Seismic Response of Isolated Nuclear Power Plant Considering Nonlinear Restoring Force Characteristics of Rubber Bearings

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SUMMARY:
In Japan, applications of seismic isolation systems using rubber bearings to new generation Nuclear Power Plants (NPPs) and Fast Breeder Reactors (FBRs) have been considered in order to enhance seismic safety. However, the isolation performance will decline in case of huge earthquakes, because of nonlinearity of both horizontal and vertical restoring characteristics of rubber bearings. In addition, Probabilistic Safety Assessment (PSA) has been introduced to seismic design. However the application of PSA to seismic isolation has not been attempted yet, and accurate seismic response simulation of isolation system required for the application. Authors carried out seismic response analysis that considers both horizontal and vertical nonlinearity of rubber bearing. Influence of nonlinearity of rubber bearing upon response of building was investigated by the analysis.

Keywords: Seismic isolation, Rubber bearings, Nonlinear analysis and Probabilistic Safety Assessment

1. INTRODUCTION

In Japan, applications of seismic isolation systems to Nuclear Power Plants (NPPs) have been expected in order to improve seismic safety. Especially, the Fast Breeder Reactors (FBRs) has higher core temperature than conventional light water reactors, so thin-wall structures are adapted for the relaxation of the thermal stress. However it is disadvantage from the viewpoint of seismic load. Therefore, Application of seismic isolation system to next generation nuclear power reactor facilities is expected.

General seismic isolation system consists of rubber bearings and oil dampers. Rubber bearings deform linearly and have linear stiffness against design seismic load in both horizontal and vertical direction. However, hardening in horizontal direction and softening in vertical direction occur in case of huge input.

"Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities" was revised in 2006 in Japan. This regulatory guide referred to existence of residual risk and introduction of Probabilistic Safety Assessment (PSA). The PSA is a method that estimates core damage probability. However the application of PSA to seismic isolation has not been completed yet. In seismic PSA, above-mentioned nonlinear characteristics of rubber bearings are important in consideration of exceptional huge earthquakes.

This paper describes results of seismic response analysis that consider nonlinear characteristics of rubber bearings. The seismic response analysis considers nonlinearity of laminated rubber bearings. Also an experience effect and a coupling effect are considered. This analytical result will contribute to the seismic PSA of isolated structure in the future.

2. PROBABILISTIC SAFETY ASSESSMENT (PSA)

Three type of the PSA are proposed for nuclear power plants. The level 1 PSA evaluates the core damage probability. The level 2 PSA evaluates behavior of fission product that is emitted by core damage. The level 3 PSA evaluates damage to public.

Final goal of this study is to apply level 1 PSA to seismic isolation system. The level 1 PSA consists of a seismic hazard evaluation, a fragility evaluation and an accident sequence evaluation. In the fragility evaluation, seismic response analysis is required in order to calculate fragility curves. This analysis considers fluctuation of various parameter caused by fabrication accuracies.

Figure 1 shows concept of the fragility curves. It is assumed that failures occur when realistic response that is expressed by probability distribution exceeds realistic capacity. The realistic response is calculated by seismic response analysis. Then probabilities of failure are obtained from the duplication area of the response and the capacity. Therefore accurate seismic response analysis is required.

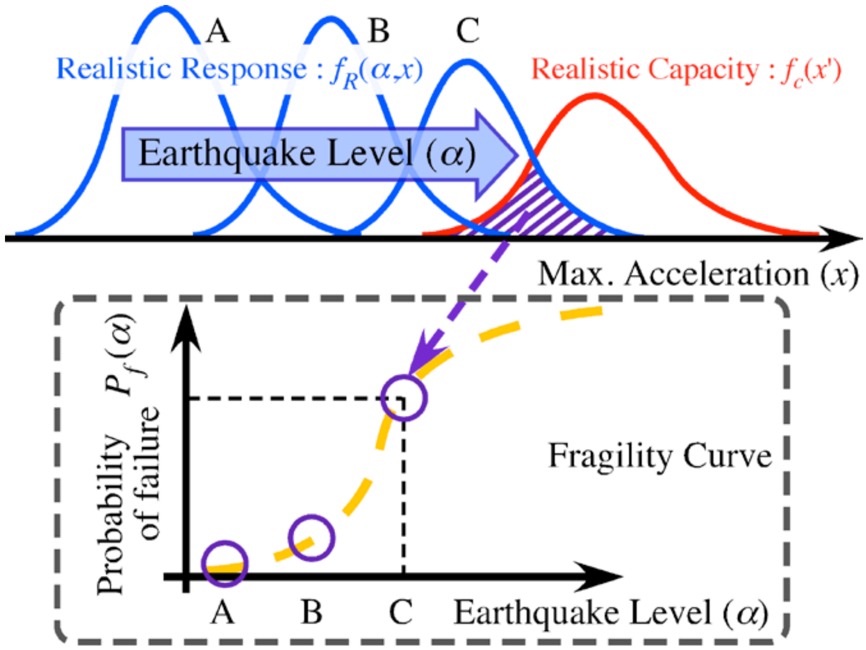
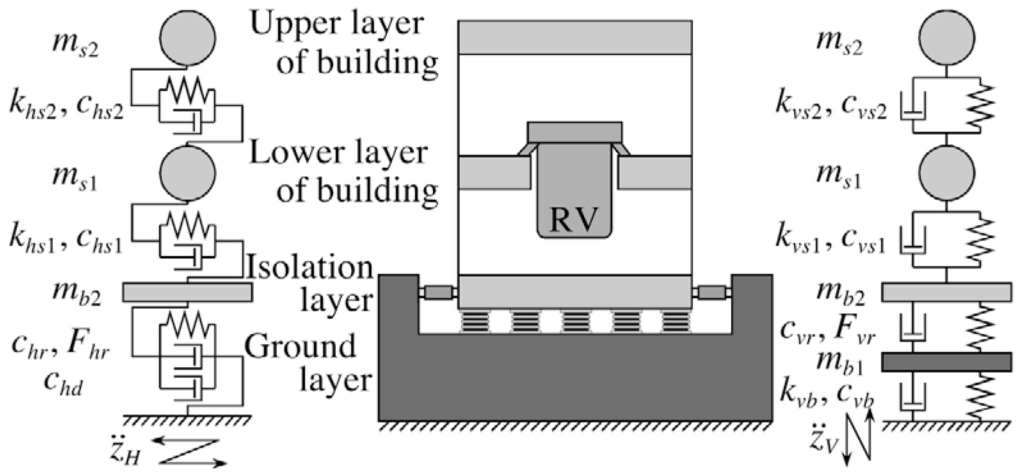


Figure 1. Concept of fragility curves

3. ANALYTICAL CONDITION

3.1. Modeling of Reactor Building

A reactor building was modeled to a mass points model. Deformation of isolation device is predominant compared with it of the upper structure in isolated building, so the modeling to mass points is permissible [1]. Figure 2 shows analytical model of a reactor building. Analytical model of the building for horizontal direction consists of 3 mass points, that is the isolation layer, lower and upper layer of the building. It for vertical direction consists of 4 mass points, that is ground layer, the isolation layer, lower and upper layer of the building. Horizontal model does not include ground layer, because horizontal stiffness of ground is so big compared with rubber bearings that dynamic behavior of ground can be ignored. The mass m_{s1} corresponds to floor where a reactor and important equipment are installed. Table 1 shows parameters of the analytical model. These parameters are selected based on an actual design of a nuclear power plant.



(a) Horizontal (b) Vertical

Figure 2. Analytical model of building

Table 1. Seismic isolation properties

		Horizontal	Vertical
Natural Period (Frequency)		3.4 [s]	8.0 [Hz]
Damping	Oil Damper	43 [%]	
	Rubber Bearing	2.0 [%]	2.0 [%]

3.2. Modeling of Rubber Bearing

Figure 3 shows the horizontal restoring property of rubber bearings. Rubber bearings have linear stiffness in the normal deformation range. However they have nonlinear stiffness in case of large deformation. Table 3 indicates parameters of the rubber bearing model for horizontal direction. As shown in Fig. 3, rubber bearings have hardening property in horizontal direction, which is caused by strain hardening of rubber material [2]. In addition, once the hardening occurs, the hardening displacement shifts in accordance with the following equation.

$$\delta_1' = \delta_1 + \alpha\left(\delta_{max} - \delta_1\right), \qquad \delta_2' = \delta_2 + \alpha\left(\delta_{max} - \delta_1\right) \tag{1}$$

Where δ_1' δ_2' are 1st and 2nd new hardening displacement, δ_1, δ_2 are 1st and 2nd normal hardening displacement, α is a coefficient of influence of this effect, and δ_{max} is the maximum displacement which rubber bearing experienced. This paper calls this effect an experience effect.

Figure 4 shows the vertical restoring property of rubber bearings. Table 4 indicates parameters of the rubber bearing models for vertical direction. As shown in Fig. 4, vertical stiffness of rubber bearings is linear for compressive load, but has a softening property for tensile load. This softening property is caused by static deformation of rubber bearings by gravity. Therefore the 1st softening load P_1 is the load that makes rubber bearings natural length, and that is equivalent to weight of the upper structure. The accumulative strength P_2 - P_1 is equivalent to allowable tensile load of rubber bearings.

In addition, coupling effect by horizontal and vertical direction exists. That is, the hardening starting displacement of horizontal direction decreases with an increase of the vertical load [3]. Figure 5 shows the vertical load dependency of the hardening starting displacement. As shown in Fig. 5, the hardening starting displacement of horizontal direction decreases, in the case that the vertical load of the rubber bearings exceeds the linear limit line that is defined by a tensile linear limit stress σ_{ty}, a tensile shear linear limit stress σ_{tcy}, a compressive linear limit stress σ_{cy}, a compressive shear linear limit stress σ_{ccy}.

These nonlinear models are based on past studies, but some parameters and behavior are assumed based on engineering point of view.

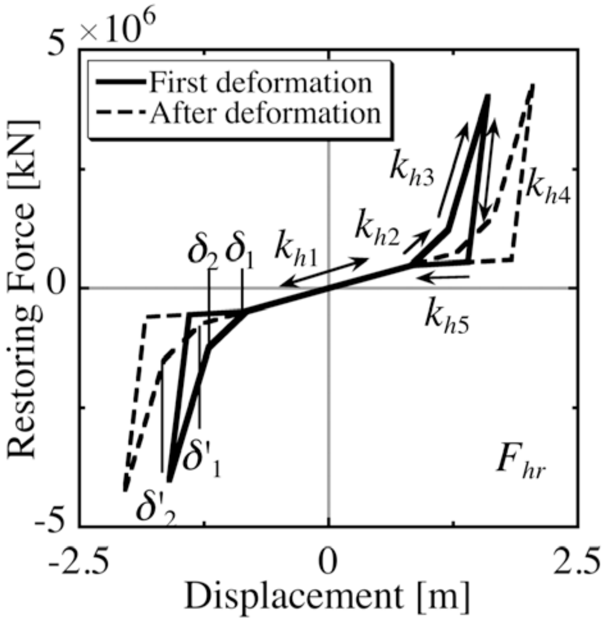


Figure 3. Horizontal restoring characteristics of rubber bearing

Table 2. Parameters of rubber bearing nonlinear model for horizontal direction

k_{h2}	k_{h3}	k_{h4}	k_{h5}	d_1	d_2
$3.5\times k_{h1}$	$12.0\times k_{h1}$	$29.5\times k_{h1}$	$0.2\times k_{h5}$	0.830[m](γ_1=250[%])	1.19[m](γ_2=360[%])

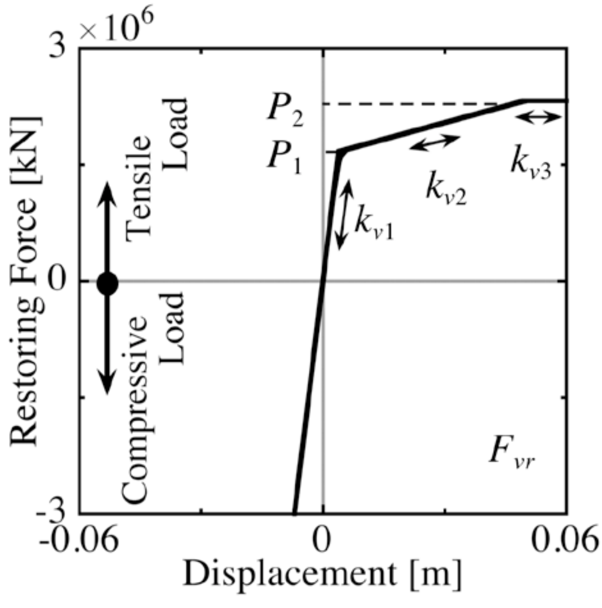


Figure 4. Vertical restoring characteristics of rubber bearing

Table 3. Parameters of rubber bearing nonlinear model for vertical direction

k_{v2}	k_{v3}	P_2-P_1	P_1
k_{v2}/30	0	1.96 [MPa]	1.67×10^6 [kN]

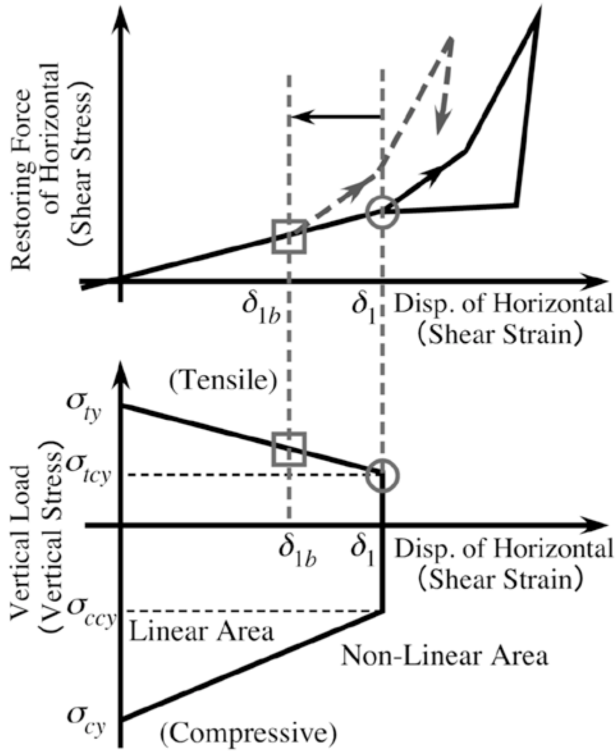


Figure 5. Vertical load dependency of hardening starting displacement

3.3. Input Wave

Figure 6 shows characteristics of input wave. This wave is suitable for seismic design of a nuclear power plant. A wave of which amplitude is 2/3 of the wave for horizontal direction is used as an input wave for vertical direction. These waves are called Ss wave in this paper. Amplitude of the Ss wave is varied in analyses in order to investigate relationships between response and earthquake level.

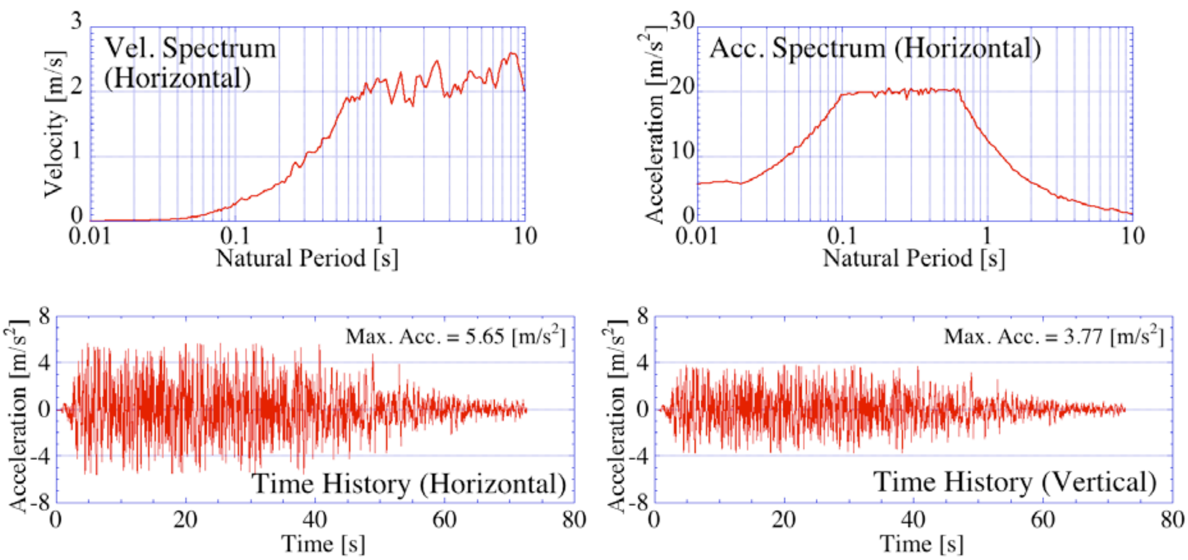


Figure 6. Characteristics of input waves

4. SEISMIC RESPONSE ANALYSIS

In order to investigate influence of nonlinearity of rubber bearings on response of the building, seismic response analysis was executed. The amplitudes of input wave were varied in order to investigate relationships between the input earthquake level and the response.

4.1. Horizontal Direction

Figure 7 shows analytical results of horizontal direction. The (a) shows relationships between input earthquake level and the maximum response, and the (b) shows the response acceleration spectra of input earthquake level of 2.2 and 5.0. The response acceleration is it of the mass m_{s1} and the response displacement is deformation of rubber bearing. In order to investigate influence of the experience effect and the coupling effect by horizontal and vertical direction, results of the analysis that does not consider the experience and the coupling effect are indicated as well.

It is confirmed that response acceleration of the isolated structure is less than with the input wave and response of the non-isolated structure, so the isolation system has good performance of isolation.

From Fig. 7 (a), in the case of analysis that does not consider the coupling effect, the 1st hardening occurs when the input earthquake level is 2.4, and the 2nd hardening occurs when the input earthquake level is approximately 4. On the other hand, in the case of analysis that considers the coupling effect, the 1st hardening occurs when the input earthquake level is 2.2, and the 2nd hardening occurs when the input earthquake level is 2.6. Each response acceleration increases nonlinearly according to the hardening of the rubber bearings. This is because that the horizontal isolation period came close to the natural period of superstructure by hardening of rubber bearings. Results that consider the coupling effect are larger than results that do not consider. Results that consider the experience effect (i.e. α=0.45) are equivalent to results that do not consider (i.e. α=0). Therefore the coupling effect has more influence than the experience effect.

From Fig. 7 (b), the spectrum of isolated structure is smaller than non-isolated structure. Thus isolation performance was confirmed. When input earthquake level is 2.2, the experience and coupling effects have little influence on isolation performance. On the other hand, when input earthquake level is 5.0, spectrum that considers the coupling effect is larger than spectrum that does not consider. Therefore the coupling effect affects the isolation performance.

4.2. Vertical Direction

Figure 8 shows analytical results of vertical direction. The (a) shows relationships between input earthquake level and the maximum response, and the (b) shows the response acceleration spectra of input earthquake level of 1.0 and 5.0. The response acceleration is it of the mass m_{s1} and the response displacement is deformation of rubber bearing.

From Fig. 8 (a), it is confirmed that the 1st softening occurred when the input earthquake level is more than 1.2, and the 2nd softening occurred when the input earthquake level is more than 3.2. The nonlinearity appeared in small input level compared with horizontal direction. The increment of response displacement increases with an increase of input earthquake level, because of the softening of rubber bearings. The increment of response acceleration increases as well, because compressive load increases by softening.

As shown in Fig. 8 (b) Ss×5.0, predominant frequencies of spectra considering nonlinear properties are broader than results of the linear system. The reason is that various modes were excited by the impact load when stiffness of the rubber bearings shifts from k_{v2} to k_{v1}. Therefore the softening of rubber bearings affects response of a reactor and important equipment that were installed in the building.

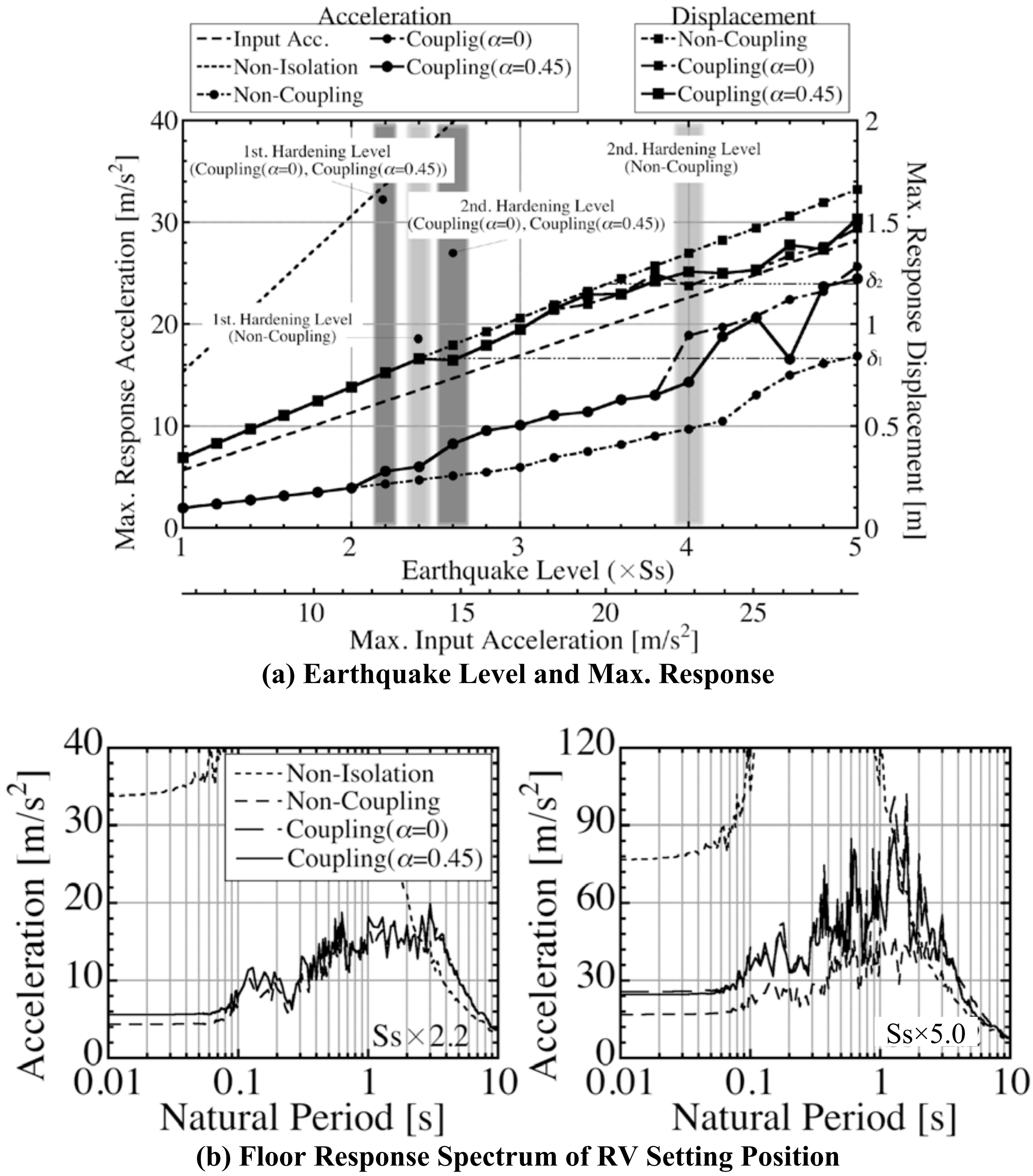
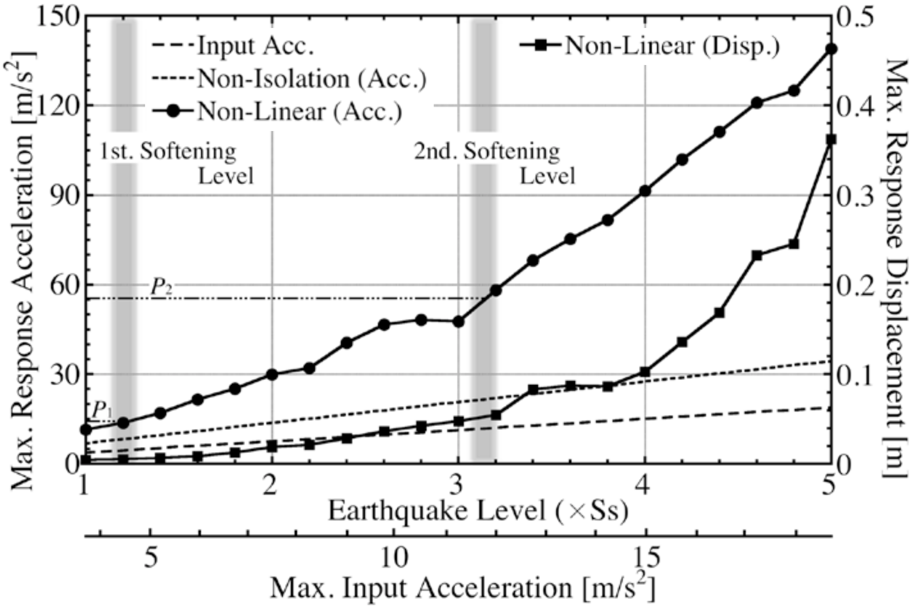
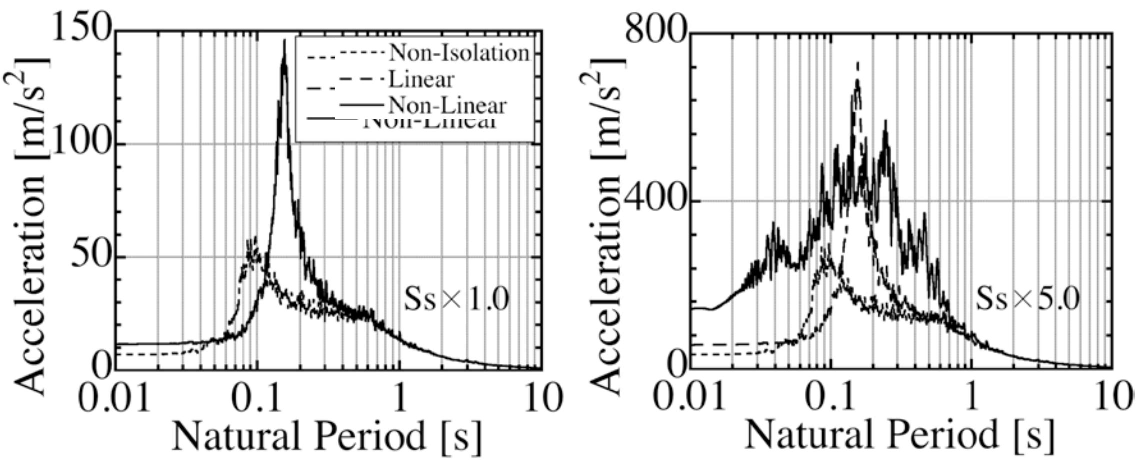


Figure 7. Analytical results of horizontal direction



(a) Earthquake Level and Max. Response



(b) Floor Response Spectrum of RV Setting Position

Figure 8. Analytical results of Vertical direction

5. CONCLUSION

This paper dealt with the seismic response analysis of the seismic isolation system in order to apply PSA to seismic isolation system, and the analyses considered nonlinearity of rubber bearings. The results of analysis are summarized as follows.

Nonlinear properties of rubber bearings appeared when input earthquake level is approximately 2 times of the design level in horizontal direction, and 1.2 times in vertical direction. Therefore the consideration of the nonlinear properties is needed in probabilistic approaches of seismic isolation system.

Seismic isolation performance of horizontal direction is retained even if nonlinear behavior appears. However the performance declines.

The horizontal isolation period came close to the natural period of superstructure by hardening of rubber bearings. As a result, horizontal response of the building increased.

The softening of rubber bearings in vertical direction caused impact load in compressive direction.

Nonlinear properties of rubber bearings have influence on the floor response spectra. Therefore the properties affect equipment installed in the building.

The experience effect and the coupling effect decline the isolation performance. The coupling effect has more influence than the experience effect.

Nonlinear models used in this paper are based on past studies, but some parameters and behavior are assumed based on engineering point of view. Therefore static and dynamic tests of rubber bearing for investigation into nonlinearity are strongly required.

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