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Innovative base-isolated building with large mass-ratio TMD at basement for greater earthquake resilience

Takuya Hashimoto, Kohei Fujita, Masaaki Tsuji and Izuru Takewaki*

Abstract

Tuned mass dampers (TMD) have been used for the reduction of building responses to wind loading in many high-rise buildings. An innovative and resilient base-isolated building with a large mass-ratio TMD is introduced here primarily for earthquake loading in which the large mass-ratio TMD is located at basement. This new hybrid system of base-isolation and structural control possesses advantageous features compared to existing comparable systems with a TMD at the base-isolation story. The TMD stroke can be reduced to a small level with the use of an inertial mass damper and its reaction can be limited to a lower level by detaching its connection to ground. The proposed hybrid system has another advantage that the TMD mass does not bring large gravitational effect on the building itself. It is demonstrated that the proposed hybrid system is robust both for pulse-type ground motions and long-period, long-duration ground motions which are regarded as representative influential ground motions.

Keywords: Earthquake resilience; Base-isolation; Tuned mass damper; Large mass-ratio TMD; Inertial mass damper; Basement; Hybrid system

Introduction

There is an increasing need and interest of construction of high-rise buildings in urban areas. This trend will be accelerated in the future. High-rise buildings and super high-rise buildings are required to resist for various external loadings, e.g. wind and earthquake loadings. Enhancement of *resilience* of such high-rise and super high-rise buildings after intensive wind and earthquake loadings is a major concern from the viewpoint of the business continuity plan (BCP) which is the most controversial issue in the sound development of society (Takewaki et al. 2011, 2012b).

Tuned mass dampers (TMD) are useful for the reduction of building responses to wind loading and are installed in many high-rise buildings all over the world (Soong and Dargush 1997). However it is well known that TMD is not effective for earthquake responses because of its limitation on stroke and realization of large mass-ratio TMD.

Nevertheless, some attempts have been made on the introduction of large mass-ratio TMD mainly for earthquake loading (Chowdhury et al. 1987; Feng and Mita 1995; Villaverde 2000; Arfiadi 2000; Zhang and Iwan 2002; Villaverde et al. 2005; Mukai et al. 2005; Tiang et al. 2008; Matta and De Stefano 2009; Petti et al. 2010; Angelis et al. 2012; Nishii et al. 2013; Xiang and Nishitani 2014). Actually several projects are being planned in Japan, e.g. installation of large-mass pendulum system at roof and usage of upper stories as TMD masses.

Recently large mass-ratio TMDs are investigated for base-isolated buildings (Villaverde 2000; Villaverde et al. 2005; Angelis et al. 2012; Nishii et al. 2013; Xiang and Nishitani 2014). While usual high-rise buildings exhibit large displacement around the top story, base-isolated buildings show relatively large displacement around the base-isolation story near ground surface. This property is very advantageous from the view point of mitigation of effect of excessive vertical load due to large mass-ratio TMD (Kareem 1997; Zhang and Iwan 2002; Mukai et al. 2005; Petti et al. 2010; Nishii et al. 2013; Xiang and Nishitani 2014).

However there still exist several issues to be resolved, e.g. avoidance of excessive vertical load by large mass-ratio TMD, reduction of TMD stroke, reduction of TMD support reactions.

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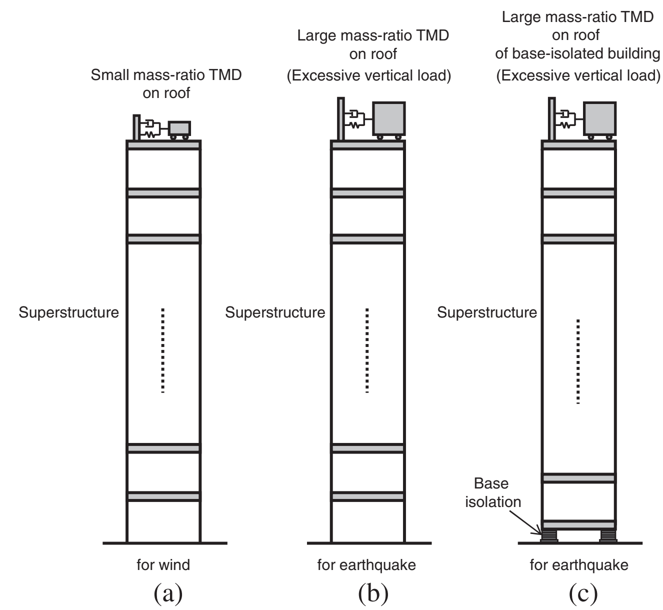


Fig. 1 Conventional model and unrealistic model with excessive vertical load

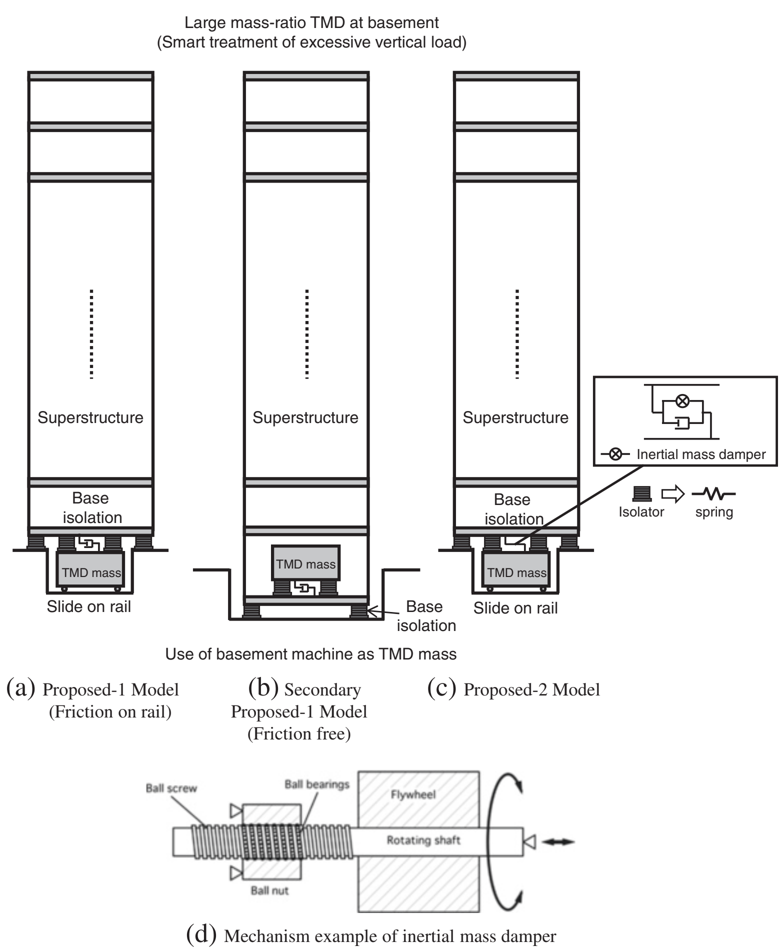


Fig. 2 Proposed-1 model and Proposed-2 model

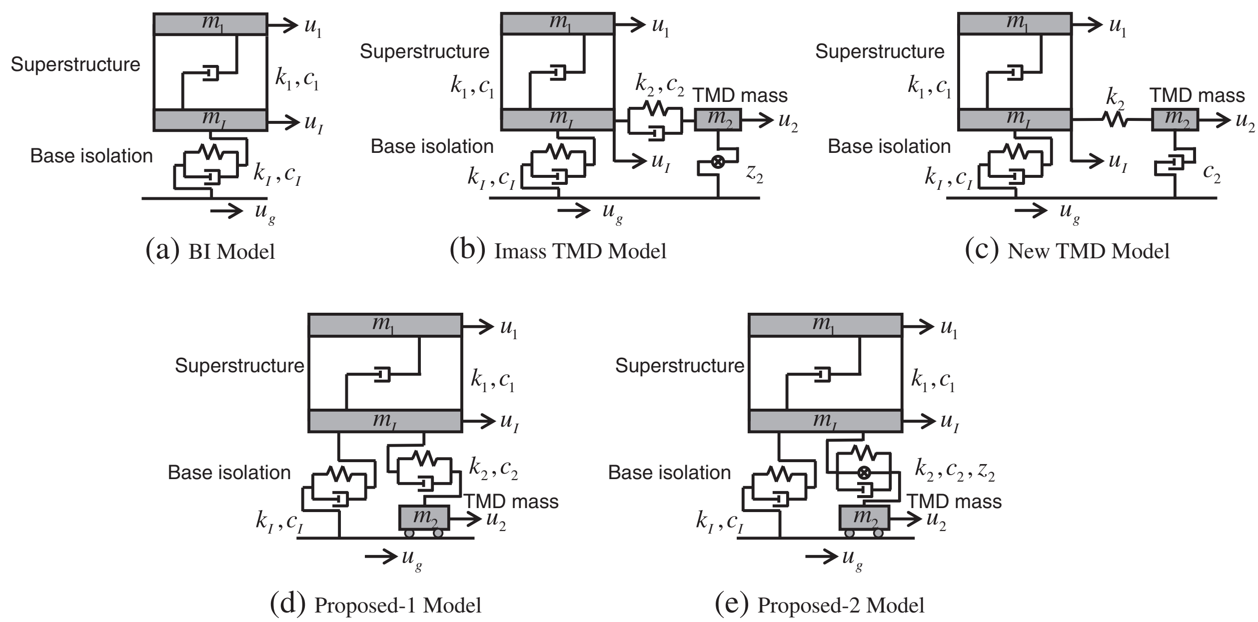


Fig. 3 Base-isolated building models treated in this paper (**a** BI Model: Simple base-isolated building, **b** Imass TMD Model: Model proposed by Nishii et al. (Nishii et al. 2013), **c** NewTMD Model: Model proposed by Xiang and Nishitani (Xiang and Nishitani 2014), **d** Proposed-1 Model: Base-isolated building with large-mass ratio TMD at basement, **e** Proposed-2 Model: Base-isolated building with large-mass ratio TMD at basement using inertial mass damper for stroke reduction)

The purpose of this paper is to propose an innovative system of base-isolated buildings with a large mass-ratio TMD at basement. The most serious issue of effect of excessive vertical load due to large mass-ratio TMD on the main building is avoided by introducing the large mass-ratio TMD at basement which is made possible due to the large displacement of a floor in the base-isolation story near basement. Another issue of large stroke of TMD even in the large mass-ratio TMD is overcome by introducing inertial mass dampers in parallel to the spring-dashpot system in the TMD system.

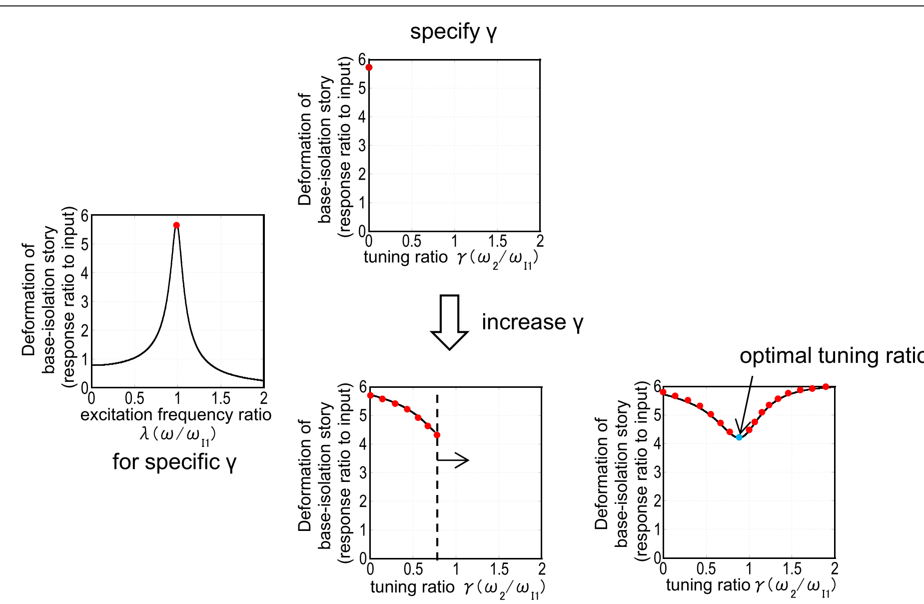


Fig. 4 Determination of stiffness of TMD (tuning of TMD)

Base-isolated building with large-mass ratio TMD at basement

Figure 1(a) shows a conventional system with small mass-ratio TMD on the roof which is effective only for wind loading. On the other hand, Fig. 1(b) presents a high-rise building with large mass-ratio TMD on the roof which is believed to be effective for long-period ground motion and to cause significant vertical load on the building. Consider next a base-isolated building system, as shown in Fig. 1(c), with large mass-ratio TMD on the roof which lengthens the fundamental natural period of the high-rise building and also causes large vertical load on the building. The models in Fig. 1(b) and (c) are thought to be unrealistic because of their excessive vertical load. Figure 2(a) indicates the proposed base-isolated building system with large mass-ratio TMD at basement using sliders and rails. This model shown in Fig. 2(a) is called the *Proposed-1 model*. In Fig. 2(a) the large mass-ratio TMD is located on the sliders and rails and in Fig. 2(b) the large mass-ratio TMD is set on the floor just above the base-isolation system.

Base-isolated building without TMD

Consider a base-isolated building without TMD. This model is called a *BI model* (see Ariga et al. 2006). Let k_I, c_I, m_I denote the stiffness, damping coefficient and mass of the base-isolation story in the BI model. Furthermore let k_1, c_1, m_1 denote the stiffness, damping coefficient and mass of the superstructure. The displacements of masses m_1 and m_I relative ground are denoted by u_1 and u_I, respectively. This model is subjected to the base ground acceleration $\ddot{u}_g$. The equations of motion for this model can be expressed by

$$\begin{pmatrix} m_I & 0 \\ 0 & m_1 \end{pmatrix}\begin{pmatrix} \ddot{u}_I \\ \ddot{u}_1 \end{pmatrix} + \begin{pmatrix} c_I + c_1 & -c_1 \\ -c_1 & c_1 \end{pmatrix}\begin{pmatrix} \dot{u}_I \\ \dot{u}_1 \end{pmatrix} + \begin{pmatrix} k_I + k_1 & -k_1 \\ -k_1 & k_1 \end{pmatrix}\begin{pmatrix} u_I \\ u_1 \end{pmatrix} = \begin{pmatrix} -m_I\ddot{u}_g \\ -m_1\ddot{u}_g \end{pmatrix} \tag{1}$$

Conventional base-isolated building with large-mass ratio TMD

Recently some systems of a base-isolated building with large-mass ratio TMD have been proposed. Mukai et al. (2005) proposed a new-type active response control system to improve the effectiveness of base-isolated buildings. In this system, the TMD mass is connected both to a superstructure and the basement (ground). A negative stiffness mechanism is used to amplify the response of the TMD mass which enables the avoidance of introduction of large mass-ratio TMD. Nishii et al. (2013) revised the system due to Mukai et al. (2005) by replacing the active damper with negative stiffness with a passive inertial mass damper system. This model is called the *Imass TMD model* in this paper. Although their system is demonstrated to be effective for the reduction of superstructure response, the performance check on the reaction of the TMD system is not conducted. Xiang and Nishitani (2014) presented a system for a base-isolated building with a TMD mass which is located on the base-isolation story level and connected directly to the ground. This model is called the *NewTMD model* in this paper. They demonstrated that their system is effective for a broad range of excitation frequency and proposed an optimization method for determining the system parameters.

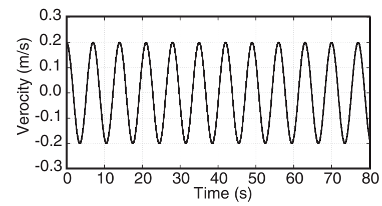


Fig. 5 Simulated long-period ground motion ($T = 7.0$ s)

Consider an Imass TMD model and a NewTMD model as shown in Fig. 3. Let k_2, c_2, m_2 denote the stiffness, damping coefficient and mass of the TMD system. z_2 indicates the inertial mass capacity of the inertial mass damper installed between TMD mass and ground in the Imass TMD model.

For later comparison, the Imass TMD model and the NewTMD model are explained in the following. The equations of motion for Imass TMD model may be expressed by

$$\begin{pmatrix} m_I & 0 & 0 \\ 0 & m_1 & 0 \\ 0 & 0 & m_2 + z_2 \end{pmatrix}\begin{pmatrix} \ddot{u}_I \\ \ddot{u}_1 \\ \ddot{u}_2 \end{pmatrix} + \begin{pmatrix} c_I + c_1 + c_2 & -c_1 & -c_2 \\ -c_1 & c_1 & 0 \\ -c_2 & 0 & c_2 \end{pmatrix}\begin{pmatrix} \dot{u}_I \\ \dot{u}_1 \\ \dot{u}_2 \end{pmatrix} + \begin{pmatrix} k_I + k_1 + k_2 & -k_1 & -k_2 \\ -k_1 & k_1 & 0 \\ -k_2 & 0 & k_2 \end{pmatrix}\begin{pmatrix} u_I \\ u_1 \\ u_2 \end{pmatrix} = \begin{pmatrix} -m_I\ddot{u}_g \\ -m_1\ddot{u}_g \\ -m_2\ddot{u}_g \end{pmatrix} \tag{2}$$

On the other hand, the equations of motion for NewTMD model may be presented by

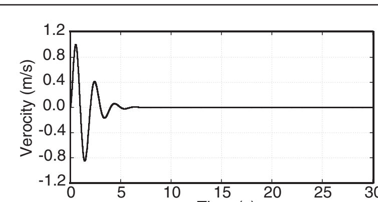


Fig. 6 Simulated pulse-type ground motion ($T = 2.0$ s)

$$\begin{pmatrix} m_I & 0 & 0 \\ 0 & m_1 & 0 \\ 0 & 0 & m_2 \end{pmatrix} \begin{pmatrix} \ddot{u}_I \\ \ddot{u}_1 \\ \ddot{u}_2 \end{pmatrix} + \begin{pmatrix} c_I + c_1 & -c_1 & 0 \\ -c_1 & c_1 & 0 \\ 0 & 0 & c_2 \end{pmatrix} \begin{pmatrix} \dot{u}_I \\ \dot{u}_1 \\ \dot{u}_2 \end{pmatrix} + \begin{pmatrix} k_I + k_1 + k_2 & -k_1 & -k_2 \\ -k_1 & k_1 & 0 \\ -k_2 & 0 & k_2 \end{pmatrix} \begin{pmatrix} u_I \\ u_1 \\ u_2 \end{pmatrix} = \begin{pmatrix} -m_I \ddot{u}_g \\ -m_1 \ddot{u}_g \\ -m_2 \ddot{u}_g \end{pmatrix} \tag{3}$$

Base-isolated building with large-mass ratio TMD at basement using inertial mass damper for stroke reduction

The equations of motion for a base-isolated building with large-mass ratio TMD at basement may be expressed by

$$\begin{pmatrix} m_I & 0 & 0 \\ 0 & m_1 & 0 \\ 0 & 0 & m_2 \end{pmatrix} \begin{pmatrix} \ddot{u}_I \\ \ddot{u}_1 \\ \ddot{u}_2 \end{pmatrix} + \begin{pmatrix} c_I + c_1 + c_2 & -c_1 & -c_2 \\ -c_1 & c_1 & 0 \\ -c_2 & 0 & c_2 \end{pmatrix} \begin{pmatrix} \dot{u}_I \\ \dot{u}_1 \\ \dot{u}_2 \end{pmatrix} + \begin{pmatrix} k_I + k_1 + k_2 & -k_1 & -k_2 \\ -k_1 & k_1 & 0 \\ -k_2 & 0 & k_2 \end{pmatrix} \begin{pmatrix} u_I \\ u_1 \\ u_2 \end{pmatrix} = \begin{pmatrix} -m_I \ddot{u}_g \\ -m_1 \ddot{u}_g \\ -m_2 \ddot{u}_g \end{pmatrix} \tag{4}$$

A base-isolated building, as shown in Fig. 2(c), with large-mass ratio TMD at basement using an inertial mass damper for stroke reduction is called the *Proposed-2 model*. A mechanism example of inertial mass dampers is shown in Fig. 2(d) (Takewaki et al. 2012a). The equations of motion for this model may be expressed by

$$\begin{pmatrix} m_I + z_2 & 0 & -z_2 \\ 0 & m_1 & 0 \\ -z_2 & 0 & m_2 + z_2 \end{pmatrix} \begin{pmatrix} \ddot{u}_I \\ \ddot{u}_1 \\ \ddot{u}_2 \end{pmatrix} + \begin{pmatrix} c_I + c_1 + c_2 & -c_1 & -c_2 \\ -c_1 & c_1 & 0 \\ -c_2 & 0 & c_2 \end{pmatrix} \begin{pmatrix} \dot{u}_I \\ \dot{u}_1 \\ \dot{u}_2 \end{pmatrix} + \begin{pmatrix} k_I + k_1 + k_2 & -k_1 & -k_2 \\ -k_1 & k_1 & 0 \\ -k_2 & 0 & k_2 \end{pmatrix} \begin{pmatrix} u_I \\ u_1 \\ u_2 \end{pmatrix} = \begin{pmatrix} -m_I \ddot{u}_g \\ -m_1 \ddot{u}_g \\ -m_2 \ddot{u}_g \end{pmatrix} \tag{5}$$

The model parameters of BI Model, Proposed-1 Model and Proposed-2 Model as shown in Fig. 3 are specified as follows. The same model parameters are used for Imass TMD Model and NewTMD Model. The influence of the rail friction on the response of the proposed

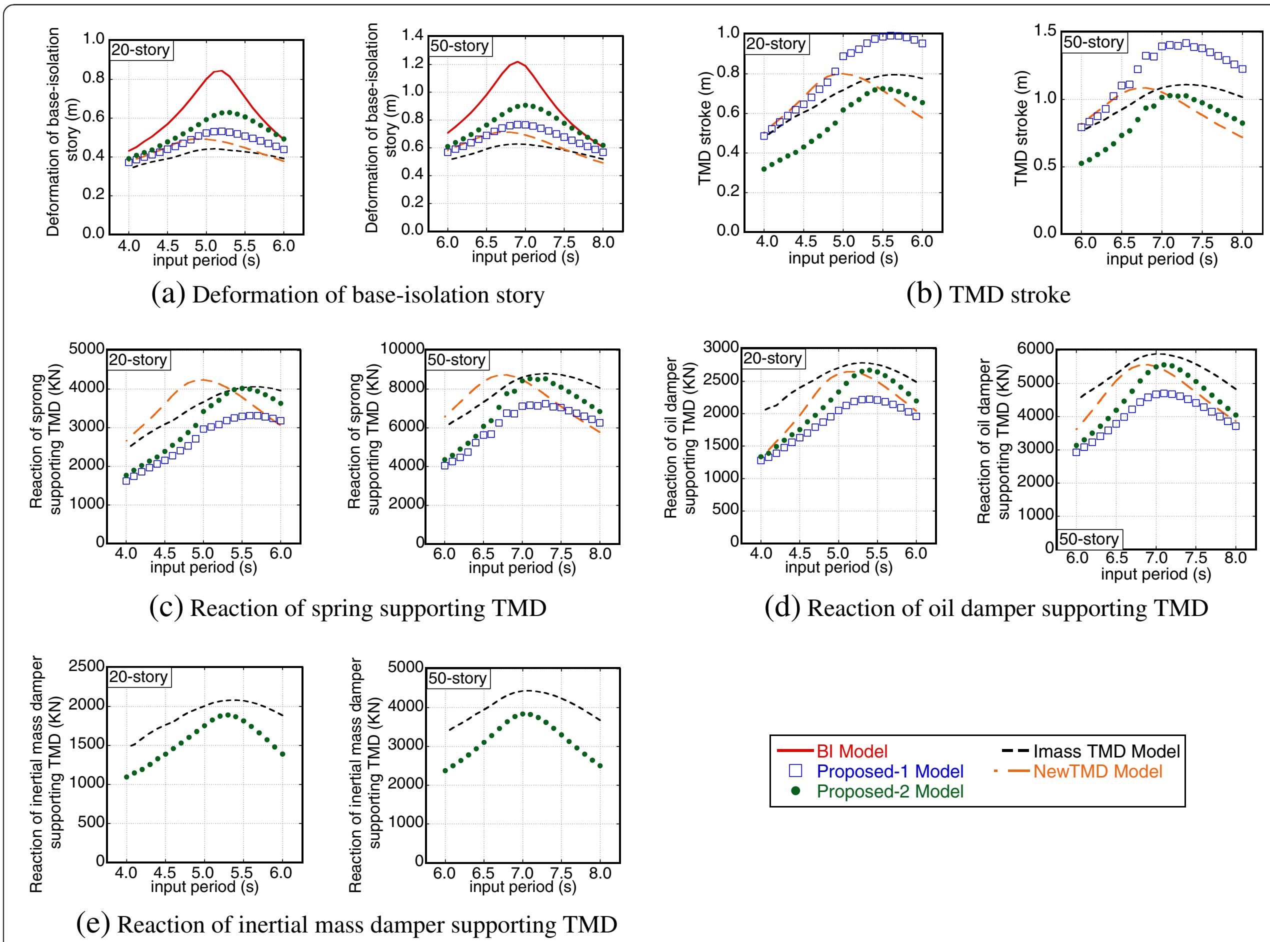


Fig. 7 Response to simulated long-period ground motion

models will be discussed in Section 'Influence of rail friction on response of proposed system'.

The superstructure is a 20-story or 50-story reinforced concrete building and is modeled into a single-degree-of-freedom (SDOF) model. This modeling into an SDOF model is thought to be appropriate in a base-isolated building. The equal story height of the original building is 3.5 m. The building has a plan of 40 × 40 m and the floor mass is obtained from 1.0×10^3 kg/m^2. The floor mass in each floor is 1.6×10^6 kg. The fundamental natural period of the superstructure with fixed base is $T_1 = 1.4$ s for a 20-story building and $T_1 = 3.5$ s for a 50-story building. The structural damping ratio is assumed to be $h_1 = 0.02$. The stiffness and damping coefficient of the SDOF model are computed by $k_1 = m_1\omega_1^2$, $c_1 = 2h_1k_1/\omega_1$ with the fundamental natural circular frequency $\omega_1 = 2\pi/T_1$.

The mass of the base-isolation story is 4.8×10^6 kg. The fundamental natural period of the BI model with rigid superstructure is $T_I = 5.0$ s for the 20-story model and $T_I = 6.0$ s for the 50-story model. The damping ratio of the BI model with rigid superstructure is $h_I = 0.1$. The stiffness and damping coefficient of the SDOF model are computed by $k_I = (m_I + m_1)\omega_I^2$, $c_I = 2h_Ik_I/\omega_I$ with the fundamental natural circular frequency $\omega_I = 2\pi/T_I$. As for TMD, the mass ratio m_2/m_1 is set to $\mu = 0.1$ and the inertial mass damper ratio z_2/m_1 is set to $\eta_s = 0.06$. The damping ratio is assumed to be $h_2 = 0.3$. The stiffness and damping coefficient of TMD are given by $k_2 = (m_2 + z_2)\omega_2^2$, $c_2 = 2h_2k_2/\omega_2$ in terms of the natural circular frequency ω_2 of TMD . The process of determining ω_2 is explained in Section 'Determination of stiffness and damping coefficient of TMD'.

Determination of stiffness and damping coefficient of TMD

In this section, the procedure of determination of stiffness and damping coefficient of TMD for the proposed model, Imass TMD model and NewTMD model is explained. The tuning of TMD is performed by minimizing the response ratio D of the deformation of the base-

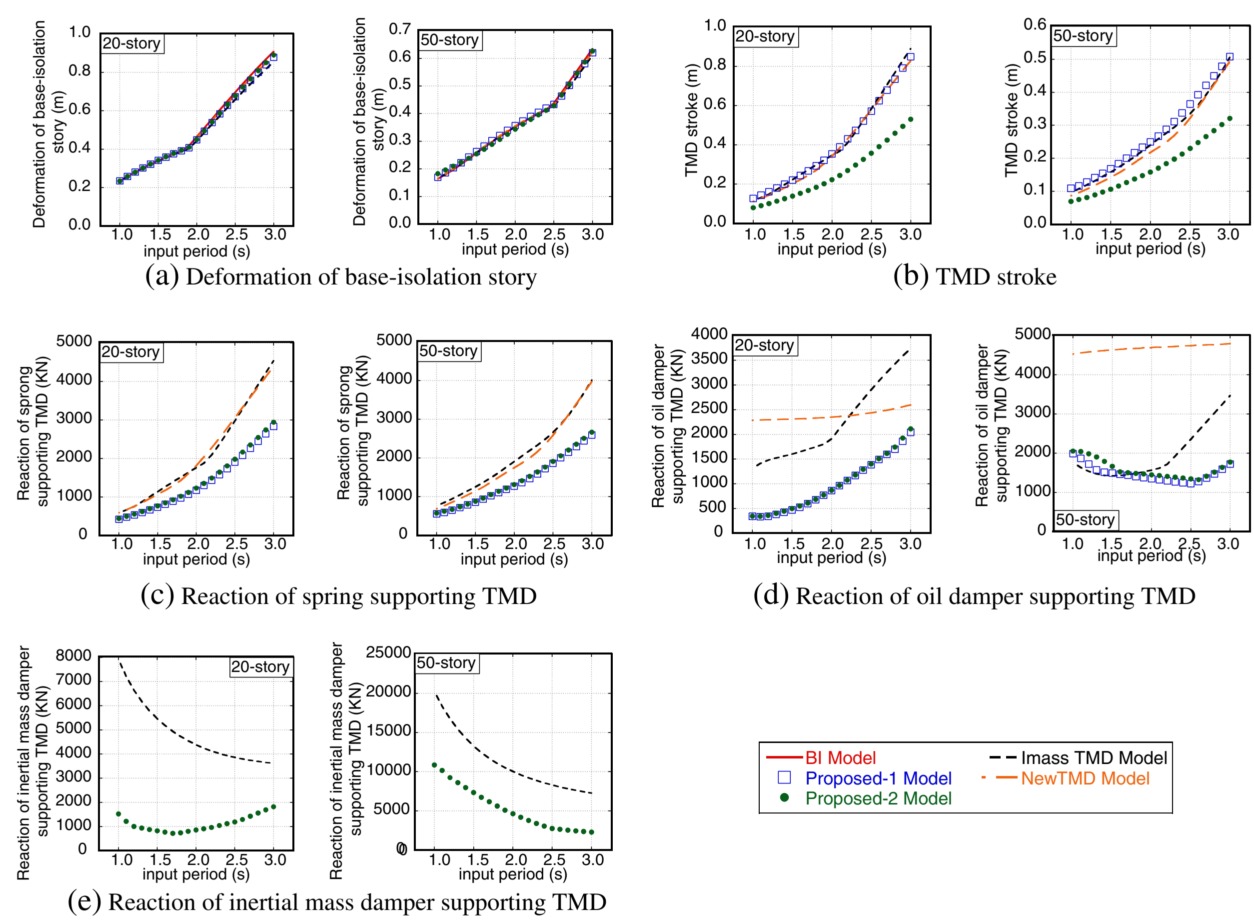


Fig. 8 Response to simulated pulse-type ground motion

isolation story to the base input (displacement amplitude) as shown in Fig. 4.

Let us assume the input ground acceleration as

$$\ddot{u}_g = Ae^{i\omega t} \tag{6}$$

The harmonic response of the systems may be expressed by

$$(\, u_I \quad u_1 \quad u_2 \,) = (\, U_I \quad U_1 \quad U_2 \,) e^{i\omega t} \tag{7}$$

By solving the equations of motion, the response amplitude may be obtained as

$$(\, U_I \quad U_1 \quad U_2 \,)^T = \left(-\omega^2 \mathbf{M} + i\omega \mathbf{C} + \mathbf{K}\right)^{-1} \times (\, -m_I A \quad -m_1 A \quad -m_2 A \,)^T \tag{8}$$

where $()^T$ indicates the matrix transpose. The displacement response ratio D can then be defined by

$$D = \left| \frac{U_I}{A/\omega_{I1}^2} \right| \tag{9}$$

where ω_{I1} is the undamped natural circular frequency of the BI model.

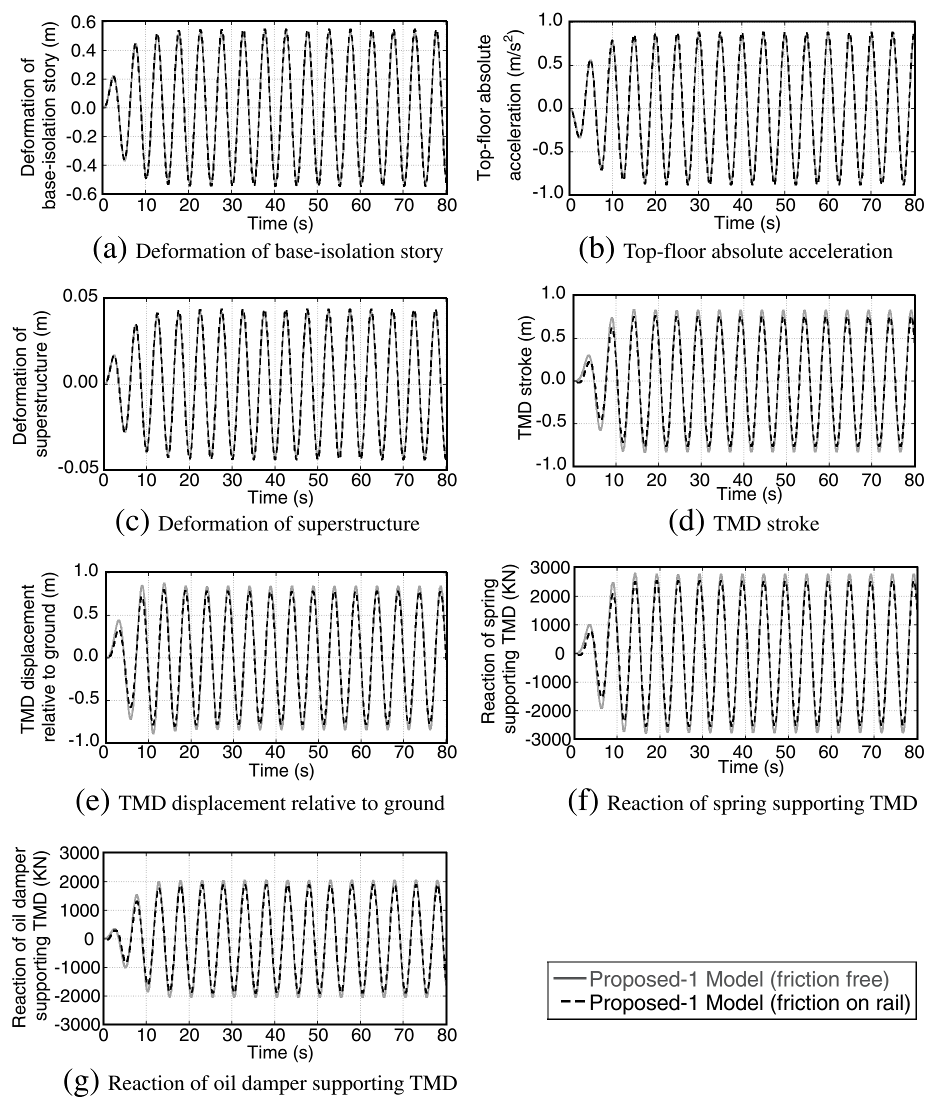


Fig. 9 Influence of friction on rail in Proposed-1 Model subjected to simulated long-period ground motion (20-story, input period $T = 5.0$ s)

Response reduction performance of proposed system for simple base-isolated building and conventional base-isolation-TMD hybrid system

Simulated long-period ground motion and simulated pulse-type ground motion

Let us assume the simulated long-period ground motion in terms of circular frequency $\omega = 2\pi/T$ (T: period) as

$$\ddot{u}_g = A\sin\omega t \tag{10}$$

Figure 5 shows a simulated long-period ground motion with $T = 7.0$(s).

On the other hand, let us assume the simulated pulse-type ground motion as

$$\dot{u}_p = Ct^n e^{-at}\sin\omega_p t \tag{11}$$

$$\ddot{u}_p = Ct^n e^{-at}\left[\left(\frac{n}{t} - a\right)\sin\omega_p t + \omega_p\cos\omega_p t\right] \tag{12}$$

where C: an amplitude coefficient, a: reduction coefficient, n: envelope shape coefficient, $\omega_p = 2\pi/T$:circular frequency (see Xu et al. 2007). C is determined so as to control the maximum velocity and a is determined from $a = 0.4\omega_p$. The maximum ground velocity is set to 0.91(m/s) (the maximum velocity of JMA Kobe NS 1995). The period of the pulse wave is specified in the range of 1.0 ~ 3.0(s) with 0.1(s) as the increment. Figure 6 shows the pulse-type wave of $T = 2.0$(s).

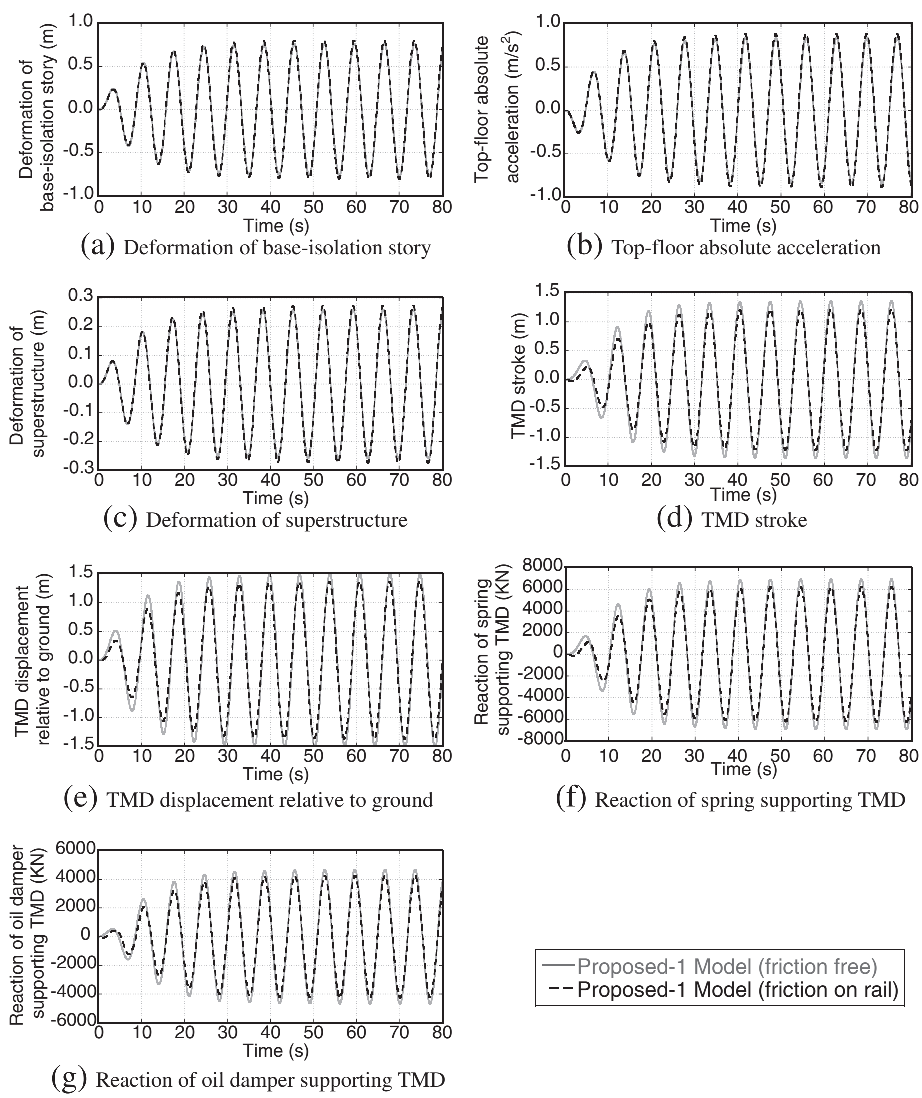


Fig. 10 Influence of friction on rail in Proposed-1 Model subjected to simulated long-period ground motion (50-story, input period $T = 7.0$ s)

Response reduction performance of proposed system for simple base-isolated building

Figure 7 shows the comparison of various performances under simulated long-period ground motion among BI model, Proposed-1 model, Proposed-2 model, Imass TMD model and NewTMD model. The performances to be compared are (a) Deformation of base-isolation story, (b) TMD stroke, (c) Reaction of spring supporting TMD, (d) Reaction of oil damper supporting TMD, (e) Reaction of inertial mass damper supporting TMD. The left figures are for 20-story models and the right figures are for 50-story models. It can be observed that Proposed-1 model can reduce the deformation of base-isolation story by about 38 % compared to BI model and Proposed-2 model can decrease TMD stroke by about 27 % compared to Proposed-1 model.

On the other hand, Fig. 8 illustrates the comparison of those performances under simulated pulse-type ground motion. As in Fig. 7, the left figures are for 20-story models and the right figures are for 50-story models. It can be observed that the deformation of base-isolation story of Proposed-1 model and Proposed-2 model does not change so much from BI model and the base-isolation performance can be kept. Furthermore Proposed-2 model can reduce the TMD stroke by about 38 % compared to Proposed-1 model.

Response reduction performance of proposed system for conventional base-isolation-TMD hybrid system

It is meaningful to note that, while TMD is connected to the base-isolation floor in the proposed models (Proposed-1 model and Proposed-2 model), TMD is connected both to the base-isolation floor and ground in the conventional base-isolation-TMD hybrid system (Imass TMD model and NewTMD model). For this reason the

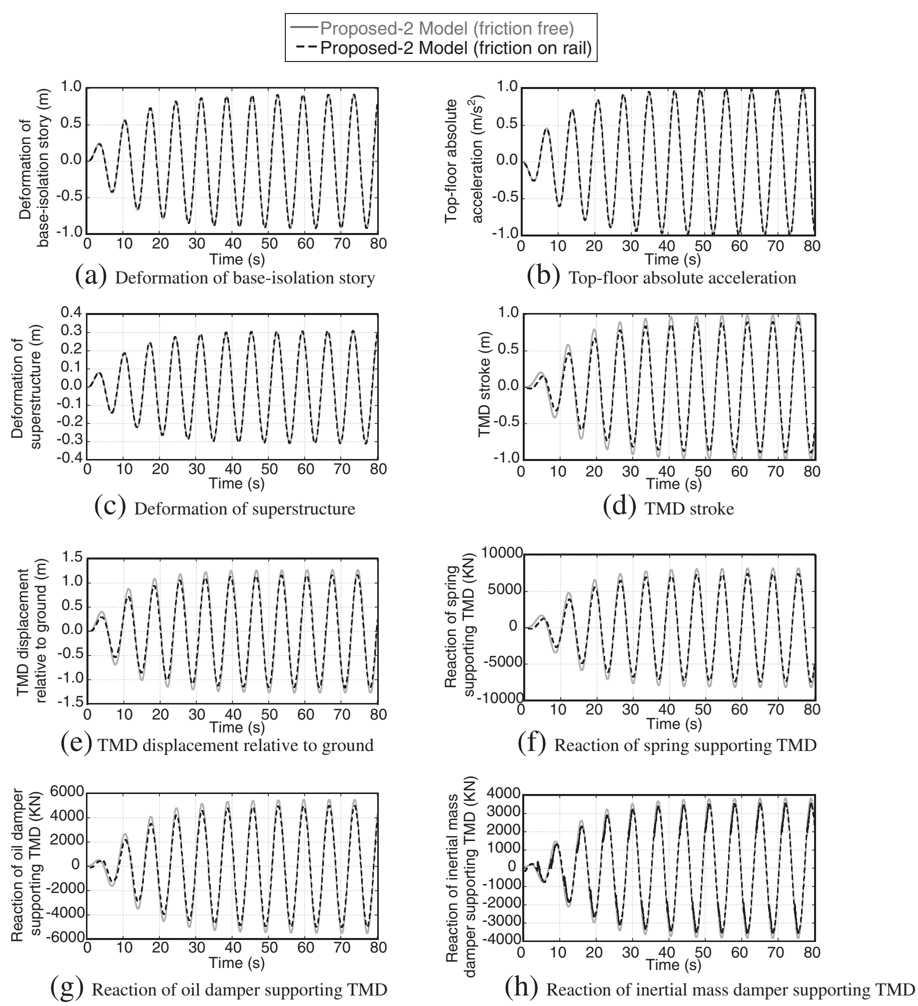


Fig. 11 Influence of friction on rail in Proposed-2 Model subjected to simulated long-period ground motion (50-story, input period $T = 7.0$ s)

TMD reactions become relatively large in Imass TMD model and NewTMD model.

Although the proposed system (Proposed-2 model) increases the building response under a long-period ground motion slightly compared to the system without an inertial mass damper (Proposed-1 model), the response is still smaller than that of a base-isolated building without TMD. In addition, the proposed system (Proposed-2 model) can reduce the TMD stroke under a long-period ground motion owing to the inertial mass damper. Furthermore, the proposed system (Proposed-2 model) can also reduce the TMD stroke under a pulse-type ground motion owing to the inertial mass damper.

It can be concluded that the proposed systems (Proposed-1 model and Proposed-2 model) can reduce the TMD stroke and TMD reaction effectively compared to the conventional NewTMD model and Imass TMD model for both long-period ground motions and pulse-type ground motions.

Influence of rail friction on response of proposed system

Since the friction on rail in the TMD system could affect the performance of the proposed control system, its influence has been investigated. Although the static friction behavior is usually different from the dynamic one, the static friction coefficient has been treated as the same as the dynamic one. In this paper, the friction coefficient 0.008 has been used. In order to simulate the friction on rail, an elastic-perfectly plastic relation has been utilized and the initial stiffness has been specified as 1.0×10^{10}(N/m).

Figure 9 shows the influence of friction on rail in Proposed-1 Model subjected to simulated long-period

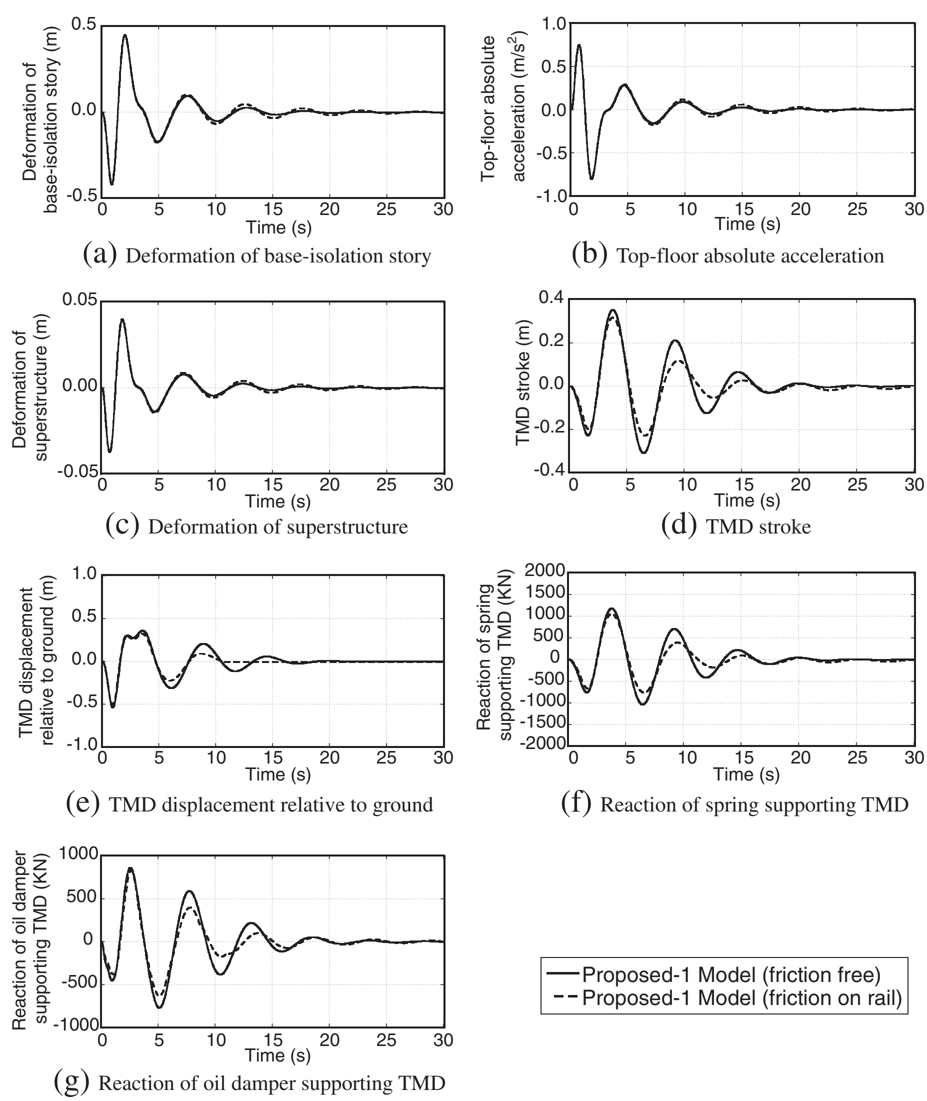


Fig. 12 Influence of friction on rail in Proposed-1 Model subjected to simulated pulse-type motion (20-story, input period $T = 2.0$ s)

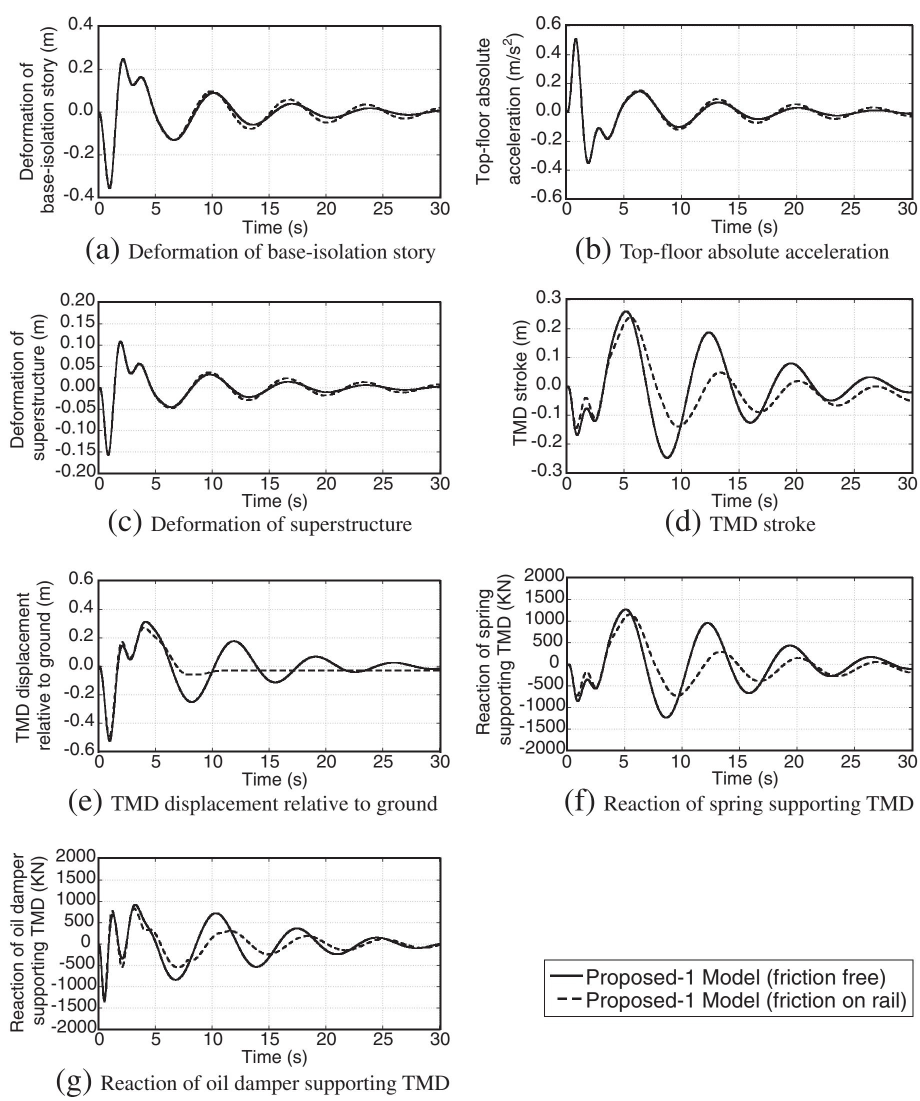
ground motion (20-story, input period $T = 5.0$ s). Figure 10 illustrates the influence of friction on rail in Proposed-1 Model subjected to simulated long-period ground motion (50-story, input period $T = 7.0$ s). Furthermore Fig. 11 presents the influence of friction on rail in Proposed-2 Model subjected to simulated long-period ground motion (50-story, input period $T = 7.0$ s).

On the other hand, Fig. 12 shows the influence of friction on rail in Proposed-1 Model subjected to simulated pulse-type motion (20-story, input period $T = 2.0$ s). Figure 13 illustrates the influence of friction on rail in Proposed-1 Model subjected to simulated pulse-type motion (50-story, input period $T = 2.0$ s). Furthermore Fig. 14 presents the influence of friction on rail in Proposed-2 Model subjected to simulated pulse-type motion (50-story, input period $T = 2.0$ s). It can be observed that, while the reactions of TMD supports and TMD stroke are affected slightly in a damped process, the superstructure response and base-isolation story response are not affected so much.

It can be concluded that, although the frictions of TMD mass on rail in the proposed systems reduce the TMD stroke for both long-period ground motions and pulse-type ground motions, those do not affect so much on the building response.

Reduction of TMD stroke using various methods

In the large mass-ratio TMD, the reduction of stroke of TMD is a key issue. Figure 15 shows several attempts to implement it. Proposed-1 model is a basic model. As its derivatives, Proposed-1-1 model (detuning), Proposed-1-2 model (increased damping) and Proposed-1-3 model (increased TMD mass-ratio) are considered. Furthermore Proposed-2 model is a derivative of Proposed-1



(a) Deformation of base-isolation story (b) Top-floor absolute acceleration (c) Deformation of superstructure (d) TMD stroke (e) TMD displacement relative to ground (f) Reaction of spring supporting TMD (g) Reaction of oil damper supporting TMD

Fig. 13 Influence of friction on rail in Proposed-1 Model subjected to simulated pulse-type motion (50-story, input period $T = 2.0$ s)

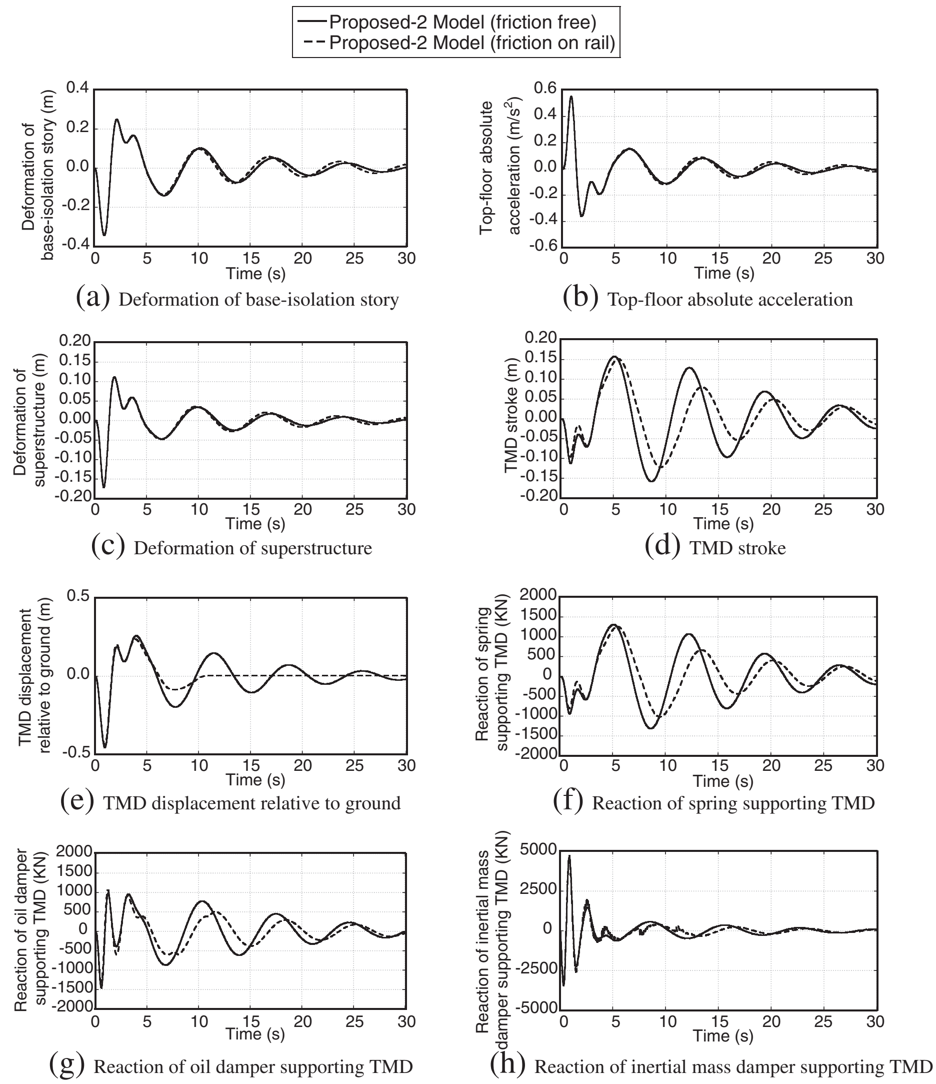


Fig. 14 Influence of friction on rail in Proposed-2 Model subjected to simulated pulse-type motion (50-story, input period $T = 2.0$ s)

model and includes an inertial mass damper in TMD. The Imass TMD model is also a derivative of Proposed-1 model and has an inertial mass damper between TMD mass and ground.

Table 1 shows design conditions on TMD parameters in above-mentioned several models for stroke reduction. The TMD parameters have been determined so as the reduction of TMD stroke from Proposed-1 model under a long-period ground motion to be almost equivalent.

Figure 16 shows the responses ((a) deformation of base-isolation story, (b) Top-floor absolute acceleration, (c) Superstructure deformation, (d) TMD stroke, (e) TMD displacement relative to ground (f) Reaction of spring supporting TMD, (g) Reaction of oil damper supporting TMD, (h) Reaction of inertial mass damper supporting TMD) to a long-period ground motion and Fig. 17 shows those responses to a pulse-type ground motion. The comprehensive comparison of the response characteristics in Fig. 16 will be shown in Fig. 20 and Table 2. A similar comparison of the response characteristics in Fig. 17 will be shown in Fig. 21 and Table 2.

Figure 18 shows the comparison with BI model under a pulse-type motion and Fig. 19 indicates the comparison with Proposed-1 model under a pulse-type motion. The comprehensive comparison of the response properties in Figs. 18 and 19 will be shown in Fig. 21 and Table 2.

Figure 20 illustrates the response comparison under a long-period ground motion. The maximum responses with respect to the input period have been taken. It can be observed that, while Imass TMD model is superior to Proposed-2 model in superstructure responses to some extent, Proposed-2 model is superior to Imass TMD model in TMD reactions. On the other hand, Fig. 21 shows the response comparison under a pulse-type ground motion

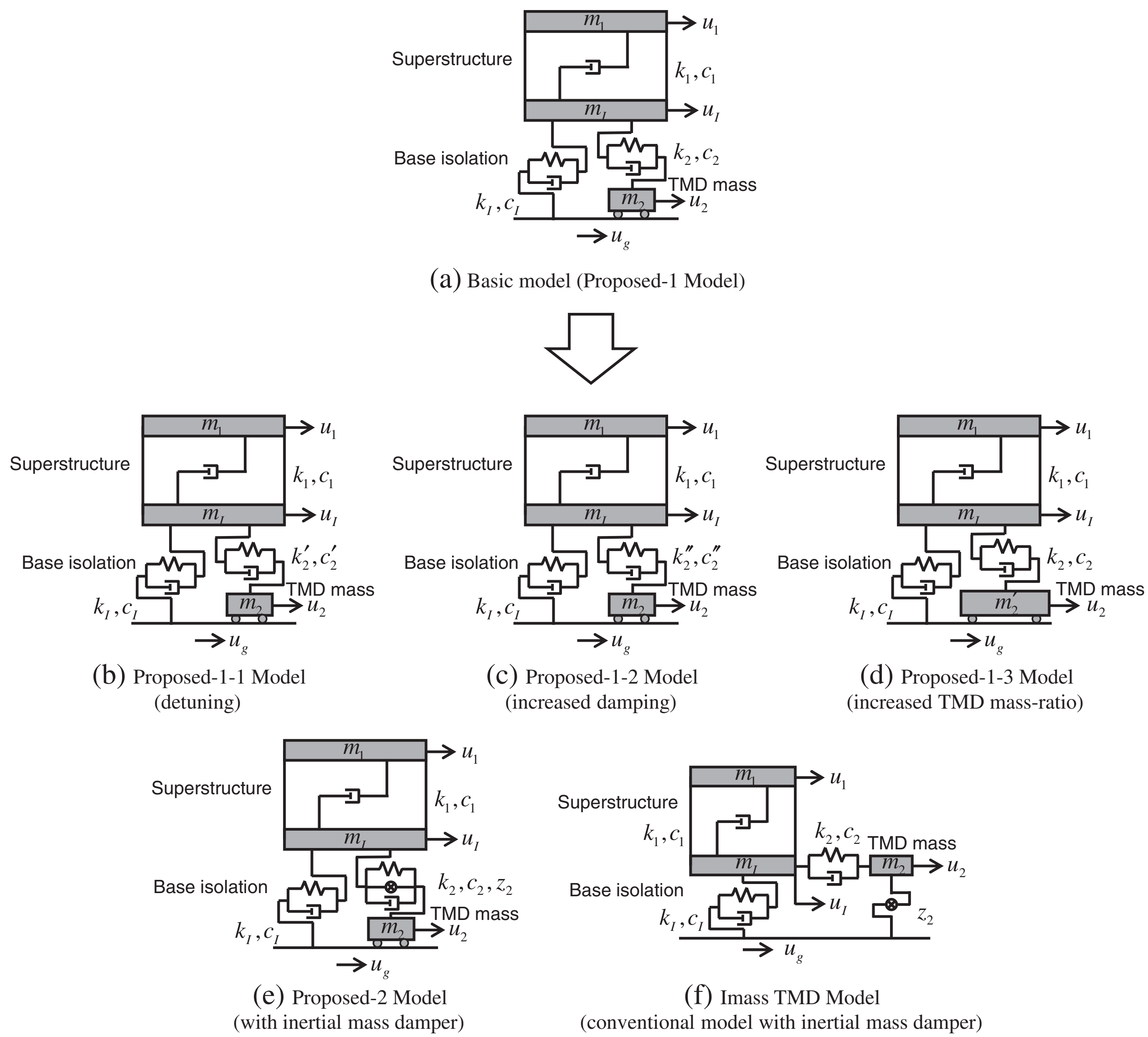


Fig. 15 Several proposed models and conventional model for TMD stroke reduction

Table 1 Design conditions on TMD parameters in several models for TMD stroke reduction

	Proposed-1 Model as basic model	Proposed-1-1 Model (detuning)	Proposed-1-2 Model (increased damping)	Proposed-1-3 Model (increased TMD mass-ratio)	Proposed-2 Model (with inertial mass damper)	Imass TMD Model (conventional model with inertial mass damper)
TMD mass-ratio μ	10 %	10 %	10 %	26.7 %	10 %	10 %
Inertial mass damper ratio η_s	–	–	–	–	0.06	0.08685
TMD damping ratio h_2	0.3	0.3	0.535	0.3	0.3	0.3
Tuning ratio γ	0.8780	1.2430	0.7540	0.7880	0.8850	0.8950

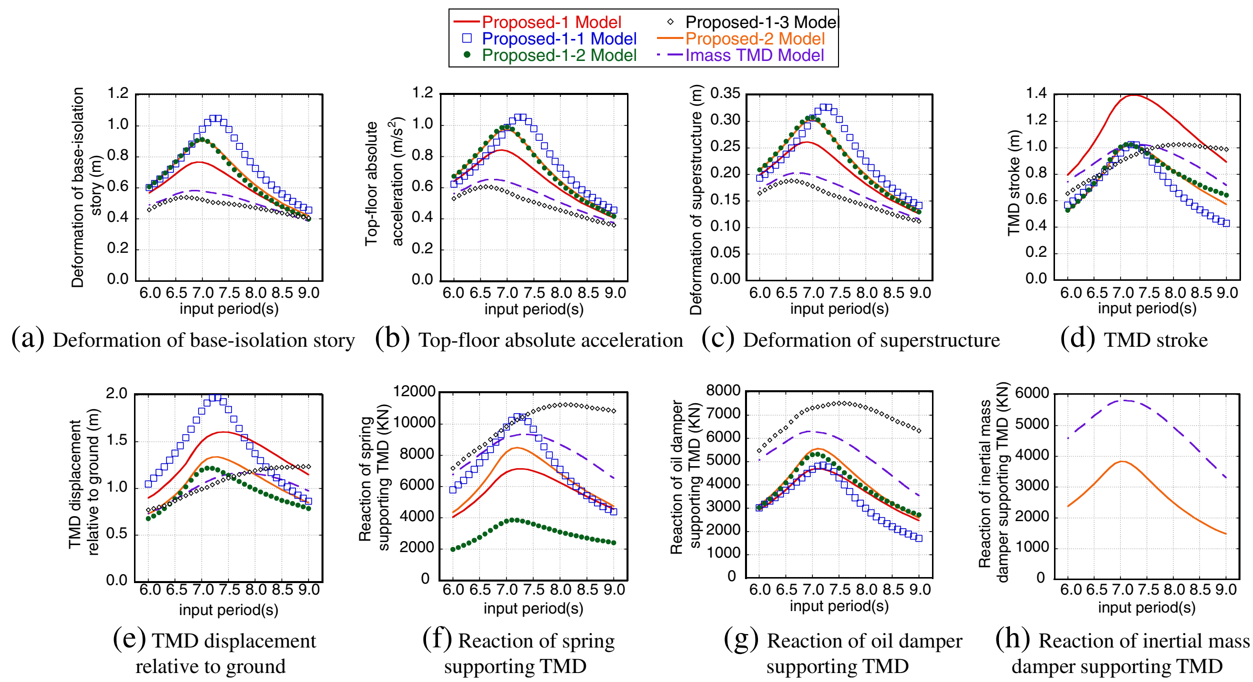


Fig. 16 Response to long-period ground motion

Table 2 Response comparison among proposed models and conventional models under long-period and pulse-type ground motions

	Proposed-1-1 Model	Proposed-1-2 Model	Proposed-1-3 Model	Proposed-2 Model	Imass TMD Model	NewTMD Model
Long-period ground motion						
Deformation of base-isolation story	×	△	◎	△	◎	○
Top-floor absolute acceleration	×	△	◎	△	◎	•
Deformation of superstructure	×	△	◎	△	◎	•
TMD stroke	Similar reduction from Proposed-1 Model					
TMD displacement relative to ground	×	◎	○	○	◎	◎
Reaction of spring supporting TMD	×	◎	×	△	×	△
Reaction of oil damper supporting TMD	•	△	×	△	×	△
Reaction of inertial mass damper supporting TMD	–	–	–	◎	×	–
Pulse-type ground motion						
Deformation of base-isolation story	•	•	•	•	•	•
Top-floor absolute acceleration	•	•	•	•	•	•
Deformation of superstructure	•	•	•	•	•	•
TMD stroke	◎	○	•	◎	•	○
TMD displacement relative to ground	•	•	•	○	◎	○
Reaction of spring supporting TMD	△	◎	×	•	△	△
Reaction of oil damper supporting TMD	△	△	×	•	×	×
Reaction of inertial mass damper supporting TMD	–	–	–	◎	×	–

◎: excellent performance, ○: good performance, △: fair performance, ×: ordinary performance
•: small change from Proposed-1 model

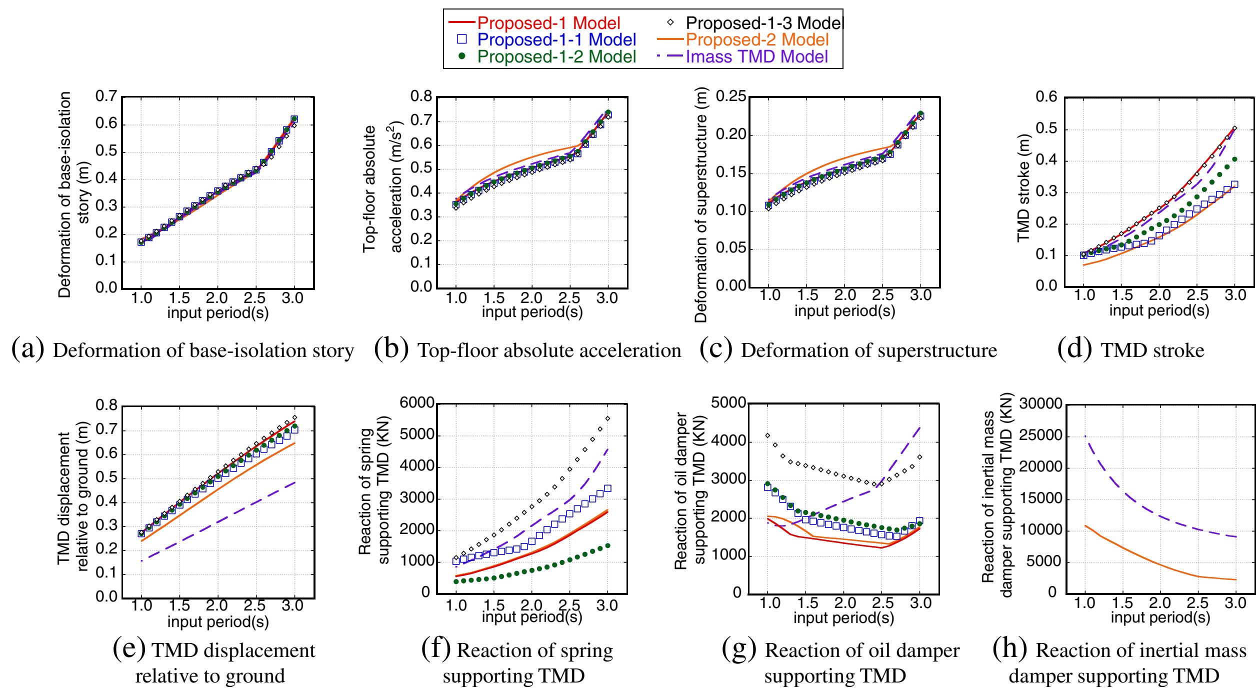


Fig. 17 Response to pulse-type ground motion

(comparison to BI Model and Proposed-1 Model, comparison of inertial mass damper reaction in Imass TMD Model to Proposed-2 Model). For pulse-type ground motions without peak with respect to input period, Fig. 21 has been derived from Figs. 18 and 19. It can be observed that, while Proposed-2 model and Imass TMD model are almost equivalent in superstructure responses, Proposed-2 model is highly superior to Imass TMD model in TMD stroke and TMD reactions.

Table 2 presents the response comparison of the proposed models and conventional models with Proposed-1 model under long-period ground motion and pulse-type ground motion. Proposed-1-1 model exhibits a good TMD stroke reduction performance under pulse-type ground motion against Proposed-1 model while the structural response under long-period ground motion increases. Proposed-1-2 model has a good reduction performance of TMD spring reaction under long-period ground motion and pulse-type ground motion against Proposed-1 model. Proposed-1-3 model shows a good reduction performance of structural response under long-period ground motion against Proposed-1 model while the TMD-supporting member reactions under long-period ground motion and pulse-type ground motion cause some problems. Proposed-2 model exhibits a good reduction performance of TMD stroke under pulse-type ground motion against Proposed-1 model and a good reduction performance of TMD-supporting inertial mass damper reaction under long-period ground motion and pulse-type ground motion against Imass TMD model. Imass model shows a good reduction performance of structural response under long-period ground motion against

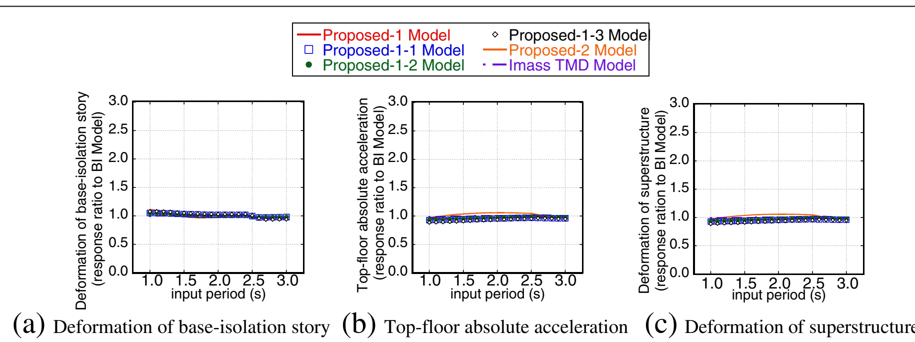


Fig. 18 Comparison with BI Model under pulse-type ground motion

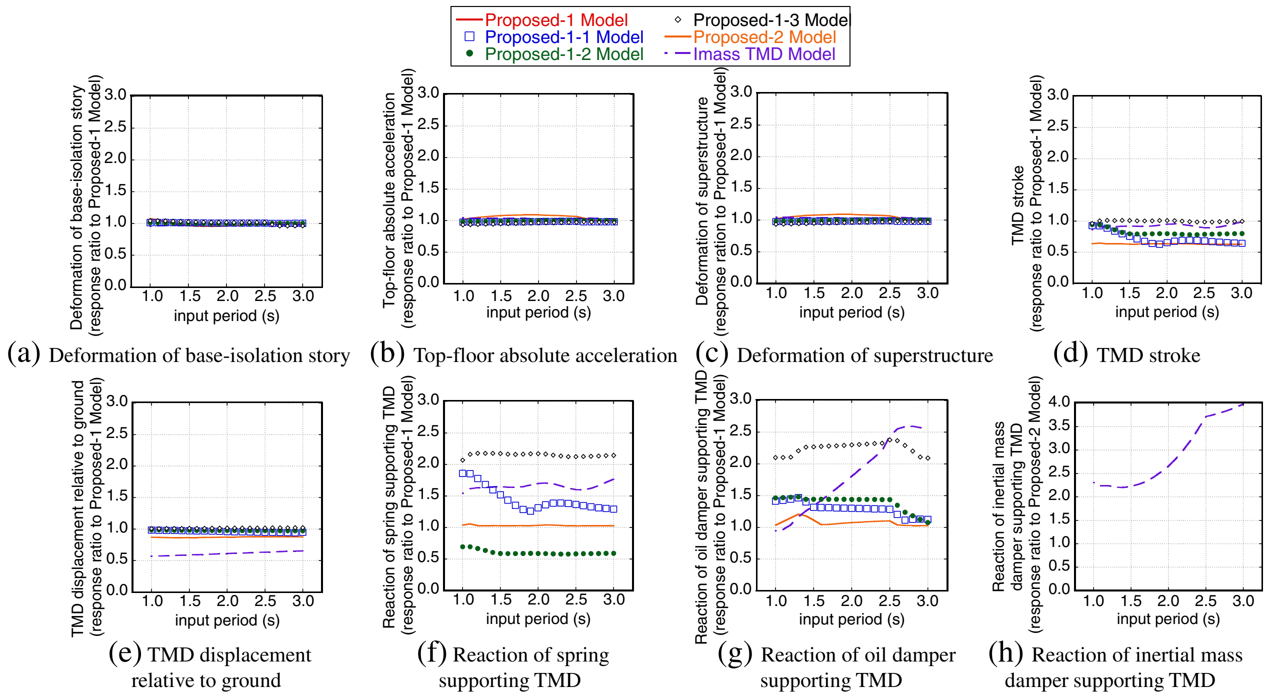


Fig. 19 Response comparison under pulse-type motion (comparison to Proposed-1 Model, comparison of inertial mass damper reaction in Imass TMD Model to Proposed-2 Model)

Proposed-1 model while the TMD-supporting member reactions under long-period ground motion and pulse-type ground motion cause some problems. NewTMD model exhibits a good reduction performance of relative displacement of TMD mass to ground under long-period ground motion against Proposed-1 model while the TMD-supporting member reactions under long-period ground motion and pulse-type ground motion cause some problems.

It is important to investigate the sensitivity of the system response to the change of the frequency of long-period ground motions. When the input frequency of long-period ground motions changes from the resonant situation, the TMD stroke and the reaction in the TMD decrease. Furthermore it has been confirmed that the response reduction performance in the TMD stroke and the reaction in the TMD is high in the proposed system compared to the conventional systems.

Conclusions

The following conclusions have been derived.

(1) In order to overcome the difficulties caused by the resonance of a base-isolated building under long-period ground motions and the ineffectiveness of TMD under pulse-type ground motions, a base-isolated building with a large mass-ratio TMD at basement has been introduced. This new base-isolated building system is also aimed at enhancing the earthquake resilience of high-rise buildings. The proposed hybrid system of base-isolation and structural control is effective for both long-period ground motions and pulse-type ground motions. This hybrid system possesses advantageous features compared to existing comparable systems with a TMD at the base-isolation story. The TMD stroke can be reduced to a small level with the use of an inertial mass damper and its reaction can be limited to a lower level by detaching its connection to ground. The proposed hybrid system has another advantage that the TMD mass does not bring large gravitational effect on the building itself because of the placement of TMD at basement.

(2) The proposed system (Proposed-1 model) can reduce the building response under a long-period ground motion by 38 % compared to the base-isolated building and keeps the base-isolation performance under a pulse-type ground motion.

(3) Although the proposed system (Proposed-2 model) increases the building response under a long-period ground motion slightly compared to the system without an inertial mass damper, the response is still smaller than that of a base-isolated building without TMD (BI model). In addition, the proposed system (Proposed-2 model) can reduce the TMD stroke under a long-period ground motion owing to the inertial mass damper. Furthermore, the proposed

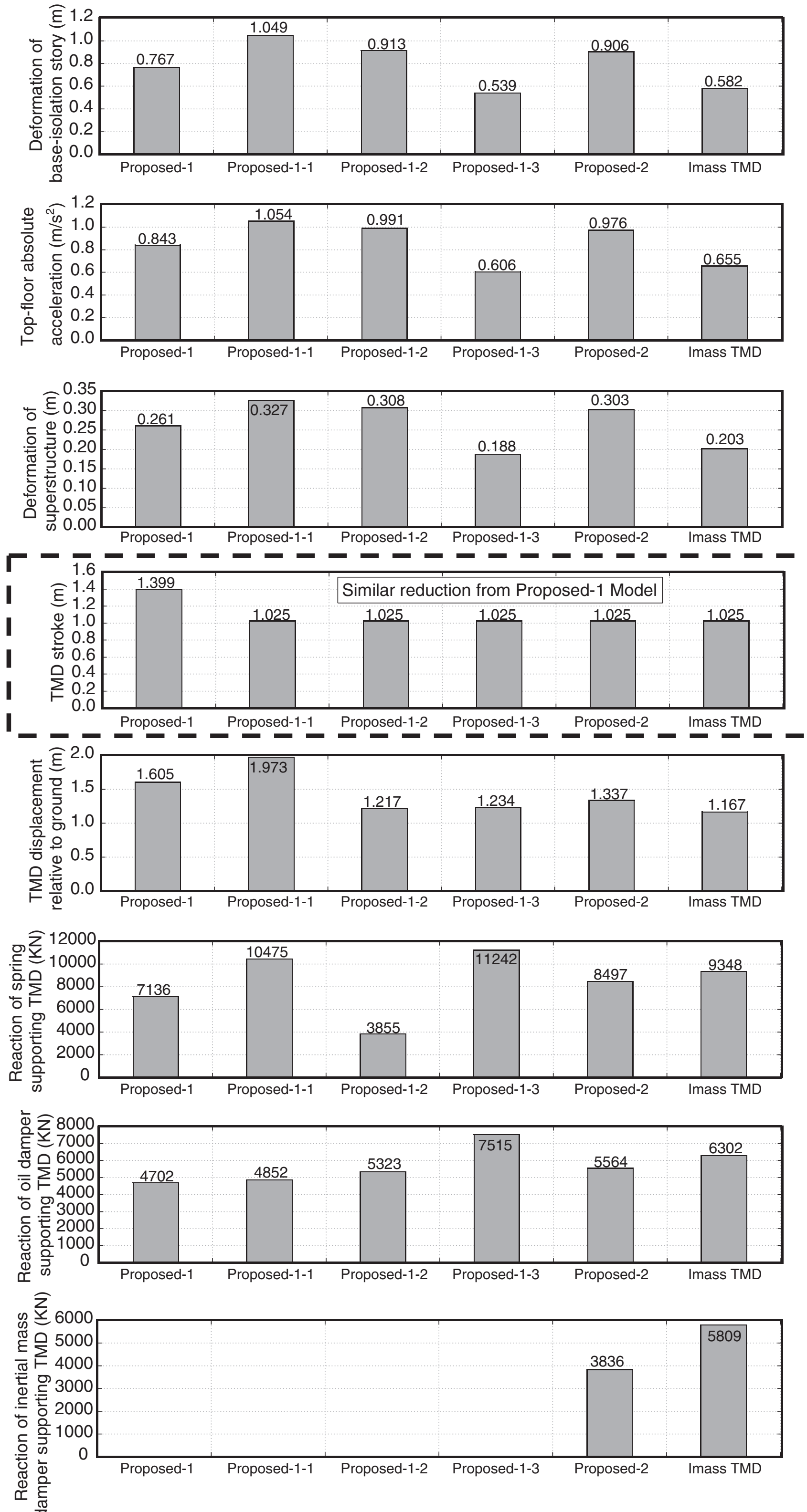


Fig. 20 Response comparison under long-period ground motion

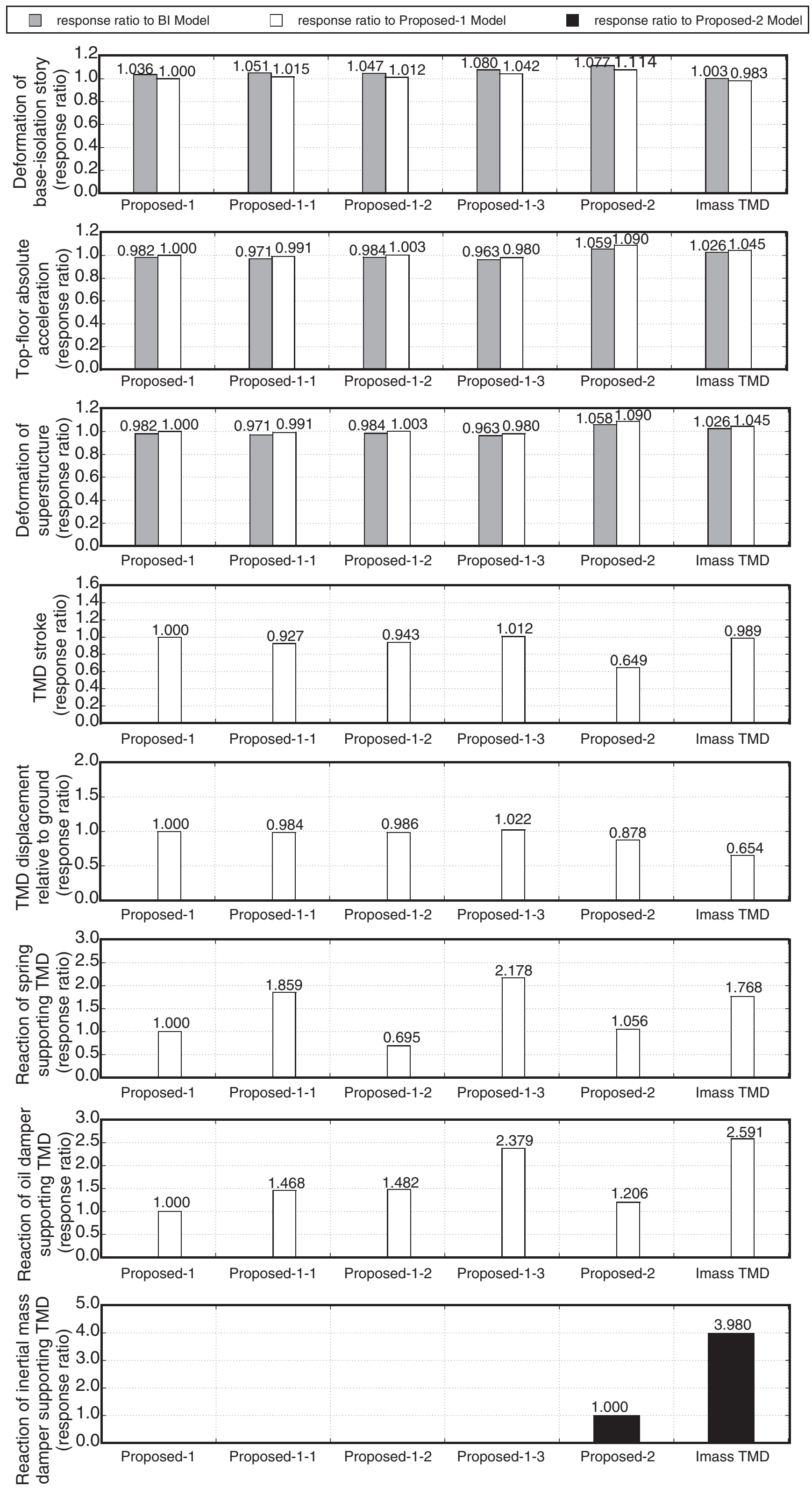


Fig. 21 Response comparison under pulse-type ground motion (comparison to BI Model and Proposed-1 Model, comparison of inertial mass damper reaction in Imass TMD Model to Proposed-2 Model)

system (Proposed-2 model) can reduce the TMD stroke under a pulse-type ground motion owing to the inertial mass damper.

(4) The proposed system (Proposed-1 model and Proposed-2 model) can reduce the TMD stroke and TMD reaction effectively compared to the conventional NewTMD model and Imass TMD model for both long-period ground motions and pulse-type ground motions.

(5) Although the frictions of TMD mass on rails in the proposed systems reduce the TMD stroke for both long-period ground motions and pulse-type ground motions, those do not affect so much on the building response.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

TH carried out the theoretical and numerical analysis of the proposed TMD system. KF helped the numerical analysis. MT strengthened the theoretical analysis. IT supervised the theoretical analysis and organized the research group. All authors read and approved the final manuscript.

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