# DEVELOPMENT OF LEVEL-1 PSA METHOD APPLICABLE TO JAPAN SODIUM-COOLED FAST REACTOR: (2) SEISMIC RESPONSE ANALYSIS CONSIDERING CHARACTERISTICS OF THE ADVANCED SEISMIC ISOLATION SYSTEM

K. Minagawa[1], S. Fujita[1], A. Yamaguchi[2], T. Takata[2], K. Kurisaka[3]
[1]Department of Mechanical Engineering, School of Engineering, Tokyo Denki University, Tokyo, Japan
[2]Department of Energy and Environment Engineering, Osaka University, Osaka, Japan
[3]Advanced Nuclear System R&D Directorate, Japan Atomic Energy Agency, Ibaraki, Japan
E-mail of corresponding author: minagawa@cck.dendai.ac.jp

## ABSTRACT

This paper deals with seismic response analysis and sensitivity analysis of a seismic isolation system. Rubber bearings have a hardening property in horizontal direction and a softening property in vertical direction in case of large deformation. Therefore the analyses considered nonlinearity of rubber bearings. Both horizontal and vertical nonlinear characteristics of rubber bearings were explained by multi-linear model. Mass point analytical models were applied. At first, seismic response analysis was executed in order to investigate influence of nonlinearity of rubber bearing upon response of the building. Then sensitivity analysis was executed. Parameters of rubber bearings, oil dampers and the building were fluctuated, and influence of dispersion of these parameters upon response of building was investigated. As a result, it was confirmed that nonlinear properties of rubber bearings have influence on response of the building and inner equipment.

## INTRODUCTION

Japan Atomic Energy Agency (JAEA) has been developing Japan Sodium-cooled Fast Reactor (JSFR) in the fast reactor cycle technology development project. The JSFR employs passive safety architectures and an advanced seismic isolation system as innovative technologies. Since no one has established the level-1 PSA method that can provide the evaluation of these innovative technologies, JAEA, Tokyo Denki University and Osaka University have started a joint study to develop the level-1 PSA method that is applicable to JSFR since August 2010. This study includes the level-1 PSA related to internal events and a seismic event as a representative external event in Japan.

The advanced seismic isolation system that is applied to the JSFR consists of rubber bearings and oil dampers. Generally, rubber bearings deform linearly and have linear stiffness against seismic load in both horizontal and vertical direction. However, hardening in horizontal direction and softening in vertical direction occur in case of large input. In seismic PSA, it is important to consider these nonlinear characteristics.

This paper describes results of seismic response analysis and sensitivity analysis of the advanced seismic isolation system. The seismic response analysis considered nonlinearity of laminated rubber bearings. In the sensitivity analysis, parameters of the rubber bearings, the oil dampers and the building were fluctuated, and influence of dispersion of these parameters upon response of building was investigated.

## ANALYTICAL CONDITION

In this chapter, analytical models and input waves for the seismic response analysis and the sensitivity analysis are described. a reactor building is modeled to simple mass point model, and rubber bearings are modeled in consideration of nonlinear stiffness. Seismic wave for design is applied for the analysis.

### Modeling of Reactor Building

A reactor building was modeled to a three mass points model, that is to say isolation layer, lower layer of structure and upper layer of structure [1]. Deformation of isolation device is predominant compared with it of the upper structure in isolated building, so the modeling to mass points is permissible for this fundamental investigation. Figure 1 shows analytical model for horizontal direction and Fig. 2 shows it for vertical direction. The mass $m_{s1}$ corresponds to floor where a reactor and important equipment are installed. Analytical model for vertical direction includes the ground layer. On the other hand, horizontal model does not include ground layer. This is because horizontal stiffness of rubber bearings is so small compared with ground that dynamic behavior of ground can be ignored. Tables 1 and 2 indicate parameters of the analytical model. These parameters are based on an actual design of a nuclear power plant.

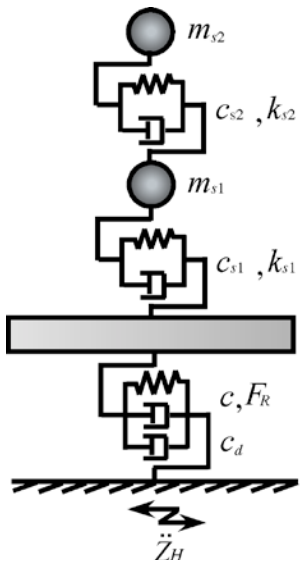


Fig. 1: Analytical model (Horizontal)

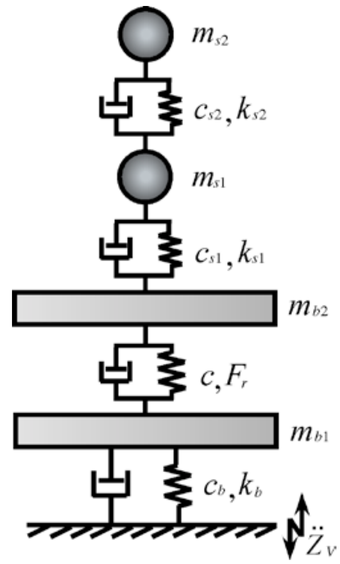


Fig. 2: Analytical model (Vertical)

Table 1: Analytical parameter of building (Horizontal)

| | Caption | Median | Variation coefficient | Log. standard variation |
|---|---|---|---|---|
| $m_{b2}$ | Mass of isolation layer | $46.0 \times 10^6$[kg] | 0.10 | 0.10 |
| $m_{s1}$ | Mass of 1st layer of building | $111 \times 10^6$[kg] | 0.10 | 0.10 |
| $m_{s2}$ | Mass of 2nd layer of building | $13.2 \times 10^6$[kg] | 0.10 | 0.10 |
| $F_R$ | Restoring force of rubber bearings | | | |
| $k_{s1}$ | Stiffness of 1st layer of building | $99.4 \times 10^9$[N/m] | 0.13 | 0.13 |
| $k_{s2}$ | Stiffness of 2nd layer of building | $11.7 \times 10^9$[N/m] | 0.13 | 0.13 |
| $c$ | Damping coefficient of rubber bearings | $12.6 \times 10^6$[Ns/m] (2[%]) | 0.10 | 0.10 |
| $c_d$ | Damping coefficient of oil dampers | $270 \times 10^6$[Ns/m] (43[%]) | 0.10 | 0.10 |
| $c_{s1}$ | Damping coefficient of 1st layer of building | $332 \times 10^6$[Ns/m] (5[%]) | 0.25 | 0.25 |
| $c_{s2}$ | Damping coefficient of 2nd layer of building | $39.3 \times 10^6$[Ns/m] (5[%]) | 0.25 | 0.25 |

Table 2: Analytical parameter of building (Vertical)

| | Caption | Median | Variation coefficient | Log. standard variation |
|---|---|---|---|---|
| $m_{b1}$ | Mass of ground layer | $22.9 \times 10^6$[kg] | 0.10 | 0.10 |
| $m_{b2}$ | Mass of isolation layer | $46.0 \times 10^6$[kg] | 0.10 | 0.10 |
| $m_{s1}$ | Mass of 1st layer of building | $111 \times 10^6$[kg] | 0.10 | 0.10 |
| $m_{s2}$ | Mass of 2nd layer of building | $13.2 \times 10^6$[kg] | 0.10 | 0.10 |
| $k_{b1}$ | Stiffness of ground layer | $1.18 \times 10^{12}$[N/m] | 0.20 | 0.20 |
| $F_r$ | Restoring force of rubber bearings | | | |
| $k_{s1}$ | Stiffness of 1st layer of building | $1.15 \times 10^{12}$[N/m] | 0.13 | 0.13 |
| $k_{s2}$ | Stiffness of 2nd layer of building | $184 \times 10^9$[N/m] | 0.13 | 0.13 |
| $c_{b1}$ | Damping coefficient of 1st layer of building | $22.7 \times 10^9$[Ns/m] | 0.20 | 0.20 |
| $c_{b2}$ | Damping coefficient of rubber bearings | $341 \times 10^6$[Ns/m] (2[%]) | 0.10 | 0.10 |
| $c_{s1}$ | Damping coefficient of 1st layer of building | $1.13 \times 10^9$[Ns/m] (5[%]) | 0.25 | 0.25 |
| $c_{s2}$ | Damping coefficient of 2nd layer of building | $151 \times 10^6$[Ns/m] (5[%]) | 0.25 | 0.25 |

**Modeling of Rubber Bearing**

Rubber bearings have linear stiffness in the normal deformation range. However rubber bearings have nonlinear stiffness in case of large deformation. Figure 3 shows the horizontal restoring property of rubber bearings, and Fig. 4 shows the vertical restoring property of rubber bearings. Tables 3 and 4 indicate parameters of the rubber bearing models.

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 $\delta_1$' $\delta_2$' are the new hardening displacement, $\delta_{max}$ is the maximum displacement which rubber bearing experienced.

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.

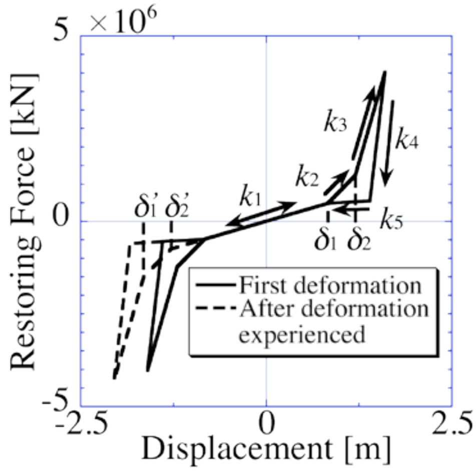


Fig. 3: Restoring model of rubber bearing (Horizontal)

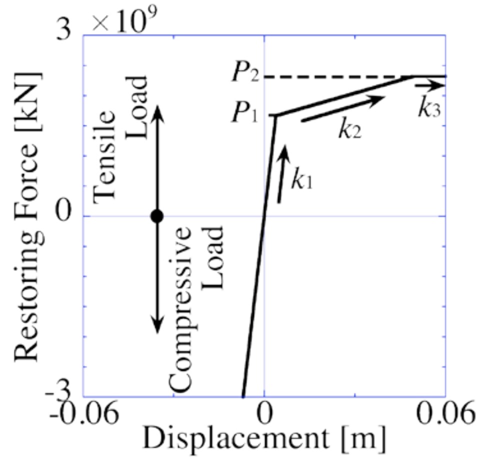


Fig. 4: Restoring model of rubber bearing (Vertical)

Table 3: Analytical parameter of rubber bearings (Horizontal)

| | Caption | Median | Variation coefficient | Log. standard variation |
|---|---|---|---|---|
| $k_1$ | 1st stiffness | $580\text{x}10^6$[N/m] | 0.10 | 0.10 |
| $k_2$ | 2nd stiffness | $2.03\text{x}10^9$[N/m] ($3.5k_1$) | 0.10 | 0.10 |
| $k_3$ | 3rd stiffness | $6.96\text{x}10^9$[N/m] ($12k_1$) | 0.10 | 0.10 |
| $k_4$ | 4th stiffness | $17.1\text{x}10^9$[N/m] ($29.5k_1$) | 0.10 | 0.10 |
| $k_5$ | 5th stiffness | $116\text{x}10^6$[N/m] ($0.2k_1$) | 0.10 | 0.10 |
| $\delta_1$ | 1st hardening displacement | 0.826[m] | 0.10 | 0.10 |
| $\delta_2$ | 2nd hardening displacement | 1.19[m] | 0.10 | 0.10 |
| $F_1$ | 1st hardening load | $479\text{x}10^6$[N] | linked with $k_1$ and $\delta_1$ | |
| $F_2$ | 2nd hardening load | $1.22\text{x}10^9$[N] | linked with $k_1$ and $\delta_1$ | |
| $\alpha$ | Repetition factor | 0.45 | 0.10 | 0.10 |

Table 4: Analytical parameter of rubber bearings (Vertical)

| | Caption | Median | Variation coefficient | Log. standard variation |
|---|---|---|---|---|
| $k_1$ | 1st stiffness | 428 x$10^9$ [N/m] | 0.10 | 0.10 |
| $k_2$ | 2nd stiffness | 14.3x$10^9$[N/m] ($k_1$/30) | 0.10 | 0.10 |
| $k_3$ | 3rd stiffness | 0 [N/m] | 0 | 0 |
| $P_1$ | 1st softening load | 479x$10^6$[N] | 0.10 | 0.10 |
| $P_2 - P_1$ | Accumulative strength | 1.22x$10^9$[N] | 0.10 | 0.10 |

**Input Wave**

A wave shown in Fig. 5 was used as an input wave for horizontal direction. 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.

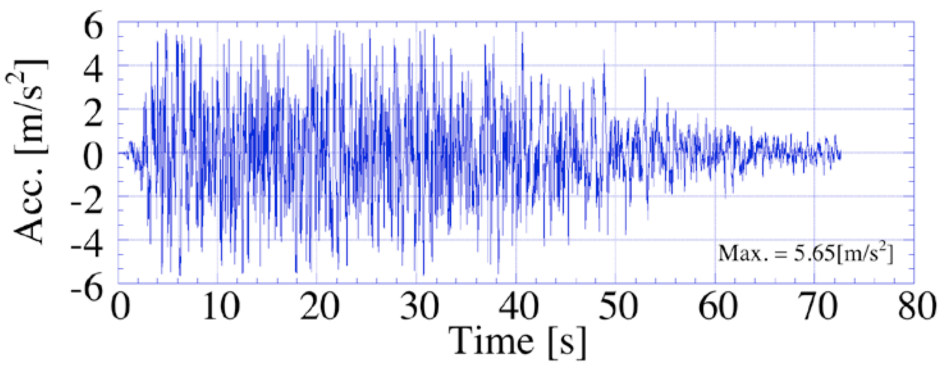


Fig. 5: Input wave

**SEISMIC RESPONSE ANALYSIS**

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

**Horizontal Direction**

Figure 6 shows relationships between input earthquake level and the maximum response. In Fig. 6, response acceleration is it of the mass $m_{s1}$ where a reactor and important equipment are installed, and response displacement indicates deformation of rubber bearings. It is confirmed from Fig. 6 that the maximum response displacement exceeds the 1st hardening displacement when the input earthquake level is 2.4, and it exceeds the 2nd hardening displacement when the input earthquake level is approximately 4. The response acceleration increases nonlinearly according to the hardening of the rubber bearings. On the other hand, the response displacement increases linearly. The reason is that the hardening displacement increases according to Eq. (1), and the maximum response displacement occurred after the hardening displacement increased.

Figure 7 shows response acceleration spectra of input earthquake level of 3.0 and 5.0. These spectra were computed from response of the mass $m_{s1}$, so response of a reactor and equipment installed in mass $m_{s1}$ can be evaluated. These spectra contain results of rubber bearings having linear property in order to investigate influence of nonlinearity. The 1st hardening occurred in the case of input earthquake level of 3.0, and the 2nd hardening occurred in the case of 5.0. When input earthquake level is 3.0, the spectrum of nonlinear simulation is almost same as linear. On the other hand, when input earthquake level is 5.0, the spectrum of nonlinear simulation is large compared with linear. Therefore hardening of the rubber bearings affects response of a reactor and important equipment that were installed in the building.

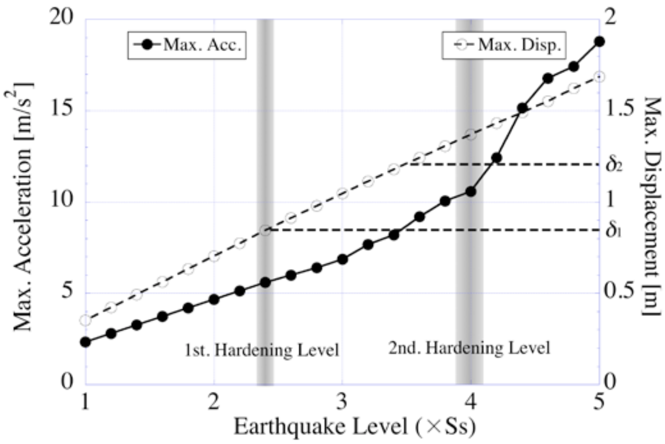


Fig. 6: Relationship between input earthquake level and Max. response (Horizontal)

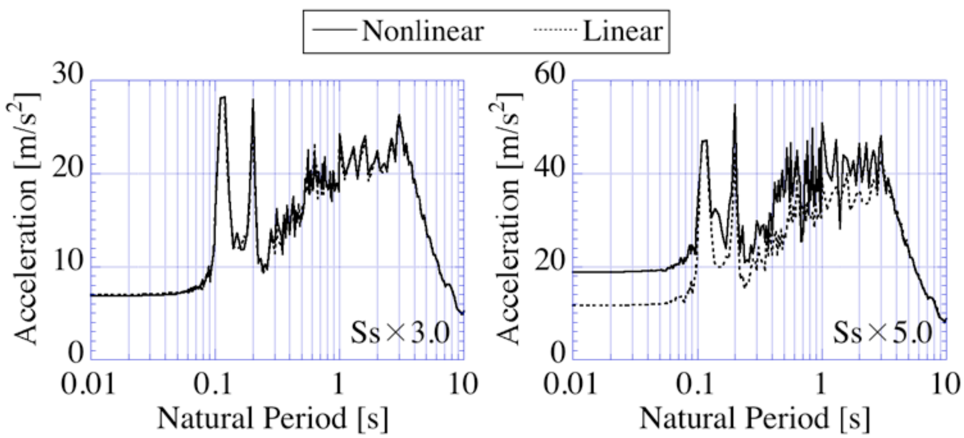


Fig. 7: Floor response spectra (Horizontal)

**Vertical Direction**

Figure 8 shows relationships between input earthquake level and the maximum response. In Fig. 8, response acceleration is it of the mass $m_{s1}$, and response displacement is deformation of rubber bearing. 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 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.

Figure 9 shows response acceleration spectra of input earthquake level of 3.0 and 5.0. These spectra were computed from response of the mass $m_{s1}$ as well as Fig. 7. The 1st softening occurred in the case of input earthquake level of 3.0, and the 2nd softening occurred in the case of 5.0. As shown in Fig. 9, 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 $k_2$ to $k_1$. Therefore the softening of rubber bearings affects response of a reactor and important equipment that were installed in the building.

## SENSITIVITY ANALYSIS

In order to investigate influence of parameter of the building and rubber bearings, sensitivity analysis was executed. In this analysis, a parameter whose sensitivity is investigated was fluctuated in consideration of fabrication accuracies, and other parameters retained median value. The dispersion was given by logarithmic normal distribution [3]. The upper and lower limit values of fluctuated parameters were yielded from Eq. (2).

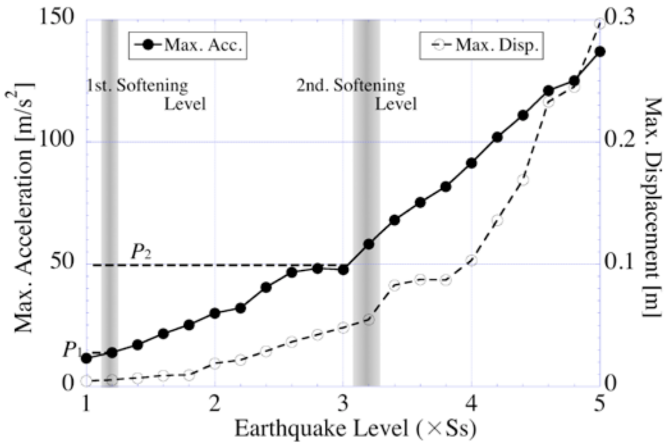


Fig. 8: Relationship between input earthquake level and Max. response (Vertical)

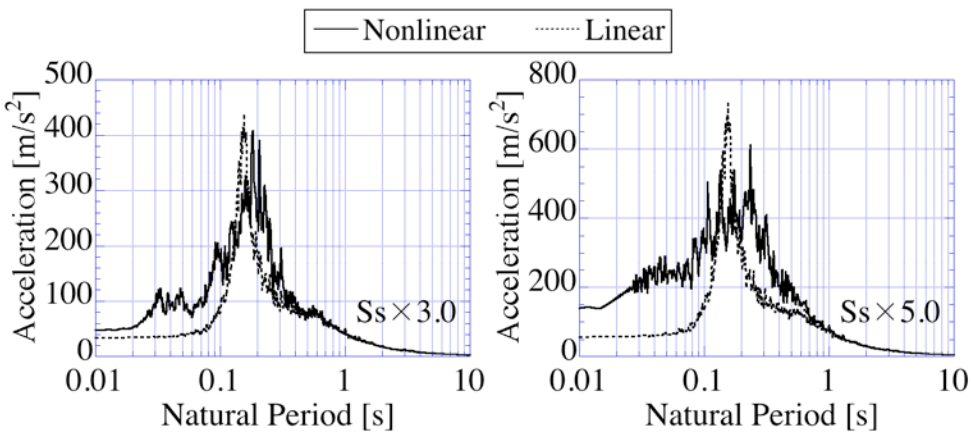


Fig. 9: Floor response spectra (Vertical)

$$X_{Upper} = \exp\left(\log X + \xi\right), \qquad X_{Lower} = \exp\left(\log X - \xi\right) \tag{2}$$

Where $X_{Upper}$ is an upper limit value of a parameter, $X_{Lower}$ is a lower limit value, $X$ is a median value and $\xi$ is a logarithmic standard variation shown in tables 1 to 4. Sensitivities were calculated from the maximum response acceleration of the mass $m_{s1}$ where a reactor and important equipment are installed, and the sensitivities were error ratio to analysis result without any variations.

**Horizontal Direction**

Figure 10 shows analytical results for horizontal direction. It is confirmed that sensitivities of parameters of the building are dominant in the case of normal input earthquake level (Ss x 1). On the other hand, sensitivities of parameters of the rubber bearings, especially the 2nd hardening displacement $\delta_2$, are dominant in the case of large input earthquake level (Ss x 5). This is because the isolation period became low in consequence of 2nd hardening, and it came close to the natural period of superstructure.

**Vertical Direction**

Figure 11 shows analytical results for vertical direction. It is confirmed that sensitivities of parameters of the rubber bearings are dominant. In addition, masses of the building $m_{b2}$, $m_{s1}$, $m_{s2}$ have high sensitivity because they influence on the isolation period. The stiffness and the damping coefficient of ground $k_{b1}$, $c_{b1}$ have high sensitivity as well because their logarithm standard variations were high compared with the other.

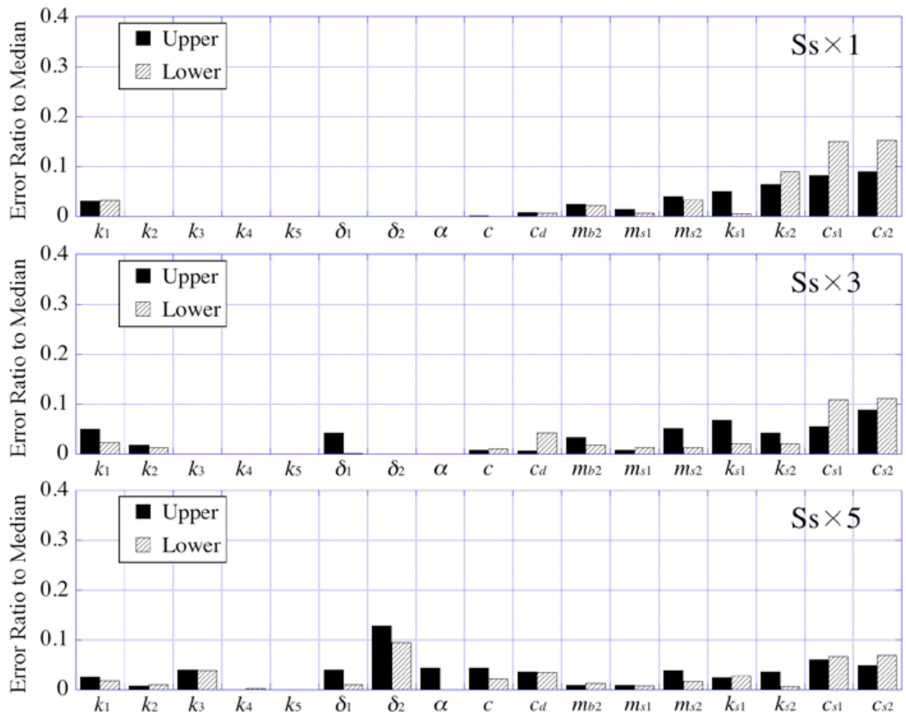


Fig. 10: Results of sensitivity analysis (Horizontal)

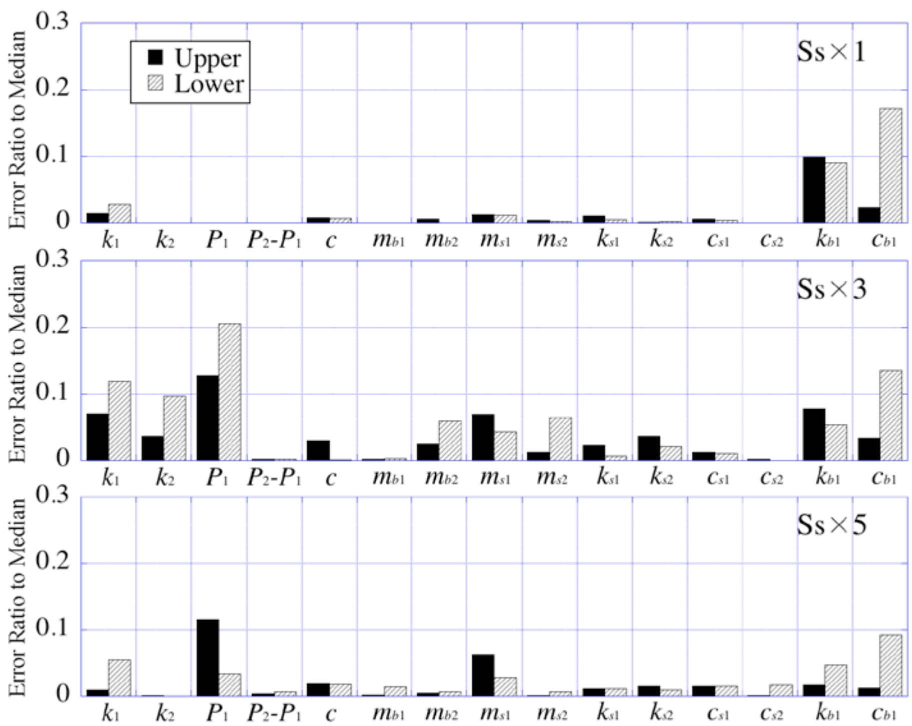


Fig. 11: Results of sensitivity analysis (Vertical)

## CONCLUSION

This paper dealt with the seismic response analysis and sensitivity analysis of the seismic isolation system, and the analyses considered nonlinearity of rubber bearings. The results of this paper are summarized as follows.

Nonlinear properties of rubber bearings appeared when input earthquake level is 2.4 times of the design wave 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.

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.

Parameters of rubber bearings have high sensitivity.

## ACKNOWLEDGEMENT

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