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Analytical Study on Torsional Motion Caused by Unbalanced Layout of Seismic Isolation Devices

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ABSTRACT

A seismic isolation system is sometimes installed to mitigate the seismic response of the equipment in the building of a nuclear power plant. However, when the layout of the seismic isolation system becomes unbalanced because of the constraints of the site conditions, torsional motion can be produced in the seismic isolation layer.

Accordingly, this study discusses the analysis of the effect of the unbalanced seismic isolation devices layout, in particular oil dampers, to the response by the building structure.

INTRODUCTION

In response to the lessons learned in the accident of the Fukushima Daiichi nuclear power plant in 2011, installation of additional structures to respond to various severe accidents is required by the new regulatory standards for nuclear power plants in Japan. One of these structures use a seismic isolation system to mitigate the seismic response of the equipment in the building and to maintain the building even after an earthquake. In some cases, it is difficult to provide adequate space for the building because of the constraints caused by the site and/or by the surrounding structures, which can cause an unbalanced in-plane layout of the seismic isolation devices, in particular oil dampers. In such cases damping forces produced by the oil dampers can act in unbalanced directions, which can cause torsional deformation of the building.

Accordingly in this study, the effect of unbalanced layout of the oil dampers on the torsional motion of the seismically isolated structure is analyzed.

OUTLINE OF THE ANALYSIS

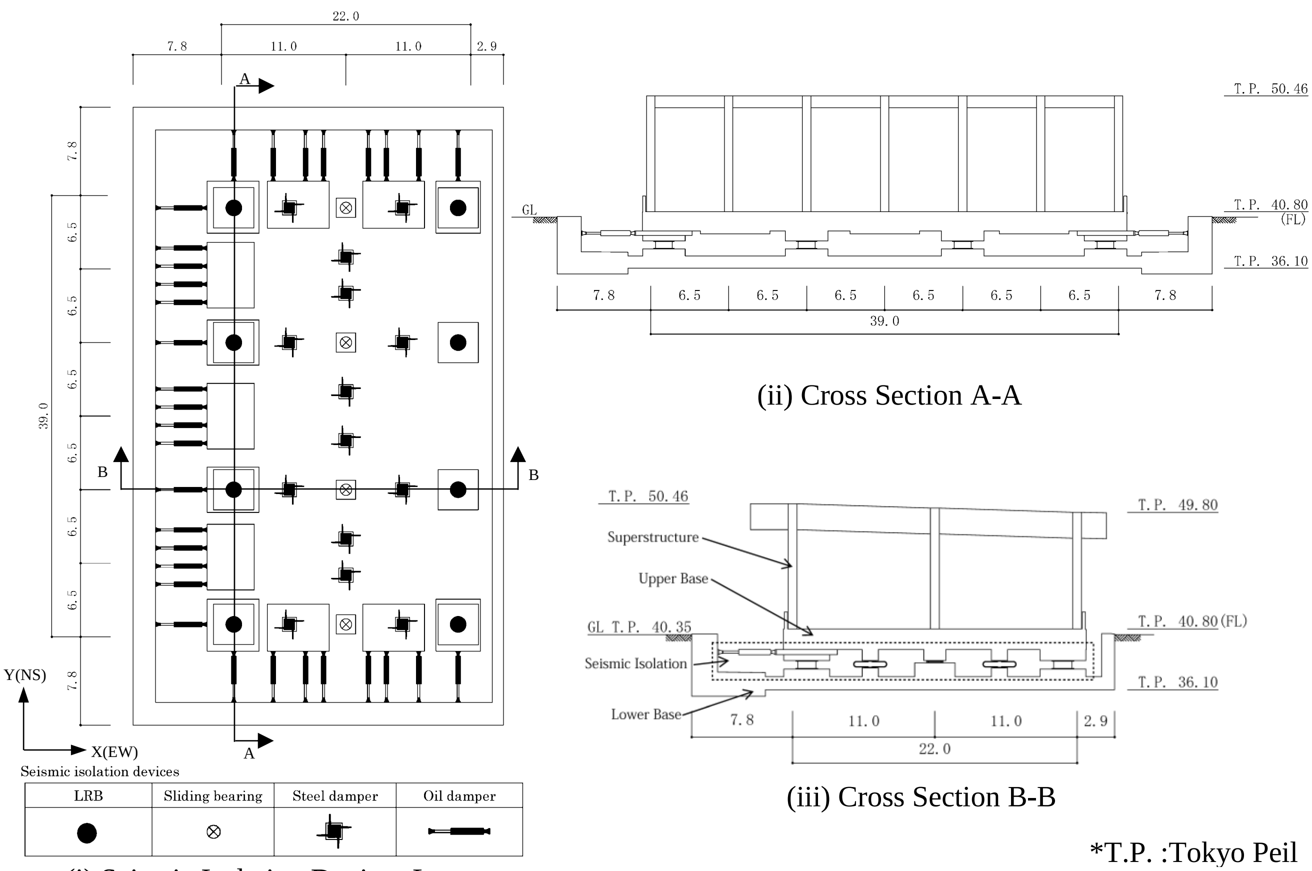
The structure we analyzed is a seismically isolated one-story steel frame structure. The oil dampers were installed additionally after completion of the building because it was required to make the building withstand bigger seismic motion, and they are installed symmetrically in a north-south direction but installed only in the west side in an east-west direction because of the constraints of the surrounding construction site. (Figure 1)

A time history response analysis was made using Abaqus, general numerical analysis software. The analysis model of the structure is a lumped mass stick model with masses of the superstructure, upper base, and lower f base concentrated at the mass points, and the superstructure is modeled using the equivalent shear beam element. The layout of the seismic isolation devices in the model reflects the actual layout where the LRBs, steel dampers, and sliding bearings are modeled using the MSS (Multiple Shear Spring) to consider coupled effect in horizontal two directions. The oil damper is modeled by dash-pot elements taking its geometric deflection into consideration to consider the effect of the damping force produced in the longitudinal direction of the actual oil damper. (Figure 2, Table 1) The nonlinear characteristics in the horizontal direction of the seismic isolation devices are assumed to have bilinear hysteresis characteristics as shown in Figure 3.

Since the geometric deflection of the oil dumpers is considered in this study as shown in Figure 4, it is considered that a response in the direction normal to seismic excitation is produced because of the damping force produced by extension/retraction of the oil damper placed in the direction normal to seismic excitation following the motion in the direction of seismic excitation.

Table 1 shows the analysis cases in this study, and Figure 5 shows the input acceleration time history and acceleration response spectrum at the bottom of the foundation base. In Case 1, sine wave input is applied in the Y (NS) direction, and the relative displacement of the seismic isolation layers and velocity response of the oil damper in the direction normal to seismic excitation are checked. The frequency of the input sine wave is set as 0.5 Hz, which is close to the natural frequency of the seismic isolation layer. Next in Cases 2 and 3, the effect of the unbalanced layout of the oil dampers on the response of the building is checked comparing the trends of the response behaviors in the Y (NS) direction where the oil dampers are placed unbalanced and in the X (EW) direction where oil dampers are placed balanced with the site specific earthquake* defined at the site applied in Y (NS) and X (EW) directions respectively.

*The site specific earthquake formulated considering geology, geological structure, seismicity, etc. of the site and its surrounding area. It was set with a focus on long-period based on the characteristics of the seismic isolation device.



(i) Seismic Isolation Devices Layout

(ii) Cross Section A-A

(iii) Cross Section B-B

*T.P. :Tokyo Peil

Figure 1. Seismic Isolation Devices Layout and Outline of the Building

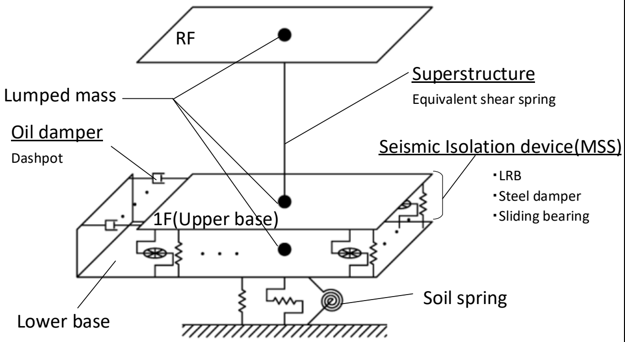
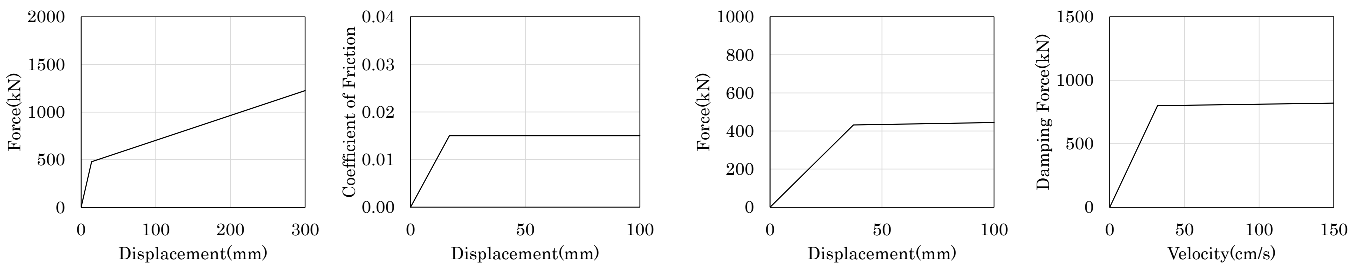


Figure 2. Analysis Model

Table 1. Specifications of the Model

Floor	Height [m]	Weight [kN]	Moment of Inertia [×10^{6}kN·m^2] Y-Dir	X-Dir	Z-Dir	Stiffness [×10^{5}kN/m] Y-Dir	X-Dir	Z-Dir
RF	13.53	8750	-	-	-			
						4.70	6.39	512.08
Upper Base	3.90	51000	8.16	2.81	10.90			
						Seismic Isolation Layer		
Lower Base	0.50	92000	22.89	8.23	-			
Ground	0.00							



(a) LRB (b) Sliding bearing (c) Steel damper (d) Oil damper

Figure 3. Horizontal Nonlinear Characteristics of Seismic Isolation Devices

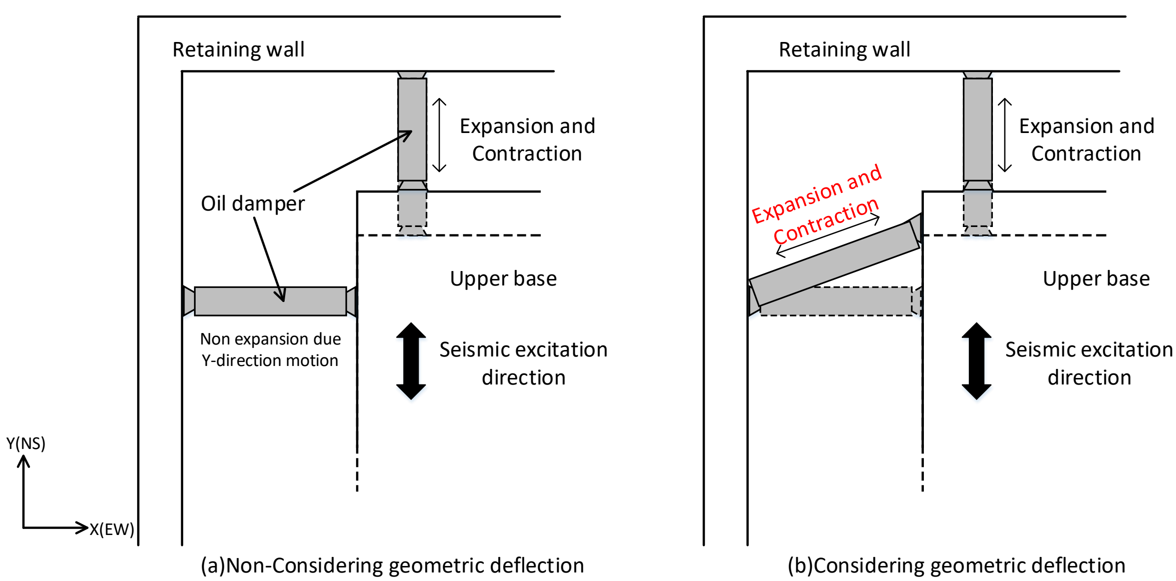
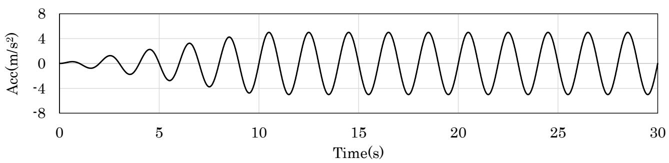


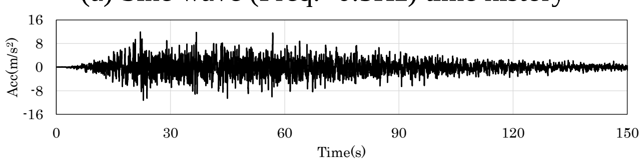
Figure 4. Oil Damper Expansion and Contraction due to Geometric Deflection

Table 2. Analysis Case

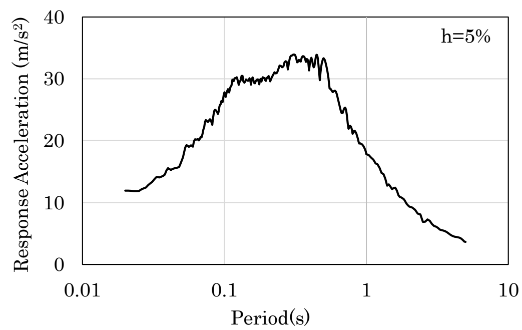
	Input Wave	Vibration Direction	Max Acceleration (cm/s^2)	Max Velocity (cm/s)
Case1	Sine wave(Freq.= 0.5 Hz)	Y(NS)	500	159
Case2	Site specific earthquake	Y(NS)	1194	157
Case3	Site specific earthquake	X(EW)	1194	157



(a) Sine wave (Freq.=0.5Hz) time history



(b) Site Specific Earthquake time history



(c) Site Specific Earthquake Acceleration Response Spectrum

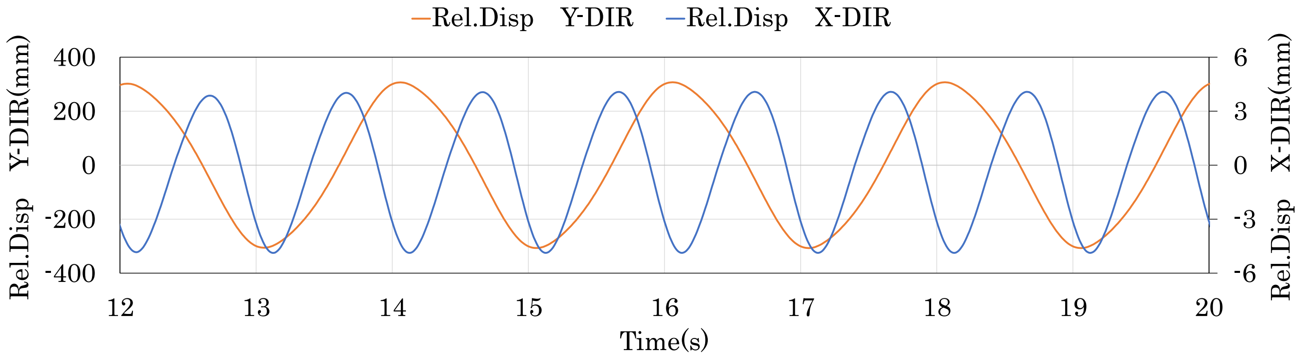
Figure 5. Input Acceleration Time History Waveform and Acceleration Response Spectrum at the Bottom of the Foundation

STUDY FOR SINE WAVE INPUT (CASE1)

Figure 6 shows the relative displacement time history between seismic isolation layers in the seismic excitation direction (Y-direction) and in the direction normal to seismic excitation (X-direction) with sine wave input during the period from 12 to 20 seconds where the steady state response is reached. Displacement is produced in the direction normal to seismic excitation, although its magnitude is smaller than the displacement in the seismic excitation direction. As explained earlier, such result is considered to occur by extension and retraction of the oil damper in the direction normal to seismic excitation following displacement in the direction of seismic excitation, which causes the component of the damping force of the oil damper in the direction normal to seismic excitation produced by the extraction and retraction of the oil damper in the axial direction to act on the upper base when geometric deflection of the oil damper is considered. It is considered that displacement in the direction normal to seismic excitation is produced because of the imbalance of the damping force acting on the upper base as the external force and because the oil damper in the direction normal to seismic excitation is located only at the west side of the structure.

While the frequency of the seismic isolation layer relative displacement in the seismic excitation direction is 0.5 Hz, which is similar to that of the input motion, the frequency of the relative seismic isolation layer displacement in the direction normal to seismic excitation is twice that of the frequency in the seismic excitation direction. This is because the oil damper in the direction normal to seismic excitation extends and retracts one full cycle during a half cycle period while the oil damper in the seismic excitation direction goes from fully extended to fully retracted as shown in Figure 7.

Figure 8 shows the relative displacement of the seismic isolation layer and orbit diagram during one cycle period of the seismic excitation direction (12 to 14 seconds), Figure 9 shows the damping force time history of the oil dampers in the respective directions, and Figure 10 shows the relationship between the oil damper velocity in the seismic excitation direction and the damping forces in the respective directions. The damping force of the oil damper in the direction normal to seismic excitation increases at the time when the oil damper velocity in the excitation direction reaches maximum. This shows that the extension/retraction of the oil damper in the direction normal to seismic excitation is produced by the motion in the excitation direction, and the damping force produced by such extension/retraction acts in the direction normal to seismic excitation.



*Note that the left and right scales are different.

Figure 6. Relative Displacement Time-history between Upper Base and Lower Base

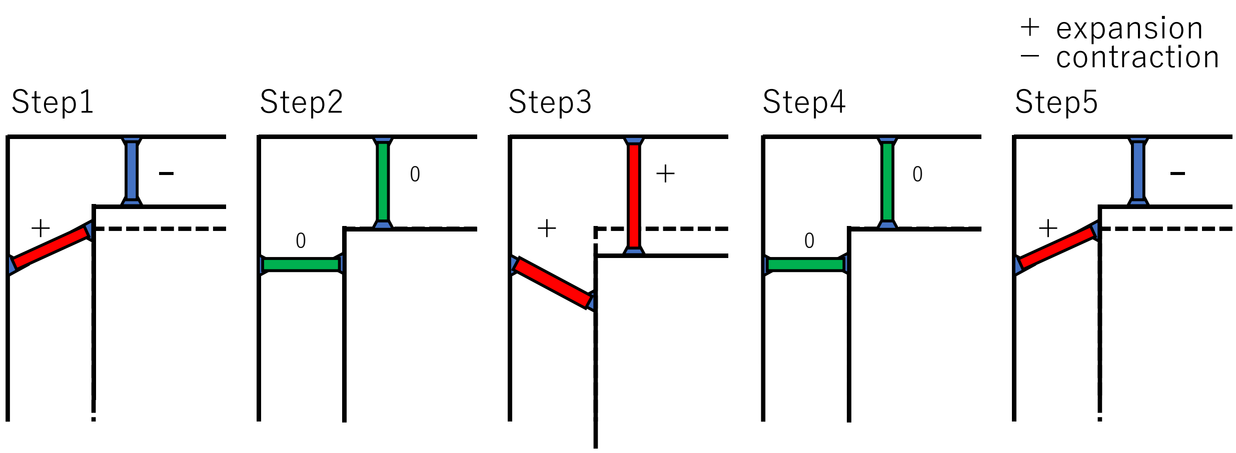
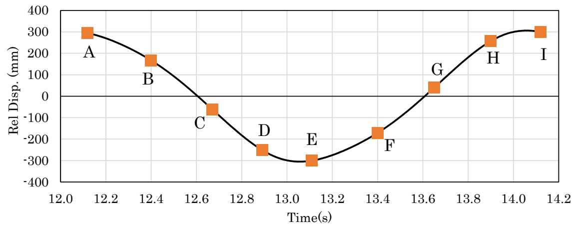
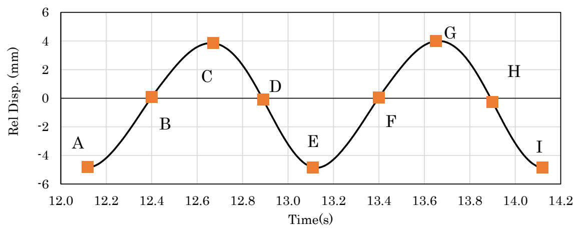


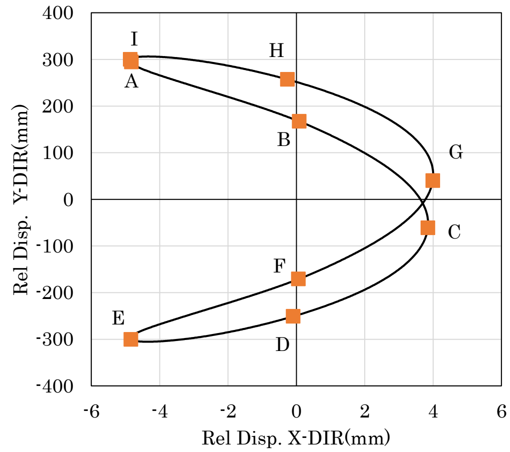
Figure 7. Schematics of Oil Damper Displacement



(i) Seismic Excitation Direction (Y direction)
Relative Seismic Layer Displacement Time History



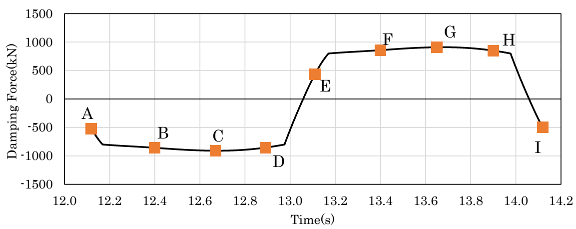
(ii) Direction Normal to Seismic Excitation (X direction)
Relative Seismic Layer Displacement Time History



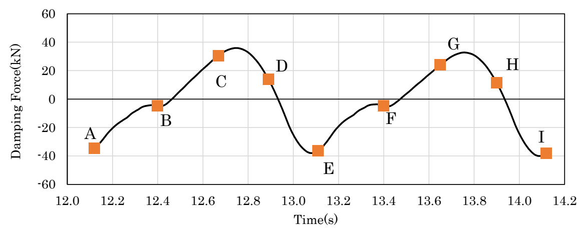
*Note that the vertical and horizontal scales are different.

(iii) Relative Seismic Layer Displacement Orbit

Figure 8. Seismic Isolation Layers Relative Displacement Time History and Orbit Diagram (12 to 14 seconds)

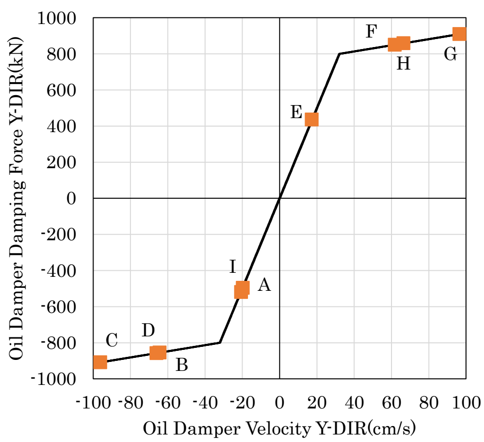


(i) Oil Damper Damping Force in Seismic Excitation Direction (Y direction)

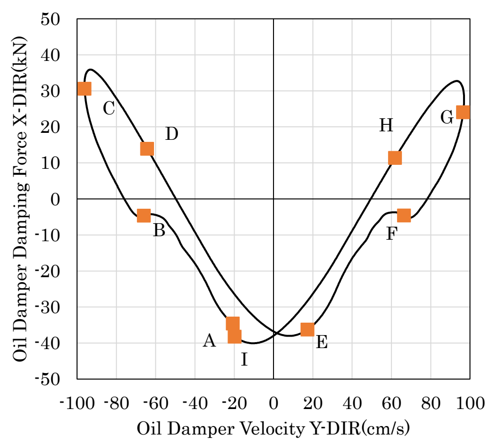


(ii) Oil Damper Damping Force in Direction Normal to Seismic Excitation (X direction)

Figure 9. Oil Damper Damping Force Time History (12-14 seconds)



(i) Oil Damper Damping Force in Seismic Excitation Direction(Y-direction)



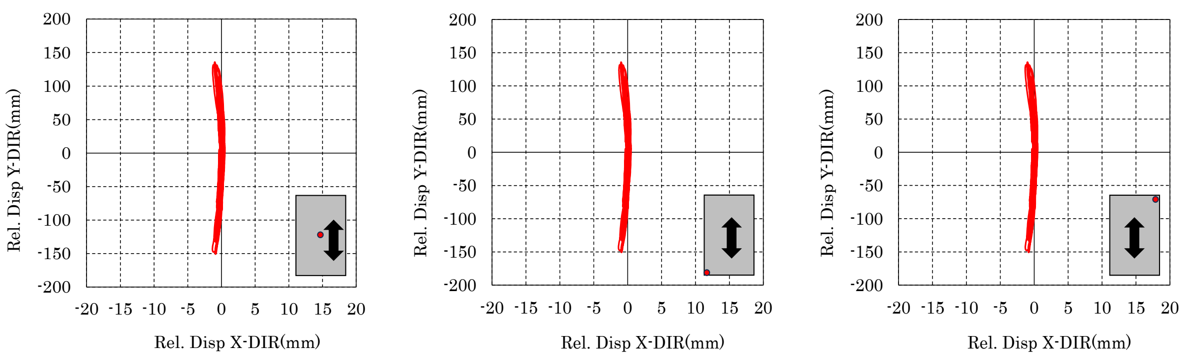
(ii) Oil Damper Damping Force in Direction Normal to Seismic Excitation (X-direction)

Figure 10. Relations between Damper Velocity and Damping Force in Seismic Excitation Direction (12 to 14 seconds)

STUDY FOR SITE SPESIFIC EARTHQUAKE ESTABLISHED FOR THE SITE (CASES 2 and 3)

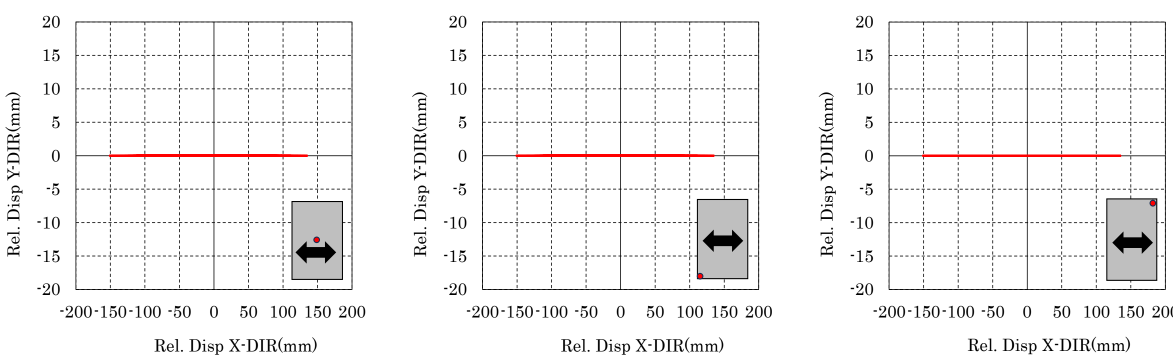
Figure 11 shows the seismic isolation layer relative displacement orbit diagrams for the site specific earthquake input established for the site, and Table 3 shows the maximum seismic isolation layer relative displacement and oil damper velocity. In the case of input in the Y (NS) direction when the oil dumper layout is unbalanced, displacement in the direction normal to seismic excitation is produced similarly as Case 1, but the displacement is very small with less than 1/100 of magnitude compared with the displacement in the direction of seismic excitation. Since the orbit of the upper base corner has a similar shape to the shape of the orbit at its center, it is considered that the upper base is in translational motion in the direction normal to seismic excitation rather than torsional movement. This is considered to occur because the oil dampers placed in the direction normal to seismic excitation always extend and retract uniformly, and no unbalanced external forces that will create torsional motion of the upper base is produced.

In the case of seismic excitation input in the X (EW) direction with the balanced layout of the oil dampers (Case 3), no displacement in the direction normal to seismic excitation is produced. It is considered that damping forces produced by the oil dampers acting as an external force on the upper base cancel each other because the oil dampers are placed symmetrically in the direction of excitation.



(i) Center (ii) Southwest Corner (iii) Northeast Corner

(a) Case 2 Excitation in the Y (NS) Direction



(i) Center (ii) Southwest Corner (iii) Northeast Corner

(b) Case 3 Excitation in the X (EW) Direction

*Note that the vertical and horizontal scales are different.

Figure 11. Seismic Isolation Layers Relative Displacement Orbit Diagram

Table 3. Maximum between Seismic Isolation Layers Relative Displacement
And Oil Damper Velocity

	Case 2 Y (NS) Excitation	Case 3 X (EW) Excitation
Seismic Isolation Layer Relative Displacement in X (EW) Direction	1.34 mm	150.60 mm
Seismic Isolation Layer Relative Displacement in Y (NS) Direction	150.83 mm	0.00 mm
Oil Damper Velocity in X (EW) Direction	1.1 cm/s	92.7 cm/s
Oil Damper Velocity in Y (NS) Direction	97.0 cm/s	1.6 cm/s

CONCLUSION

Seismic response analysis was made for the seismic isolation structure with an unbalanced layout of the oil dampers using the general numerical analysis software Abaqus.

By the analysis for sine wave excitation, it is confirmed that displacement in the direction normal to seismic excitation is produced in the seismic isolation layer because of the unbalanced damping force of the oil dampers produced as an external force against the upper base due to the geometrical deflection of the oil dampers in the direction normal to the seismic excitation.

It is also confirmed that displacement in the direction normal to seismic excitation is about 1/100 of the displacement in the seismic excitation direction, and its effect is very small based on the analysis for the site specific earthquake. In this case, because the oil dampers placed in the direction normal to the seismic excitation direction always extend and retract evenly and no offset of external forces that will create torsional motion against the upper base is produced, the upper base will move translationally in the direction normal to seismic excitation.

Although some torsional motion occurs due to the difference in long-term axial force of each seismic isolation device, it is confirmed that the response is very small.

REFERENCES

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