CONTROL EFFECT OF LARGE TUNED MASS DAMPER APPLIED TO EXISTING HIGH-RISE BUILDING FOR SEISMIC RETROFIT

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Abstract

This paper reports the control effect of a large tuned mass damper (TMD) developed for an existing high-rise building as a seismic retrofit. The developed large TMD was applied to an existing high-rise building located in the Shinjuku area of Tokyo. The seismic retrofit was completed in April 2015 and the TMD has been in operation since then. The target building has recently been subjected to several earthquakes, and observation records have been obtained. Analysis of these records confirms that the TMD behaved just as expected during real earthquakes. The superior response reduction effect of the TMD was verified by comparing the responses from the observed records with that estimated from an analytical seismic design model without a TMD. This paper first outlines the developed TMD and the actual retrofit project. The details of the analytical seismic design model are presented and discussed. Finally, this model and the observed records are used to demonstrate the TMD's actual response reduction effect.

Introduction

In the last two decades, a lot of research has been carried out on structural control devices, and many high-rise buildings in Japan are being equipped with them. Moreover, since the Great East Japan Earthquake of 2011 (GEJE), demand has increased in Japan for retrofit measures to effectively reduce vibrations of existing high-rise buildings. To reduce cumulative damage to old steel members and bodily sensation to vibration, high-performance devices with both sensitivity and toughness, such as oil dampers, are required. However, it is difficult to find enough space to install such devices in existing buildings because structural core areas are often already occupied by original earthquake resistant elements such as RC walls or steel braces. In these cases, the only alternative is to install devices into habitable room spaces. However, this always meets with strong resistance. Thus, there is a pressing need for seismic control technologies that do not affect these spaces.

TMDs (Tuned Mass Dampers) are well-known control devices. Since they can be installed on a specific floor such as a roof floor, they can be applied without affecting habitable room space. However, no conventional TMD systems can control the responses of high-rise buildings in major earthquakes. To realize a target TMD system, two problems need to be overcome. The first is to devise a rational mechanism that keeps the mass of several hundred tons stable, tunes the vibration period with that of the high-rise building, and permits several meters of translation in any direction. The second, which is more important and more difficult, is to control large mass displacements of about 2 meters three dimensionally, and to prevent system failure even when the earthquake level exceeds the assumed design level. Because of these problems, the target disturbances of conventional TMDs and hybrid TMDs have been limited to small earthquakes or wind forces. We have employed new techniques to solve these problems, and realized an earthquake-proof large TMD system for high-rise buildings. (Yaguchi *et al*. 2014[1] and Kurino *et al*. 2017[2])

A seismic retrofit project applying a large TMD system was completed in April 2015 and has been in operation since then. Although it is important to verify the control performance of newly developed devices introduced to actual buildings, few reports have discussed the control effects based on observation records during earthquakes. This paper reports control effects verified by establishing an accurate analytical seismic design model and examining the observed records during earthquakes.

Outline of Seismic Retrofit Project

Target high-rise building. The target building, the Shinjuku Mitsui Building, was completed in 1974 and is located in the Shinjuku area of Tokyo. It is a 220m-high structural-steel office building with 55 floors above ground. Its natural vibration period is 5.6 seconds in the longitudinal direction and 5.9 seconds in the transverse direction. Although it maintains enough anti-seismic strength, the TMD was chosen as an effective countermeasure to long-period earthquakes expected in the near future. Considering the scale of the building, we planned to install TMDs with a total weight of 18,000kN, which is equal to 6.5% of the effective building weight. Considering the size of its parts and the construction method, and the influence of the additional load on the existing frame, we decided to divide the weight into six units and arrange them symmetrically on the roof floor.

Fig. 1(a) shows a photograph of the target building and Fig. 1(b) shows an elevation. Fig. 6(c) shows the arrangement of the TMDs on the roof floor. As shown in Fig. 1(b), a total of 48 high-performance semi-active oil dampers (Kurino *et al*. 2006)[2] are also installed on the 5th-10th floors in the transverse direction to increase the seismic safety margin of this direction, whose vibration period is longer than in the longitudinal direction. To avoid affecting residents, the oil dampers are installed in the wall of the public space in the core area shown in Fig. 1(d), and construction work was carried out mainly at night and on holidays.

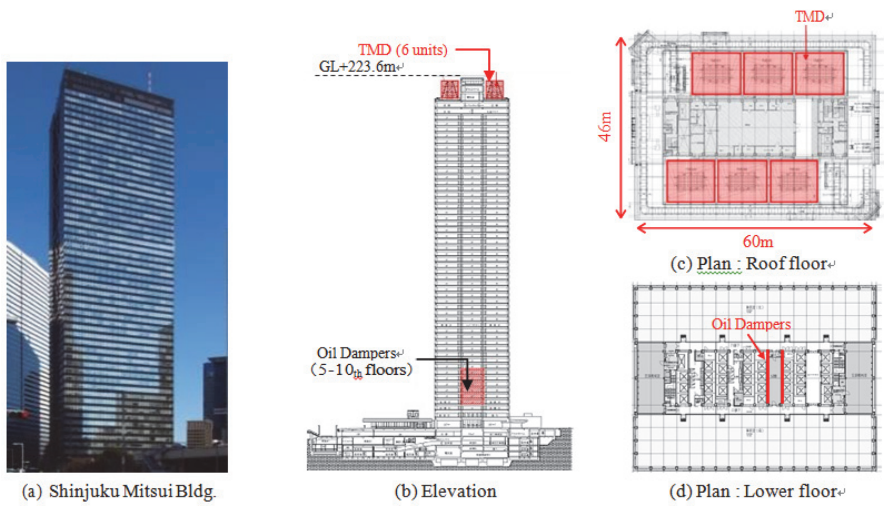
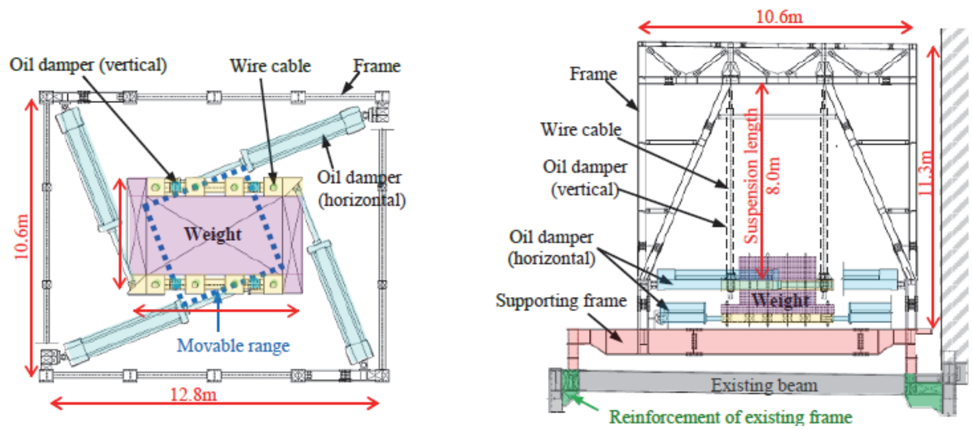


Figure 1. Target Building and Arrangement of TMD

Large TMD with stroke control function. Fig. 2 shows the configuration of the developed TMD for the target building. One unit of the TMD is composed of the following components: (1) A weight made of steel plates piled up on each other and bound by a post-tensioned steel bar, (2) Eight steel wires to support the weight, (3) Four oil dampers with a velocity limit function in the horizontal direction (horizontal damper), (4) Four oil dampers to reduce fluctuations of the wire's tension force against vertical earthquake (vertical damper), and (5) A steel covering frame. We placed the horizontal dampers radially in order to avoid interference with the weight in case of large displacement. Considering the movable range of the weight restricted by the size of the covering frame, we set the maximum stroke of the horizontal dampers to ±205cm. The movable displacement of the weight is determined by the stroke of the horizontal damper, and the maximum displacement of 270cm occurs in the diagonal direction, as shown in Fig. 2(a). In order to avoid imposing a heavy load on the existing steel members, a new supporting frame is to be constructed above the existing beam, as shown in Fig. 2(b). Fig. 3 describes the oil damper for the horizontal direction. This damper contains a unique hydraulic circuit that automatically switches its damping coefficient to realize the velocity limit function. Its load capacity is 1000kN, and its length and weight are about 8m and 40kN, respectively.



(a) Plan (b) Elevation

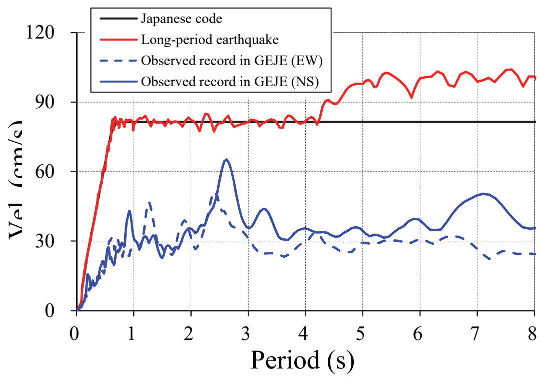
Figure 2. Configuration of TMD

(a) Appearance (b) (b) Force–velocity relation

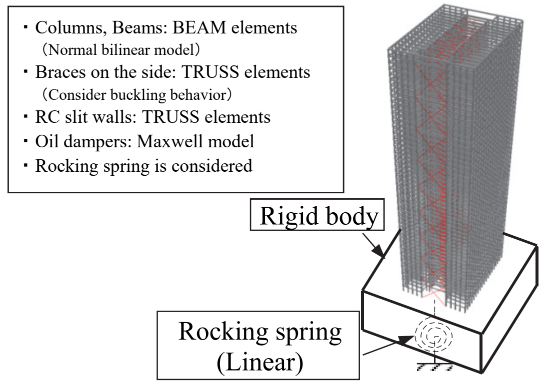
Figure 3. Developed Oil Damper with Velocity Limitation Function

Seismic design. For the seismic design, we selected a long-period earthquake in addition to the usual simulated earthquakes regulated by the Japanese code. Fig. 4(a) shows their velocity response spectra and those of the ground motions observed at the site during the GEJE are also shown for comparison. As we can see, the level of the observed records in the GEJE is almost half that of the usual design earthquakes in Japan.

Fig. 4(b) shows a three-dimensional analytical model of the building developed for response analysis. Each column and beam is modeled as a beam element. Bending, shear and axial deformations are considered at columns, and bending and shear deformations are considered at beams. Steel braces on the side and RC slit walls at the core are modeled as truss elements in which only axial deformation is considered. Panel elements in which only shear deformation is considered are set at each column/beam connection. Oil dampers are modeled as Maxwell models. A rocking spring at the basement is also considered.



(a) Velocity Response Spectrum of Earthquakes (h=0.05)



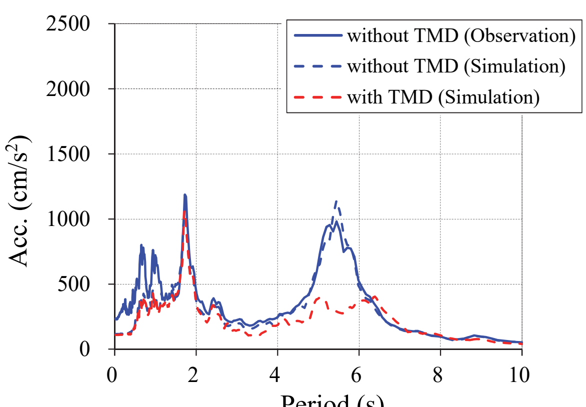
(b) 3D Analytical Model

Figure 4. Earthquake for design and Analytical model

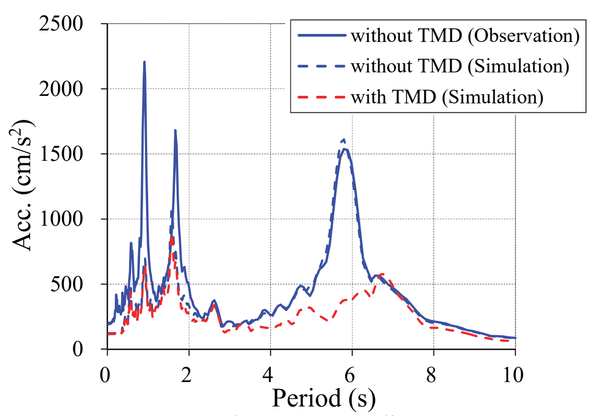
A simulation analysis using records observed at this building in the GEJE was conducted to evaluate the model's validity. Fig. 5 shows the floor response acceleration spectra on the roof floor. The simulation results before retrofitting agree very well with the observed records, and this confirms the accuracy of the developed building model.

We also conducted simulation analyses using the building model with TMD to determine its control effect of the TMD in the GEJE. In addition to the building model, the TMD models composed of mass, linear spring elements and dashpots are incorporated. Fig. 6(a) shows the displacement time histories of the roof floor. By introducing the TMD, not only the maximum amplitude but also the bodily sensation duration are greatly reduced. Fig. 6(b) shows the displacement orbit of the roof floor. It is also observed that the proposed TMD reduces the responses in every direction. The roof floor's acceleration response spectrum "with TMD" is also shown in Fig. 6. A large damping ratio (about 5%) is thus augmented to the building.

Fig. 7 shows the maximum story drift angle and the ductility factor of the beam element for a long-period earthquake. The results without TMD are also shown for comparison. With the proposed TMD, the building responses against the severe earthquake are drastically reduced to almost half of the response of the original structure and the stresses in the old steel members are mostly kept within the elastic region.

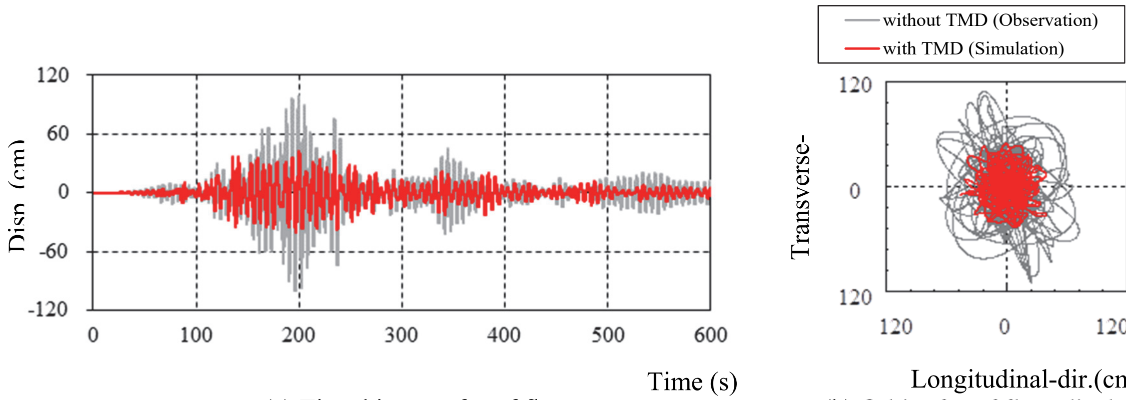


(a) Longitudinal-dir.



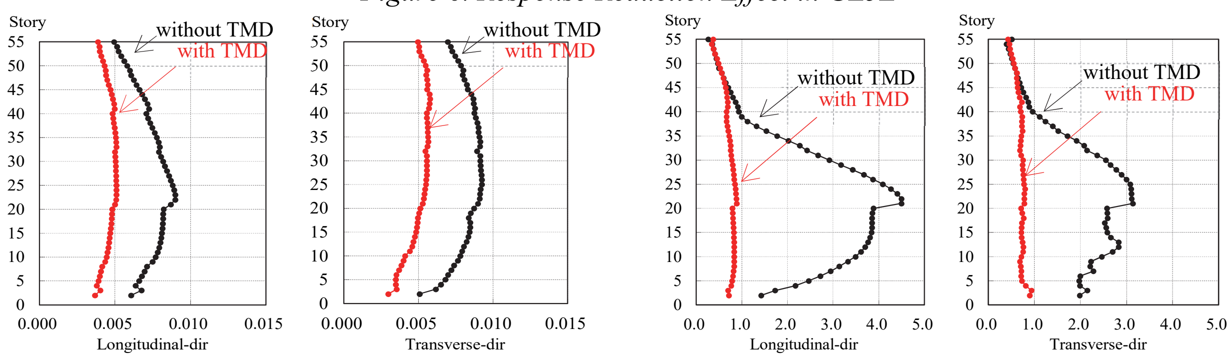
(b) Transvers-dir.

Figure 5. Comparison of Acceleration Response Spectrum on Roof Floor in GEJE (h=0.02)



(a) Time history of roof floor (b) Orbit of roof floor displacement

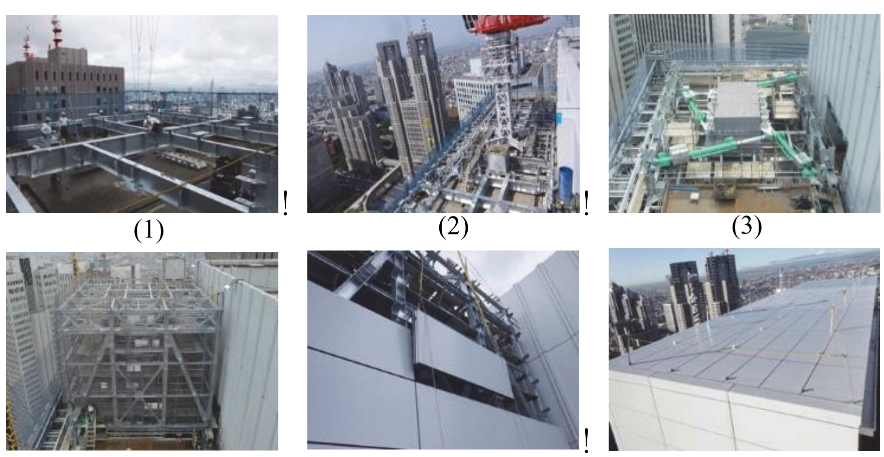
Figure 6. Response Reduction Effect in GEJE



(a) Story drift angle (b) Ductility factor of beam member

Figure 7. Distribution of Maximum Response for Long-period Earthquake

Construction. The seismic retrofit was started in August 2013 and completed in April 2015 (21 months). The TMD's construction procedure is outlined as follows (refer to Fig. 8). (1) Build up support frames on existing reinforced beams. (2) Set up two tower cranes on support frame. (3) Place weight and horizontal oil dampers on support frames. (4) Build steel frame and lift weight with hydraulic jacks, and set wires and vertical oil dampers. Then release jacks, introduce tension force into wire and hang weight. (5), (6) Set exterior panels on side and roof surfaces of frame. Fig. 9 shows the interior and exterior of the TMD.



(1) (2) (3)

(4) (5) (6)

Figure 8. Progress of TMD Construction

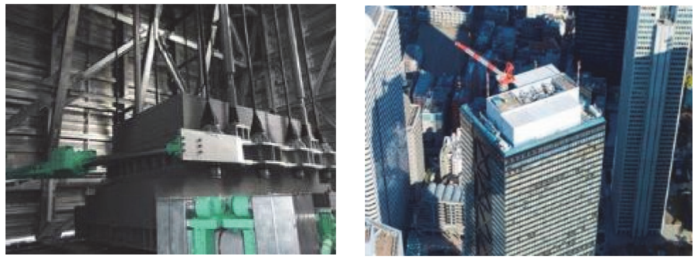
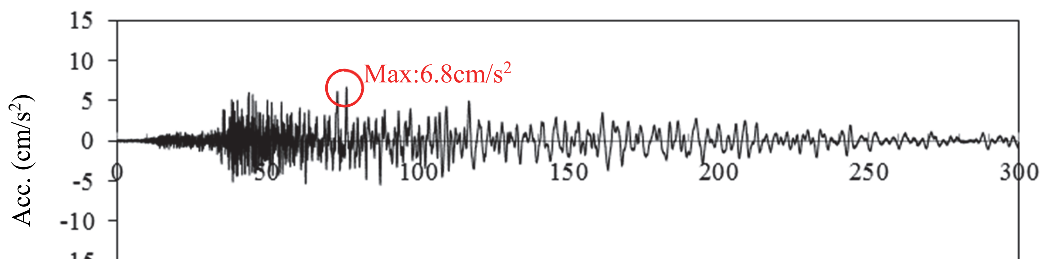


Figure 9. Interior and Exterior of TMD

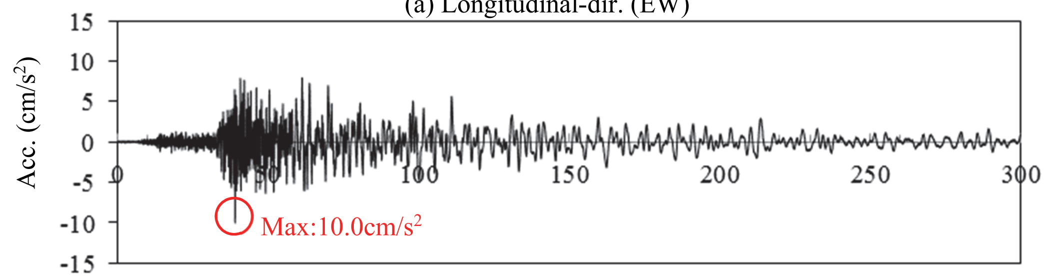
Control Effect of Large TMD based on Observation Record

In this section, we demonstrate the control effect of the large TMD, which became apparent through observed records obtained since retrofit.

Observed response during earthquakes with TMD. On November 22 2016, the building was subjected to the Fukushima-oki Earthquake whose JMA (Japan Meteorological Agency) magnitude was 7.4 and focal depth was about 25km. Fig. 10 shows the observed acceleration time history at the ground level of the building. Maximum acceleration was 6.8 cm/s^2 in the longitudinal direction, and 10.0 cm/s^2 in the transverse direction. Fig.11 shows the velocity response spectra. The spectrum of the Japanese code ground motion is also shown for comparison. As we can see, the level of the observed records is about 1/5 that of the GEJE.



(a) Longitudinal-dir. (EW)



(b) Transverse-dir. (NS)

Figure 10. Acceleration Time History at the Ground Level in the Fukushima-oki Earthquake 2016.

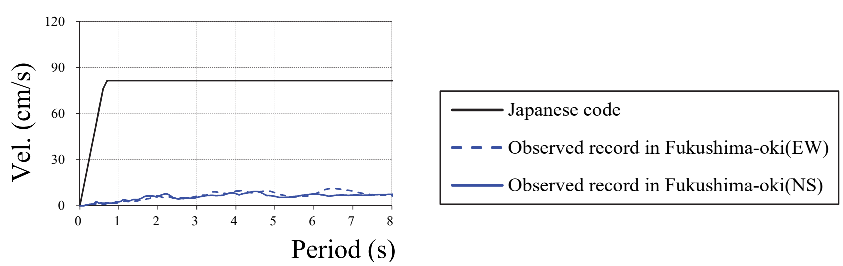


Figure 11. Velocity Response Spectra of Observed Earthquakes

Fig.12 shows the maximum displacement at the observed point with TMD. These displacements are achieved by integrating the data from accelerometers installed in each TMD and every few floors of the building. The displacement at the roof floor was 9.6cm in the longitudinal direction, and 8.4 cm in the transverse direction. The observed strokes of the TMD was 24cm and 22cm in each direction, which is not large enough to make the hardening function of the oil dampers work. According to the information from monitoring cameras set to each TMD unit, we also confirmed that the all six TMD units operated normally. The simulation analysis results using the model shown in Fig. 4(b) are indicated in Fig.12. They agree very well with the observed records, thus confirming the accuracy of the developed building model after retrofitting.

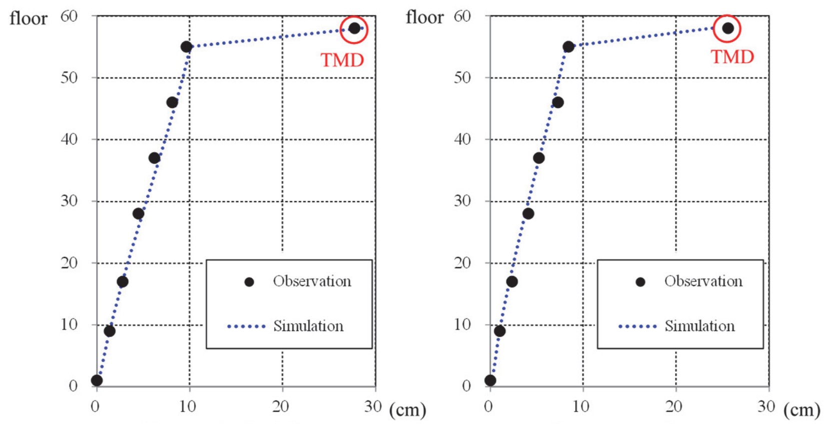


Figure 12. Distribution of Maximum Displacement (Observation / Simulation)

Control effect of large TMD. Fig.13 shows the floor response acceleration spectra on the roof floor. It compares the results of simulation "without TMD" and observed record "with TMD". In addition, the results of simulation "with TMD" are also indicated for reference. It is observed that the amplitude around the building's 1st mode is greatly reduced by introducing the TMD just as expected in the seismic design.

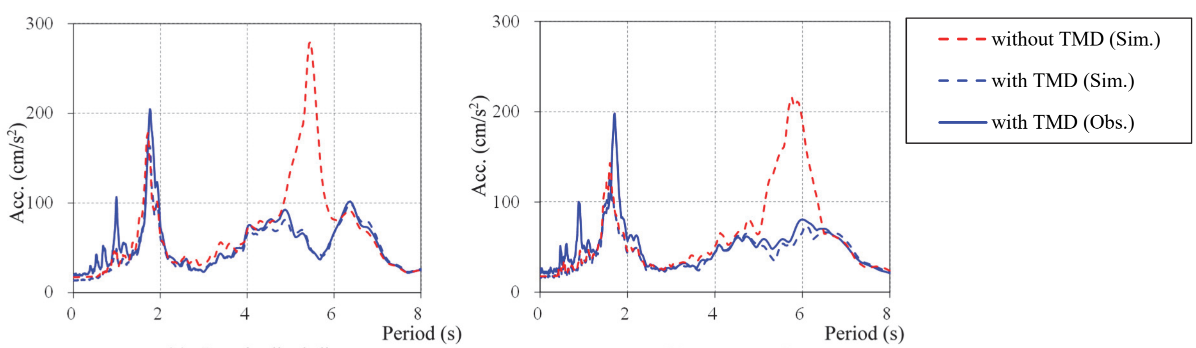


Figure 13. Response Reduction Effect based on Observed Record (h=0.02).
(Response Spectrum of Roof Floor Acceleration)

Fig.14 compares the roof floor's displacement time history of "simulated without TMD" against that of "observed with TMD". Focusing on the entire duration, here we employ RMS values of the time history. The vibration of the building without TMD would double and uncomfortable vibration would continue for a long time. Focusing on maximum amplitude, they are reduced to 90% in the longitudinal direction, and 70% in the transverse direction. It is assumed that this directional difference results from the difference of the earthquake's component around the building's natural period.

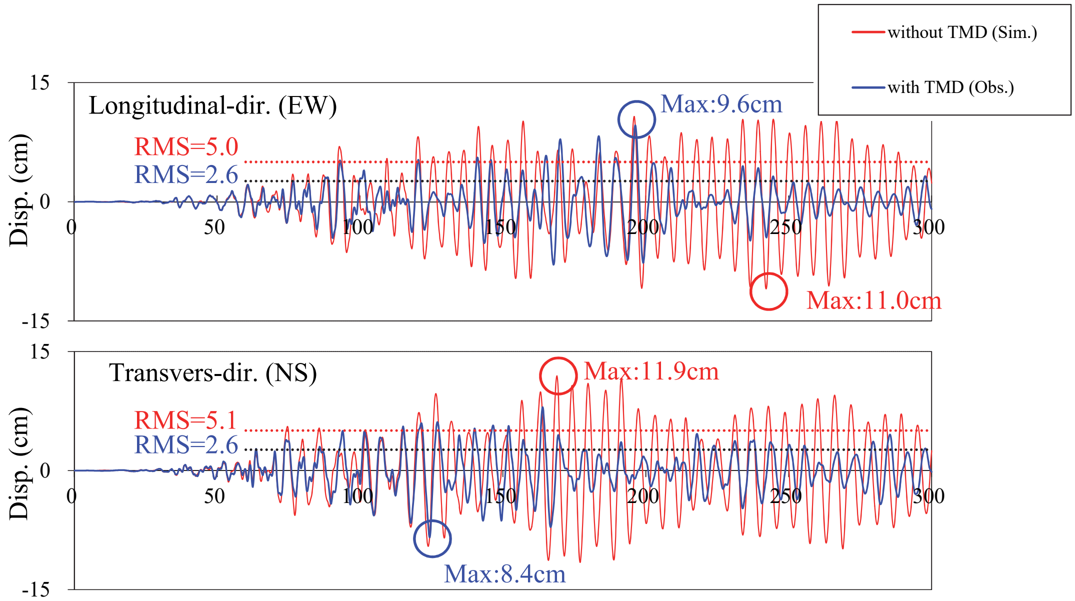


Figure 14. Response Reduction Effect based on Observed Record
(Time History of Roof Floor Displacement)

Conclusions

This paper has reported the control effect of a large TMD developed for an existing high-rise building as a seismic retrofit. The target building had recently been subjected to several earthquakes, and observation records had been obtained. By estimating these records, although the earthquake's level was much smaller than considered in the seismic design, we confirmed that the TMD behaved just as expected. We also compared the responses with and without TMD using observed records and an analytical seismic design model whose accuracy was verified. It was confirmed that habitability and safety during earthquakes were greatly improved.

References

[1] Yaguchi T., Kurino H., Kano N., Nakai T., Fukuda R. (2014) : Development of Large Tuned Mass Damper with Stroke Control System for Seismic Upgrading of Existing High-rise Building. *6th World Conference on Structural Control and Monitoring*, No.181, Barcelona, Spain.

[2] Kurino H., Kurokawa Y., Kano N., Fukuda R. (2017) : Development of Large Tuned Mass Damper with Stroke Control System for Seismic Upgrading of Existing High-rise Building. *16th World Conference on Earthquake Engineering*, No.3533, Santiago, Chile.

[3] Kurino H., Yamada T., Matsunaga Y., Tagami J. (2006) : Switching Oil Damper with Automatic Valve Operation System for Structural Control. *Proc of 4th World Conference on Structural Control and Monitoring*, No.217, San Diego, USA.