Development of a 3-Dimensional Seismic Isolation Floor for Computer Systems

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1 INTRODUCTION

In this paper, we investigated the applicability of a seismic isolation floor as a method for protecting computer systems from strong earthquakes, such as computer systems in nuclear power plants. Assuming that the computer system is guaranteed for 250 cm/s^2 of input acceleration in the horizontal and vertical directions as the seismic performance, the basic design specification of the seismic isolation floor is considered as follows. Against S_1 level earthquakes, the maximum acceleration response of the seismic isolation floor in the horizontal and vertical directions is kept less than 250 cm/s^2 to maintain continuous computer operation. Against S_2 level earthquakes, the isolation floor allows large horizontal movement and large displacement of the isolation devices to reduce the acceleration response, although it is not guaranteed to be less than 250 cm/s^2. By reducing the acceleration response, however, serious damage to the computer systems is reduced, so that they can be restarted after an earthquake.

Usually, seismic isolation floor systems permit 2-dimensional (horizontal) isolation. However, in the case of just-under-seated earthquakes, which have large vertical components, the vertical acceleration response of this system is amplified by the lateral vibration of the frame of the isolation floor. Therefore, in this study a 3-dimensional seismic isolation floor, including vertical isolation, was developed.

This paper describes 1) the experimental results of the response characteristics of the 3-dimensional seismic isolation floor built as a trial using a 3-dimensional shaking table, and 2) comparison of a 2-dimensional analytical model, for motion in one horizontal direction and the vertical direction, to experimental results.

2 BASIC CONCEPTS OF THE SEISMIC ISOLATION FLOOR

A general view of the 3-dimensional seismic isolation floor built for shaking table tests is shown in Fig. 1(a). The 3-dimensional seismic isolation floor consists of floor panels, a floor frame, eight horizontal coil springs, four isolation-supporting devices, and four devices for controlling rocking-motion. The eight horizontal coil springs are installed at the four corners of the floor frame. These provide restoring force in the horizontal direction. As shown in Fig. 1(b), the isolation-supporting device is composed of sliding pads, laminated rubber bearings, a vertical coil spring, a viscous damper, and four wire devices. The rated load of an isolation-supporting device is 15 KN. Sliding pads with liner plate work as a friction damper. Between the sliding pads and liner plate there is a small amount of grease. According to a loading test with a hydraulic cylinder, the coefficients of static and dynamic friction were estimated to be about 0.1 and 0.05, respectively. The rubber bearings decrease the radical change in the friction force of the sliding pads, reducing the high-frequency vibration (Kurihara et al., 1987). The four wire devices are located around an isolation-supporting device in order to prevent the vertical coil spring from horizontal deformation. The viscous damper is used to dissipate the energy of vertical vibrations, by created shear forces in a high viscosity liquid that is forced between a piston and casing during vertical motion. As shown in Fig. 1(c), the device for controlling rocking-motion is composed of a link mechanism, ball bearings, and a guide. The link mechanism and guide are used to keep the isolation floor parallel to the shaking table. The ball bearings are used to make movement of the device for controlling rocking-motion easy in the horizontal direction.

The following guidelines are used to design the compoments of the isolation floor. In general, as the natural frequency of the isolation system is lowered, the acceleration response decreases and the displacement response increases. Therefore, in order to decrease the displacement response as much as possible and keep the acceleration response less than 250 cm/s^2, the horizontal natural frequency is designed to be 0.5 Hz. The vertical natural frequency and damping ratio are designed to be 1.5 Hz and 30% respectively. It is desirable to lower the vertical natural frequency below 1.5 Hz for isolation effect, but because we want to maintain small vertical displacements, a natural frequency of 1.5Hz was chosen as a compromise. Design specifications are shown in Table 1.

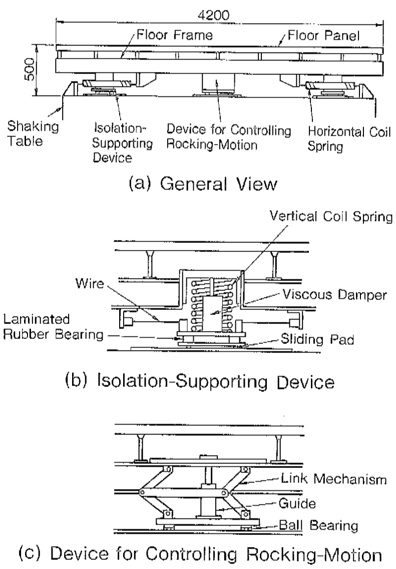

Fig. 1 Structure of a 3-dimensional isolation floor

Table 1 Design specifications of a 3 -dimensional isolation floor

① Horizontal Direction (Spring + Elasto-Plastic Damper)

Parameter	Design Value	Notes
f_1 (Hz)	1.0~2.0	$f_1 = \frac{1}{2\pi}\sqrt{\frac{K_1 g}{W}}$
f_2 (Hz)	0.5	$f_2 = \frac{1}{2\pi}\sqrt{\frac{K_2 g}{W}}$
μ	0.05~0.1	$\mu = \frac{Q}{W}$
Δ_H *1 (cm)	±20 *2 (±40) *3	W : Loading Weight

*1 : Allowed Range *2 : Test Model *3 : Actual Model

② Vertical Direction (Spring + Viscous Damper)

Parameter	Design Value	Notes
f_v (Hz)	1.5	f_v : Natural Frequency
ξ_v	0.3	ξ_v : Damping Ratio
Δ_v (cm)	±5	Δ_v : Allowed Range

3 EXPERIMENTAL METHOD

In order to examine the dynamic characteristics and effectiveness of the 3-dimensional seismic isolation floor, ① sweep tests and ② seismic excitation tests were performed using the shaking table.

First, in order to examine the natural frequencies and damping ratio of the isolation floor, sweep tests were carried out. The sweep input levels were acceleration of 25 cm/s^2 in the horizontal direction and 50 cm/s^2 in the vertical direction in the range of 1 Hz to 20 Hz. Acceleration of 25 cm/s^2 in the horizontal direction was chosen to prevent the isolation floor from sliding.

Second, in order to examine the seismic response of the isolation floor, 3-dimensional earthquake input was simulated as follows. Since the basic natural frequency of the isolation floor system is about 0.5 Hz, the seismic response of the isolation floor is strongly influenced by the low frequency components of earthquake waves. Therefore, as a seismic spectrum for evaluation, an artificial earthquake wave, having spectrum characteristics of the Japanese conventional spectrum (S_1) and the U.S. NRC spectrum, as shown in Fig. 2, was used (Sonoda et al., 1987). Using this combined seismic spectrum for evaluation, an artificial 3-dimensional earthquake wave was generated. As the input waves for the shaking table, the seismic acceleration response waves at the elevation of a computer room in a BWR building were obtained by simulation analysis. However, since there is a displacement limitation of the shaking table the longer period components, which do not affect the performance of the isolation floor, were removed with a high-pass filter. The vertical input level was assumed to be half of the maximum value of the horizontal inputs in 3-dimensional excitation. Test models are shown in Table 2. In order to confirm that a computer ran normally during seismic excitation tests, an actual computer was operated on the frame of the isolation floor. The computer equipment included an operating disk assembly. Two models of computers were also installed on the floor flame to simulate actual equipment weight.

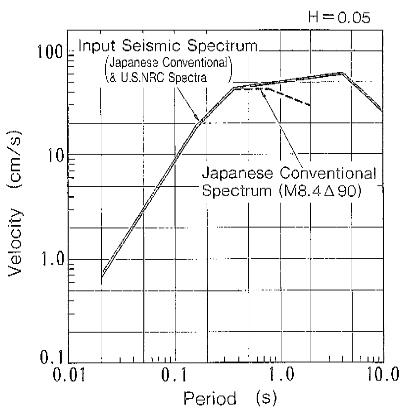

Fig. 2 Response spectrum of input seismic wave

Table 2 Test models

Model	Vertical Coil Spring	Laminated Rubber Bearing	Device for Controlling Rocking-Motion	Comment
I	○	○	○	3-Dimensional Isolation Floor
II	○	×	○	
III	○	×	×	
IV	×	○	—	2-Dimensional Isolation Floor

○ : with × : without

4 SWEEP TEST RESULTS

The result of a sweep test in the horizontal direction for model I (the 3-dimensional seismic isolation floor with rubber bearings) is shown in Fig. 3(a). From this figure the natural frequency and damping ratio of the isolation floor were estimated to be about 1.9 Hz and 0.08, respectively. This damping is mainly due to rubber bearings. The sweep test result in the vertical direction for model I is shown in Fig. 3(b). From this figure the first natural frequency and damping ratio of the isolation floor in the vertical direction were estimated to be about 1.6 Hz and 0.38, respectively. This damping is mainly due to the viscous effect of the viscous dampers and the friction in dampers is also estimated to contribute to the damping from analytical simulation results. A peak of about 20 Hz is the natural frequency due to the lateral vibration of the floor frame.

5 SEISMIC EXCITATION TEST RESULTS

5.1 Effect of rubber bearings on response

In order to examine the effect of rubber bearings on the seismic response, tests using model I (rubber bearings) and model II (no rubber bearings) were performed. The floor response spectra of the isolation floors of both models I and II are shown in Fig. 4. As shown in this figure, the floor response spectrum of model I is less than half of that of model II at 8 Hz. This is an important result because vibrations in the frequency range of 7~14 Hz have the largest effects on computers. Therefore, it is seen that rubber bearings used in the isolation-supporting device are effective in reducing high-frequency components excited by sliding and are able to provide isolation protection for computer equipment.

5.2 Effect of vertical coil springs on seismic response

In order to examine the effect of vertical coil springs on seismic response, tests using model Ⅰ (3-dimensional isolation floor) and model Ⅳ (2-dimensional isolation floor) were performed. The maximum responses of the 3-dimensional and 2-dimensional isolation floor models are shown in Fig. 5. According to our assumption, the computers will run normally if the maximum acceleration response of the isolation floor against S_1 level earthquakes is less than 250 cm/s^2. Using the simulation analysis of a BWR building model against an S_1 level earthquake for evaluation, the maximum acceleration of the input wave to the shaking table in the vertical direction was about 250 cm/s^2. As shown in Fig. 5, in the case of the 3-dimensional isolation floor the maximum vertical acceleration response of the isolation floor against an input level of about 250 cm/s^2 is about 120 cm/s^2. However, in the case of the 2-dimensional isolation floor, since the maximum vertical acceleration response is about 330 cm/s^2, the computer model is not guaranteed to run normally.

Therefore, it is advisable to use the 3-dimensional isolation floor in order to maintain an environment where the computer system can run normally during S_1 level earthquakes. As shown in Fig. 5, the maximum vertical displacement response of the 3-dimensional isolation floor against an S_1 level earthquake is about 10 mm. For displacements of this magnitude, it is thought that the structure between the 3-dimensional isolation floor and its circumference does not become a serious problem. The floor response spectra of the 3-dimensional and 2-dimensional isolation floor models and the shaking table in the vertical direction are shown in Fig. 6. The floor response spectrum of model Ⅰ is about 1/3 of that of model Ⅳ at 7 Hz.

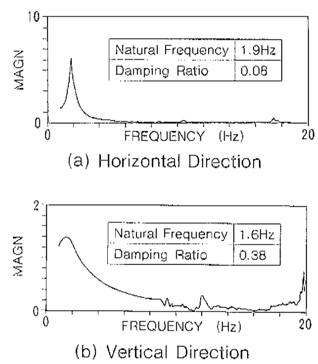

Fig. 3 Resonant curves

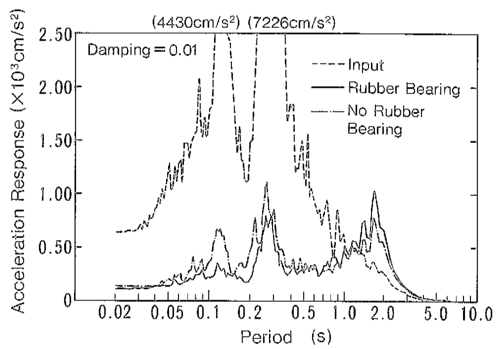

Fig. 4 Horizontal floor response spectrum (3-dimensional excitation)

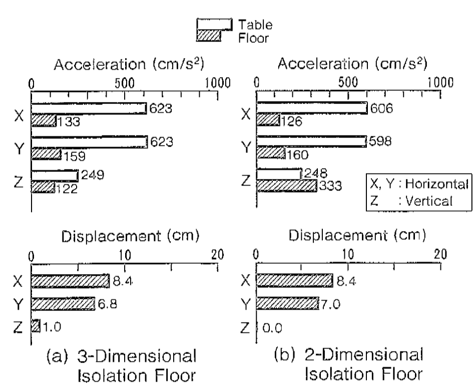

Fig. 5 Maximum responses

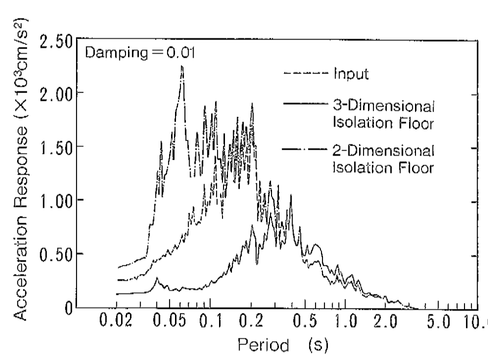

Fig. 6 Vertical floor response spectrum (3-dimensional excitation)

6 SIMULATION ANALYSIS

Simulation analysis was performed to confirm the applicability of the analytical model. The analytical model is a 2-dimensional model for one horizontal direction and the vertical direction and is shown in Fig. 7. The 3-dimensional isolation floor was represented by five lumped masses and the horizontal coil spring is modeled as a spring (spring constant K_2). For the isolation-supporting device, in the horizontal direction the rubber bearing is modeled as a spring (spring constant K_D) and a dash pot (damping coefficient C_D); and the sliding pad is modeled as a friction model (coefficient of friction μ_D) and a dash pot (damping coefficient C_2), which accounts for the existence of grease. In the vertical direction the vertical coil spring was modeled as a spring (spring constant K_V) and the viscous damper was modeled as a dash pot (damping coefficient C_V). Moreover, the friction between the piston and casing in the viscous damper was modeled as sliding friction (coefficient of friction μ_V). The three computer models were represented as three lumped masses, and rubber insulation between the computer models and the isolation floor was modeled as rocking, swaying, and vertical springs. A device for controlling rocking-motion was not modeled, because rocking motion in the absence of devices for controlling rocking-motion (model Ⅲ) was negligible in shaking table tests. This is because the computer models were light, compared with the isolation floor. The characteristics of the isolation devices used in simulation analysis are shown in Table 3. In simulation analysis, the coefficient of dynamic friction was used as the coefficient of friction μ_D of the sliding pad, for in the case of 3-dimensional excitation the sliding pad was considered to be mostly in a state of dynamic friction because there is a difference between time histories of two input waves to the shaking table in the 2-dimensional horizontal direction.

As examples of the analytical results, the acceleration and displacement time histories in the horizontal direction are shown in Fig. 8, and the horizontal and vertical floor response spectra are shown in Fig. 9. From these figures it can be seen that calculated results agree well with the experimental results.

7 CONCLUSIONS

In this study, shaking table tests and simulation analysis were performed in order to examine the isolation performance of a 3-dimensional seismic isolation floor. The results are summarized as follows:

1) The isolation floor was adequate for horizontal and vertical isolation against S_1 level earthquakes. Abnormal computer operation was not observed during the shaking table tests.

2) Rubber bearings control the excitement of high frequency components that result from the acceleration response of the seismic isolation floor with sliding pads.

3) The simulation analysis method can be used to design 3-dimensional isolation floors, since it is effective for estimating the seismic response of isolation floors.

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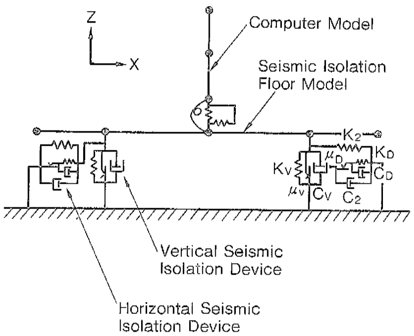

Fig. 7 Analytical model

Table 3 Characteristics of isolation devices

Parameter		Notes
f_1 (Hz)	1.9	$f_1 = \frac{1}{2\pi}\sqrt{\frac{K_1 g}{W}}$
f_2 (Hz)	0.6	$f_2 = \frac{1}{2\pi}\sqrt{\frac{K_2 g}{W}}$
ζ_D	0.05	$\mu_D = Q/W$
ζ_2	0.05	$K_1 = K_2 + K_D$
μ_D	0.02	W : Loading Weight

Parameter		Notes
f_v (Hz)	1.6	f_v : Natural Frequency
ζ_v	0.25	ζ_v : Damping Ratio
μ_v	0.01	μ_v : Coefficient of Friction

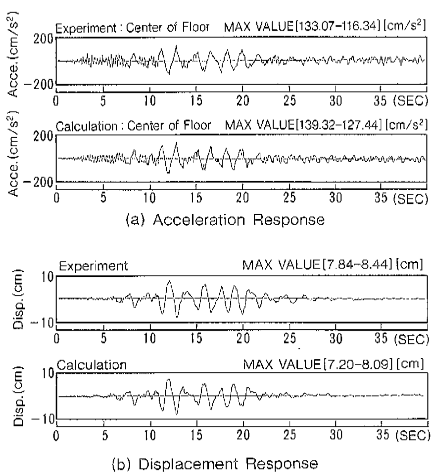

Fig. 8 Comparison of calculation with experiment for horizontal response time history

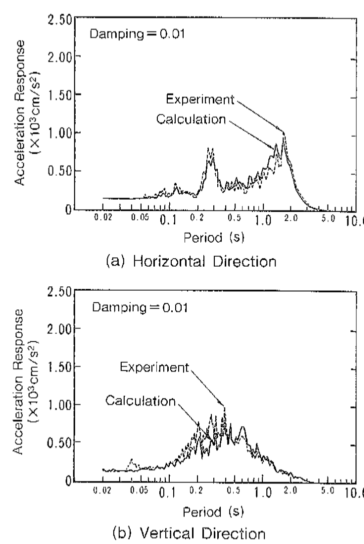

Fig. 9 Comparison of calculation with experiment for floor response spectrum