is sufficient to consider only the variability of earthquake when we perform the earthquake analyses.

III.B. Extended design basis (EDB)

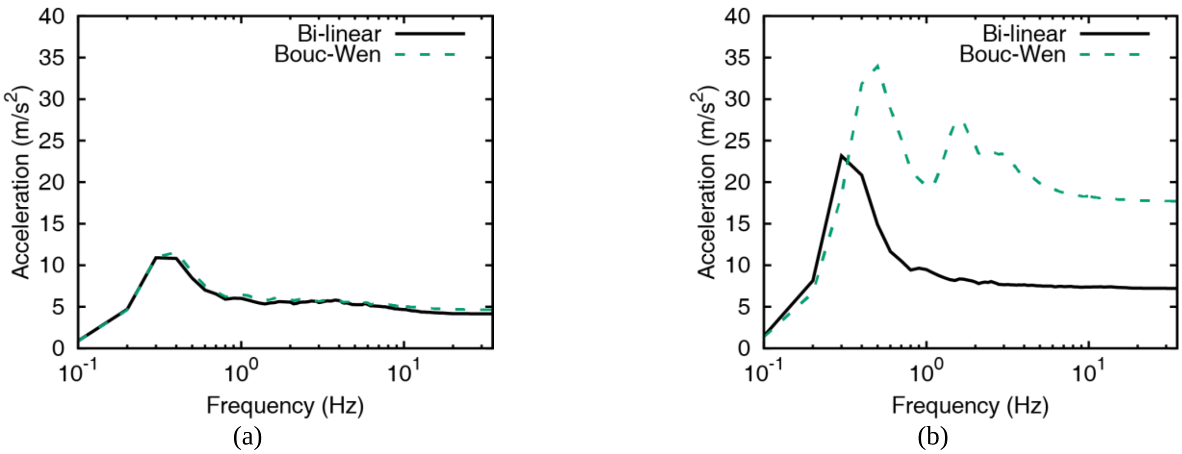


Fig. 8. Comparison between bi-linear and Bouc-Wen model for (a) 1.0 g and (b) 1.5 g PGA levels..

Fig. 8 shows the comparison of the responses at the h = 47.55 m according to the PGA level (1.0 and 1.5 g) between bi-linear and Bouc-Wen model. When the PGA level is equal to 1.0 g, responses from the two models are almost same because the isolation device is in the bi-linear region. The responses of Bouc-Wen model are much larger than bi-linear model in range of the 1.5g PGA level. Because the increase of the PGA level makes the isolation device much stiffer in the high strain region, the significant increase of the responses is confirmed in the frequency region of the superstructure. Also, the frequency of first peak point which represents the frequency of isolation system is changed in the Bouc-Wen model as the PGA level increases. The reason is that the stiffness of the isolation device is continuously changed in the second hardening region, and the frequency of the isolation system is also changed. Consequently, the bi-linear model is valid for evaluating the floor response spectrum in the PGA level smaller or equal than 1.0 g. However, larger PGA level than 1.0 g cause the 2nd hardening behavior of the isolation device, and the responses are significantly different compared with the response of bi-linear model. Therefore, the element model which can describe the 2nd hardening should be used in PGA level larger than 1.0 g.

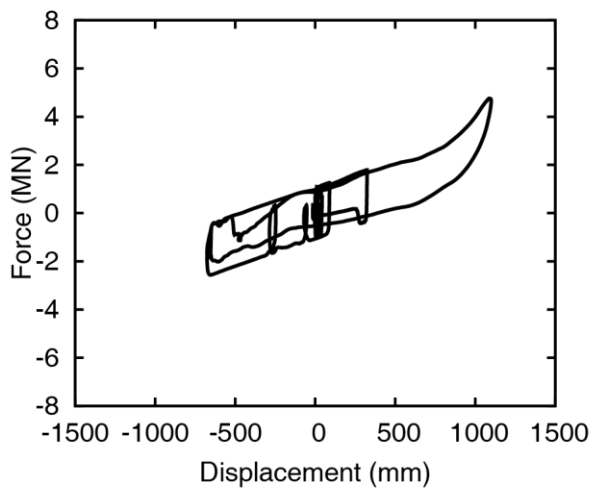


Fig. 9. Force-displacement curve of isolation device using Bouc-Wen model (1.02 g PGA level).

According to the experimental result performed by Korea Atomic Energy Research Institute (KAERI), the isolation device is destroyed in the 500% strain (1120 mm) range. Therefore, if the shear displacement is over the 500% strain, the FRS is meaningless because the isolation system itself is destroyed. The maximum displacement of the isolation device during the simulation is confirmed considering the subdivided PGA level. As a result, it is confirmed that the PGA level which is over 1.02 g causes the maximum displacement exceeding 1120 mm. Finally, the FRS is confirmed in the 1.02 g PGA level in order to more clear comparison (Fig. 10). As a result, the difference between bi-linear model and Bouc-Wen model is more clearly confirmed at the lower floor rather than the higher floor. Also, it is confirmed that the acceleration response is amplified about 20~30% due to the hardening effect.

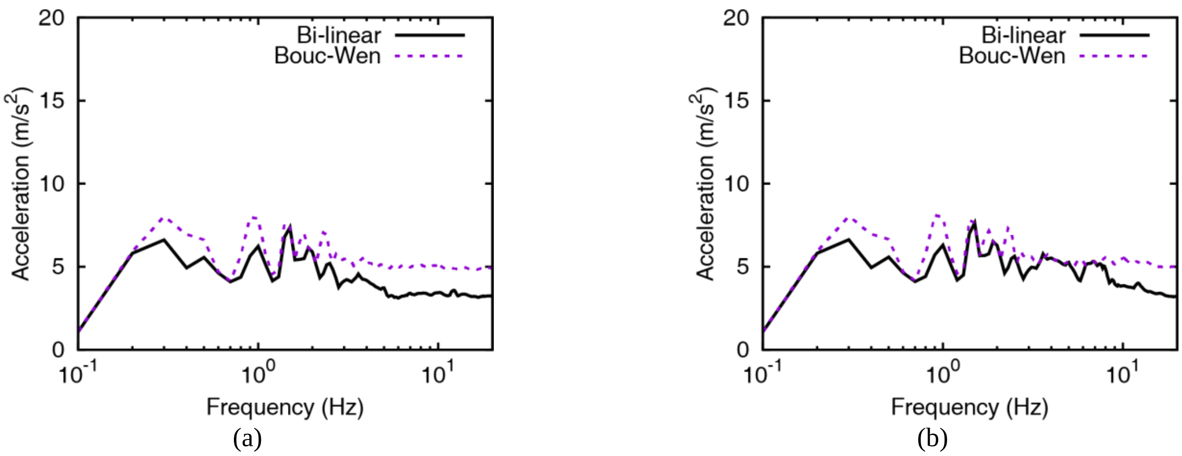


Fig. 10. Floor response spectrum at (a) h = 23.77 m and (b) h = 47.55 m for 1.02 g PGA level.

IV. CONCLUSIONS

In this research, the floor response spectrum of the base isolated nuclear power plant is evaluated. As a numerical model for the nuclear power plant, APR1400 knows as Korean next generation reactor (KNGR) is selected. Numerous earthquake analyses are carried out in order to evaluate the effect of the variability of the input earthquake and isolator parameters. And, it is confirmed that the variability of earthquake governs the variability of isolator parameters. Because the original numerical model is constructed based on the structural analysis program, SAP2000, the model is converted to use the model in OpenSees which provide the various bearing element model. And then, the effect of the 2nd hardening behavior is confirmed according to the various PGA level. Consequently, it is confirmed that the bi-linear model is valid in the PGA level equal or smaller than 1.02 g. In contrast, the 2nd hardening behavior should be taken into consideration larger PGA level than 1.02 g because the changed stiffness of isolator causes the significant effect on the floor response.

ACKNOWLEDGMENTS

This work was supported by the Nuclear Power Core Technology Development Program of the Korea Institute of Energy Technology Evaluation and Planning (KETEP), the Ministry of Trade, Industry & Energy, Republic of Korea. (Grant No. 2011T100200080), and the Korean Minister of the Ministry of Land, Infrastructure and Transport (MOLIT) through the U-City Master and Doctor Course Grant Program.

REFERENCES

[1] Datta TK. Seismic analysis of structures. John Wiley & Sons; 2010.
[2] Kanee ART, Kani IMZ, Noorzad A. Elastic floor response spectra of nonlinear frame structures subjected to forward-directivity pulses of near-fault records. Earthquakes Struct 2013;5:49.
[3] Nuclear Regulatory Commission. Regulatory Guide 1.122, Development of Floor Design Response Spectra for Seismic Design of Floor-Supported Equipment or Components 1978.
[4] Adachi Y, Unjoh S. Seismic response characteristics of seismically isolated bridge considering hardening effect of seismic isolator. Proc. 10th Work. Conf. Reliab. Optim. Struct. Syst., 2003, p. 161–71.
[5] Mazzoni S, McKenna F, Scott MH, Fenves GL. OpenSees command language manual. Pacific Earthq Eng Res Cent 2006.
[6] Nelder JA, Mead R. A simplex method for function minimization. Comput J 1965;7:308–13.