17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

CONTROL EFFECT OF A TUNED MASS DAMPER INCORPORATING A FAILSAFE MECHANISM USING A FRICTION DEVICE

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Abstract

When a huge earthquake occurs along the Nankai Trough in Japan, there is a concern that long-period, long-duration ground motion will cause high-amplitude shaking, especially for high-rise buildings located in metropolitan areas. Some existing high-rise buildings with old design criteria have low seismic performance and require improved seismic safety measures. Aseismic technologies to deal with this issue by vibration control include in-frame devices and additional mass devices. The latter involves the installation of a tuned mass damper (TMD) at the top of a building and has the advantage of influencing the inside of the building less.

When TMDs are used for seismic protection, it is necessary to ensure the robustness of their control performance against variations in the natural period of buildings. To this end, a large mass ratio of approximately 2% or more with respect to the building mass is preferable. In addition, the maximum displacement of members such as laminated rubber or dampers constituting the TMDs, must be limited to approximately ±200 cm or less, considering manufacturing and testing. Furthermore, if a building with a TMD directly mounted to its top experiences excessive earthquake motion exceeding the design assumptions of the TMD, serious accidents, such as a rapid response increase due to damage of the TMD members or the detachment of the additional mass, may occur. For this reason, a fail-safe (FS) mechanism must be installed with TMDs as a countermeasure against excessive ground motion.

The present study proposes a TMD system incorporating a friction FS mechanism. In the proposed system, the TMD is connected in series to the top of a building via the FS mechanism using a friction device. The FS mechanism does not function when the response of the TMD is within a predetermined displacement range during an earthquake at or below the design level. When the response of the TMD exceeds the threshold, the FS mechanism slides and controls the displacement of the additional mass in order to mitigate damage to the TMD and the main structure.

In order to numerically assess the effect of the proposed friction FS mechanism, an earthquake response analysis was conducted using a three-degree-of-freedom model consisting of a structure, a TMD, and the proposed friction FS mechanism. This structural model assumes a 30-story steel frame building. The response behavior under various magnitudes of input ground motion was investigated, and the obtained response was compared to that in the case without the FS mechanism. The results demonstrate that applying the proposed friction FS mechanism to a TMD would make it possible to suppress the excessive displacement of the additional mass, the sudden reduction in control performance, and the increase in the response of the building that normally occur when the building is subjected to an excessively strong earthquake.

Keywords: high-rise building; long-period ground motion; tuned mass damper; fail-safe mechanism; friction device

1. Introduction

When a huge earthquake occurs along the Nankai Trough in Japan, there is a concern that long-period, long-duration ground motion will cause high-amplitude shaking, especially for high-rise buildings located in metropolitan areas. Some existing high-rise buildings with old design criteria have low seismic performance and require improved seismic safety measures. Aseismic technologies to deal with this issue by vibration control include in-frame devices and additional mass devices. The latter involves the installation of a tuned mass damper (TMD) at the top of a building and has the advantage of influencing the inside of the building less.

When TMDs are used for seismic protection, it is necessary to ensure the robustness of their control performance against variations in the natural period of buildings. To this end, a large mass ratio of approximately 2% or more with respect to the building mass is preferable. In addition, the maximum displacement of members such as laminated rubber or dampers constituting the TMDs must be limited to approximately ±200 cm or less, considering manufacturing and testing. Furthermore, if a building with a TMD mounted directly to its top experiences excessive earthquake motion exceeding the design assumptions of the TMD, serious accidents, such as a rapid response increase due to damage of the TMD members and the detachment of the additional mass, may occur.

For this reason, a fail-safe (FS) mechanism must be installed with TMDs as a countermeasure against excessive ground motion. As a FS mechanism, a method of braking the movement of the added mass when the displacement of the TMD approaches the design limit displacement has been proposed [1-3]. However, such a method may lead to a decrease in vibration control performance or an increase in building response. In addition, verifying the performance of the braking mechanism of TMD components that operate with a large displacement of ±200 cm at a high speed is not easy.

The present study proposes a TMD system incorporating a friction FS mechanism. In the proposed system, the TMD is connected in series to the top of a building via the FS mechanism using a friction device. In the present paper, an earthquake response analysis using a three-degree-of-freedom model consisting of a structure, a TMD, and the proposed friction FS mechanism is presented in order to numerically assess the effect of the proposed friction FS mechanism. The response behavior under various input magnitudes of a ground motion is investigated, and the obtained response is compared to that in the case without the FS mechanism.

2. Description of the Fail-safe Mechanism

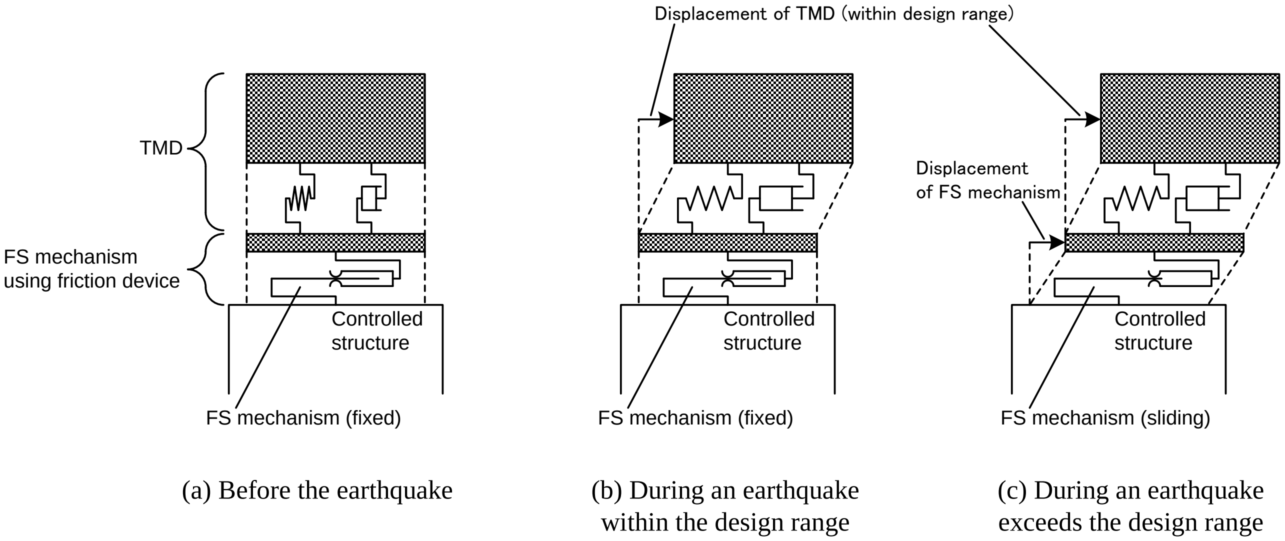
2.1 Operation and expected effect of the fail-safe mechanism

The proposed FS mechanism transmits the horizontal vibration control force of a TMD to a building during an earthquake and bears the TMD weight. Fig. 1 shows the concept of operation for the horizontal direction of a TMD incorporating the FS mechanism. The FS mechanism includes a friction device, which slides horizontally when a predetermined force is applied. By designing the frictional force of the friction device to be smaller than the maximum allowable control force of the TMD corresponding to the design limit displacement of the TMD, it is expected that damage to the TMD can be avoided.

2.2 Ground motion intensity and operation of the tuned mass damper and fail-safe mechanism

Within the range of the design seismic motion (i.e., the TMD response is within the design range), the FS mechanism using the friction device does not slide in a fixed state, and only the TMD moves horizontally, as shown in Fig. 1(b).

As shown in Fig. 1(c), when the building encounters excessively strong ground motion and the TMD operation approaches the design limit displacement, the FS mechanism starts sliding and moves while transmitting the control force of the TMD to the building. At this time, the force acting on the TMD from the building (and also the control force acting on the building from the TMD) is limited owing to the sliding of the FS mechanism. Therefore, damage due to collision of the TMD or detachment of the additional mass would be prevented. Furthermore, the FS mechanism absorbs vibration energy approximately proportional to the cumulative sliding displacement by converting the energy into frictional heat. For this reason, even when the FS mechanism slides, a sudden decrease in the vibration control effect of the TMD does not occur, and an increase in response would be suppressed.



(a) Before the earthquake

(b) During an earthquake within the design range

(c) During an earthquake exceeds the design range

Fig. 1 – Concept of a tuned mass damper (TMD) incorporating the proposed fail-safe (FS) mechanism

3. Methods of Seismic Response Analysis

3.1 Building model

The behavior of the FS mechanism using the friction device and the vibration control effect of the TMD were assessed by a seismic response analysis.

A three-dimension 30-story steel building structure model [4], which was a half-model with a total weight of 140,544 kN, was selected to model the assumed building. Based on a static pushover analysis [5] using the three-dimensional 30-story model, an equivalent shear-type 30-degree-of-freedom (30DOF) system model was first created. Then, an equivalent single-degree-of-freedom (SDOF) system model was generated. The mass of the SDOF model was given as an effective mass for the first mode evaluated at the top of the 30DOF model. Fig. 2(a) shows the SDOF model, which was an uncontrolled model, referred to as Model U. The natural period of this SDOF model was 3.69 s. The weight w_1 of this model was 58,612 kN, and the stiffness k_s was 173.6 kN/cm. The damping factor was assumed to be 1.5% and the corresponding viscous damping coefficient c_s was 3.06 kN/(cm/s).

3.2 Tuned mass damper and fail-safe models

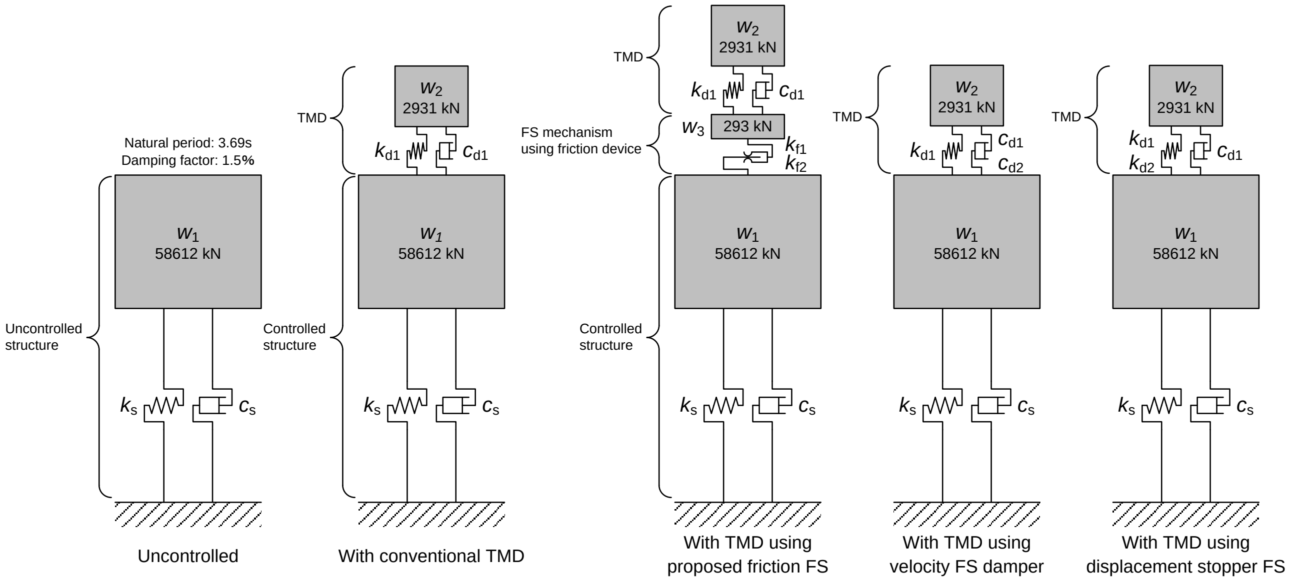
Four different TMD models, with or without FS mechanisms mounted on the same SDOF building model described in Section 3.1, were used. The first model, referred to as Model C, was a model with a conventional TMD without any FS mechanism, as shown in Fig. 2(b). The second model, referred to as Model F, was a model with a TMD mounted via the proposed FS mechanism using a friction device, as shown in Fig. 2(c). The third and fourth models were prepared for comparison with Model F. The third model, referred to as Model V, was a model with a TMD, the damping force of which was set to be increased to brake the movement of the additional mass when the response of TMD approached the design limit velocity, as shown in Fig. 2(d). The fourth model, referred to as Model D, was a model with a TMD, the movement of the additional mass of which was set to be stopped by colliding with the displacement stopper when the response of the TMD approached the design limit displacement, as shown in Fig. 2(e).

Table 1 gives the specifications of the TMD models. The weight w_2 of the additional mass of the TMD was the same for each of Models C, F, V, and D. The weight w_2 was 2,931 kN, corresponding to a mass ratio of 5% to the weight w_1 (= 58,612 kN) of the uncontrolled model (Model U). The design of the TMD was based on the fixed-point theory [6]. The optimum tuning period T_d with the TMD alone was 3.87 s. The stiffness k_{d1} and the damping coefficient c_{d1} for the TMD were 7.87 kN/cm and 1.30 kN/(cm/s), respectively. The design limit displacement of the TMD was assumed to be ±200 cm.

In Model F, the weight w_3 of the FS platform provided between the friction device of the FS mechanism and the TMD was taken to be 293 kN, corresponding to a ratio of 10% of the weight w_2 of the TMD. As shown in Fig. 3(a), the initial stiffness k_{f1} of the friction device of the FS mechanism was set to be a sufficiently large value, i.e., 12,986 kN/cm. The friction device was designed to slide with a force of 1,259 kN when the horizontal spring of the TMD deformed to 160 cm (i.e., 80% of the design limit displacement). The secondary stiffness k_{f2} of the friction device was set to be zero.

In Model V, the viscous damper of the TMD was designed to increase the damping force when the displacement exceeded 160 cm (i.e., 80% of design limit displacement). As shown in Fig. 3(b), the initial damping coefficient c_{d1} in the low-velocity range was 1.30 kN/(cm/s), but the second damping coefficient c_{d2} in the high-velocity range (238 cm/s or more) was set to be 1,300 kN/(cm/s).

In Model D, when the displacement of TMD exceeded 160 cm, the movement of the additional mass was restrained due to the collision with the stopper. As shown in Fig. 3(c), the initial stiffness k_{d1} of the TMD horizontal spring was 7.87 kN/cm in the low-amplitude range. However, when the displacement exceeded 160 cm, the stiffness k_{d2} increased 100 times k_{d1} (i.e., the second stiffness k_{d2} = 787 kN/cm).

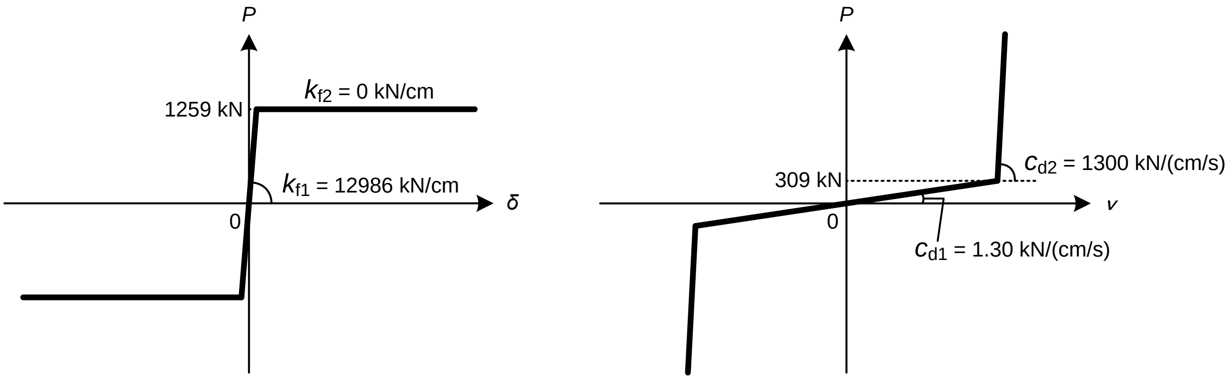


(a) Model U (b) Model C (c) Model F (d) Model V (e) Model D

Fig. 2 – Analytical models

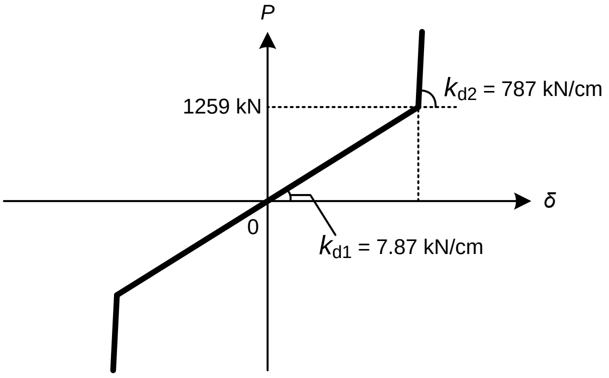
Table 1 – Specifications of tuned mass damper and fail-safe mechanism models

Model	Parameter	Symbol	Value	Unit
C,F,V,D	Weight of additional mass of the TMD	w_2	2,931	kN
	(Initial) stiffness of the TMD spring	k_{d1}	7.87	kN/cm
	(Initial) viscous damping coefficient of the TMD damper	c_{d1}	1.3	kN/(cm/s)
F	Weight of the FS mechanism platform	w_3	293	kN
	Initial stiffness of the friction device of the FS mechanism	k_{f1}	12,986	kN/cm
	Second stiffness of the friction device of the FS mechanism	k_{f2}	0	
V	Second viscous damping coefficient of the TMD damper	c_{d2}	1,300	kN/(cm/s)
D	Second stiffness of the TMD spring	k_{d2}	787	kN/cm



(a) Force-displacement relationship of the friction FS mechanism in Model F

(b) Force-velocity relationship of the viscous damper of the TMD in Model V

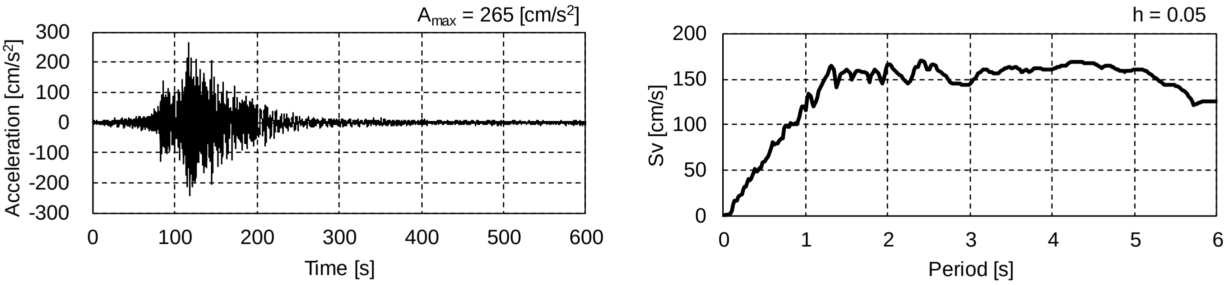


(c) Force-displacement relationship of the TMD spring in Model D

Fig. 3 – Force-displacement or force-velocity characteristics of the elements in Models F, V, and D

3.3 Input ground motion

Fig. 4(a) shows the simulated input ground motion waveform of the wave, referred to as CH1, used for the analysis. Here, CH1 is described in “Countermeasures for high-rise buildings etc. against long-period ground motions due to huge earthquakes along the Nankai Trough”, as reported by the Ministry of Land, Infrastructure, Transport and Tourism in 2016. This wave has been applied to the design of newly built high-rise buildings in the Chukyo district in Japan. Fig. 4(b) shows the velocity response spectrum of CH1 drawn with a damping factor of 5%. A total of 20 levels of input magnitudes from ×0.1 through ×2.0 (with an increment of ×0.1) were multiplied by the CH1 wave, and the results were used for the earthquake response analysis for each model. The peak ground accelerations for ×0.5, ×1.0, ×1.5, and ×2.0 inputs were 132.5, 265.0, 397.5, and 529.9 cm/s^2, respectively.



(a) Time history acceleration

(b) Velocity response spectrum

Fig. 4 – Input motion (input magnification: ×1.0)

4. Results of Analysis

4.1 Maximum response displacement of the tuned mass damper and fail-safe mechanism

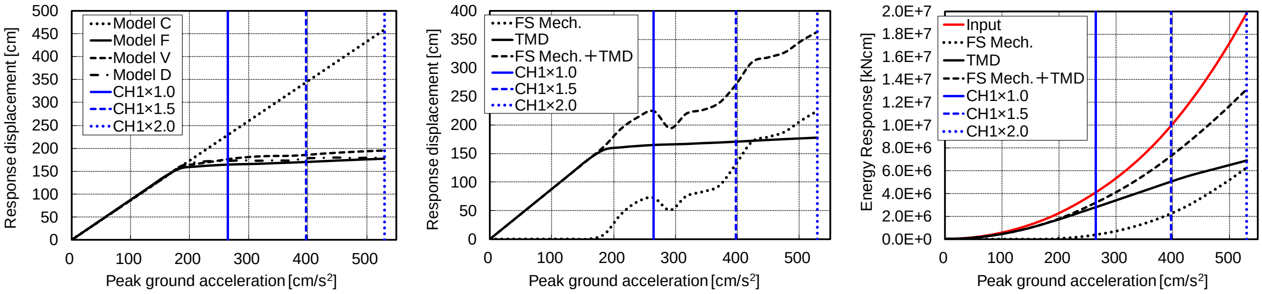
Fig. 5(a) shows the relationship between the maximum response displacement for each TMD and the input acceleration of the ground. When the original simulated ground motion CH1 (×1.0) was input, the maximum response displacement of the TMD exceeded the design limit displacement (i.e., 200 cm) and reached 230 cm in Model C, which was equipped only with the conventional TMD, indicating that damage to the TMD may occur. On the other hand, for Model F with the friction FS mechanism, Model V with the increasing damping force, and Model D with the increasing stiffness, the responses of the TMDs were controlled to within 200 cm. The control effects regarding the TMD response displacement were approximately the same for Models F, V, and D.

Fig. 5(b) plots the maximum response displacements observed at the TMD part, the FS mechanism part, and the combined TMD and FS mechanism parts, all obtained from the results for Model F. When the displacement of the TMD exceeded approximately 160 cm, the FS mechanism was activated, such that the excessive displacement of the TMD was controlled. The maximum response displacement at the FS mechanism increased with increasing input magnification of the ground motion. However, since the friction device had a non-linear characteristic, the increase did not exhibit a linear trend.

4.2 Energy absorption

Fig. 5(c) shows the total input energy by the ground motion, the energy absorption by the TMD damper part, the energy absorption by the FS mechanism part, and the total energy absorption by the TMD and FS mechanism parts, all obtained from the results for Model F. When the displacement of the TMD exceeded 160 cm and the input acceleration exceeded 185 cm/s^2, the increase in energy absorption by the damper of the TMD part was controlled to be small, and the energy absorption at the FS mechanism increased gradually.

Compared to the total input energy, the ratio of the energy absorption of the sum of the TMD and FS mechanism part was 78% under ×0.5 input when the friction FS mechanism was not activated, whereas after the FS mechanism was activated under ×1.0, ×1.5, and ×2.0 inputs, the ratios were 78%, 73%, and 66%, respectively.



(a) Response displacement
of the TMD for each TMD model

(b) Response displacement
at each part in Model F

(c) Energy response
at each part in Model F

Fig. 5 – Obtained earthquake response of the TMD with respect to peak ground acceleration

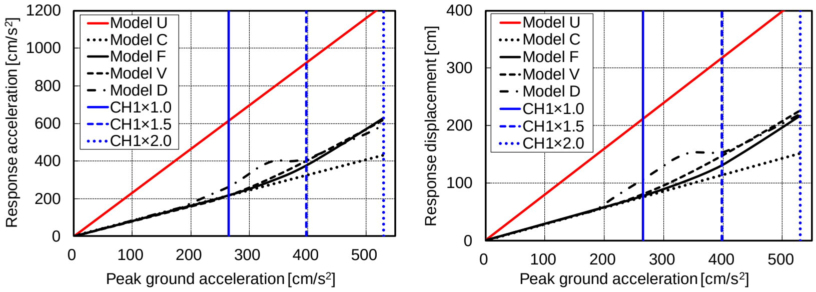
4.3 Maximum response of the building

Fig. 6(a) compares the maximum response acceleration of the building. Compared to Model U without TMD, the maximum building acceleration of Model C, which has no displacement limit of TMD, was reduced by about 65%. In Model D with the displacement stopper at the TMD, the control effect began to decrease when the TMD displacement exceeded 160 cm and the input acceleration exceeded 185 cm/s^2. The reduction in the maximum response acceleration was approximately 60% when a ×1.0 input was used. On the other hand, Model F with the friction FS mechanism and Model V with the increased damping force of the TMD showed approximately the same response acceleration reduction effects as Model C when subjected to ×1.0 input. When the input acceleration exceeded ×1.0, the effect of reducing the response acceleration decreased in all of Models F, V, and D. However, even under an input magnification of ×2.0, the response acceleration was reduced by approximately 50% compared to that for Model U.

Fig. 6(b) shows the maximum response displacement of the building, which exhibits approximately the same characteristics as the maximum response acceleration shown in Fig. 6(a). Compared with Model U without the TMD, the maximum response displacement for Model C with only the conventional TMD was reduced by approximately 65%. In Model D, when the displacement of the TMD exceeded 160 cm and the input acceleration exceeded 185 cm/s^2, the control effect started to decrease. The reduction of the maximum response displacement was approximately 50% under ×1.0 input. On the other hand, Models F and V yielded approximately the same response displacement reduction effects as Model C under ×1.0 input. When the input acceleration exceeded ×1.0, the effect of reducing the response displacement decreased in Models F, V, and D. However, even under ×2.0 input, the response displacement was reduced by approximately 50% in comparison with Model U.

Furthermore, as shown in Fig. 6(b), among Models F, V, and D, the reduction of the response displacement after the FS mechanism operated was smallest in Model F, in which the TMD with the friction FS mechanism was installed.

In the proposed friction FS mechanism, a residual displacement occurred after the operation. Recovery work may be required for a large residual displacement. In order to reduce the residual displacement, the FS mechanism reported in [7], which is a combination of a hydraulic device exhibiting the same characteristics as the friction device and a low-stiffness restoring spring, would be effective.



(a) Response acceleration of the building for each model

(b) Response displacement of the building for each model

Fig. 6 – Obtained earthquake response of the building with respect to peak ground acceleration

5. Conclusions

As a countermeasure against excessive strong ground motions exceeding the design limit of the TMD, a method of mounting a TMD with a FS mechanism using a friction device was proposed. The effect of the proposed FS mechanism was confirmed by a seismic response analysis. A summary of the results of the present study is given below.

- Mounting the TMD with a FS mechanism using a friction device prevented the TMD from operating beyond its design limits. A friction FS mechanism would prevent collision and damage caused by the TMD.
- After the friction FS mechanism was activated, the increase in the energy absorption by the TMD damper was controlled to be small with the increase of the input seismic motion, and the energy absorption of the FS mechanism gradually increased.
- Even after the input seismic motion increased and the friction FS mechanism operated, the damping performance of the TMD did not decrease sharply. In addition, there was no sudden increase in the building response.

6. Acknowledgements

In the present study, a response analysis was carried out using the design earthquake motion published by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT). We would like to express our gratitude for providing the design earthquake motion.

7. References

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