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Sensitivity Analyses on Seismic Isolation System using Elastic Sliding Bearings and Multi-Laminated Rubber Bearings

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ABSTRACT

Several seismic isolation devices are developed and put into practical use. A seismic hybrid isolation system using elastic sliding bearings and multi-laminated rubber bearings is one of them. Since the elastic sliding bearing has a damper function so that any damper system is not needed, the seismic hybrid isolation systems excel in cost, compared with the multi-laminated rubber bearings only. Additionally, it can make the primary period of horizontal response 4 - 5 seconds easily, without reducing the axial stiffness, because of few laminations of rubber in the elastic sliding bearing.

We have constructed an analysis model, which could simulate the results of shaking table excitation tests on responses of structure isolated with the seismic hybrid isolation system, including acceleration response spectra, which are important for the seismic design of equipments and piping in a nuclear power plant station. However, when our analysis model is used in practical seismic design, there still remain the following problems: (i) how do we treat the randomness in such model parameters as a coefficient of friction of sliding surface, (ii) procedure to make a damping matrix is somewhat complicate. Then, in order to solve these problems, we carried out sensitivity analyses and confirmed the effect of randomness in model parameter on the structural responses. From the results of the sensitivity analyses, this paper showed seismic design implications for the structure isolated with seismic hybrid isolation system using elastic sliding bearings and multi-laminated rubber bearings.

KEY WORDS: base-isolation, elastic sliding bearing, friction coefficient, response spectrum, shaking table excitation test

INTRODUCTION

Seismic hybrid isolation system using Elastic Sliding Bearings (ESBs) and Multi Laminated Rubber Bearings (MLRBs) is one of the practical isolation systems and have been applied widely to the buildings such as hospital, factory and so on, because it can make the primary period of horizontal responses comparatively long easily, not changing that of vertical responses. However, there have been few studies on frequency characteristics of structure isolated with this hybrid isolation system, which is important for seismic design of equipments and/or piping systems attached to the nuclear plant structure. Then, we have presented a model for structure isolated with this hybrid isolation system, and have confirmed that the appropriate model can simulate the structural responses of shaking table excitation test, including their frequency characteristics [1].

Though this presented model can be applied to a simulation, it is not appropriate for a design. Because, such model parameters as stiffness and friction on sliding plate in the presented model is suitable for simulation analysis so that it does not give the conservative responses, and the procedure to make the damping matrix is complicated. For seismic design, more conservative responses and simple damping matrix are desirable.

Then, in this paper, we carry out the sensitivity analyses in order to investigate the structural responses when the following parameters are dealt with practically.

- Coefficient of friction on sliding surface of sliding bearing
- Stiffness of rubber
- Damping of rubber

From the results of sensitivity analyses, we obtained some implications to give appropriate parameters and damping matrix to a design model of structure with seismic hybrid isolation system using ESBs and MLRBs.

ANALYSIS MODEL

We use an analysis model for sensitivity analysis, which is presented in previous study [1]. This model was constructed such that it could simulate the results of shaking excitation test. Outline of tests and analysis model is shown briefly below.

Shaking Table Excitation Test

We have carried out shaking table excitation tests of a scale model shown in Fig.1, which was a three-storied steel frame structure isolated with the seismic hybrid isolation system using ESBs and MLRBs [2]. Table 1 shows scaling ratios of the shaking table excitation tests.

The isolation system consists of four MLRBs under outer columns and four ESBs under the inner columns. Fig. 2 illustrates details of the isolating devices. The ESB has a lamination of chloroprene rubber and the steel plate coated with PTFE (poly-tetra-fluoro-ethylene), which slides on the stainless plate. On the other hand, the natural rubber is used for MLRB.

Three strong motion records of EL CENTRO1940, JMA KOBE1995 and HACHINOHE 1968 were prepared for shaking table motions. Each record was normalized with respect to the maximum horizontal acceleration of $0.5 m/s^2$ and the maximum horizontal velocity of 0.25m/s, 0.5m/s and 0.75m/s in actual scale. The horizontal (X and Y directions) and vertical records of each earthquake were applied into the isolated scale model simultaneously.

The shaking table and scale model were instrumented with several sensors. Black dots in Fig. 1 indicate the accelerometers on shaking table and beam of each story, which provide horizontal (X and Y directions) and vertical response acceleration. Black and white triangles in Fig. 1 on the base beam provide relative response displacement between base beam and shaking table in Y-direction and X-direction, respectively. In addition to these responses, axial forces are measured at each bearing. These signals are low pass filtered at 50Hz, and A/D converted by sampling frequency of 128Hz.

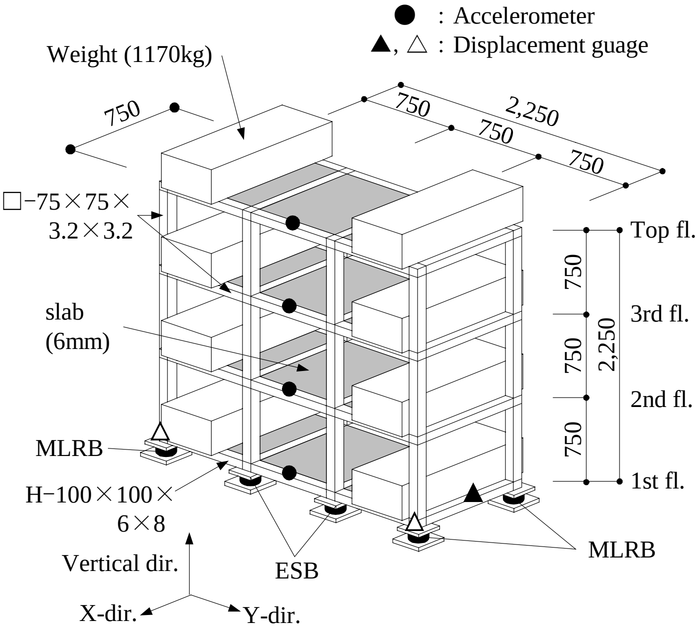

Fig. 1 Isolated scale model for shaking table excitation test

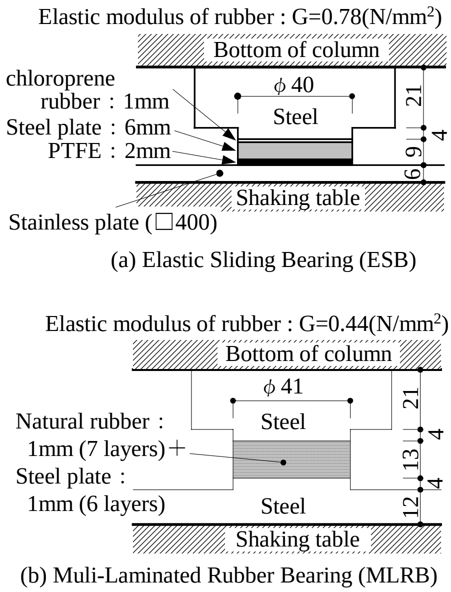

Fig. 2 Details of isolating devices

Table 1 Scaling ratios of the shaking table excitation tests

	Scaling ratio		Scaling ratio		Scaling ratio
Time (Period)	$1/\sqrt{17}$	Velocity	$1/\sqrt{17}$	Force (Weight)	1/289
Length (Displacement)	1/17	Acceleration	1.0	Axial pressure	1.0

Analysis Model

Fig. 3 shows a three-dimensional analysis model. Beam elements are used for the steel columns and beams, shell elements for the steel slab of each story with a thickness of 6mm, and the concentrated mass with six degree-of-freedom (D.O.F.) for the weight of each story. The isolation models shown in Fig. 4 are attached under each column.

The model of the ESB consists of non-directional shear spring, axial spring and GAP element. Shear and axial spring represent chloroprene rubber, and GAP element represents sliding bearing. When horizontal shear force exceeds frictional resistance, which is expressed as the product of a coefficient of friction and axial force, the model starts sliding for horizontal direction (stiffness of shear spring becomes near zero). Furthermore, the GAP element makes stiffness of both shear and axial springs zero, when the tensional force occurs in the axial spring.

On the other hand, the model of the MLRB consists of non-directional shear spring and axial spring only. Referring to literature [3], the axial spring has the nonlinear characteristics that tensional stiffness is one-tenth of compressive stiffness.

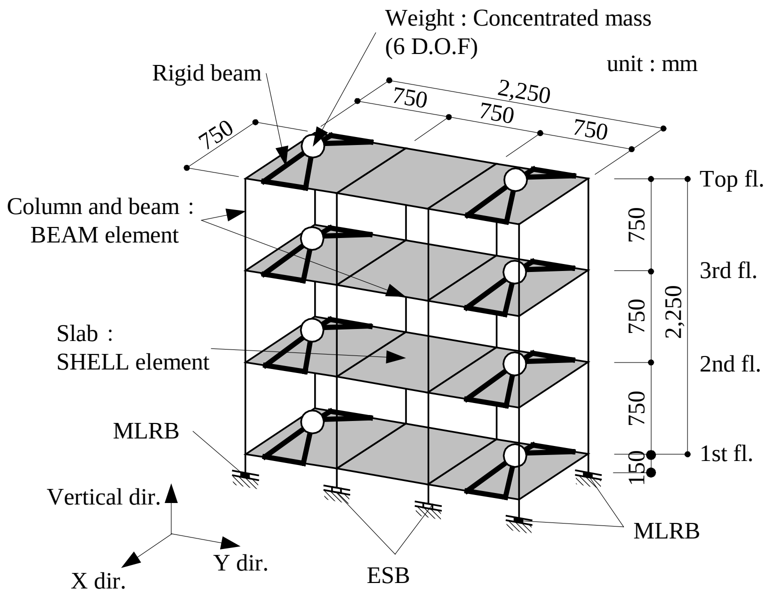

Fig. 3 Analysis model

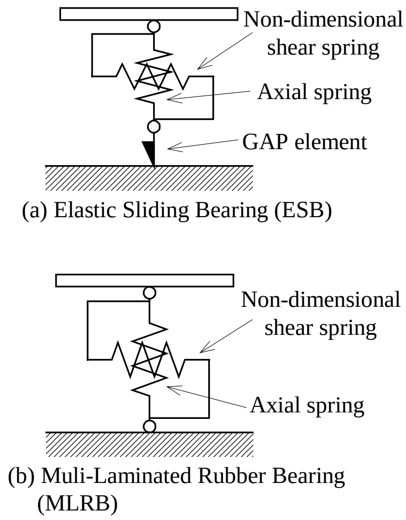

Fig. 4 Details of analysis model for bearings

PARAMETERS OF SENSITIVITY ANALYSIS

In our previous paper, it has been shown that the analysis model mentioned above with proper model parameters, such as stiffness and damping factor for spring elements, coefficient of friction for GAP element and so on, were able to simulate the results of shaking table excitation test very well, including acceleration response spectra. However, these model parameters are for ‘post-diction’ of responses. In practice, because of the randomness inherent in these model parameters, it is difficult to determine the most appropriate values of them. Thus, we should use the values, which give conservative responses, in practical design.

Then, in order to obtain the seismic design implications for the structure isolated with the hybrid isolation system, we carried out the sensitivity analyses on the following three parameters, and confirmed the effect of their randomness on the responses of structure.

- Coefficient of friction on sliding surface of sliding bearing
- Stiffness of rubber
- Damping of rubber

Friction on Sliding Surface of Sliding Bearing

Two values are used as parameters of the coefficient of friction on sliding surface of sliding bearing. One is good for simulation, and another is selected as a practical value considering the uncertainties in the coefficient of friction. The former is 0.12, which is used for simulation analyses as shown in [1]. The latter is 0.18, which is deviated from 0.12 by a standard deviation, assuming that the coefficient of variation is 0.5. In this study, we do not use the value of 0.06 deviated from 0.12 by a standard deviation in negative direction, because we focus on the acceleration responses spectrum, which is conservative for larger coefficient of friction.

A coefficient of friction between steel sliding plate coated with PTFE and stainless plate depends on axial force and/or sliding speed. Generally, an empirical formula to evaluate the coefficient of friction is prepared as a function of axial force and/or sliding speed. Furthermore, the uncertainties in the formula cannot be disregarded. However, it is not practical for earthquake response analysis to change the coefficient of friction at every time steps, taking the dependence on axial force and/or sliding speed into consideration. Actually, the results in literature [1] show that the analysis model with an appropriate constant value of the coefficient of friction was able to simulate the shaking table excitation test results very well, including their frequency characteristics.

Stiffness of Rubber

In order to obtain the seismic design implications, the responses of analysis model using design stiffness of rubber are compared with those using the appropriate stiffness for simulation.

Table 2 shows the design stiffness of rubber for the scale model evaluated using Japanese design recommendation of base isolated buildings [3] (see appendix). Also, Table 2 shows the stiffness of rubber for the simulation analyses in our previous study [1], which is evaluated such that both natural frequencies of analysis model and calculated axial forces of each bearing agree with test results.

The primary natural frequency of analysis model with ESBs and MLRBs having design stiffness is 2.77Hz for X direction and 2.89Hz for Y direction, while that having appropriate stiffness for simulation is 2.68Hz for X and 2.78Hz for Y. The former is higher than the latter about 3 to 4 %.

TABLE 2 Stiffness of rubber (unit:N/mm²)

	Elastic sliding bearing (ESB)		Multi-laminated rubber bearing (MLRB)	
	Design	Simulation	Design	Simulation
Horizontal	980	883	83.1	74.7
Vertical	251000	196000	39700	53900

Damping of Rubber

The procedure to make the damping matrix for simulation in literature 1 is too complicated for practical use. Therefore, as the sensitivity analysis, the detailed damping matrix with appropriate damping factor for simulation is compared with the simplified one with practical damping factor, which is presented here.

There is the randomness inherent in damping of the MLRBs and ESBs. Generally, damping factor of a natural rubber and chloroprene rubber fluctuate with about 0 to 3% and about 5 to 10%, respectively. While 1.5% damping as the former and 7% as the latter are appropriate for simulation of the shaking table excitation test in literature 1, conservative values, 0% and 5%, are used here as practical values.

If a fixed-base (non-isolated) structure model is inaccurate, we cannot verify that a base-isolated model is good or not. For the simulation analysis in the [1], the detailed damping matrix of base-isolated structure is made after the damping characteristics of the fixed-base structure are tuned up in the following Step A1 to A3. A simplified procedure to evaluate damping matrix is presented here as Step B.

<u>Step A1</u>: Assuming all the modal damping of 1.0% for fixed-base structure gives the different peak values of transfer function of top floor to the bottom of the analysis model from those of the test result. Then, the first three modal damping in horizontal and vertical direction is tuned up such that the analytical transfer function coincided with the experimental one. Damping matrix, $[C_{FS}]$, which is equivalent to the tuned modal damping of fixed-base model, is given by the following equation:

$$[u]^T[C_{FS}][u] = \begin{bmatrix} 2h_1\omega_1\overline{m}_1 & & 0 \\ & \ddots & \\ 0 & & 2h_n\omega_n\overline{m}_n \end{bmatrix} \quad \text{(diagonal matrix)} \qquad (1)$$

Where, $[u]$ is an eigenvector matrix, in which i th column is i th eigenvector of the fixed-base model, h_i and ω_i are i th modal damping and circular frequency, respectively, $\overline{m}_i$ is a diagonal element of the diagonal matrix, $[u]^T[M][u]$, in which $[M]$ is a mass matrix.

<u>Step A2</u>: The $[C_{FS}]$ for the fixed-base model is extended to $[C_S]$, which is a damping matrix including the D.O.F. of isolation system as the following:

$$[C_S] = \begin{bmatrix} [C_{FS}] & 0 \\ 0 & 0 \end{bmatrix} + \begin{bmatrix} 0 & [C_{FI}] \\ [C_{IF}] & [C_{II}] \end{bmatrix} \qquad (2)$$

Where, $[C_{FI}]$, $[C_{IF}]$ and $[C_{II}]$ are evaluated such that the damping force due to response velocity of isolation system part do not applied to the structure model part. If no force occurred on the any part of structure as

$$\begin{bmatrix} [K_{FS}] & [K_{FI}] \\ [K_{IF}] & [K_{II}] \end{bmatrix} \begin{Bmatrix} u_{FS} \\ u_I \end{Bmatrix} = \begin{Bmatrix} 0 \\ F_I \end{Bmatrix}, \qquad (3)$$

the relationship between the response displacement of structure part, $\{u_{FS}\}$, and that of isolation system, $\{u_I\}$ is given by

$$\{u_{FS}\} = -[K_{FS}]^{-1}[K_{FI}]\{u_I\}. \qquad (4)$$

Where, $[K_{FS}]$ and $[K_{FI}]$ are parts of a stiffness matrix for overall base-isolated model.

Since the same relation holds for the response velocity, the $[C_{FI}]$, $[C_{IF}]$ and $[C_I]$, which do not provide any damping force due to the response velocity of isolation system, are found from

$$\begin{bmatrix} [C_{SF}] & [C_{FI}] \\ [C_{IF}] & [C_{II}] \end{bmatrix} \begin{Bmatrix} \{\dot{u}_{FS}\} \\ \{\dot{u}_I\} \end{Bmatrix} = \begin{bmatrix} [C_{SF}] & [C_{FI}] \\ [C_{IF}] & [C_{II}] \end{bmatrix} \begin{Bmatrix} -[K_{FS}]^{-1}[K_{FI}]\{\dot{u}_I\} \\ \{\dot{u}_I\} \end{Bmatrix} = \{0\}\,. \tag{5}$$

<u>Step A3</u>: Since the extended damping matrix, $[C_S]$, do not include the damping of isolation system, we should add a damping matrix for isolation system, $[C_I]$, to the $[C_S]$. The $[C_I]$ is the equivalent damping matrix to the modal damping h_i of the base isolated structure model, and is evaluated in the same way of Eq. (1). The modal damping h_i is evaluated as the weighted average of element damping, which is given by

$$h_i = \sum_{j=1}^{n} he_j \cdot W_{ij} \Bigg/ \sum_{j=1}^{n} W_{ij}\,. \tag{6}$$

Where, he_j is the damping factor of j th element, such as 1.5% for spring element of MLRB, 7.0% for ESB and all 0.0% for structure elements. They are assumed to be constant and independent of frequency. Strain energy of the j th element is used for the weight, W_{ij}, in Eq.(6), which is given by

$$W_{ij} = \frac{1}{2}\{u_i\}^T \left[K^j\right]\{u_i\}\,. \tag{7}$$

Where, $\left[K^j\right]$ is a zero matrix except for stiffness matrix for j th element, and the eigenvector $\{u_i\}$ of i th mode is regarded as the strain of element.

<u>Step B</u>: In the same way of Eq. (1), a damping matrix equivalent to the modal damping h_i for base isolated model is evaluated. The modal damping h_i is evaluated as the weighted average of element damping using Eq. (6), in which the damping factor of j th element he_j are 1% for all structural elements, 0% for spring element of MLRB and 5% for ESB, respectively. The weight, W_{ij}, in Eq. (6) is given by Eq. (7)

INPUT MOTIONS

EL CENTRO 1940, JMA KOBE 1995 and HACHINOHE 1968 normalized to the maximum velocity of 50 m/s were applied into the analysis model. EL CENTRO represents relatively high frequency input motion, while HACHINOHE is low frequency one. JMA KOBE has medium characteristics between them. In this paper, the results of only EL CENTRO and HACHINOHE are shown in next chapter.

RESULTS OF SENSITIVITY ANALYSIS

Table 3 shows the maximum acceleration responses on 1st floor and top floor. For reference, results of test and simulation model with tuned parameters are also shown in Table 3. The maximum acceleration responses of the analysis model with practical parameters approximate to test results or those with tuned parameters for simulation.

Figs. 5 and 6 show acceleration response spectra due to EL CENTRO and HACHINOHE, respectively.

As shown in Figs. 5(1) and 6(1), acceleration response spectrum of structure increases as the coefficient of friction on sliding surface of sliding bearing increases. The reason of this is that increasing of friction on sliding surface make hard to slide, so that the bearings loses their reduction effect on structural acceleration responses.

The design stiffness of rubber gives larger acceleration response spectra than the stiffness of rubber tuned for simulation as shown in Figs. 5(2), and that is not shown clearly in Figs 6(2). As shown in Table 2, the design stiffness is harder than the stiffness for simulation. It suggests that the reduction effect of harder stiffness of rubber on structural acceleration responses loses for high frequency input motions.

Acceleration response spectra of the analysis model with damping matrix constructed by practical procedure (practical *C* matrix) are compared with those with damping matrix constructed by the detailed procedure (detailed *C* matrix). Figs. 5(3) and 6(3) show that the former is bigger in middle frequency range, and smaller in high frequency (low period) range than the latter.

TABLE 3 Comparisons of maximum acceleration responses at top floor and 1st floor

Input	Position	Direction	Maximum acceleration (m/s^2)				
			Test	Tuned parameters	μ=0.18	Design Stiffness	Practical C matrix
EL CENTRO (Vmax*=0.5m/s)	Top floor	X	3.22	2.63	3.31	2.69	2.60
		Y	2.40	2.56	2.95	2.68	2.78
		Vertical	5.03	4.32	5.83	6.37	4.42
	1st floor	X	2.93	2.84	5.08	3.53	2.71
		Y	2.13	2.24	2.34	2.39	2.38
		Vertical	4.53	4.29	4.33	5.96	4.13
HACHINOHE (Vmax*=0.5m/s)	Top floor	X	2.38	2.41	2.67	2.44	2.60
		Y	2.43	1.69	1.88	2.07	1.78
		Vertical	3.13	3.03	3.04	3.17	3.00
	1st floor	X	2.25	2.24	2.67	2.26	2.33
		Y	2.13	1.37	2.30	1.26	1.50
		Vertical	2.94	2.81	2.81	2.73	2.82

*: converted value for actual size

CONCLUSIONS

We carried out sensitivity analyses and confirmed the effect of randomness in model parameter on the structural responses. With respect to response acceleration spectra, which are important for the seismic design of equipments and piping systems attached to nuclear plant structure, we obtained the following seismic design implications of structure isolated with seismic hybrid isolation system using elastic sliding bearings and multi-laminated rubber bearings:

- As the coefficient of friction on sliding surface of sliding bearing increases, acceleration response spectrum of structure increases
- Harder initial stiffness of rubber gives larger structural acceleration response spectrum. That is apt to be occurred for high frequency input motion.
- Damping matrix for practical use gives the smaller acceleration response spectra in high frequency range.

The increasing of friction on sliding surface and initial stiffness of rubber give the conservative response spectra, while the damping for design use provides the smaller one. Thus, we may carry out well-balanced seismic designs considering these contrary effects to each other.

APPENDIX

According to Japanese design recommendation of base isolated buildings [3], the stiffness of rubber in bearings is given by the following formulas.

$$K_h = \frac{G \cdot A}{t_e \cdot n} \quad \text{for horizontal stiffness,} \quad K_v = \eta \frac{E_m \cdot A}{t_e \cdot n} \quad \text{for vertical (axial) stiffness} \qquad \text{(A1)}$$

Where, G is shear modulus of rubber, A is effective area for axial force, t_e is thickness of a lamination, n is number of lamination, η is a coefficient of correlation for vertical stiffness, which is equal to 1.0 for MLRB and $\eta = -0.0067S_1 + 0.807$ for ESB, and E_m is modified Young's modulus defined as $E_m = E_a \cdot E_b / (E_a + E_b)$. E_a is Young's modulus of rubber considering the restraint of horizontal expansion when the rubber is axially stressed, E_b is bulk modulus of rubber. They are given by $E_a = E_0 \left(1 + 2\kappa S_1{}^2\right)$ and $E_b = -57G^2 + 316G + 1880$, respectively. E_0 is Young's modulus of rubber under the ordinary condition, κ is a constant evaluated by $\kappa = 0.347G^2 - 0.959G + 1.197$ empirically and S_1 is a coefficient that represents the degree of restraint for horizontal expansion of the rubber when it is axially stressed, which is defined as $S_1 = D/(4t_e)$, where D is a diameter of bearing.

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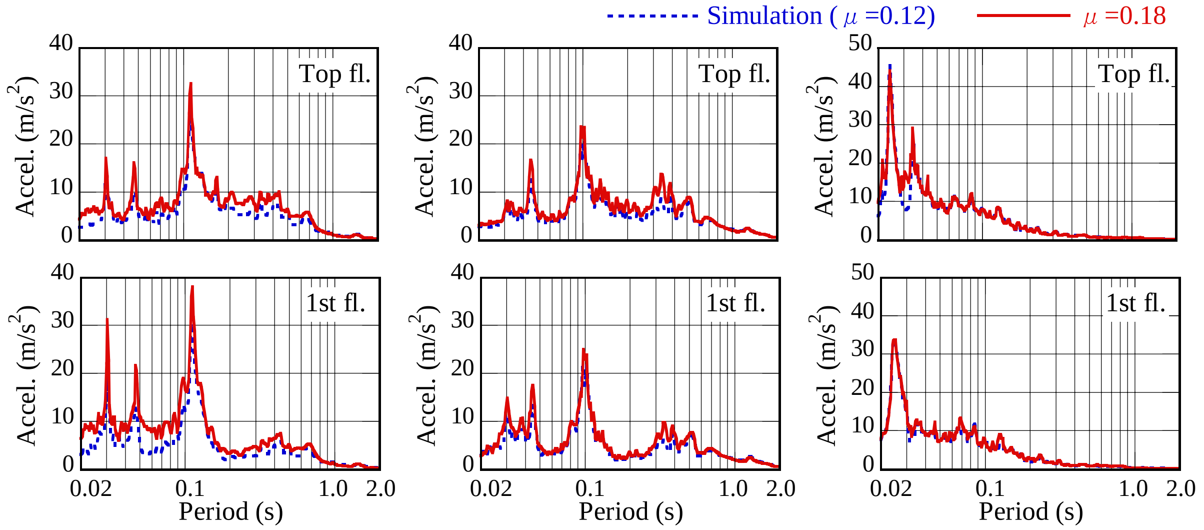
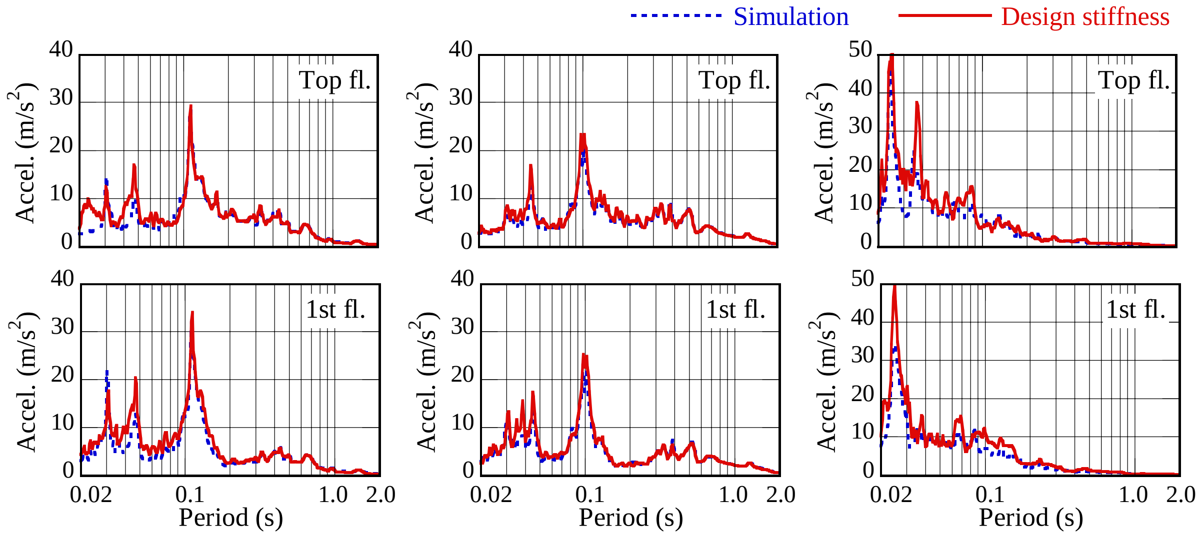


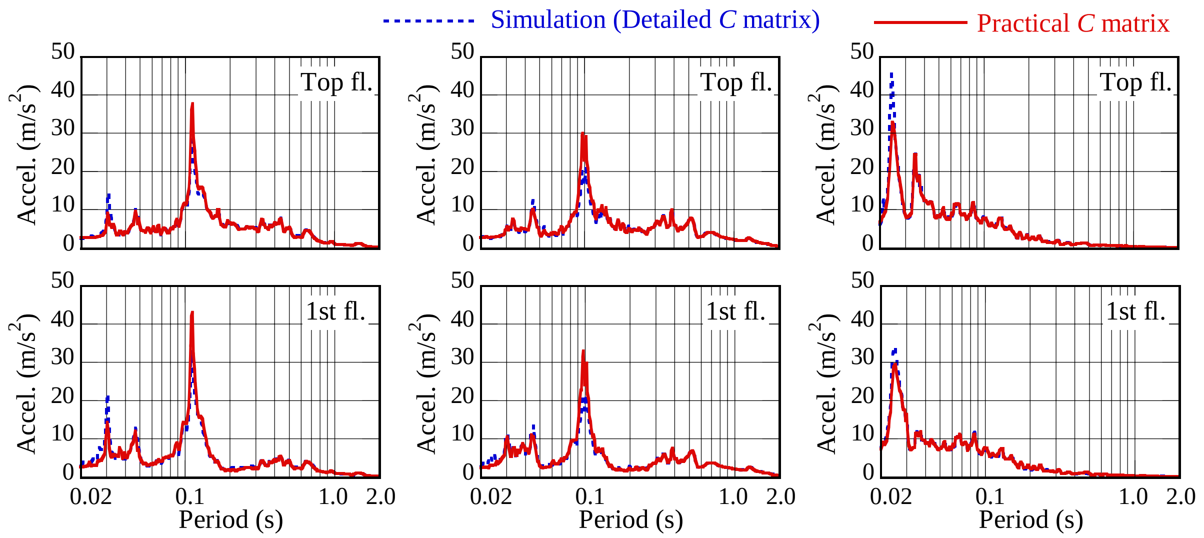
(a) X-direction (b) Y-direction (c) Vertical direction

Fig. 5(1) Effects of the coefficient of friction on 1% damped acceleration response spectra due to EL CENTRO



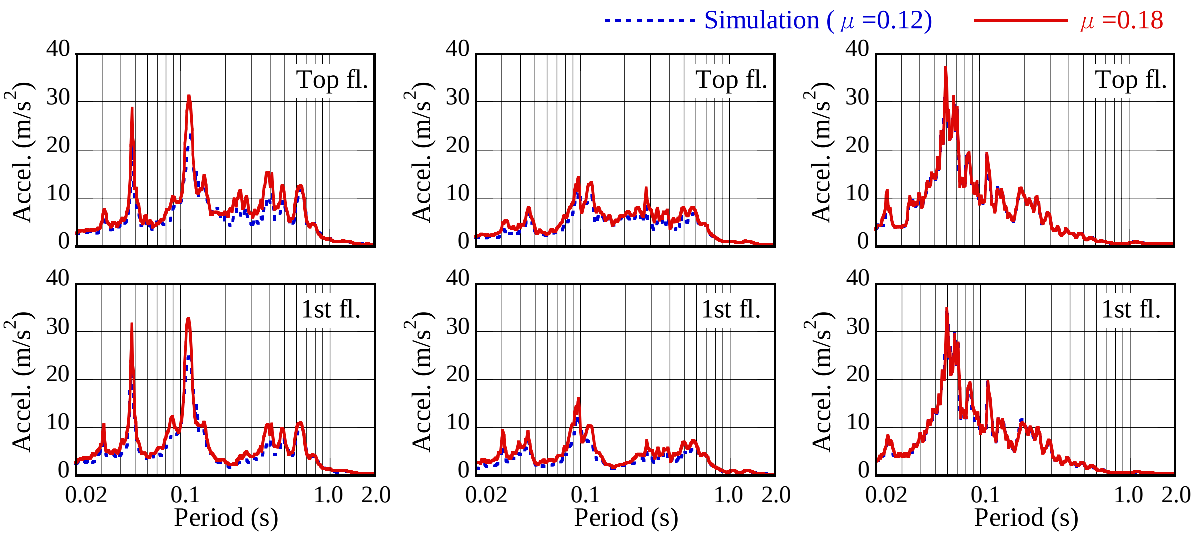
(a) X-direction (b) Y-direction (c) Vertical direction

Fig. 5(2) Effects of bearing stiffness on 1% damped acceleration response spectra due to EL CENTRO



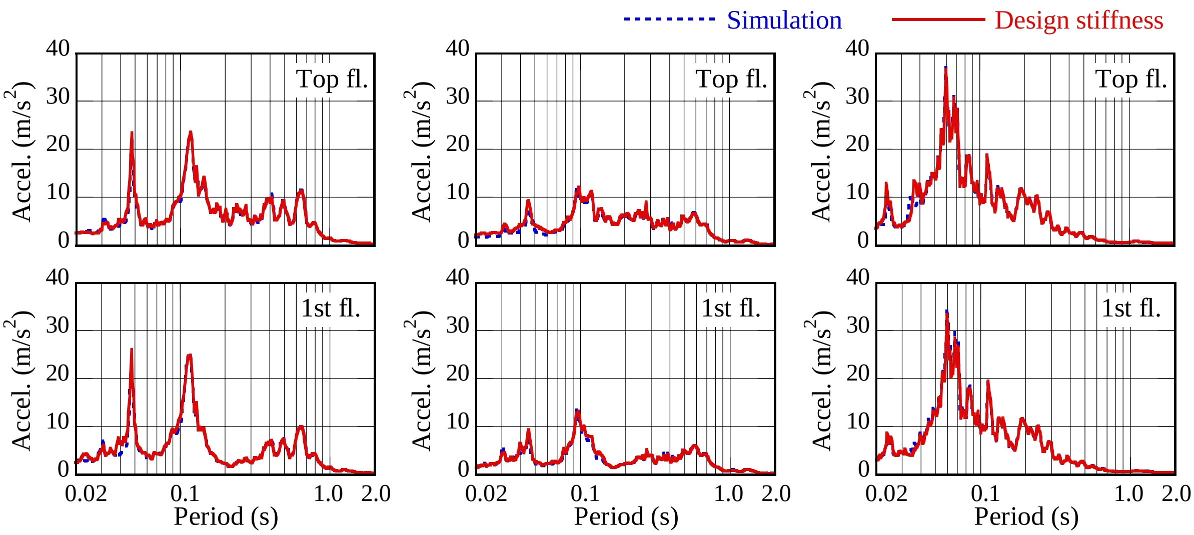
(a) X-direction (b) Y-direction (c) Vertical direction

Fig. 5(3) Effects of damping matrix on 1% damped acceleration response spectra due to EL CENTRO



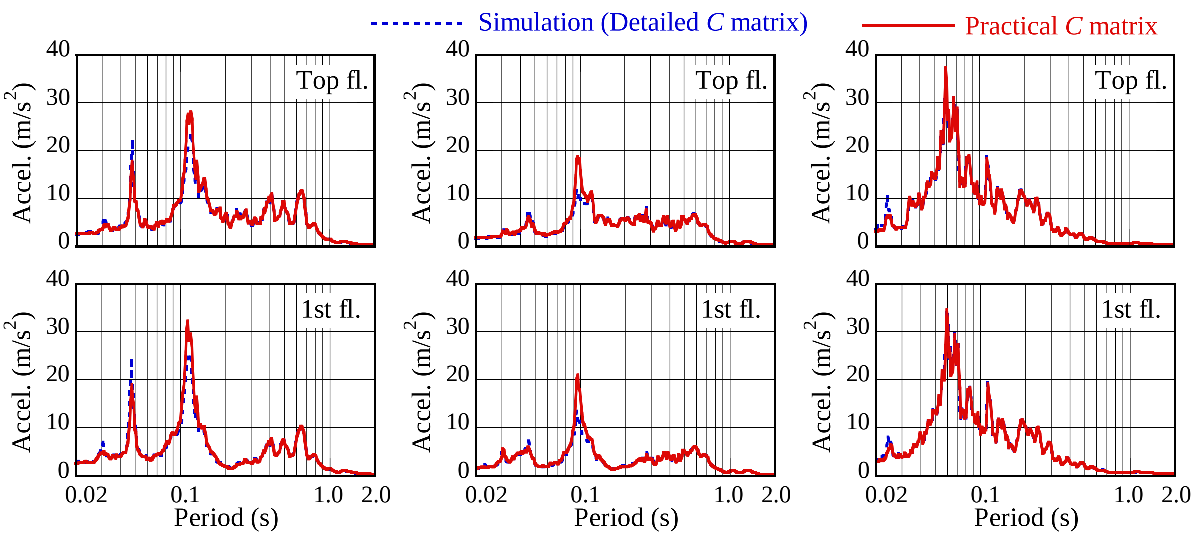
(a) X-direction (b) Y-direction (c) Vertical direction

Fig. 6(1) Effects of the coefficient of friction on 1% damped acceleration response spectra due to HACHINOHE



(a) X-direction (b) Y-direction (c) Vertical direction

Fig. 6(2) Effects of bearing stiffness on 1% damped acceleration response spectra due to HACHINOHE



(a) X-direction (b) Y-direction (c) Vertical direction

Fig. 6(3) Effects of damping matrix on 1% damped acceleration response spectra due to HACHINOHE