Vibration test in a Building named "Chisuikan" using Three-dimensional Seismic Isolation System

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SUMMARY:
The authors have been reporting development of a three-dimensional seismic isolation system that is capable of isolating the horizontal and vertical seismic movements at the same time, as well as the building to that such system is applied. In this paper, we report the vibration test before the building completion.
The purpose is to confirm seismic isolation efficacy against vertical and rocking seismic movements. Vibration test was conducted rapidly releasing the jack oil pressure lifting the building up. The natural period obtained from the test results was almost consistent with the analysis results at the time of design. And it was successfully confirmed that the damping effects on the rocking vibration with the oil damper system was functioning, by comparing the response between the case that the oil damper system with rocking suppression is installed and the case where there is no such oil damper system.

Keywords: Seismic Isolation, Vibration Test, Vertical Seismic Movement, Damping, Rocking

1. INTRODUCTION

Traditional seismic isolation system has, in general, only been effective against horizontal seismic movements. The reason for this is that horizontal seismic movements were thought to be dominant over vertical seismic movements in terms of damage to buildings. However, recent records such as those recorded for the 2008 Iwate-Miyagi Nairiku earthquake, where an intensely large acceleration near 4,000 gal was observed for the vertical component of the earth surface at the KiK-net Observation Point IWTH25 (Ichinoseki-Nishi), the closest point to the seismic origin, are telling a different story. Following the recent enhancement of the nationwide seismic array and an improvement in the accuracy of observation sensors, it has become clear that vertical motion is a much larger element of ground motion than was previously thought. In the case of suffering from an earthquake exceeding assumptions made in the design stage, the possibility of harmful damage occurring in buildings with long span beams, etc., is growing. In addition to the viewpoint of structural safety in and of itself, vertical seismic isolation is also needed in order to prevent the dispersal of medical equipment in medical facility bases and enable medical activities to start immediately after an earthquake as well as from the viewpoint of preserving property inside buildings, such as the case of research facilities handling dangerous materials and factories that include high-value manufacturing facilities, exemplified by semiconductor manufacturing facilities. In recent years, horizontal seismic isolation is implemented at the base of a building and vertical seismic isolation floors are partially implemented as necessary in some cases. Depending on the number of floors and size of a building, however, cost effectiveness might be expected by seismically isolating the base in both horizontal and vertical directions. The effect of seismic isolation can also be expected on interior parts mounted on walls such as paintings in an art museum. From the above viewpoint, authors newly developed a three-dimensional seismic isolation system with which both horizontal and vertical directions are

seismically isolated at the same time. The building using the three-dimensional seismic base isolation system was completed on March 3, 2011, and named as "Chisuikan".

In this paper, we report the vibration test in "Chisuikan". Vibration test was conducted when the framework of the building was completed in December 2010. The purpose of this testing was to confirm seismic isolation efficacy on vertical and rocking vibration on the overall building. Free vibration test was conducted rapidly releasing the jack oil pressure in the overall building in the case of vertical vibration, and in one side of the building in the case of rocking vibration with the jackup, respectively. The first natural period in the vertical direction obtained from the measurement results in the testing was almost consistent with the first natural period obtained from the numerical analysis at the time of design. High damping effects were also successfully confirmed in regards to damping characteristics. Regarding to the rocking vibration intrinsic problem in the three-dimensional seismic isolation, it was successfully confirmed that the damping effects on the rocking vibration with the oil damper system was functioning, by comparing the response at the superstructure between the case that the oil damper system with rocking suppression is arranged at the four corners of the building with the case where there is no such oil damper system.

2. BUILDING “CHISUIKAN” AND SEISMIC ISOLATION SYSTEM

The appearance of "Chisuikan" and the photograph of a seismic pit floor are indicated in Figure 1, the overview of the building in Table 1, the three-dimensional seismic isolation device in Figure 2, and the oil damper system with rocking suppression in Figure 3, respectively.

Figure 1. Photograph “Chisuikan”

Table 1. The Building Data for “Chisuikan”

Location	:	Asagaya-minami, Suginami-ku, Tokyo
Completion	:	March, 2011
Usage	:	Apartments
Total floor area	:	548.78m^2
Stories	:	3 stories
Building height	:	9.00m
Structure format	:	Reinforced concrete
Seismic isolation member	:	Three-dimensional seismic isolation device (laminated rubber bearings made with natural rubber, air springs, sliders (steel rods for shear force transmission)) Oil damper system with rocking suppression Horizontal oil dampers

The seismic isolation device has a construction wherein an iron frame trestle (steel member) is added under the laminated rubber bearings made with natural rubber that are generally used in Japanese seismic isolation, and these are supported with air springs. Also, sliders (shear force transmission devices) are included to transmit the shear force of the building to the foundation while sliding in the vertical direction. In this way, making the device independent in the horizontal and vertical axes ensures clarity of analysis for the three-dimensional seismic isolation system and enables a freedom of combination that allows selection of devices in the horizontal and vertical axes underneath each fulcrum. In the long term, the air spring releases air if the fulcrum location is higher than a fixed level and takes in air through a compressor if the location is lower than that level. It does this via an automatic sustained level device. Thus, the air spring provides the mechanism of constantly maintaining a fixed height.

When each fulcrum can move freely along the vertical axis, the building becomes unable to resist the rocking movements that come from seismic action. Therein, as shown in Figure 3, two oil dampers are connected to the building by a diagonal cross from the piping and oil flows between the dampers. Against the vertical seismic movements, this allows absorption of energy along the vertical axis with moderate damping via the piping resistance and the damping valve in the pipe lines. And against the rocking movements, it suppresses rocking movements with high damping from the squeezing action of the damper. Because these are passive devices actualized by a mechanical mechanism using oil pressure, they ensure a high level of reliability without worry of breakdown or malfunction due to electrical trouble.

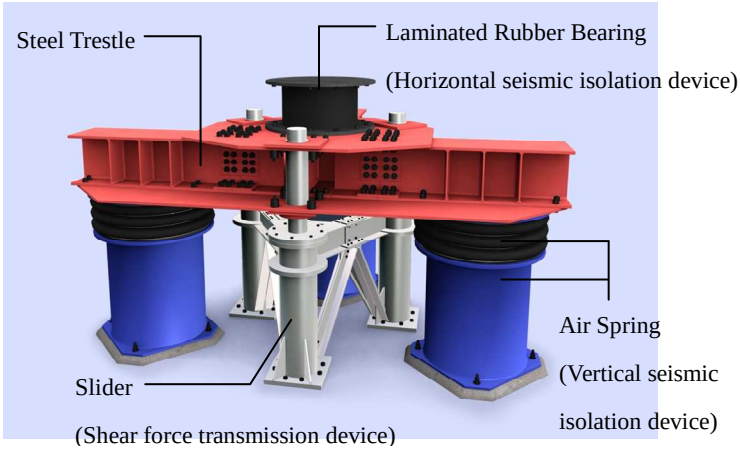


Figure 2. Three-dimensional seismic isolation device

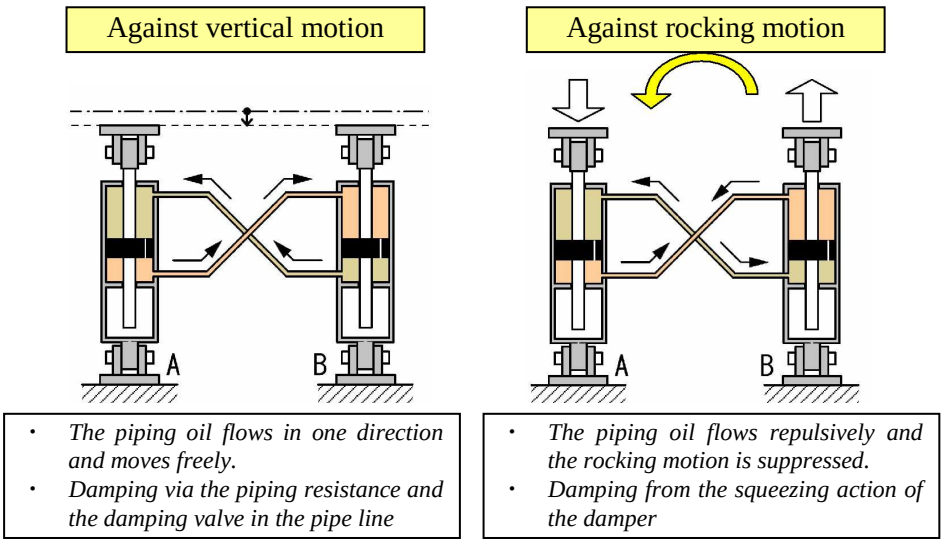
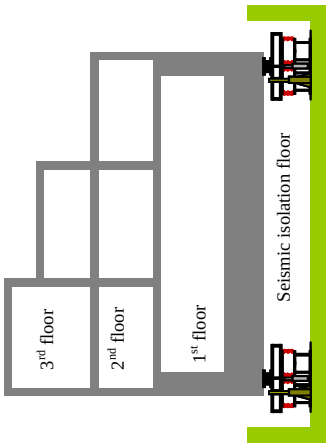


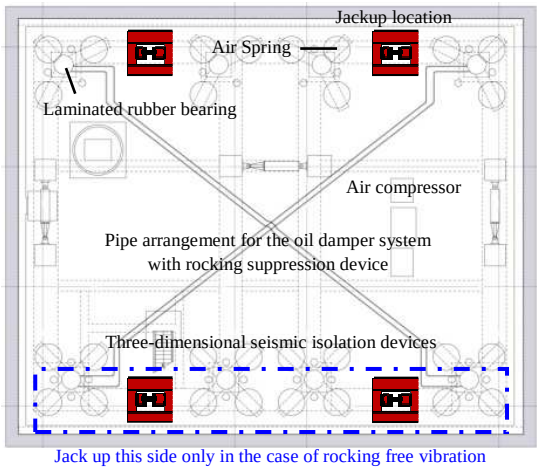
Figure 3. Mechanism of the oil damper system with rocking suppression

3. VIBRATION TEST

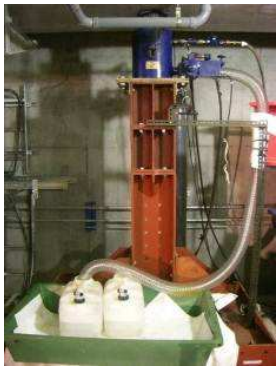
Vibration test is conducted by exciting free vibration at the upper building through rapid release of the jack load after lifting up the overall building with 4 jacks and giving initial displacement toward the upper direction, as indicated in Figure 4. Table 2 indicates the test case. There are two types of free vibration to be excited: (1) vertical free vibration where the overall upper building is evenly lifted up with jacks at four points as indicated in Figure 4 then the four points are evenly released, and (2) rocking free vibration where only two points on one side (within the dotted and dashed line in Figure 4) are jacked up then released. There is a total of six test parameter patterns based on the combination of initial displacement (10, 30, 50mm) and presence or absence of the oil damper system with rocking suppression, and each test is conducted two to three times. Oil dampers for horizontal seismic isolation are arranged in this building as damping members to the horizontal direction; however tests were conducted after removing them.



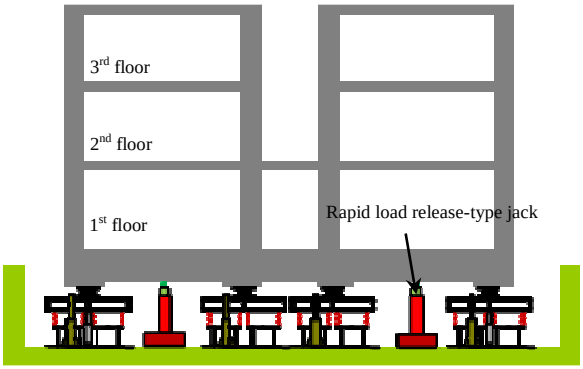
(a) Y-axis (NS) section



(b) Seismic isolation floor



(c) Rapid load release-type jack



(d) X-axis (EW) section

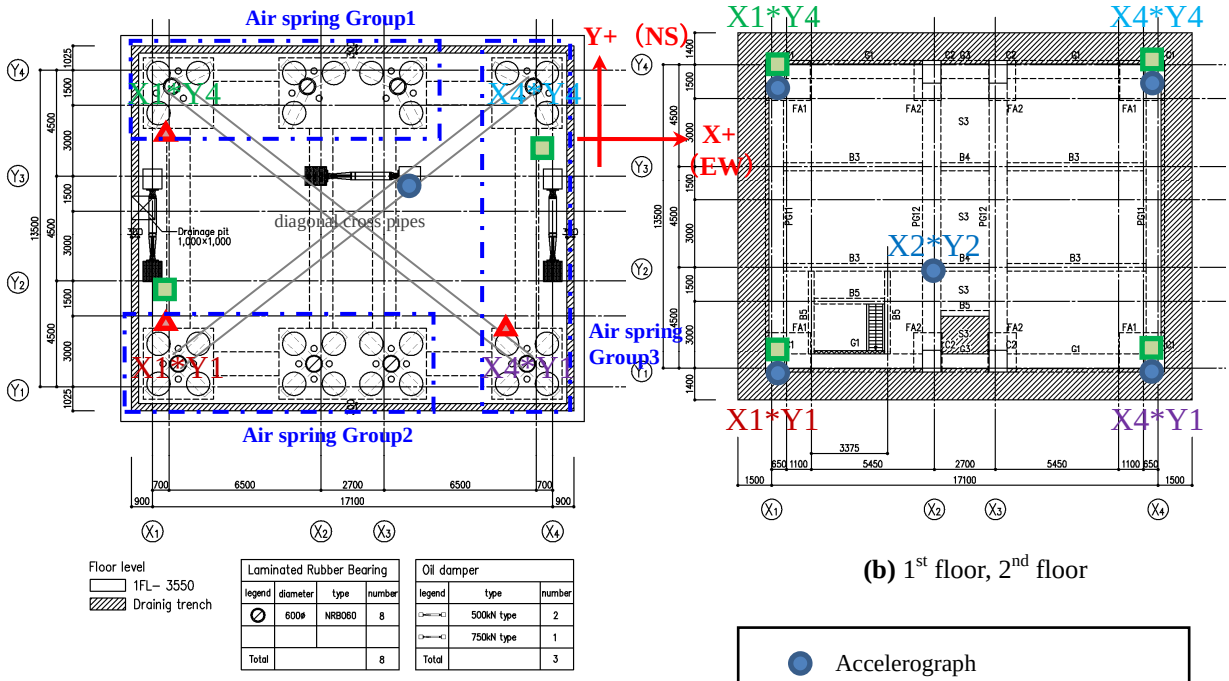
Figure 4. Outline of vibration test

Table 2. Test Cases

Vibration case	Vertical initial displacement	Oil damper system with rocking suppression	Number of tests
Vertical free vibration	10mm 30mm 50mm	Installed Not installed	3 times each
Rocking free vibration	10mm 30mm 50mm	Installed Not installed	3 times each 2 times each in the case with damper

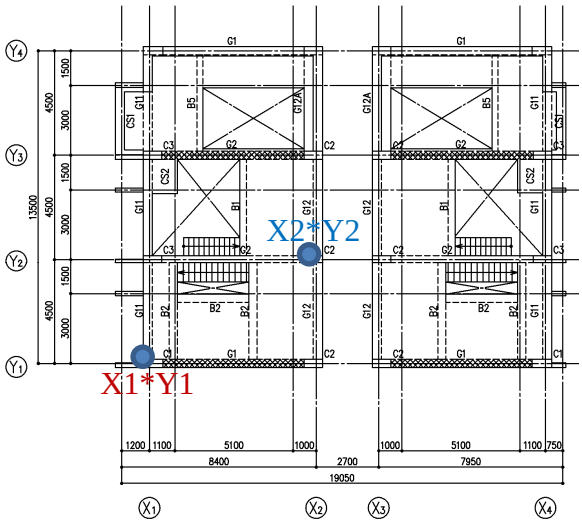
4. MEASUREMENT PLAN

Table 3 indicates a list of measuring points and Figure 5 indicates monitoring locations. Three components are measured with X direction at the time of design of this building as EW direction, Y direction as NS direction and Z direction as UD direction. Within the building, two accelerographs are placed on RF and 3F; and one accelerograph in the center and one accelerograph at each of the four corners are placed on 2F and 1F. On 1F, displacement meters are placed at the same locations as the accelerographs at the four corners. At the seismic isolation floor, 28 air springs are divided into three groups, and air pressure for each group is measured with a pressure gauge. In regards to relative displacement on the seismic isolation floor, displacement to horizontal and vertical directions is measured at two ends to the EW direction, and vertical displacement meters are installed at the three seismic isolation devices out of four corners of the seismic isolation floor for measurement. The load and displacement at oil dampers with rocking suppression at the four corners are also measured in the same way.



(a) Seismic isolation floor

(b) 1st floor, 2nd floor



(c) 3rd floor, Roof floor

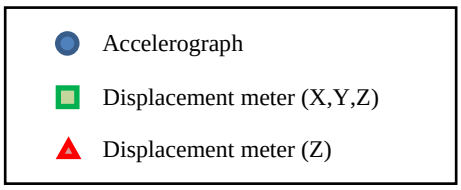


Table 3. List of Measuring Points

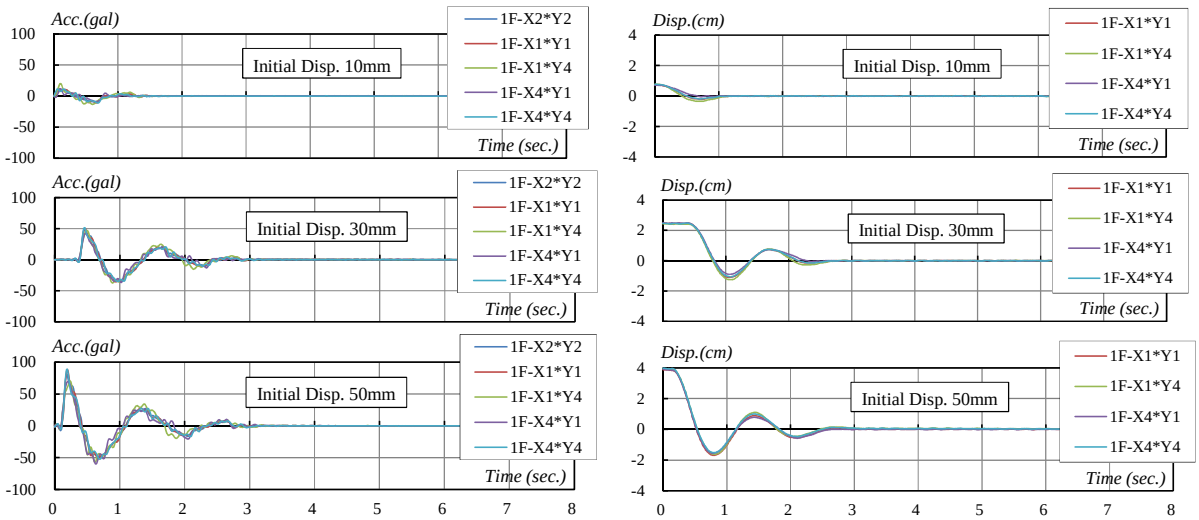
Site	Measured items	Measuring point (Floor-X axis*Y axis)	Direction
Building	Acceleration	RF－X2*Y2	X, Y, Z
		RF, 3F－X1*Y1	Z
		3F, 2F, 1F－X2*Y2	Y, Z
		2F, 1F－X1*Y1, X1*Y4, X4*Y1, X4*Y4	X, Y, Z
		BF－X3*Y3	Z
	Displacement	1F－X1*Y1, X1*Y4, X4*Y1, X4*Y4	X, Y, Z
Seismic isolation device	Air pressure	BF－Group1, Group2, Group3	－
	Oil damper load, displacement	BF－X1*Y1, X1*Y4, X4*Y1, X4*Y4	－
Seismic isolation floor	Relative displacement	BF－X1*Y2, X4*Y3	X, Y, Z
		BF－X1*Y1, X1*Y4, X4*Y1	Z

Figure 5. Monitoring locations

5. RESULT OF FREE VIBRATION TEST

5.1. Vertical Free Vibration Test Result

Figure 6(a) shows the acceleration time history at the time of vertical free vibration when the initial displacement is 10mm, 30mm and 50mm, respectively. The values of the accelerographs located at the center and four corners of the 1st floor are indicated in the figure. For example, legend "1F-X1*Y1" means the measuring point where X1 axis and Y1 axis cross on the 1st floor. The test results are all from the third test. It is confirmed from the acceleration time history that acceleration at a total of five points including the center and four corners of the building transitions at a similar amplitude and phase, and that the ideal vertical free vibration at the overall building is successfully reproduced. When the initial displacement is considered, the maximum acceleration increases when the initial displacement volume given in advance is larger, e.g., approximately 90 Gal of acceleration is generated by giving 50mm of initial displacement. Figure 6(b) indicates the displacement time history at the time of vertical free vibration for the same test case as Figure 6(a). The displacement time history also indicates the waveform with the same amplitude and phase at the four corners of the building, similar to the acceleration in the above. When the degree of convergence for the free vibration waveform is considered, the vertical displacement converges at the transition of one wavelength if the initial displacement given in advance is 10mm; however time equivalent to two wavelengths is required for the vertical displacement to converge, when the initial displacement is 50mm.



(a) Vertical acceleration time history **(b)** Vertical displacement time history

Figure 6. Vertical acceleration and displacement time history at vertical free vibration

Based on the waveform of displacement time history obtained from vertical free vibration test, the natural period and damping constant to the vertical direction are estimated for this building. With d_0 as the initial displacement, ω_0 as the natural circular frequency and h as the damping constant, the displacement waveform $\delta(t)$ to the vertical direction by free vibration can be expressed with the following formula as a function of time t.

$$\delta(t) = e^{-h\omega_0 t}\left(d_0 \cos\sqrt{1-h^2}\,\omega_0 t + \frac{hd_0}{\sqrt{1-h^2}} \sin\sqrt{1-h^2}\,\omega_0 t\right) \tag{5.1}$$

With this formula, the natural circular frequency ω_0 and damping constant h at the time of vertical free vibration for this building is regressed. The initial displacement d_0 was set at the maximum value immediately prior to rapid release of the jack load. The waveform used for regression is displacement time history at two points including X1*Y1 and X4*Y1. Figure 7 indicates the test results for initial displacement of 50mm and an example of fitting with regression curve in the Formula (5.1). While damping is evaluated slightly higher with the regression curve than the test results around the 2.0-second spot, they generally correspond well to each other. The vertical free vibration for this building is considered to be accurately reproducible with this vibration model. Figure 8 indicates the

relationship between the natural period and damping constant for this building at the time of vertical free vibration. The natural period is 1.28 seconds and damping constant is approximately 25% from the figure. The first natural period to the vertical direction is 1.284 seconds in the analysis model, and it is confirmed that the seismic isolation characteristic assumed at the time of design is successfully reproduced. Damping in the vertical direction is considered to be due to pipe resistance at the oil damper system with rocking suppression as well as to damping at the orifice of air spring and friction at the slider or Exp.J. Since the damping constant to the first natural period is approximately 25%, it seems that the overall building has a high damping performance. While the natural period tends to be slightly shorter when the vertical initial displacement is small and the free vibration amplitude is small, the damping constant is approximately 25% in any case and it is considered that the seismic isolation performance of this building would not be significantly affected by the amplitude.

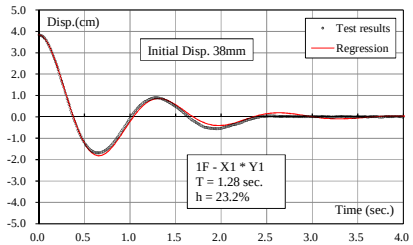


Figure 7. Regression results

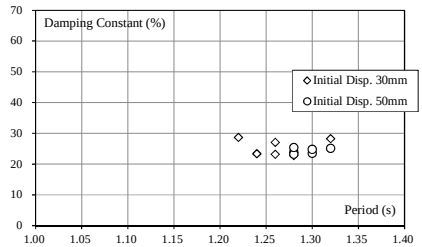
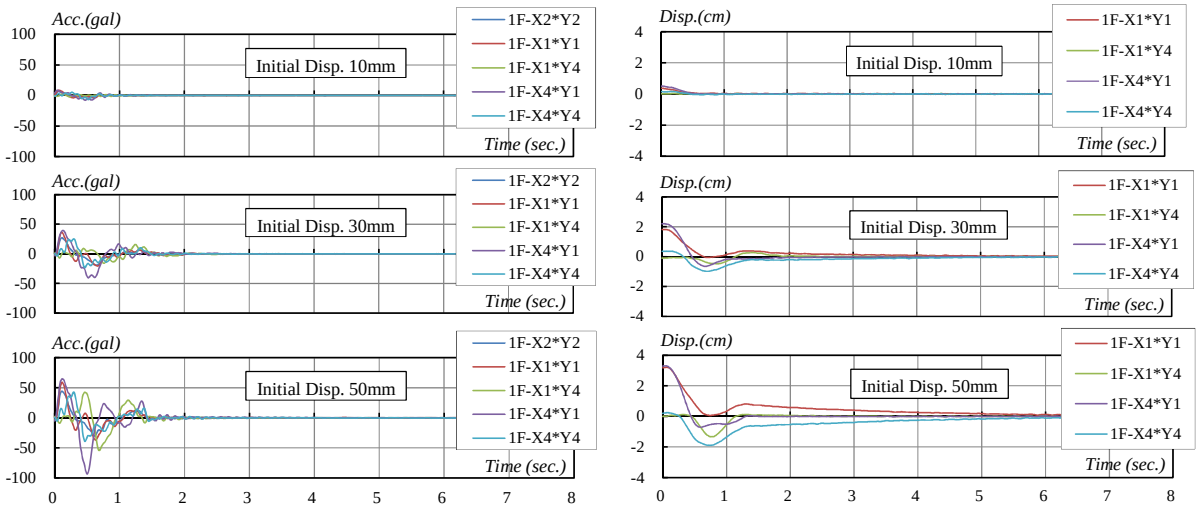


Figure 8. Relationship between natural period and damping constant

5.2. Rocking Free Vibration Test Result

Figure 9(a) indicates the acceleration time history at the time of rocking free vibration when the initial displacement is 10mm, 30mm and 50mm. From the acceleration time history, the acceleration at the total of all five points including the center and four corners of the building is different from the case of vertical free vibration: The acceleration peak is recorded on the side of Y1 line immediately after rapid release of the jack load, and as if dragged by the behavior, the peak is generated to the opposite direction on the side of the Y4 line with a staggered phase and no jackup. The maximum acceleration is approximately 90 Gal when 50mm of initial displacement is given, generating a similar to the case of vertical free vibration. Figure 9(b) indicates the displacement time history at the time of rocking free vibration in the same test case as Figure 9(a). When the degree of convergence for the free vibration waveform is considered, there is a slight difference between the sides of the X1 line and X4 line, while the vertical displacement rapidly converges at the transition equivalent to approximately one wavelength regardless of the vertical initial displacement, confirming the high damping performance of the oil damper with rocking suppression.



(a) Vertical acceleration time history **(b)** Vertical displacement time history

Figure 9. Vertical acceleration and Displacement time history at rocking free vibration

Based on the waveform of displacement time history obtained from the rocking free vibration test, the natural period and damping constant at the time of rocking vibration are assumed for this building, similar to the above section. The waveform used for regression is the displacement time history at two points including X1*Y1 and X4*Y1 with jackup at the time of rocking free vibration. Figure 10 indicates the test results for initial displacement of 50mm and an example of fitting with the regression waveform. As an overall tendency, vertical displacement converges at the transition less than one wavelength after rapid release of the jack load; therefore it is rather difficult to accurately quantify the natural period and damping constant in this vibration model. In particular, there is a tendency that the regression results around the 1.2-second spot equivalent to one wavelength from vertical initial displacement evidently evaluates damping higher than the test results. At the same time, however, we can see that the rocking vibration of the building is suppressed with a very large damping. Figure 11 indicates the relationship between the natural period and damping constant for the building at the time of rocking free vibration. The natural period is 1.13 seconds and the damping constant is approximately 50% from the figure. The natural period at the time of rocking free vibration tends to be shorter than the time of vertical free vibration. Since the rocking movements of the building are suppressed by utilizing repulsive resistance of the oil flow in a pipe, vertical rigidity is considered to have slightly increased with this repulsive spring. However, the change in the natural period is approximately 10% which is not within the range that adversely influences the seismic isolation characteristics to the vertical direction for this building, and rocking movements are considered to be effectively suppressed while allowing vertical movements. Changes in the natural period and damping constant due to the vertical initial displacement volume are small, and the damping constant at the time of rocking free vibration is approximately twice as much as the time of vertical free vibration.

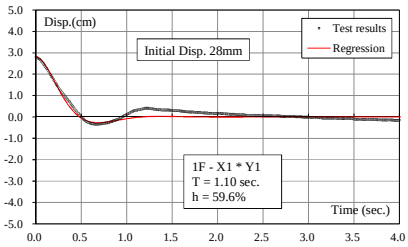


Figure 10. Regression results

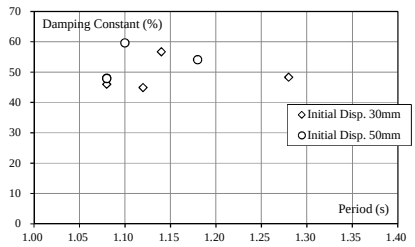
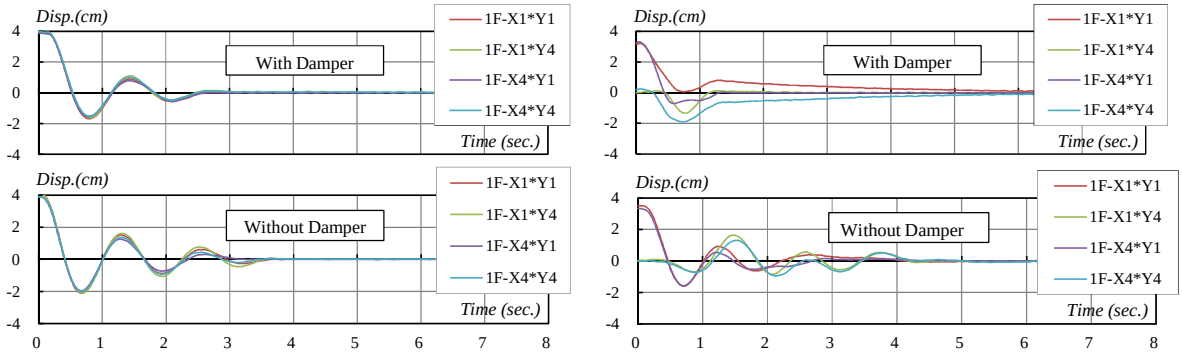


Figure 11. Relationship between natural period and damping constant

6. DAMPING EFFECTS ON THE ROCKING VIBRATION WITH THE OIL DAMPERS

From the results of vertical free vibration test and rocking free vibration test, free vibration waveforms are compared when the oil damper system with rocking suppression (referred to as the “Damper” in the following for short) is installed and not installed, to confirm the efficacy of oil damper system with rocking suppression.

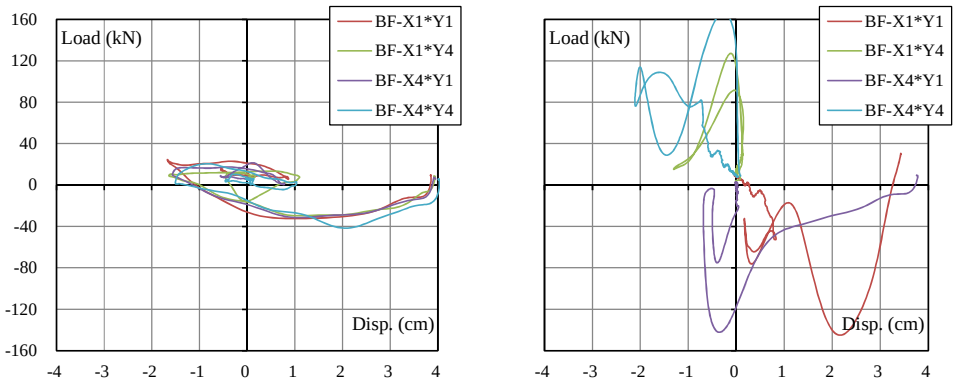
Figures 12 indicates the displacement time history to the vertical direction for vertical and rocking free vibration when the “Damper” is installed and not installed. From Figure 12(a), damping performance deteriorates without the “Damper”, and the time required for convergence of initial displacement becomes one wavelength longer in the case of vertical free vibration. In the rocking free vibration indicated in Figure 12(b), the displacement rapidly converges within the time of less than one wavelength with the “Damper”, while convergence of displacement requires the time equivalent to three to four wavelengths without the “Damper”, clearly indicating the damper efficacy. We can assume that this phenomenon is more evident when disturbance enters for a certain time such as seismic movements, confirming from the displacement time history that a building supported with vertically flexible springs shakes like a ship floating on the surface of the water without the “Damper”.



(a) Vertical free vibration **(b)** Rocking free vibration

Figure 12. Comparison of vertical displacement time history with or without damper

Figure 13 indicates the load-displacement relation of the "Damper" at the time of vertical and rocking free vibration. All oil dampers at the four corners indicate the same loop at the time of vertical free vibration, converging into zero in the form of a spiral curve. While there is a slight delay in the phase at the time of rocking free vibration, on the other hand, the sides of Y1 line and Y4 line behave in a phase opposite to each other, confirming that rocking movements are suppressed with a large damping force: 167kN at maximum within the range of a small-amplitude. It can be confirmed that the extra time equivalent to approximately three wavelengths is required for convergence of rocking movements in the case without the "Damper" from the time history of rocking angle to the Y (NS) direction indicated in Figure 14, in comparison with the case with the "Damper".



(a) Vertical free vibration **(b)** Rocking free vibration

Figure 13. Load-displacement relation of damper

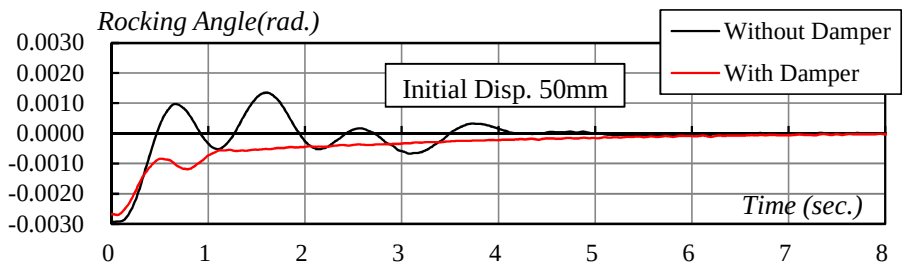
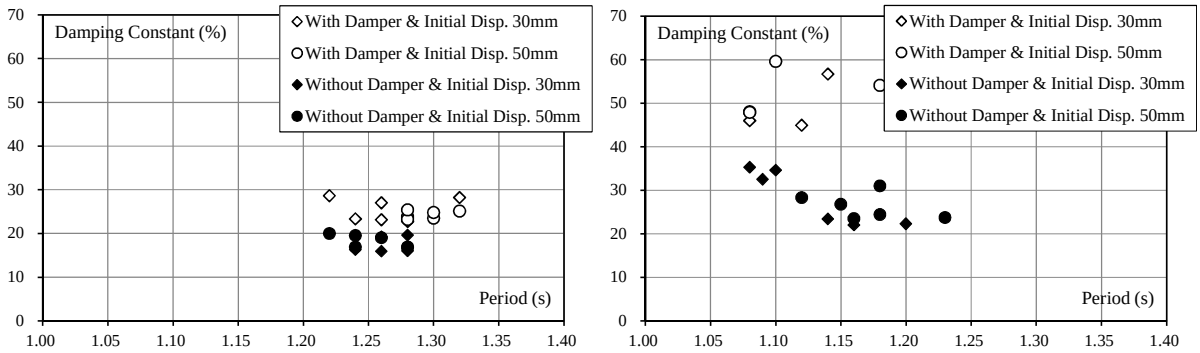


Figure 14. Time history of rocking angle to the Y (NS) direction

Figure 15 indicates the regression results of natural period and damping constant. Without the "Damper", the change in the natural period is small, but the damping performance significantly changes: approximately 18% at the time of vertical free vibration and approximately 27% at the time of rocking free vibration. If the difference from the case with the "Damper" is considered to be damping of the "Damper", it can be assumed as approximately 7% and 23% at the time of vertical and rocking free vibration, respectively.



(a) Vertical free vibration **(b)** Rocking free vibration

Figure 15. Relationship between natural period and damping constant

7. CONCLUSION

We reported on the vibration test conducted prior to completion of the building to which the three-dimensional seismic isolation system was applied. From the free vibration test results, the three-dimensional seismic isolation characteristics assumed at the time of design were confirmed.

The natural period obtained from the test results was almost consistent with the analysis results at the time of design. And it was successfully confirmed that the damping effects on the rocking vibration with the oil damper system was functioning, by comparing the response between the case that the oil damper system with rocking suppression is installed and the case where there is no such oil damper system.

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