SEISMIC PERFORMANCE OF THREE-DIMENSIONALLY BASE-ISOLATED NUCLEAR POWER PLANT

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ABSTRACT

In order to render nuclear power plants a larger seismic margin from design earthquakes and standardize the seismic design procedure for different locations with various seismic fortification intensities, the base isolation technique that has been successfully applied in traditional civil engineering, is proposed for nuclear power plants. Considering the seismic demand from installed facilities and pipes within the plants, a three-dimensional base isolation technique is developed in this study. It was first examined by simplified single-degree-of-freedom models to search for the suitable parameters for the base isolation layer. It is found that the vertical frequency of the base-isolated plant shall be larger than 1.0Hz to avoid the dominated rocking mode. A set of time history analyses were then conducted to further explore the damping effect of the base isolation layer on the structural response indices. It is observed that the damping within the reasonable range, commonly less than 30%, is helpful to suppress structural displacement, velocity and acceleration.

INTRODUCTION

Nuclear power plant is one of the sustainable and green power sources, playing significant role in human society. However, recent earthquakes, particularly the 2011 Sendai earthquake and tsunami of Japan lead to the deadly failure of Fukushima Nuclear Power Plant. Massive radioactive material was burst out, resulting in serious environment problem. It was reported that all reactors of Fukushima plant automatically shut down when being hit by the huge earthquake. However, the emergency power failed during earthquake which was supposed to provide coolant water to reactors. Also in Japan, the Kashiwazaki-Kariwa Nuclear Power Plant, one of the largest nuclear generating stations in the world, locates approximately 24 kilometers from the epicenter of the Mw 6.6 July 2007 Chuetsu offshore earthquake. The seismic intensity was larger than the design basis earthquake and initiated an extended shutdown for inspection, which indicated that greater earthquake-proofing was needed before operation could be resumed. The plant was completely shut down for 21 months following the earthquake. To mitigate the disaster resulted by potential earthquakes, the seismic reliability shall be enhanced in the design stage.

To support China's quick development, nuclear power plants are being constructed in many places of mainland, China. The dominated reactors are AP1000 and EPR600 introduced from American and Europe, respectively. The design earthquakes for these two types of reactor are 0.3 and 0.2g, correspondingly. Some plants, however, are to be constructed at the region with higher seismic intensity, and the investigated seismic intensity with the expected probability of exceedance is higher than the design earthquake. To avoid redesigning the station, the seismic effect shall be reduced effectively.

To this end, the base isolation technique, which has been successfully applied in traditional civil engineering, is proposed. It is a reasonable option for nuclear power plants and is able to render nuclear power plants a larger seismic margin from design earthquakes and standardize the seismic design procedure for different locations with various seismic fortification intensities. France is the first country to have constructed two isolated nuclear power plants. Consequently, the standard design of nuclear facilities has been propelled [1]. Since the 1980's, Japan has developed a series of research on the isolation technology for nuclear power plants, and published a guideline of the base isolation design for nuclear power plants [2], systematically discussing structural dynamics and extreme load analysis, seismic response analysis and design, structural reliability and probabilistic safety assessment and qualification management and maintenance of isolators. In 1995, European Atomic Energy Community (EAEC) raised a proposal for design guidelines of base isolated nuclear facilities, mainly using high damping steel-laminated rubber bearings (HDRB) [3]. Numerous experiments and analyses of three dimensional models by both simple bearing models and detailed finite-element were completed, which verified that isolation technology is feasible and economic.

Traditional horizontal isolation technique, however, still allows the seismic energy to pass through vertically into the superstructure. The vertical response commonly vibrates within a frequency range of 10-20Hz, which covers most facility frequencies, indicating an adverse effect of the horizontal base isolation. Therefore, the concept of three-dimensional base isolation was introduced into the seismic design of nuclear power plant. The practice so far is still limited within laboratories, and can be classified into two categories, i.e., overall three-dimensional base isolation, and separated base isolation combining both overall horizontal isolation of nuclear building and local vertical isolation of specific facilities.

Proposed in this paper is an overall three-dimensional base isolation system consisting of polymeric bearings and a hydraulic rocking suppression system. The polymeric bearing is featured with thick rubber layers. The hydraulic rocking suppression system is used not only to limit the rocking response of the superstructure, but also to provide extra damping in the vertical direction. In this preliminary study, the design parameters of the three-dimensional base isolation system, such as the horizontal and vertical frequencies and damping ratios, were identified through numerical analysis using a simplified mass-spring model. The modal analysis was first conducted to find suitable values for the vertical stiffness of the base isolation layer. Then time history analyses were conducted to examine the damping effect.

PARAMETRIC STUDY USING RIGID BLOCK MODEL

Two models were adopted to examine the parameters of the base isolation layer. The first model is shown in Fig.1 where, the superstructure is treated as a rigid block with the gravity center half height above the base isolation layer. The base isolation layer is modeled with distributed vertical springs representing the isolators, while the horizontal behavior is represented by a horizontal spring. The damping is implemented by the similar way as the dashpots. Under the small displacement condition, the vertical response is decoupled with the horizontal and the rocking responses. To examine the coupling between the horizontal and the rocking response, the natural frequencies are calculated and compared, taking the aspect ratio of h/b and the vertical frequency f_v as the parameters. The equation of motion of rigid-block model is then formulated as Eq.1, and the symbols are listed in Table.1. The nominal frequencies are calculated for reference by Eqs.2-4 without considering the coupling between the rocking and horizontal components.

$$\begin{bmatrix} m & 0 & mh_0 \\ 0 & m & 0 \\ mh_0 & 0 & m_\theta + mh_0^2 \end{bmatrix} \begin{Bmatrix} a_h \\ a_v \\ a_\theta \end{Bmatrix} + \begin{bmatrix} c_h & 0 & 0 \\ 0 & c_v & 0 \\ 0 & 0 & c_\theta \end{bmatrix} \begin{Bmatrix} v_h \\ v_v \\ v_\theta \end{Bmatrix} + \begin{bmatrix} k_h & 0 & 0 \\ 0 & k_v & 0 \\ 0 & 0 & k_\theta \end{bmatrix} \begin{Bmatrix} d_h \\ d_v \\ d_\theta \end{Bmatrix} = \begin{bmatrix} -m & 0 \\ 0 & -m \\ -mh_0 & 0 \end{bmatrix} \begin{Bmatrix} a_{gh} \\ a_{gv} \end{Bmatrix} \tag{1}$$

$$f_{v0} = \frac{1}{2\pi}\sqrt{\frac{k_v}{m}} \tag{2}$$

$$f_{h0} = \frac{1}{2\pi}\sqrt{\frac{k_h}{m}} \tag{3}$$

$$f_{\theta 0} = \frac{1}{2\pi}\sqrt{\frac{k_\theta}{m_\theta + mh_0^2}} = \sqrt{\frac{1}{1+(2h/b)^2}}\, f_{v0} \tag{4}$$

Table1: Symbols used in rigid-block model

Symbol	Physical meaning
b, h, h_0	Width, total height, and height of gravity center of rigid block
C, X	Gravity center, and center of base-isolation layer
m, m_θ	Mass and inertial of rotation around gravity center
k_0, c_0	Distributed vertical stiffness and damping at base isolation layer
k_h, c_h	Horizontal stiffness and damping at base isolation layer
k_v, c_v	Vertical stiffness and damping at base isolation layer
k_θ, c_θ	Rocking stiffness and damping at base isolation layer
d_h, d_v, d_θ	Relative displacements at center of base isolation layer
$d_{hc}, d_{vc}, d_{\theta c}$	Relative displacements at gravity center

a_{gh}, a_{gv}	Horizontal and vertical ground accelerations
$a_{hc}^{total}, a_{vc}^{total}, a_{\theta c}^{total}$	Absolute accelerations at gravity center
f_h, f_v, f_θ	Frequencies of the horizontal, vertical and rocking components
$f_{h0}, f_{v0}, f_{\theta 0}$	Nominal frequencies without considering coupling effect

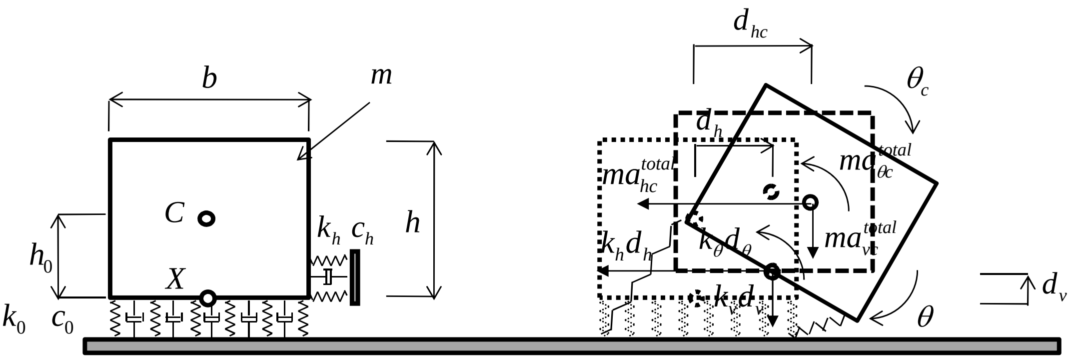


Fig.1 Rigid-block model and its motion along with base isolation layer

The first study took the aspect ratio h/b as the variable, while set the nominal horizontal frequency f_{h0} as a constant, 0.5Hz. Five cases were considered, each adopts different nominal vertical frequency f_{v0} as 0.5, 1.5, 2.5, 3.5, and 4.5Hz. Note that the vertical motion is uncoupled from the rocking motion because small displacement was considered here, so that the actual vertical frequency f_v is identical as the nominal vertical frequency f_{v0}. The eigen values of rigid-block model are calculated and plotted in Fig.2 with respect to the aspect ratio. Several findings are listed as follows:

(1) The rocking frequency is always smaller than the vertical frequency;

(2) If the vertical frequency is as low as the case with $f_v = 0.5$ Hz, the rocking mode is always dominated regardless of the aspect ratio;

(3) For other cases, with the increase of the aspect ratio, the horizontal frequency decreases at first then increases, while the rocking frequency keeps decreasing. It is noteworthy that the horizontal mode and the rocking mode interchange at some special aspect ratio. Taking the case with $f_v = 1.5$ as an example, the horizontal mode jumps to be the third mode at the aspect ratio of about 1.4, while the rocking mode becomes to be the first vibration mode, meaning that for cases with the aspect ratios larger than 1.4, the rocking mode dominates. The frequency jumping points are denoted in Fig.2 as the switching points, which can also be determined by the intersection between the nominal rocking frequency and the nominal horizontal frequency.

Further study examines the influence from the vertical stiffness of base isolation layer. The aspect ratios are selected as 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0. Similar conclusions are obtained as the previous study. The other information obtained from Fig.3 is that the vertical frequency shall not be too small for a given aspect ratio, otherwise the rocking mode dominates. For the case with the aspect ratio of 1.0, the vertical frequency is suggested larger than 1.1Hz approximately.

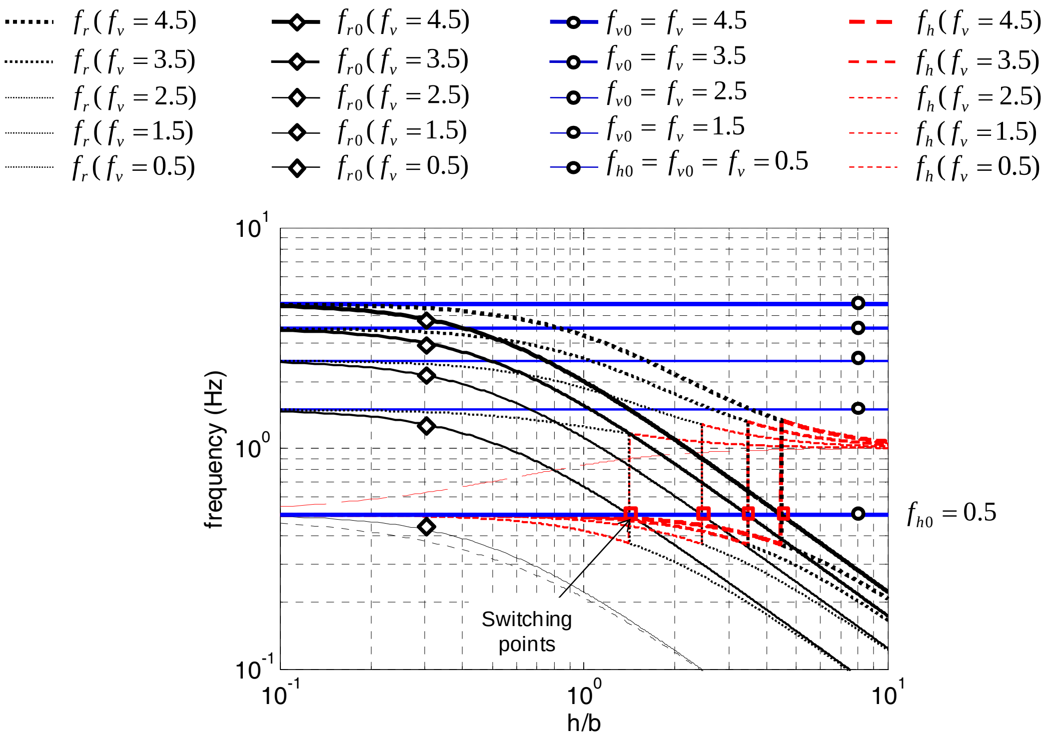


Fig.2 Mode switching curves of rigid-block model with respect to aspect ratio

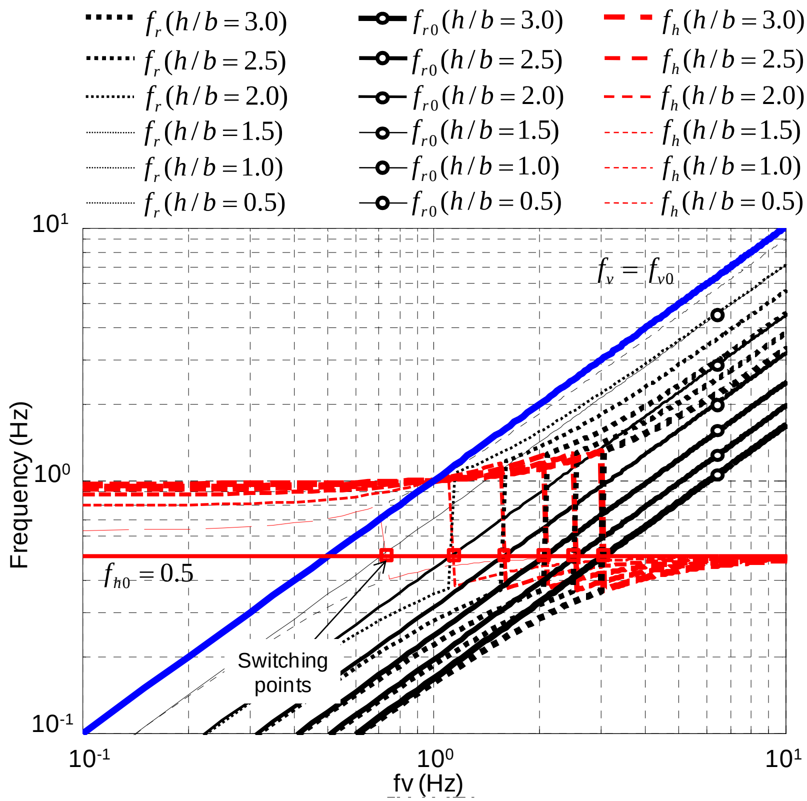


Fig.3 Mode switching curves of rigid-block model with respect to vertical frequency

PARAMETRIC STUDY USING FLEXIBLE MODEL

In this section, a flexible model is developed. Time history analyses using a set of 20 near fault ground motions [4] were conducted to find the influence of damping ratios. The model represents a virtual nuclear power plant. It is simplified as a single-degree-of-freedom model with a mass at the top of a flexible column, as shown in Fig.4. The section of the column is selected to reproduce the horizontal and vertical flexibility of the nuclear power plant. The periods in both horizontal and vertical direction are 0.2s and 0.07s, respectively. The mass of the superstructure is taken as 8.95e7kg, while the bottom slab above the base isolation layer is 3.61e7kg. The effective height was calculated to reproduce the same overturning moment at the bottom slab, which is 27.5m. Three springs were inserted in the base isolation layer to represent the isolators, two in vertical and one in horizontal. The distance between the two vertical springs is decided by the expected rocking stiffness. Similar implementation is also given to the dash pots which represent the damping coefficients in three directions.

Analysis parameters are shown in Table.2 where, the horizontal frequency varies from 0.5 to 0.25 Hz, which are typical frequencies that can be easily achieved by using of steel-laminated rubber bearings. Based on the previous parametric study, the vertical frequency is adopted from 1.0 to 20Hz, where the vertical frequency of 20Hz represents the traditional horizontal base isolation buildings. Previous study [5] indicated that larger damping ratio may result in larger acceleration in the superstructure, so that the damping ratio is selected ranging from 2 to 30% for both directions. The damping ratio of 2% implies no damper is installed while a bigger ratio is necessary to mitigate response of nuclear structures and reactor components.

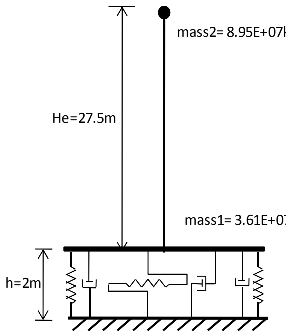


Fig.4 Flexible model with base isolation layer

Table.2 Analysis parameters

Th(s)	1.0	1.5	2.0	2.5	3.0	3.5	4.0
Hh(%)	2.0	5.0	10.0	15.0	20.0	25.0	30.0
Tv(s)	0.05	0.1	0.2	0.25	0.5	1.0	
Hv(%)	2.0	5.0	10.0	15.0	20.0	25.0	30.0

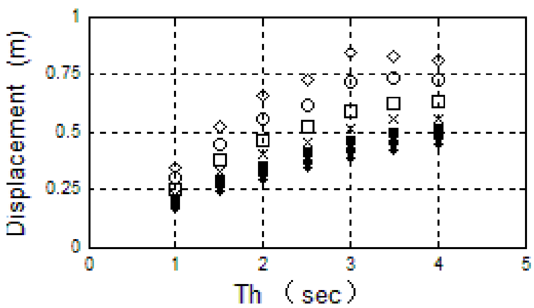
Note:
(1)Th(Hh):Period(damping ratio) in horizontal direction;
(2) Tv(Hv): Period(damping ratio) in vertical direction.

The averaged maximum responses of each model are given in Fig.5 in terms of displacements, velocities and absolute accelerations. It is observed from these figures that:

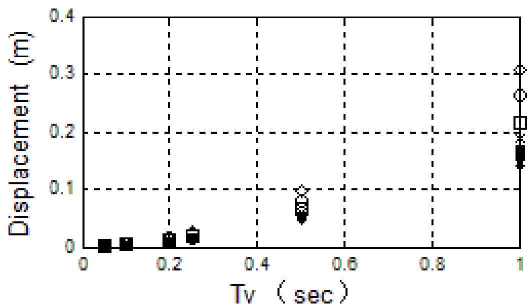
(1) A system that has a longer period exhibits smaller acceleration and bigger displacement, no matter in horizontal or vertical direction. And damping is able to effectively suppress maximum responses, includes displacement, velocity and acceleration. Without additional damping (damping ratio equals to 2%), the maximum horizontal displacement and vertical displacement are 0.8m and 0.3m, respectively. However, if the damping ratio of 30% is adopted, the values decrease to 0.4 and 0.15m, correspondingly;

(2) Comparatively, the damping is more effective in horizontal than in vertical direction regarding of the displacement. However, it is more effective to reduce the acceleration response in the vertical direction than in horizontal;

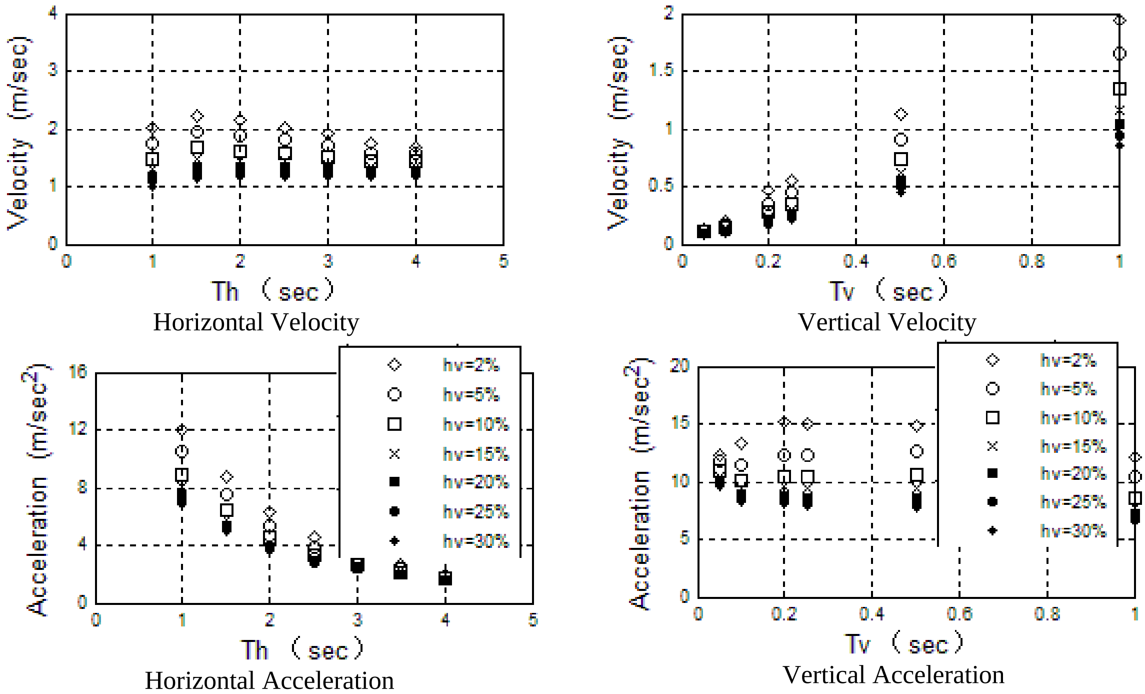
(3) The velocity is not sensitive to horizontal period, while vertical velocity becomes bigger when vertical period increases.



Horizontal Displacement



Vertical Displacement



Horizontal Velocity Vertical Velocity

Horizontal Acceleration Vertical Acceleration

Fig.5 Seismic responses of flexible model

CONCLUSIONS

This preliminary study searches for suitable parameters for the base-isolation design of nuclear power plants. A rigid-block model was used to find the suitable vertical stiffness of the base isolation layer, while a flexible model was employed to examine the damping effect. Major findings are as follows:

(1) To effectively suppress the adverse rocking motion and to reduce the initial deformation under the gravity of the superstructure, the vertical stiffness shall not be too small. Also considering the acceleration reduction effect, the vertical stiffness shall not be too large as well. The suggested value ranges from 1Hz to 5Hz;

(2) To suppress the deformation of the base isolation layer, a large damping ratio is needed. The suitable damping ratio can be selected from Fig.5 for any expected responses. However, the damping ratio shall not be too large. It is better limited within 30%.

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