Transactions, SMiRT-22
San Francisco, California, USA - August 18-23, 2013
Division VII

SEISMIC RESPONSE ANALYSIS OF ISOLATION SYSTEM CONSIDERING COUPLING EFFECT BETWEEN HORIZONTAL AND VERTICAL DEFORMATION OF RUBBER BEARINGS

Keisuke Minagawa[1], Satoshi Fujita[2], Akira Yamaguchi[3], Takashi Takata[4] and Kenichi Kurisaka[5]

[1] Researcher, Dept. of Mechanical Eng., School of Eng., Tokyo Denki Univ., Tokyo, Japan
(Present: Lecturer, Dept. of Mechanical Eng., Saitama Institute of Tech., Saitama, Japan mina@sit.ac.jp)
[2] Professor, Dept. of Mechanical Eng., School of Eng., Tokyo Denki Univ., Tokyo, Japan
[3] Professor, Dept. of Sustainable Energy and Environment Eng., Osaka Univ., Osaka, Japan
[4] Associate Professor, Dept. of Sustainable Energy and Environment Eng., Osaka Univ., Osaka, Japan
[5] Principal Researcher, Advanced Nuclear System R&D Directorate, Japan Atomic Energy Agency, Ibaraki, Japan

ABSTRACT

Application of seismic isolation system using rubber bearings into nuclear power plants has been expected. Generally, rubber bearings have nonlinear characteristics in case of large deformation. In addition, the horizontal nonlinear characteristics depend on vertical load. Therefore it is important to consider these nonlinearity and coupling effect. Authors have already reported results of seismic response analysis of an isolated reactor building considering the nonlinearity of rubber bearings. In this paper, seismic response analysis considering the coupling effect of horizontal and vertical deformation of rubber bearings is investigated by numerical simulations. The summaries of the simulations are as follows. The vertical motion affected the start displacement of hardening, so that the coupling effect decreased isolation performance of horizontal direction. However the isolation system is still effective to reduce seismic force even if the nonlinearity and the coupling effect were considered.

INTRODUCTION

In Japan, applications of seismic isolation systems to new generation nuclear power plants and fast breeder reactors (FBRs) have been expected in order to enhance seismic safety. The seismic isolation is a system that extends the natural period of the superstructure and prevents superstructure from resonating with ground motion. In general, rubber bearings that consist of rubber and steel plates are used as the isolation device.

For example, FBRs utilize sodium having high thermal conductivity as coolant and are operated at higher core temperature than a conventional light water reactor. Therefore, thin-wall structure is adapted for the FBRs for the relaxation of the thermal stress. However the thin-wall structure is weak to the seismic load. Therefore, it is very important to reduce seismic force by applying seismic isolation systems.

Moreover, Japanese regulatory guide for reviewing seismic design of nuclear power reactor facilities refers to residual risks [1]. In the assessment of residual risks, extreme earthquake ground motion should be considered. In general, 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 addition, the horizontal nonlinear characteristics depend on vertical load. In other words, rubber bearings have coupling effect between horizontal and vertical direction. Therefore it is important for risk assessments to consider these nonlinear characteristics and coupling effect. However no seismic response simulation technique that considers the nonlinearity and the coupling effect is established.

Authors deal with development of the seismic response simulation technique considering the nonlinearity and the coupling effect. Results of seismic response analysis of an isolated reactor building considering the nonlinearity of rubber bearings were reported in the previous SMiRT [2]. In this paper, seismic response analysis considering the coupling effect of horizontal and vertical deformation of rubber bearings is investigated by numerical simulations.

ANALYTICAL MODEL

In this section, the analytical models of an isolated reactor building and a rubber bearing are described. The isolated reactor building was modeled by mass points. The restoring force characteristics were explained by multi-linear models.

Modeling of building

In this study, the isolated reactor building was modeled by a four mass points model as shown in Fig. 1 [3]. Table 1 indicates parameters of the analytical model. These parameters are based on an actual design of a nuclear power plant.

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. The model consists of the ground layer, the isolation layer, the 1st and 2nd layer of the building. The mass m_{s1} corresponds to floor where a reactor and important equipment are installed. As shown in Fig. 1, horizontal ground motion $\ddot{z}_h$ is input to the upper part of the ground layer, and vertical ground motion $\ddot{z}_v$ is input to the lower part of the ground layer. The reason is that horizontal stiffness of rubber bearings is so small compared with ground that dynamic behavior of ground is negligible. Horizontal and vertical motion of the ground layer, 1st and 2nd layer of the building do not interact each other. On the other hand, horizontal motion of the isolation layer depends on vertical motion as described later.

The horizontal isolation period is 3.4 seconds and the vertical is 1/8 seconds, respectively.

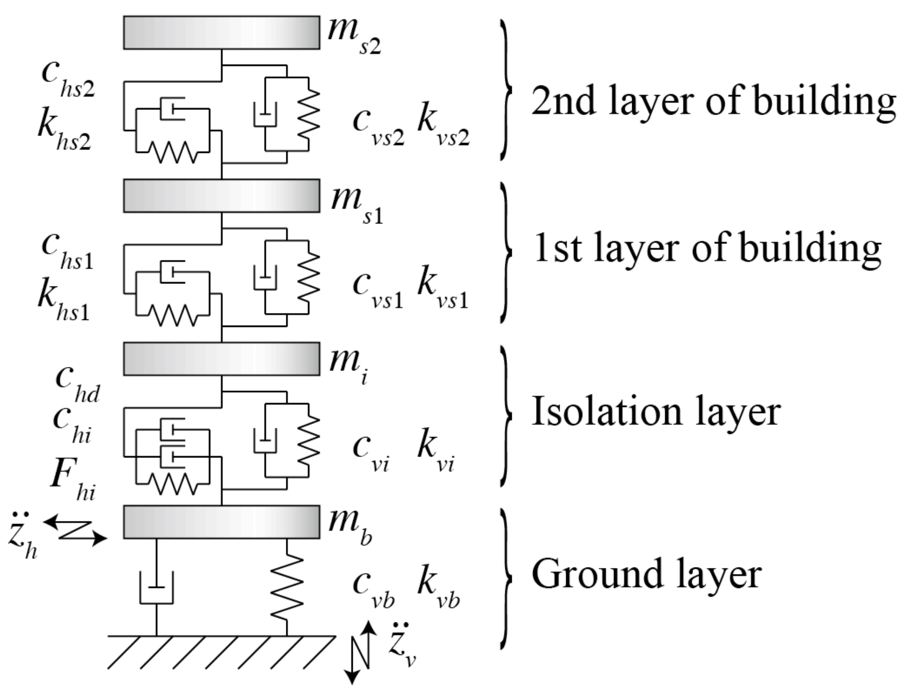

Figure 1. Analytical model of isolated building.

Table 1: Parameters of analytical model of isolated building.

	Caption		
m_b [kg]	Mass of ground layer		44.8×10^6
m_i [kg]	Mass of isolation layer		88.2×10^6
m_{s1} [kg]	Mass of 1st layer of building		213×10^6
m_{s2} [kg]	Mass of 2nd layer of building		25.3×10^6
F_{hi} [N]	Horizontal	Restoring force of rubber bearings	-
k_{hs1} [N/m]		Stiffness of 1st layer of building	177×10^9
k_{hs2} [N/m]		Stiffness of 2nd layer of building	14.5×10^9
c_{hi} [Ns/m]		Damping coefficient of rubber bearings	24.1×10^6 (2.0 [%])
c_{hd} [Ns/m]		Damping coefficient of oil dampers	528×10^6 (43 [%])
c_{hs1} [Ns/m]		Damping coefficient of 1st layer of building	614×10^6
c_{hs2} [Ns/m]		Damping coefficient of 2nd layer of building	60.5×10^6
k_{vb} [N/m]	Vertical	Stiffness of ground layer	1.67×10^{12}
F_{vi} [N]		Restoring force of rubber bearings	-
k_{vs1} [N/m]		Stiffness of 1st layer of building	2.05×10^{12}
k_{vs2} [N/m]		Stiffness of 2nd layer of building	327×10^9
c_{vb} [Ns/m]		Damping coefficient of ground layer	45.6×10^9
c_{vi} [Ns/m]		Damping coefficient of rubber bearings	656×10^6 (2.0 [%])
c_{vs1} [Ns/m]		Damping coefficient of 1st layer of building	2.09×10^9
c_{vs2} [Ns/m]		Damping coefficient of 2nd layer of building	288×10^6

Modeling of Rubber Bearings

Rubber bearings have linear stiffness in the normal deformation range. However they have nonlinear stiffness in case of large deformation.

Figure 2 and table 2 show horizontal restoring force model and its parameter, respectively. In horizontal direction, nonlinear behavior that is caused by the strain hardening occurs. The hardening behavior is expressed by multi-linear model as shown in Fig. 2 [4]. When deformation of the rubber bearing exceeds δ_1, 1st hardening occurs. In addition, when deformation of the rubber bearing exceeds δ_2, further hardening occurs. The 1st hardening displacement δ_1 shifts by the following condition.

Condition (a) : δ_1 increases depending on the maximum displacement that the rubber bearing experienced.
Condition (b) : δ_1 decreases depending on the vertical load for the rubber bearing.

In condition (a), once the hardening occurs, the hardening displacement increases in accordance with the following equations.

$$\delta_{1a} = \delta_1 + \alpha\left(\delta_{\max} - \delta_1\right) \tag{1}$$

$$\delta_{2a} = \delta_2 + \alpha\left(\delta_{\max} - \delta_1\right) \tag{2}$$

Where δ_{1a} and δ_{2a} are the new hardening displacement by condition (a), $\delta_{\max}$ is the maximum displacement that the rubber bearing has experienced, and α is a influence coefficient of repetition. In this paper, the α of 0.45 was selected.

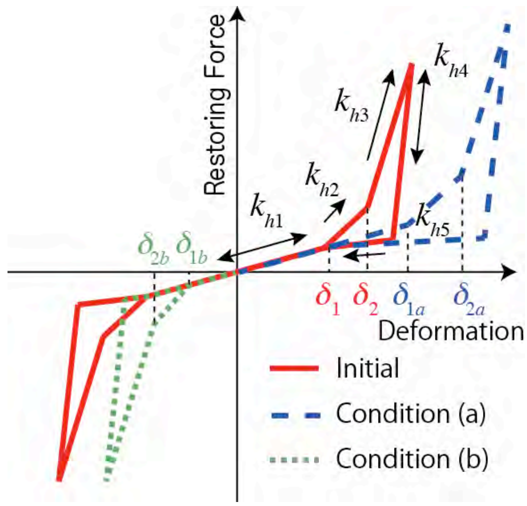

Figure 2. Restoring force model of rubber bearings (Horizontal).

Table 2: Parameters of analytical model of rubber bearing (Horizontal).

	Caption	
k_{h1} [N/m]	1st stiffness	1.12×10^9
k_{h2} [N/m]	2nd stiffness	3.92×10^9 ($3.5k_{h1}$)
k_{h3} [N/m]	3rd stiffness	13.4×10^9 ($12k_{h1}$)
k_{h4} [N/m]	4th stiffness	33.0×10^9 ($29.5k_{h1}$)
k_{h5} [N/m]	5th stiffness	224×10^6 ($0.2k_{h1}$)
δ_1 [m]	1st hardening displacement	0.830 (γ_1=250[%])
δ_2 [m]	2nd hardening displacement	1.20 (γ_1=360[%])

In condition (b), the hardening displacement decreases, when vertical load increases. This paper calls condition (b) the coupling effect. As shown in Fig. 3, rubber bearings retain initial performance, when the vertical load is in between σ_{tty} and σ_{ccy}. On the other hand, the hardening displacement decreases from δ_1 to δ_{1b}, when vertical load exceeds σ_{tty} or is less than σ_{ccy}. The parameters σ_{ty}, σ_{tty}, σ_{ccy} and σ_{cy} that provide the linear limit of the rubber bearings have not been verified by experiments yet. Thus the parameters were determined by interpolation from fracture characteristics [5, 6].

Figure 4 and table 3 show vertical restoring force model and its parameter, respectively. As shown in Fig. 4, rubber bearings have linear stiffness for compressive load. On the other hand, rubber bearings have softening property for tensile load. This softening property is caused by difference of characteristics between compression and tension of rubber bearings. The 1st softening load P_1 is equivalent to weight of the upper structure. The Accumulative strength P_2 - P_1 is equivalent to allowable tensile load of rubber bearings.

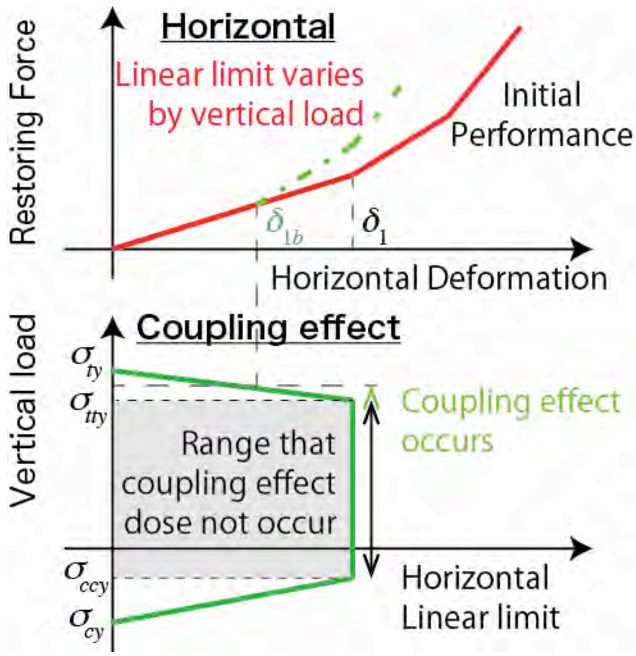

Figure 3. Coupling effect between horizontal restoring force and vertical load.

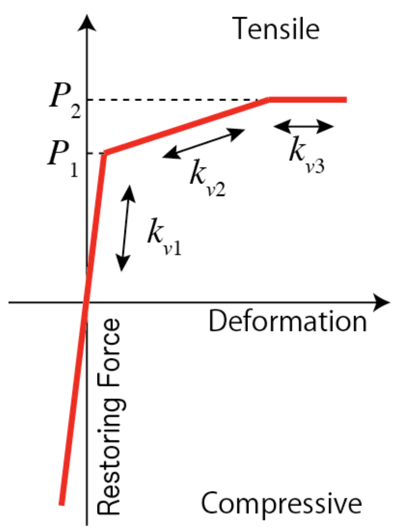

Figure 4. Restoring force model of rubber bearings (Vertical).

Table 3: Parameters of analytical model of rubber bearing (Vertical).

	Caption	
k_{v1} [N/m]	1st stiffness	825×10^9
k_{v2} [N/m]	2nd stiffness	27.5×10^9 ($k_{v1}/30$)
k_{v3} [N/m]	3rd stiffness	0
P_1 [N]	1st softening load	3.20×10^9
P_2-P_1 [N/m]	Accumulative strength	1.25×10^9

ANALYTICAL PROCEDURE

In this paper, an artificial wave shown in Fig. 5 was used as an input wave. The input wave was made in consideration of a target spectrum of design basis earthquake ground motion. A wave of which amplitude is 2/3 of the wave for horizontal direction is used for vertical direction. These waves are called Ss wave in this paper. Amplitude of the wave is varied in analyses in order to investigate relationships between response and earthquake level.

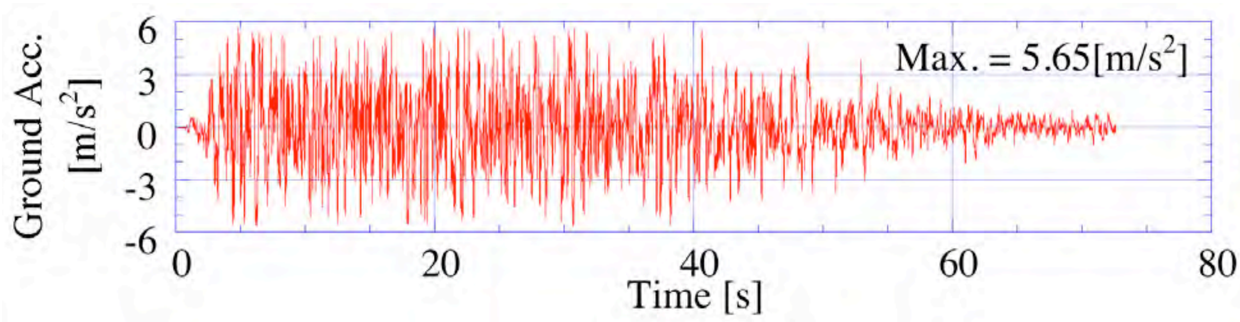

Figure 5. Input wave (Horizontal).

ANALYTICAL RESULTS

In this paper, analytical results are reported from the viewpoint of the coupling effect mainly. The coupling effect does not affect response of vertical direction, and the influence of nonlinearity on vertical direction has been reported by the authors in the previous SMiRT [2]. Therefore this section describes analytical results of horizontal direction.

Figure 6 shows relationship between earthquake level and the maximum horizontal response acceleration at m_{s1}. It is confirmed that response acceleration increases and the linear limit decreases by the consideration of coupling effect. In the case of analyses considering the coupling effect, the earthquake levels that lead the rubber bearing to hardening were small compared with the results that didn't consider the coupling effect. In fact, the 1st hardening and the 2nd hardening occur from the design basis level × 2.4 and 3.0 when the coupling effect was considered, and they occur from the design basis level × 2.6 and 4.0 when the coupling was not considered. The maximum response acceleration increases nonlinearly with the hardening of the rubber bearings, because the horizontal isolation period came close to the natural period of superstructure by hardening of rubber bearings. In the case of analyses considering the coupling effect, this tendency is remarkable and thus the acceleration was larger compared with the results that didn't consider the coupling effect. Meanwhile, the isolation system retained performance of isolation even if the coupling effect was considered, since response acceleration of the isolated structure is smaller than the input wave.

Figure 7 shows relationship between earthquake level and horizontal response displacement at m_i, namely deformation of the rubber bearings. As shown in Fig. 7, the maximum response displacement is comparable with linear analysis, because the condition (a) extends δ_1 and δ_2, once hardening occurs. In addition, deformation of the rubber bearing is suppressed by the considering of the coupling effect, because response acceleration increased instead of displacement.

Figures 8 and 9 shows analytical results of design basis level × 2.6 and 4.2. These figures consist of the time history of acceleration at m_1, the hysteresis loop of the rubber bearing, the relationship of the horizontal response displacement and the vertical load at m_i. The result of the design basis level ×2.6, that is Fig. 8, is a result that 1st hardening occurred, and the result of the design basis level ×4.2, that is Fig. 9, is a result that 2nd hardening occurred.

From Fig. 8, time history of acceleration considering the coupling effect resembles it that didn't considers the effect. The difference was confirmed only at around 20 seconds. In addition, the relationship between horizontal displacement and the vertical load exceeded the linear limit, and the hardening starting displacement decreased as shown in the hysteresis loop.

From Fig. 9, time history of acceleration considering the coupling effect differed from it that didn't considers the effect. Especially the large difference was confirmed at around 20 and 40 seconds, and the maximum response acceleration was twice as large as results not considering the coupling effect. The relationship between horizontal displacement and the vertical load exceeded the linear limit very much. As shown in the hysteresis loop, the hardening occurred from small displacement, as a result the response displacement was suppressed.

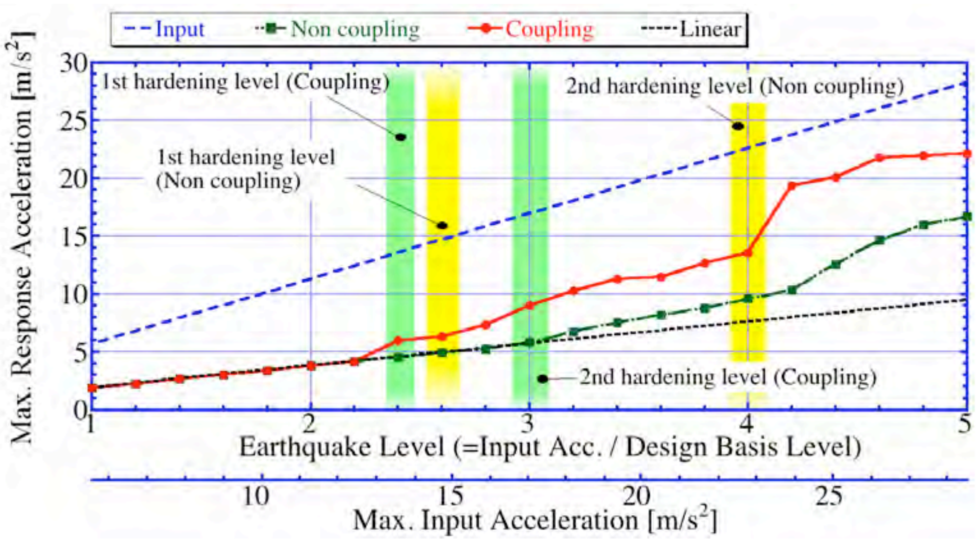

Figure 6. Relationship between earthquake level and response acceleration (Horizontal).

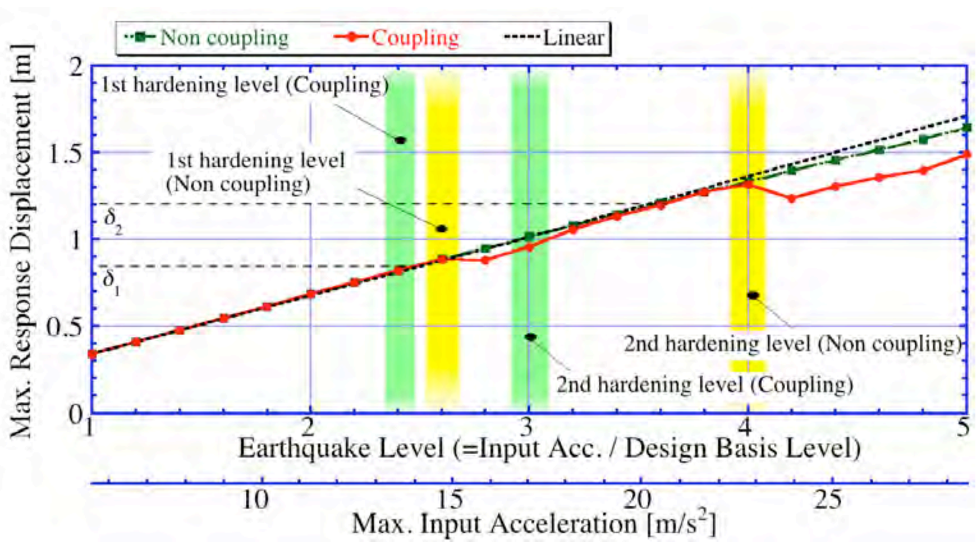

Figure 7. Relationship between earthquake level and response displacement (Horizontal).

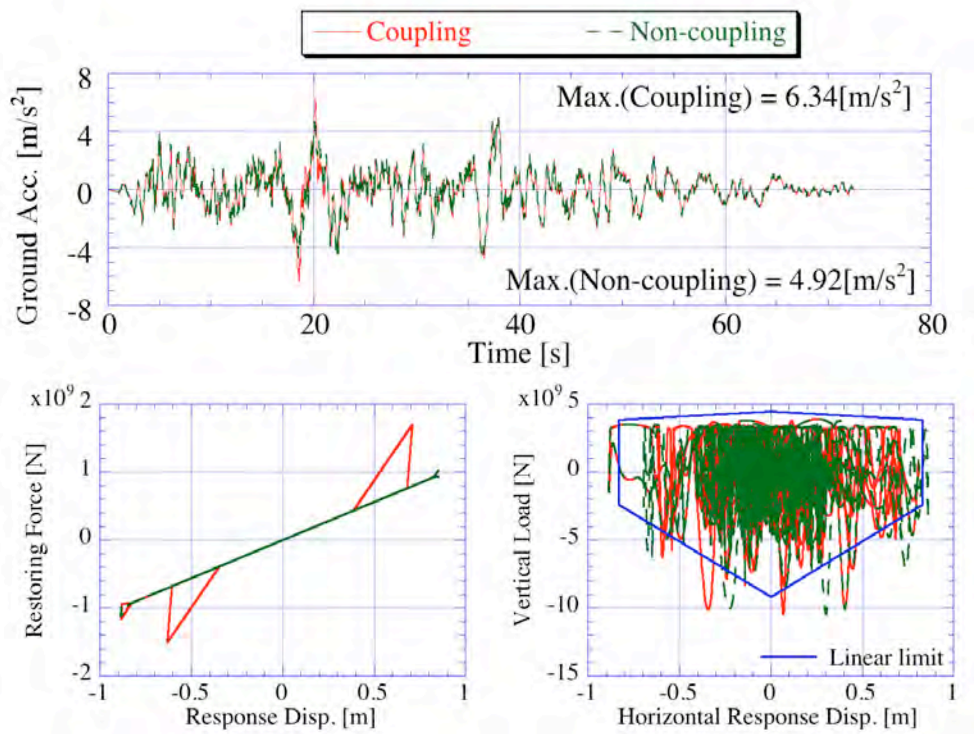

Figure 8. Analytical results (Design Basis Level × 2.6).

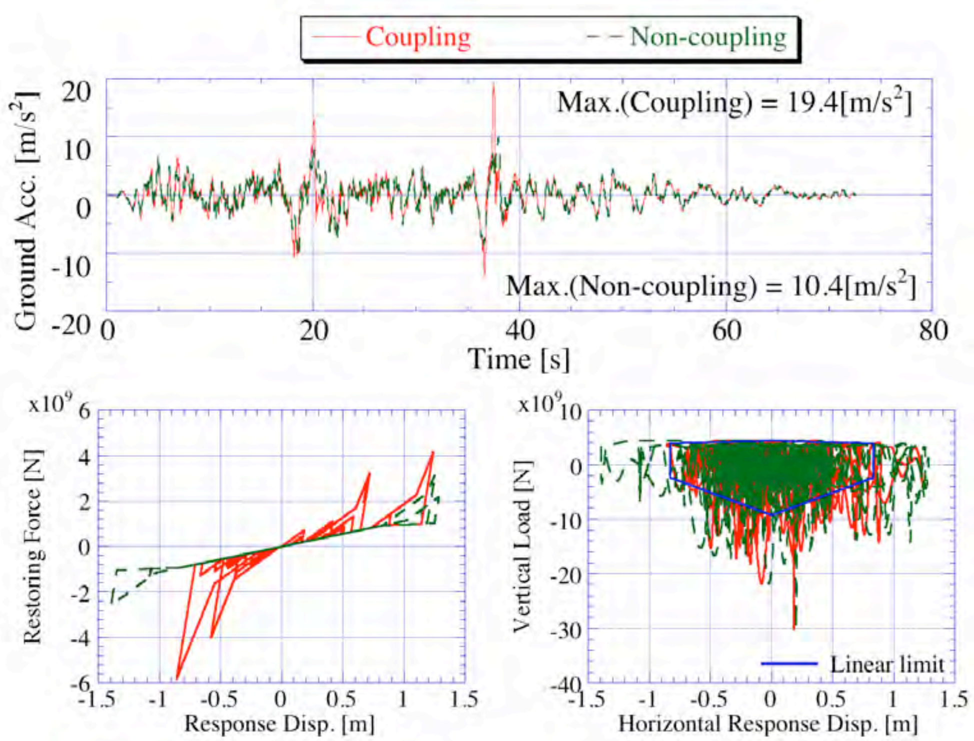

Figure 9. Analytical results (Design Basis Level × 4.2).

CONCLUSION

This paper described results of seismic response analysis considering the coupling effect of horizontal and vertical motion of rubber bearings. Influence of the coupling effect is summarized as follows.

In the case of analysis considering the coupling effect, the nonlinear behavior occurs from smaller input earthquake compared with analysis not considering the coupling effect.

In the case of analysis considering the coupling effect, the deformation of the rubber bearings is suppressed compared with analysis not considering the coupling effect.

Although the nonlinear behavior decreases the isolation performance, the isolation system is still effective.

As a result of this study, importance of consideration of the coupling effect was confirmed. However the investigation regarding nonlinear characteristics by experiment, especially combination of the horizontal and vertical motion, is not enough. Therefore further investigations regarding this problem by experiment and analysis are required in the future.

ACKNOWLEDGEMENT

Present study is the result of “Development of level-1 PSA method for sodium-cooled fast breeder reactors” entrusted to Japan Atomic Energy Agency by the Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT). The authors would like to express his appreciations to Mr. M. Oguro of graduate school of Tokyo Denki University for his devoted assistance.

REFERENCES

[1] Nuclear Safety Commission of Japan (2006). “Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities”, Nuclear Safety Commission of Japan Decision No. 2006-D59, http://www.nsr.go.jp/archive/nsc/NSCenglish/documents/decisions/2006/2006_59_1.pdf

[2] Minagawa, K., Fujita, S., Yamaguchi, A., Takata, T., Kurisaka, K. (2011). “Development of Level-1 PSA Method Applicable to Japan Sodium-cooled Fast Reactor: (2) Seismic Response Analysis Considering Characteristics of the Advanced Seismic”, *Transactions of SMiRT 21*, 2011, p263.pdf.

[3] Japan Electric Association (2000). “*Japan Electric Association Guide 4614-2000*”, Japan Electric Association, 5-18, [in Japanese].

[4] Katoh, A., Nagura, S., Nojima, O., Yoneda, G. (1993). “Study on concept of seismic isolation type plant for FBR: Part 28 Ultimate Behavior of Base-Isolated Reactor Building (Sensitivity Analysis on Hysteresis Curve Modeling Method)”, *Proceedings of Architectural Institute of Japan*, 1595-1596, [in Japanese].

[5] Nishikawa, I., Isono, M., Shimada, J., Ozawa, Y., Sakaguchi, T. and Takayama, M. (2004). “Performance of Natural Rubber Bearings by Compression-shear Test : Part 3 Ultimate Compression-shear Properties”, *Proceedings of Architectural Institute of Japan*, 441-442, [in Japanese].

[6] Muramatsu, Y., Inoue, K., Katoh, R., Kamitani, N., Sakaguchi, T., Sasaki, T., Suzuki, S., Sera, S., Miyazaki, M. and Kitamura, H. (2004). “Test Results of Ultimate Properties of Rubber Bearings for Building”, *Architectural Institute of Japan J. Technol. Des.*, No. 20, 67-70, [in Japanese].