



Seismic performance analysis of structure equipped with tuned mass dampers considering nonlinear soil-structure interaction effects

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ABSTRACT

Tuned mass dampers (TMDs) as a vibration control device are widely implemented in many types of structures subjected to seismic loading. The conventional design theory of TMD is based on the assumption of a fixed foundation. When the soil-structure interaction (SSI) effect is prominent, the vibration characteristics of the controlled structure will be changed, which may limit the effectiveness of TMD. In the present study, we aim to comprehensively investigate the effectiveness of TMD by performing seismic response analysis considering nonlinear soil-structure interaction effects. A three-dimensional (3D) finite element model of soil-pile foundation-structure-TMD system is first built. The reduced seismic response of the TMD considering SSI is investigated. The comprehensive parametric sensitivity analysis is carried out, including ground motions, and soil shear wave velocity. The effect of different main structure frequencies on the seismic reduction performance of the TMD is investigated. The results reveal that the SSI effect has a detrimental effect on the effectiveness of TMD. The structural seismic response can be reduced after considering the soil nonlinear, and the soil nonlinear is favorable to the effectiveness of TMD. The performance of TMD is significantly related to the characteristics of the input ground motions. The TMD reduction performance is improved for large mass ratios. The dampers' stiffness and damping of the TMD system are specified according to the TMD design criteria, and the TMD provides better effectiveness performance. The design criterion based on soil-structure system frequency can significantly increase TMD performance for soft soil conditions compared with the design criterion based on the fixed foundation.

1. Introduction

Structural control techniques have been widely adopted to mitigate the vibration of structures subjected to earthquakes. In the past, numerous structural control devices have been developed, which can be divided into three main categories: passive control, active control, and semi-active control. As an effective passive control device, the tuned mass damper (TMD) has been applied in civil engineering fields including building structures, bridges, tall towers, and offshore platforms [1–5]. The TMD composed of a mass, viscous damper, and spring is attached to the structure and arranged at a specific location to tune the response of the controlled structure [6]. The efficiency of TMD in reducing structural response depends on the frequency ratio between TMD and the main structure, so the structural dynamic characteristic information is very important for the optimal design of TMD. Many

studies have been done to optimize the TMD parameters including mass, stiffness, and damping [7–9], and enhance TMD tuning robustness by large mass ratio TMD [10,11], particle TMD [12], MTMD [13], and semi-active TMD [14–16]. The structure will enter a nonlinear stage under the excitation of strong earthquakes. Wang uses the Bouc-Wen (BW) model to model the nonlinear problem of the structure. After considering structural nonlinear, the traditional TMD's reduced performance may have an undesirable effect. The semi-active TMD still has better reduction performance for structural seismic response [17–19]. The TMD design parameters have an impact on the reduction of seismic response. Therefore, Reza Kamgar [20–22] investigated the optimization of the design parameters of the TMD to improve the performance level of steel structures in earthquakes. The results show that the TMD with the optimized design has a better performance. Mohammad Alibabaei Shahraki [23] further investigated the reduction of damage's

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value in the structure by TMDs. The Park-Ang damage index was utilized as an objective function to determine the optimal number and parameters of TMDs. The results show that the proposed method's ability to improve the structure's seismic performance is greater than the Den-Hartog method.

The classic design method [24] for TMD is based on the assumption of a fixed foundation, while many buildings are built on flexible foundations and there is dynamic interaction between soil and structure. Soil-structure interaction (SSI) effects may significantly change the structural dynamic characteristics, especially for soft soil sites or high-stiffness structures, and therefore reduce the effectiveness of TMD [25–28]. In recent research, SSI effects have been taken into account in the investigation of TMD-tuned vibration mitigation performance. Mohammad Alibabaei Shahraki [29] proposed a novel elastoplastic-tuned mass damper inverter (PTMDI). The performance of the PTMDI is investigated under the SSI effects. The results show that the PTMDI control system has dramatically reduced the Park-Ang damage index in the controlled structure, and the dynamic responses of the structure can be better controlled with a small mass. Reza Kamgar [30] studied the effect of the SSI on the response of a single-degree-of-freedom system equipped with a modified tuned liquid damper (TLD) device. The results show that the seismic design of the modified TLD can be more effective in reducing the structural responses. Ghosh and Basu [31] investigated the effect of SSI on the TMD performance for seismic vibration control. The results showed that the dynamic characteristics of the structure-foundation system changed considerably when the soil became less stiff. The conventional tuning of the mass damper to the natural frequency of the fixed-foundation structure loses its effectiveness in controlling the structure's vibrational response. Gorini and Chisari [32] studied the effect of SSI on the performance of TMD. The results indicated that both SSI and TMD tend to reduce structural response, while their relative contribution depends on the relative stiffness between the structure and the foundation soil. Wu et al. [33] and Fu et al. [34] studied the effect of SSI on the performance of TMD by considering these parameters concerning the aspect ratio, height, and type of site soil. The investigations indicated that the SSI effects were not accounted for in the design of the TMD, resulting in un-optimized structural performance in the research. Khoshnoudian et al. [35] investigated the effect of soil nonlinearity on the seismic performance of the TMD-structure system by analyzing the seismic response of the structure under the variation of key parameters such as the vertical bearing safety factor of the foundation, ground vibration characteristics, and the number of stories. The investigation indicated that the SSI effects can degrade the effectiveness of TMD and even be more pronounced after considering soil nonlinearity. Gorini and Chisari [36] investigated the dynamic interaction of the TMD with the whole soil-structure system by an interpretative model of the soil-structure-TMD system expressed in a rigorous nondimensional form and carries out an extensive global sensitivity analysis on its performance under harmonic loading. Zhang et al. [37] investigated the effectiveness of TMD by performing seismic vulnerability on a 20-story steel structure equipped with TMD and considering the SSI effects. It was demonstrated that TMD can remarkably reduce the structural demands, while the SSI effects can increase the fragility of the structure. The effect of the SSI effects on the dynamic characteristics of the structure needs to be considered when the TMD design is carried out. The optimization algorithms [38] have also been used to find optimal parameters for TMDs considering the SSI effects, including multi-population genetic algorithms, bat algorithms, and cuckoo search algorithms [39–44]. Salvi et al. [45] adopted the classical gradient-based nonlinear optimization algorithm to design the TMD parameters and investigated the effectiveness of TMDs in reducing the seismic response of high-rise frame structures subjected to strong earthquakes. The TMD parameters obtained by the optimization algorithm are better than the design criterion, but the parameters are more influenced by the ground motions, which brings difficulties to the engineering design.

The time-domain substructure method [46] in the soil is simulated by spring and the damping system. The substructure method is mainly used in the above research. The direct method [46] can effectively simulate the SSI and soil nonlinearity, which is also used in this paper. The seismic performance of a structure equipped with TMD considering the nonlinear SSI effects is investigated. A comprehensive sensitivity analysis is carried out by considering different design parameters. The effect of different main structure frequencies on the seismic reduction performance of the TMD is investigated. The remaining parts are arranged as follows. Four three-dimensional (3D) finite element models including fixed foundation-structure model (Original), fixed foundation-structure with TMD (Original+TMD), soil-foundation-structure (Original+SSI), soil-foundation-structure with TMD (SSI+TMD) are first built. The details of the TMD design and ground motions are provided in Section 2. In Section 3, the effects of SSI on TMD performance are studied by varying the critical parameters. In Section 4, another design criterion that uses the natural frequency of the soil-structure system to calculate the TMD parameters is also evaluated and compared with the common criterion based on a fixed foundation. Discussion is given in Section 5. Conclusions are provided in Section 6.

2. Numerical models

In this section, a 3D finite element model of a 10-story steel frame equipped with TMD considering the SSI effect is first built, and detailed information on the SSI model is also introduced in Subsection 2.1. In Subsection 2.2, the TMD design criteria are provided, and the parameters of the TMD system are listed. The information on ground motions is given in Subsection 2.1.

2.1. Soil-foundation-structure system

A 3D finite element model of a 10-story moment-resisting steel frame is established using the ABAQUS finite element software [47], as shown in Fig. 1. The superstructure designed by Ohtori et al. [48] initially is simplified. The TMD is installed on the top floor. The beams and columns are modeled by inelastic materials, and their initial elastic modulus and Poisson's ratio are 210 GPa and 0.25, respectively. Some basic information on the beams and columns of the superstructure is given in Table 1. More detailed information on the superstructure is shown in the reference [48]. The length, width, and height of the soil model are 152.5 m, 183 m, and 40 m respectively. The bottom of the soil model is fixed, and the four sides of the soil model are constrained vertical motions. The foundation is embedded directly in the soil model. The structure and pile foundations are discretized with the 2-node beam element (B31) and the soil is discretized with the 8-node reduced integration element (C3D8R). The mesh size of both the structure and pile foundation is taken as 0.5 m. The mesh size of the soil is taken as 2 m, where the mesh size satisfies the requirement of less than 1/8–1/10 minimum wavelength [49].

To investigate the effectiveness of TMD for different site conditions, three different sites are selected, corresponding to soft soil, medium soil, and dense soil identified as I, II, and III. The distance from the surface of the site to the bedrock is 40 m. The three soils are simulated by the equivalent linear visco-elasto model to approximately consider the nonlinear behavior of the soil under seismic excitation. When performing the time-domain analysis, the final equivalent soil parameters that can reflect the soil nonlinearity need to be used. The degraded shear modulus is directly used in the SSI analysis. However, the hysteretic damping of soil cannot be used directly in the time-domain analysis. Therefore, the hysteretic damping is transformed into the Rayleigh damping by a simple and approximate scheme presented in [50]. Moreover, in order to consider plastic deformation and study the actual soil nonlinearity effect in the soft soil, a visco-elasto-plasticity model formed by combining the equivalent linear visco-elasto model and the Mohr-coulomb elasto-plasticity model [51] is used. The mechanical

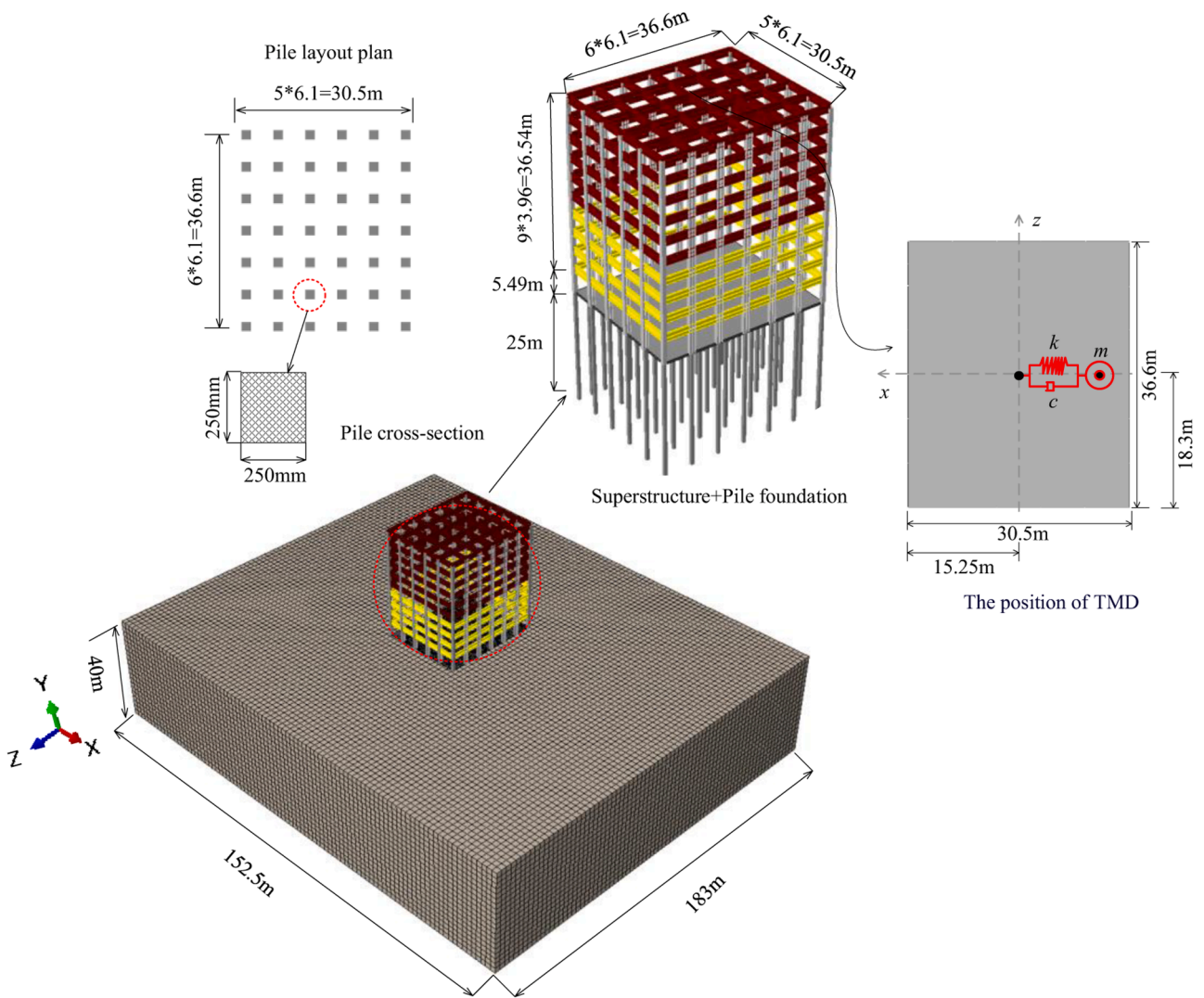


Fig. 1. 3D Finite element model for the soil-structure system.

Table 1
Information on the beams and columns of the superstructure.

Storey	Beams ($\sigma_y = 248MPa$)	Columns ($\sigma_y = 345MPa$)	
		Corner columns	Other columns
1st-4th	W30 × 99	ASTM A500	W24 × 335
5th-10th	W30 × 108		W24 × 229

parameters of the soil are shown in Table 2, and the variation curves of the dynamic shear modulus ratio and damping ratio of the soil with peak shear strain are shown in Fig. 2.

2.2. Parameter design of TMD devices

The TMD design is to obtain the mass ratio, stiffness, and damping of

Table 2
Mechanical parameters of the soil material.

Soil type	Shear wave velocity (m/s)	Poisson's ratio	Density (kg/m ³)	Shear Modulus (GPa)	Friction angle (°)	Cohesion (kPa)
I	150	0.30	1850	19.92	20	23.9
II	250	0.30	1850	89.71	/	/
III	350	0.30	1900	187.54	/	/

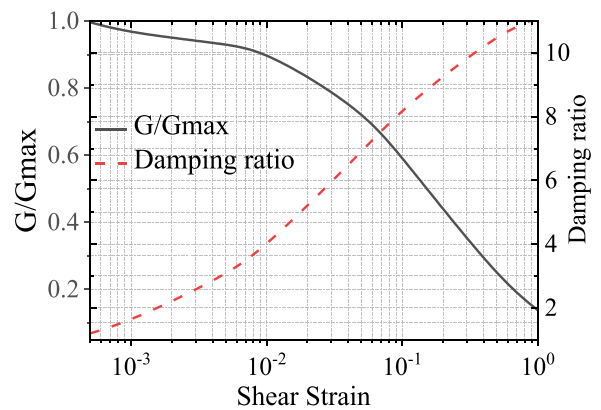


Fig. 2. The curves of dynamic shear modulus ratio and damping ratio of soil with peak shear strain.

the TMD system. The design criterion for Den Hartog [24] is used in this paper. The design criterion for TMD was derived based on a single-degree-of-freedom structure equipped with TMD rested on a fixed base subjected to simple harmonic load, with widespread validity and application. The TMD design parameters including the frequency ratio (f_{opt}) and damping ratio (ξ_{opt}) are as follows:

$$f_{opt} = \frac{f_t}{f_s} = \frac{1}{1 + \mu_m} \tag{1}$$

$$\xi_{opt} = \sqrt{\frac{3\mu_m}{8(1 + \mu_m)}} \tag{2}$$

The frequency ratio (f_{opt}) and damping ratio (ξ_{opt}) are calculated by Eqs. (1) and (2), then substituting into Eqs. (3) and (4), the equivalent stiffness and equivalent damping of the TMD system are obtained.

$$K_{opt} = (2\pi f_t)^2 m_t \tag{3}$$

$$C_{opt} = 2m_t(2\pi f_t)\xi_{opt} \tag{4}$$

where f_t and f_s are the natural frequencies of the TMD and controlled structure, respectively; and the mass ratio μ_m is the ratio of the TMD mass to the main structure mass.

The mass ratio is usually assumed as an input in the design as it is mainly dictated by practical needs. Therefore, the effect of different mass ratios on TMD attenuation performance is investigated in Subsection 3.4. The design parameters of the TMD system for the mass ratio μ_m taken as 3 % are given in this subsection. The mass of TMD is 165,930 kg. The equivalent stiffness and the equivalent damping are 387,995 kN/m and 167,760 kN.s/m, respectively.

2.3. Different spectral characteristic earthquakes

The seismic performance of the TMD is affected by ground motions with different frequency content. Based on Chandler’s Classification for ground motion, the earthquake frequency is classified as low-frequency, intermediate-frequency, and high-frequency by the ratio of PGA/PGV [52]. The low-frequency and intermediate-frequency ground motions are selected in this paper. The four different earthquakes, including the Kobe, Loma, Friuli, and Northridge earthquakes are selected with the peak acceleration adjusted to 0.1 g. These earthquakes are first inputted at the rock outcrop, and the corresponding bedrock motions and surface motions are calculated by performing an equivalent linear site response analysis with the EERA code [53]. The information on ground motions used in this paper is given in Table 3. The acceleration time-history curves and Fourier amplitude spectra of bedrock earthquakes are presented in Fig. 3. The Kobe wave for bedrock and surface are also given in Fig. 3(a), respectively. The surface motions are used as the input of a fixed foundation.

3. Effect of design parameter sensitivity on the performance of TMD consider SSI

In this section, the effects of design parameter sensitivity on the TMD performance are studied, and the SSI effects are also considered. The TMD performance for the structures without SSI and with SSI is first compared in subsection 3.1. The effects of SSI on the TMD performance are then studied by varying the critical parameters including ground motions and soil shear wave velocity as well as soil nonlinearity, and the TMD system design parameters in subsections 3.2 to 3.4. It needs to be noted that the traditional TMD design criterion based on the fixed

Table 3
The information on ground motions used in this paper.

ID	Name	Station	Years	PGA/PGV	AI (m/s)	HI (cm)
1	Kobe	Kobe University	1995	0.499	0.138	41.09
2	Loma	Los Gatos-Lexington Dam	1989	0.517	0.122	50.29
3	Friuli	TOLMEZZO(000)	1976	0.098	0.063	20.80
4	Northridge	Canoga Park-Topanga Can	1994	1.059	0.086	33.07

foundation assumption is adopted in subsections 3.1 to 3.4. In addition, the two most interesting parameters in engineering including peak relative floor displacement (PRFD) and peak floor acceleration (PFA) are used to estimate the effectiveness of TMD subjected to seismic exaction.

3.1. SSI effect on the TMD performance

Four models including the Original, Original+TMD, Original+SSI, and SSI+TMD are used. Only the medium soil is considered in the SSI models. The Kobe record is used here. The PRFD and PFA for the four models are shown in Fig. 4. It can be seen from the figure that the PFA and PRFD for the Original+TMD model are reduced compared with the responses of the Original model. Fig. 5 shows the displacement time-history curve on the top of the first floor and the acceleration time-history curve on the top of the top floor. The structure response of displacement and acceleration can be effectively reduced by the Original+TMD model compared to the Original model. The same conclusion is observed for the Original+SSI and SSI+TMD models under the medium soil. The effectiveness of TMD in reducing seismic response is less apparent when soil-structure interactions are considered. This is mainly because the parameters of the TMD system are designed using the design criteria of Den Hartog. The design criteria were derived based on a single-degree-of-freedom structure equipped with TMD rested on a fixed base subjected to simple harmonic load. The SSI effect was not considered. The TMDs designed using the design criteria of Den Hartog are affected in reduction performance when SSI effects are considered.

Fig. 6 summarizes the PRFD and PFA on the first, middle (fifth), and top floors of the four models. The maximum PRFD and PFA for the four models occur at the first and top floors of the models, respectively. The maximum PRFD and PFA for the Original+SSI model are reduced by 22 % and 18.7 %, respectively, compared with that for the Original model. Furthermore, the TMD can reduce the maximum PRFD and PFA of the Original model by 51.6 % and 49.3 %, respectively. The TMD can reduce the maximum PRFD and PFA of the Original+SSI model by 37.0 % and 26.2 %, respectively. The results show that the SSI effects can reduce the performance of TMD.

In order to quantify the effect of SSI on the effectiveness of TMD, this paper introduces the reduction rate, which mainly refers to the proportion of TMD reducing the structural seismic response. When the reduction rate is less than zero, the TMD amplifies the structural response of the controlled structure. Fig. 7 shows the reduction rates for the Original+TMD and SSI+TMD models. The reduction rates are all much greater than zero, indicating that the TMD has a reducing effect on the seismic response of the controlled structure. When ignoring the SSI effects, the TMD can effectively reduce the structural response by about 17 % to 53 %. Once the SSI effects are considered, the reduction rates are about 12 % to 38 %. It is shown that the SSI effects have a negative effect on the performance of TMD. Hence the effects of SSI on the design of TMD need to be considered in practical engineering.

3.2. Different spectral characteristic earthquakes on the TMD performance

The Original+SSI and SSI+TMD models subjected to the Kobe, Loma, Friuli, and Northridge records, respectively, are studied. Only the medium soil is considered in the SSI models. Figs. 8 and 9 show the PRFD and PFA of the structures under different ground motions. It can be seen from the figure that the PFA and PRFD for the SSI+TMD model are obviously reduced compared with the responses of the Original+SSI model. The results indicate that the TMD can effectively reduce the seismic response of the structure under different ground motions.

Fig. 10 shows the reduction rates for PRFD and PFA of structures under different ground motions. Only the first, middle, and top floors of the structure results are given. The reduction rates of PRFD are all greater than 0 under the four ground motions. The reduction rates of the PFA under the Friuli record are the smallest and even less than 0. These

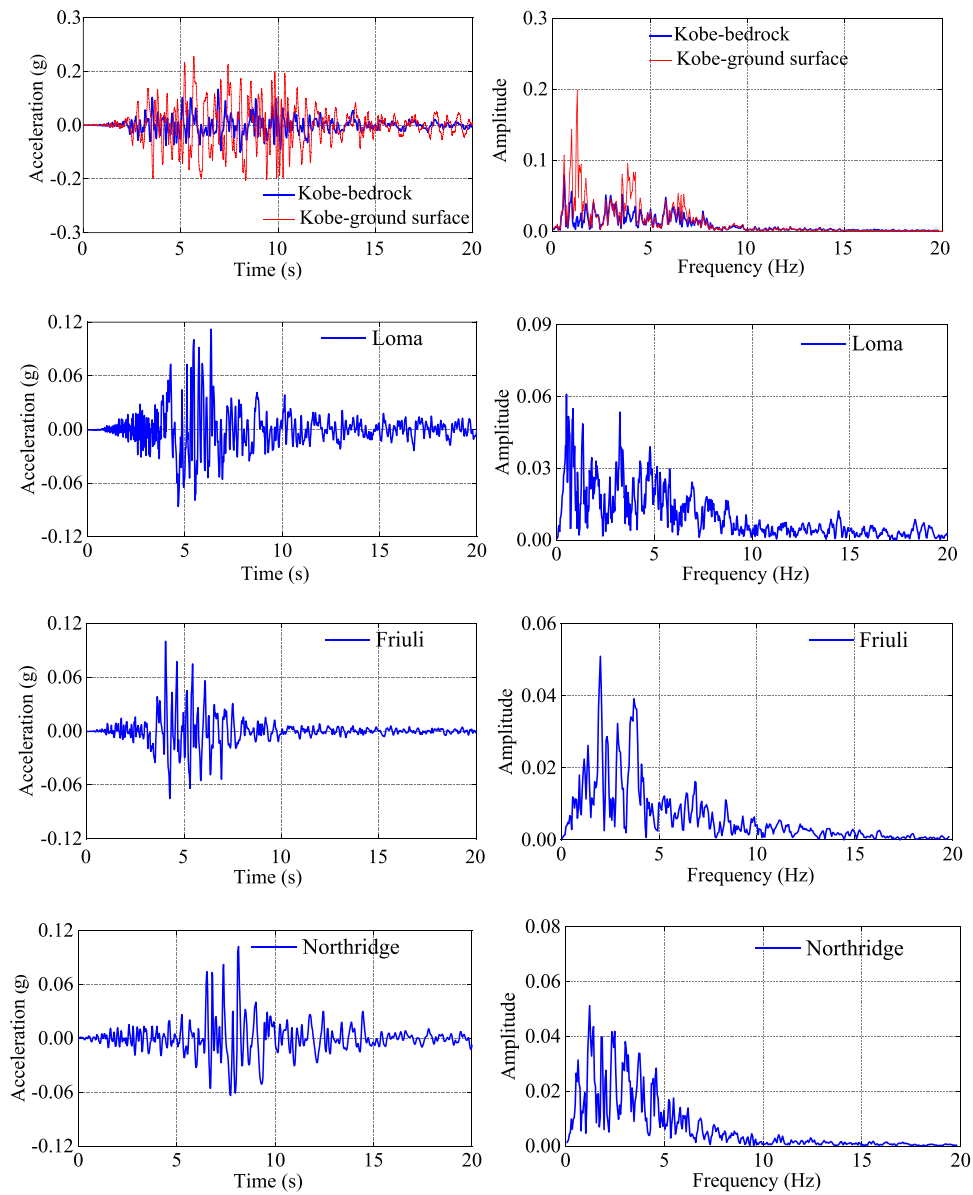


Fig. 3. The acceleration time-history curves and Fourier amplitude spectra.

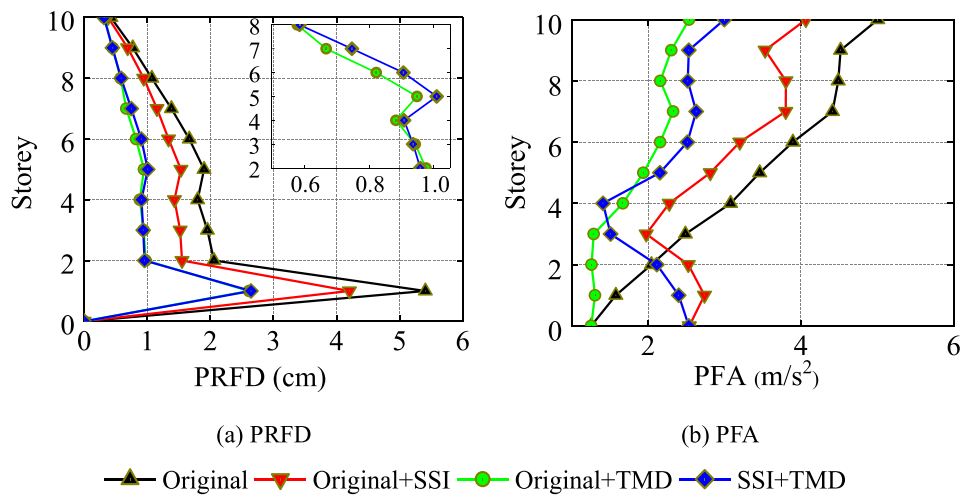
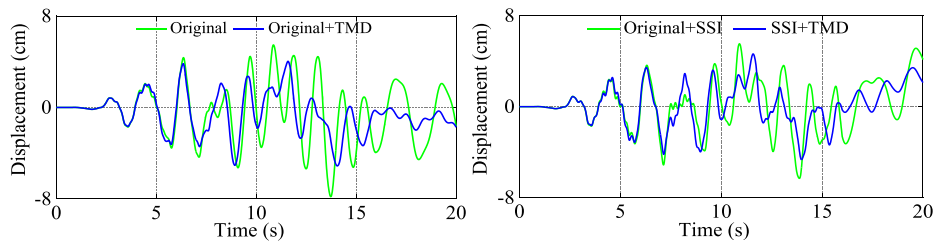
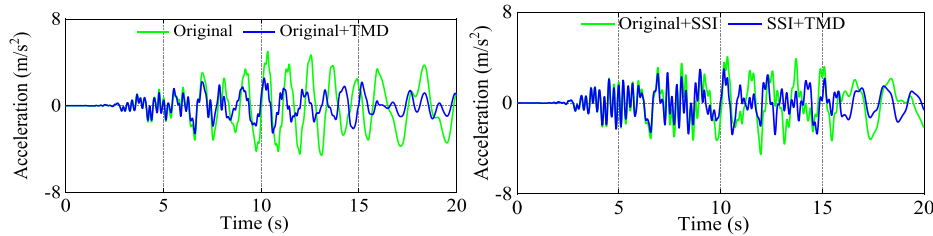


Fig. 4. The peak relative floor displacement (PRFD) and peak floor acceleration (PFA) for four models considering the SSI effect.

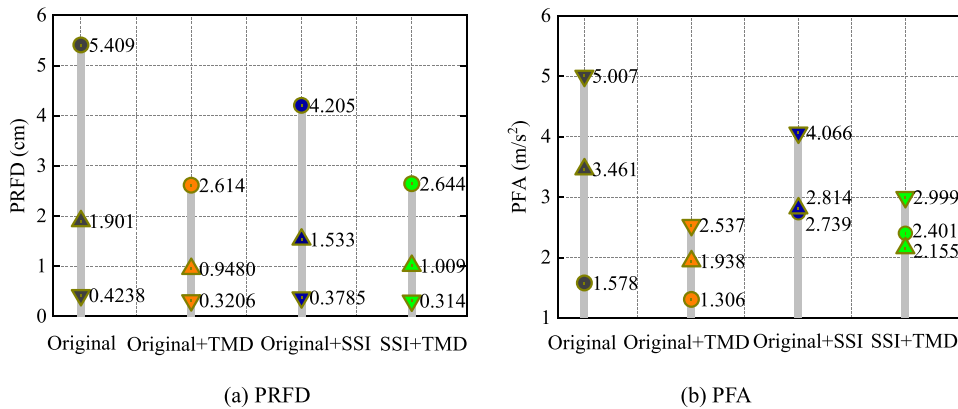


(a) Displacement time-history curve for the models of the Original, Original+TMD, Original+SSI, and SSI+TMD.



(b) Acceleration time-history curve for the models of the Original, Original+TMD, Original+SSI, and SSI+TMD.

Fig. 5. The displacement and acceleration time-history curves considering the SSI effect under the Kobe record.



(a) PRFD

(b) PFA

Fig. 6. The PRFD and PFA considering the SSI effect under the Kobe record ("▼" Top floor of the structure; "▲" Fifth floor of the structure; "●" First floor of the structure).

results indicate that the performance of TMD is affected by ground motions.

3.3. Shear wave velocities and soil nonlinearity on the TMD performance

To investigate the effects of different soil shear wave velocities and soil nonlinearity on the performance of TMD, this subsection performs the seismic response analysis of the Original+SSI and SSI+TMD models under the Kobe record. Different site conditions including Site I (soft soil), Site I-NL (soft soil and soil nonlinearity), Site II (medium soil), and Site III (dense soil) are considered. Figs. 11 and 12 show the PRFD and PFA of the structures under different site conditions. For Site I, TMD amplifies the seismic response of the controlled structure whether the soil nonlinearity is considered or not. Moreover, the seismic response of the Original+SSI and SSI+TMD models is reduced after considering soil nonlinearity. For Site II and Site III conditions, the PRFD and PFA of the SSI+TMD model are reduced compared to the Original+SSI model. When the structure is located on a soft soil site, the TMD designed according to the fixed foundation assumption may amplify the seismic response of the controlled structure, while TMD still shows good performance when the structure is located on medium and hard soils.

Fig. 13 shows the reduction rates for PRFD and PFA of structures under different soil conditions. For the reduction rates of story drift in

soft soil, TMD shows a negative tuning, and the reduction rate for the first floor even reaches -45% . Under medium and dense soils, TMD has a good performance for story drift, and the reduction rates are all more than 10% . The performance of TMD for acceleration is decreased in some conditions. These results indicate that the performance of TMD is affected by site conditions.

3.4. TMD system design parameters on the TMD performance

The stiffness and damping of the TMD system are obtained with the design criterion for Den Hartog. The damping and stiffness of the TMD system may deviate from the optimal parameters during installation and operation. Therefore, the effect of the TMD system design parameters on the seismic response of the main structure is investigated, including the TMD system mass ratio (μ_m), the TMD system damping (K_{opt}), and the TMD system stiffness (C_{opt}). The SSI effect is also considered in this subsection. The Kobe seismic record was used, and only the medium soil was considered in the SSI models.

To investigate the effect of the mass ratio of the TMD system on the main structure seismic response, the mass ratio is taken as 1% to 5% , and the five cases of M1, M2, M3, M4, and M5 are designed. M1–5 represents the mass ratio of 1% , 2% , 3% , 4% , and 5% , respectively. The effect of the TMD system stiffness (K_{opt}) on the seismic mitigation

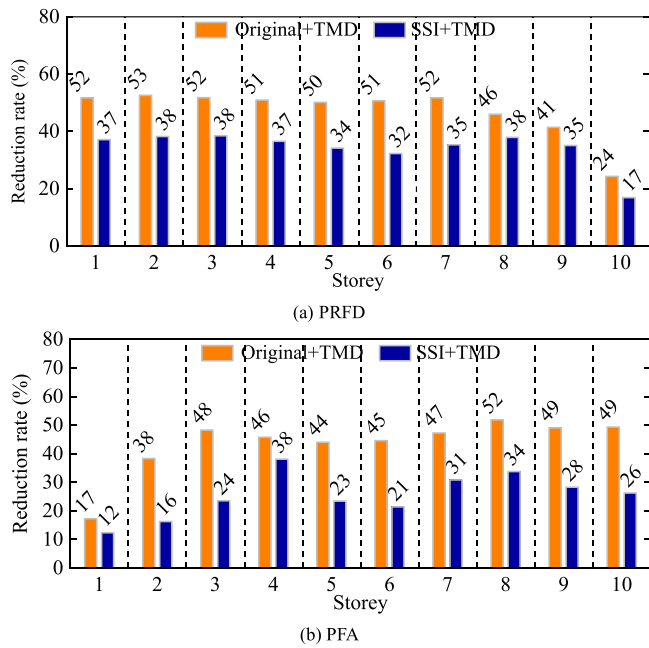


Fig. 7. The reduction rates for PRFD and PFA considering the SSI effect under the Kobe record.

performance of the main structure is investigated. Five cases of S1, S2, S3, S4, and S5 have been designed according to the TMD system stiffness K_{opt} , which is $0.5K_{opt}$, $0.8K_{opt}$, $1.0K_{opt}$, $1.2K_{opt}$ and $1.5K_{opt}$, and the value of the TMD system damping C_{opt} is unchanged. The effect of the TMD system damping C_{opt} on the seismic mitigation performance of the main structure is also investigated. Five cases of D1, D2, D3, D4, and D5 have

been designed according to the TMD system damping C_{opt} , which is $0.5C_{opt}$, $0.8C_{opt}$, $1.0C_{opt}$, $1.2C_{opt}$ and $1.5C_{opt}$, and the value of the TMD system stiffness K_{opt} is unchanged. In addition, the TMD mass ratio is 3 %, and the design criteria in Subsection 2.2 were calculated for C_{opt} and K_{opt} .

The structural response of the PFA and PRFD under different TMD system design parameters is given in Table 4. The seismic response of some floors is amplified by the TMD system when the mass ratio is less than 2 %. The structural response of PFA and PRFD decreases as the mass ratio increases. The TMD system in which the stiffness and damping of the dampers are given using the design criteria, the TMD has a better reduction performance. When the stiffness and damping in the TMD system are either less or more than the optimal values, the TMD is still effective in reducing the vibration response of the main structure.

The reduction rates of the peak response of the structure for different TMD system design parameters are given in Fig. 14. The peak reduction rate increases with increasing the mass ratio of the TMD system. The peak reduction rates are 47.9 % and 44.5 % for PRFD and PFA, respectively. In all cases, considering the TMD system with different damping and stiffnesses, the peak reduction rates are greater than 0. The largest peak reduction rates occur in the optimum parameter of the TMD system damping and stiffnesses, for cases D3 and S3, with peak reduction rates of 37 % and 33 % for the PRFD and PFA, respectively.

4. Effect of designed frequency on seismic reduction performance of the TMD

The dynamic properties of the main structure are significantly changed when considering the SSI effect. The TMD design is closely related to the dynamic characteristics of the main structure. The detuned TMD may occur when the TMD is designed according to the frequency of the main structure of the fixed base. Therefore, the SSI effects need to be

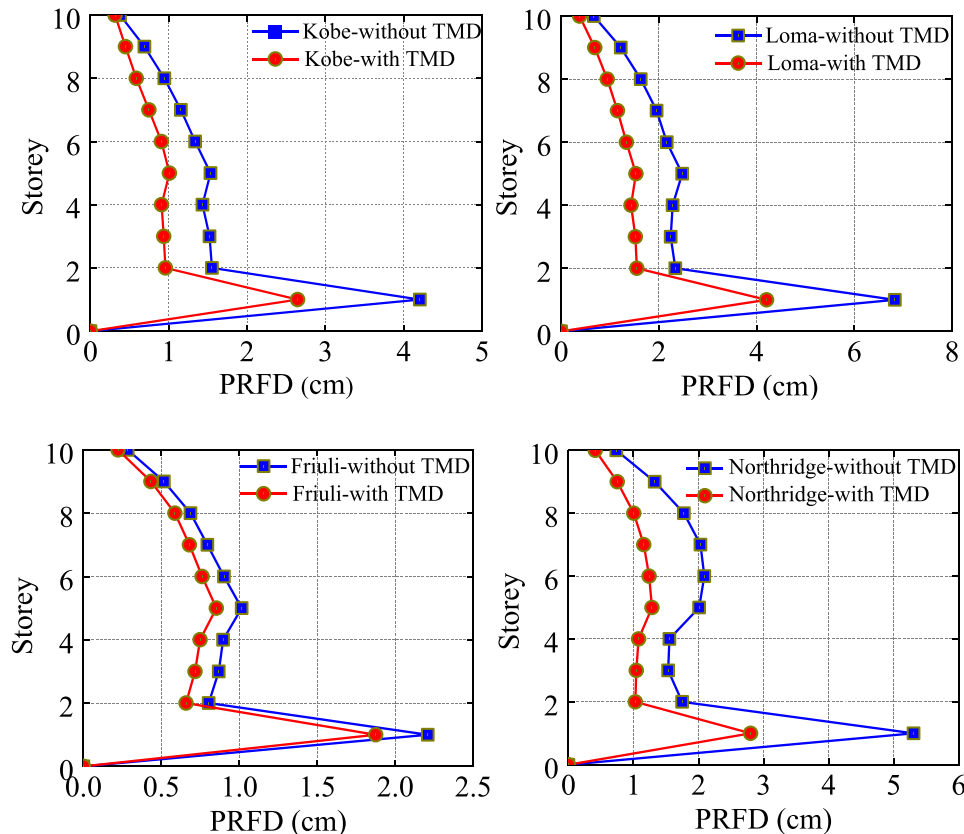


Fig. 8. The PRFD of the structures under different ground motions.

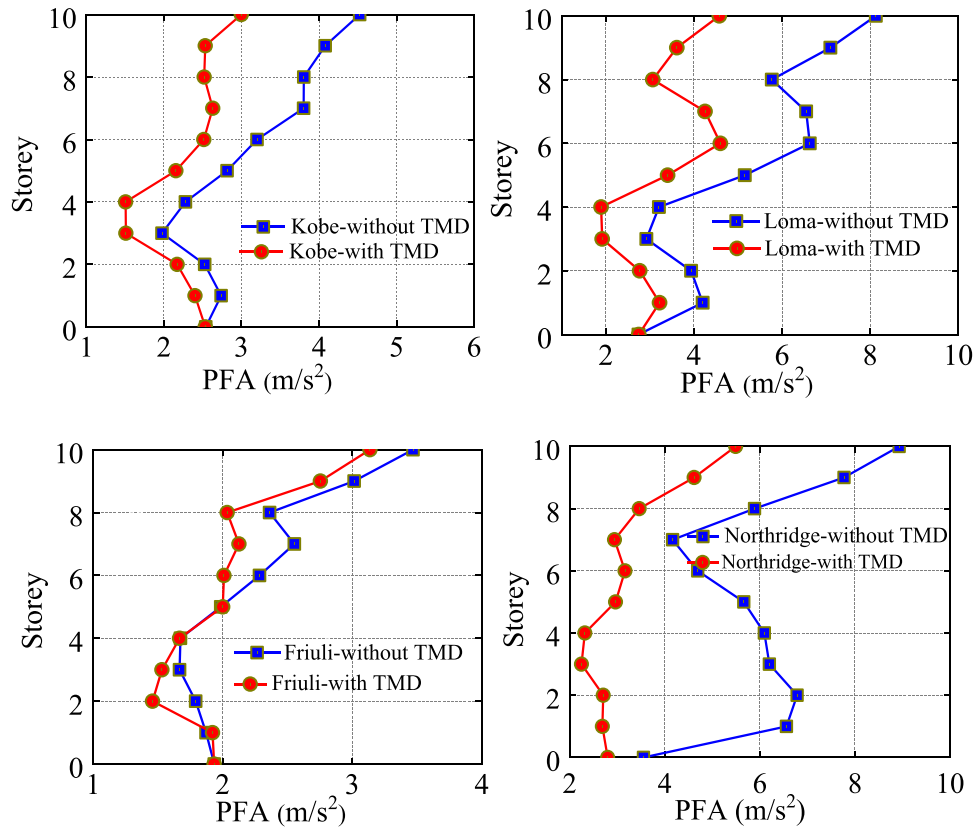


Fig. 9. The PFA of the structures under different ground motions.

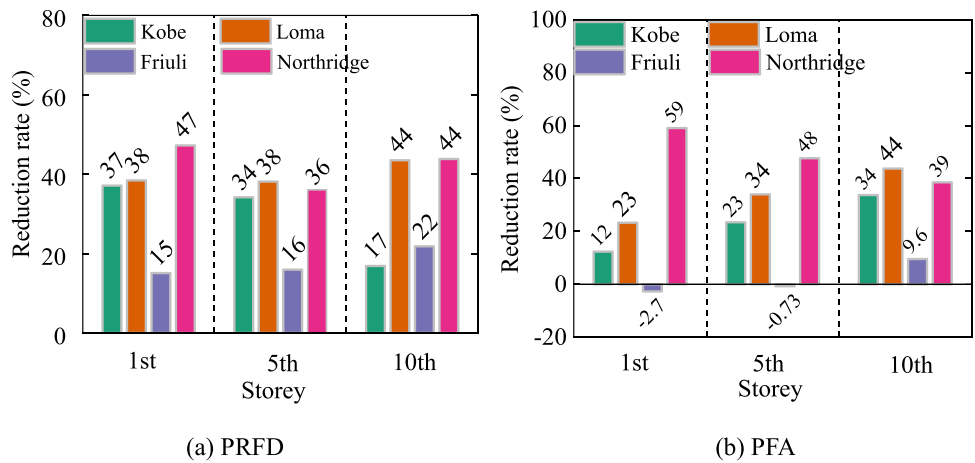


Fig. 10. The reduction rates for PRFD and PFA of structures under different ground motions.

considered in the TMD design. The influence of SSI effects on structural frequencies is first studied in Subsection 4.1. In this subsection, the modal analysis is carried out for the Original model and the Original+SSI model, where the Original+SSI model takes into account the effects of three different sites. The effect of different main structure frequencies on the seismic reduction performance of the TMD is investigated in Subsection 4.2, including the frequency of the main structure of the Original model and the fundamental frequency of the original + SSI model. In addition, the structural responses for PRFD and PFA, and corresponding reduction rates are used to evaluate the effectiveness of TMD subjected to seismic exaction.

4.1. The dynamic characteristic of the SSI system

The first ten-order natural frequencies of the uncontrolled and controlled models are given in Table 5. The fundamental frequencies of the uncontrolled models are 0.793 Hz, 0.641 Hz, 0.771 Hz, and 0.776 Hz respectively. The results indicate that the frequency of the soil-structure system is reduced compared to the frequency of the fixed foundation structure. The fundamental frequency reduction rate of the three SSI models is respectively 19.16 %, 2.77 %, and 2.14 % compared with the Original model. The fundamental frequencies of the controlled models are 0.897 Hz, 0.664 Hz, 0.884 Hz, and 0.887 Hz respectively. The controlled model fundamental frequency is greater than the fundamental frequency of the uncontrolled model. The first-order modes

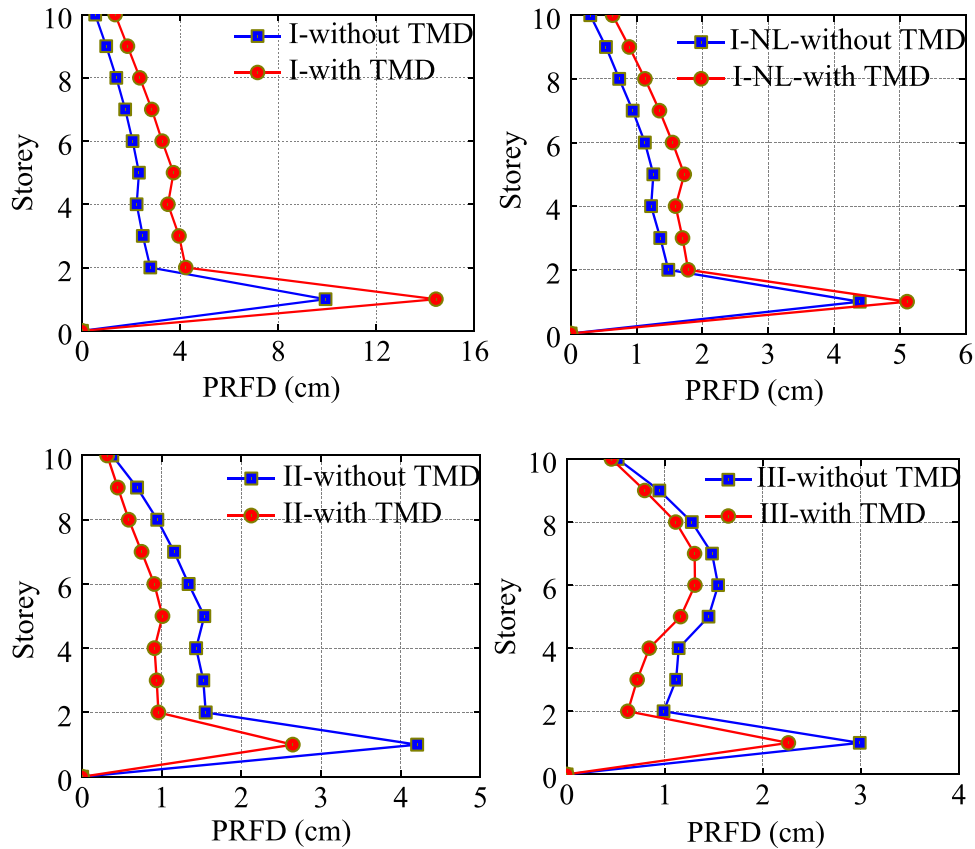


Fig. 11. The PRFD of structures under different soils.

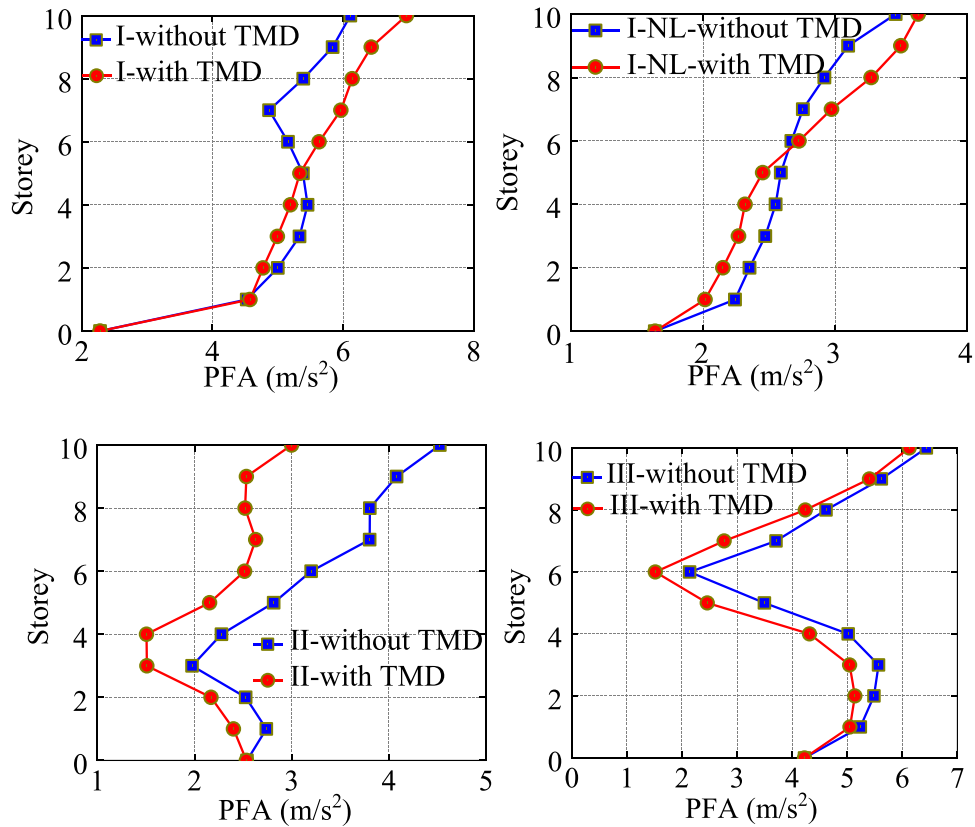


Fig. 12. The PFA of structures under different soils under the Kobe record.

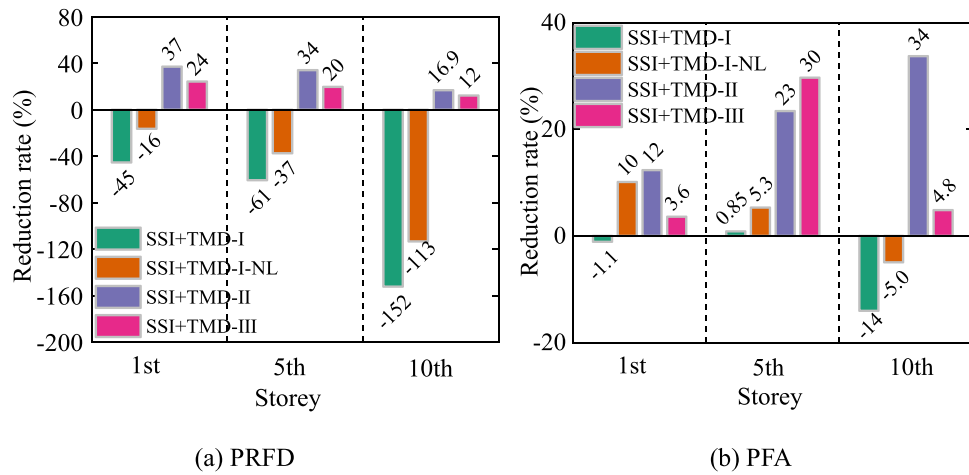
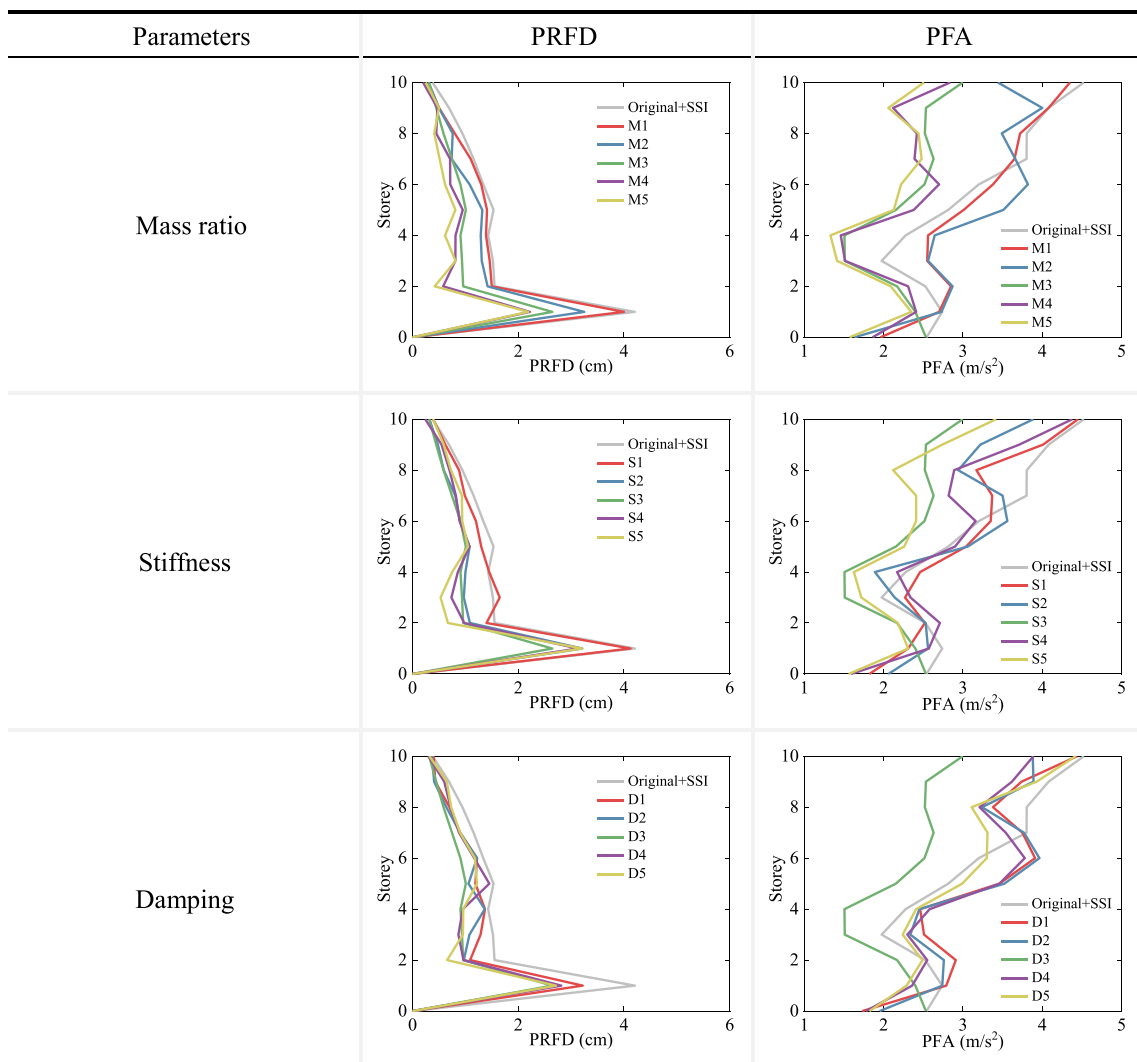


Fig. 13. The reduction rates for PRFD and PFA of structures under different soils under the Kobe record.

Table 4
The PFA and PRFD under different TMD system design parameters under the Kobe record.



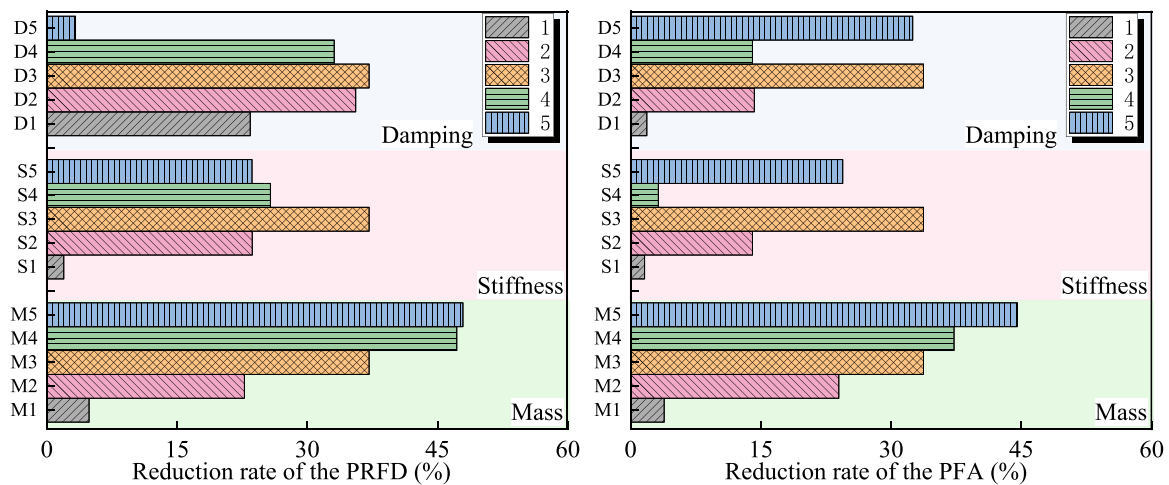


Fig. 14. The reduction rates for PRFD and PFA of structures under different soils under the Kobe record.

Table 5

First ten-order natural frequencies (Hz).

Number	1	2	3	4	5	6	7	8	9	10
Original	0.793	1.395	1.791	2.329	4.001	4.154	5.269	5.642	7.048	7.145
Original+TMD	0.897	1.395	1.791	2.341	4.015	4.153	5.268	5.645	7.048	7.146
SSI-I	0.641	0.732	0.780	0.814	0.871	0.927	0.941	0.988	0.995	0.980
SSI-I+TMD	0.664	0.732	0.780	0.814	0.871	0.927	0.943	0.988	0.994	0.980
SSI-II	0.771	1.313	1.335	1.515	1.553	1.661	1.677	1.909	1.931	2.033
SSI-II+TMD	0.884	1.313	1.335	1.515	1.553	1.661	1.677	1.909	1.931	2.033
SSI-III	0.776	1.318	1.649	1.929	2.185	2.299	2.338	2.423	2.759	2.794
SSI-III+TMD	0.887	1.318	1.649	1.929	2.185	2.315	2.338	2.423	2.759	2.794

for the uncontrolled models are shown in Fig. 15. It can be clearly seen that the soil produces an obvious vibration for the SSI-I model, while the other two SSI models only have an obvious vibration for the structure.

4.2. Evaluation of the seismic reduction performance of the TMD

The performance of TMD is directly related to the natural frequency of the controlled structure. The study in this paper shows that the frequencies of the structure will be reduced by the SSI effects, and the maximum reduction rate of the fundamental frequency of the structure in soft soil is 25.4 %. When the SSI effects are strong, the TMD performance degrades seriously. Therefore, another design method is also adopted in this section to calculate the TMD parameters, that is, the fundamental frequency of the soil-structure system is used to replace the frequency of the structure, which is called Method 2. The TMD design parameters for different site conditions are shown in Table 6. The design method under the fixed foundation assumption is called Method 1.

Figs. 16 and 17 show the PRFD and PFA of the structures. Two models including the Original+SSI and SSI+TMD subjected to the Kobe record are considered. The TMD parameters are computed by the Method 1 and Method 2, respectively. The results demonstrate that the TMD designed by Method 2 can effectively reduce the seismic responses of structure in the soft soil compared with that designed by Method 1. Under the medium soil and dense soil, seismic responses of the structures obtained by the two TMD design methods are very close. The results indicate that when the SSI effects are strong, the TMD needs to be designed according to the natural frequencies of the soil-structure system.

Figs. 18 and 19 show the reduction rates for PRFD and PFA under different TMD design methods. For soft soil sites, the reduction rates obtained by Method 2 are significantly improved compared with those obtained by Method 1. The reduction rates obtained by Method 2 are less than 0 for the 10th-floor story drift, but the structural response is very small on this floor. Under the medium soil and dense soil, the reduction

rates obtained by the two TMD design methods are very close. The results further indicate that when the SSI effects are strong, the TMD needs to be designed according to the natural frequencies of the soil-structure system.

5. Discussion

In this paper, the effect of nonlinear soil-structure interaction on TMD reduction performance is investigated by numerical methods. The direct method is used to simulate the SSI and soil nonlinearity. The structure is considered to be linear. The TMD parameters are designed by the common criterion based on a fixed foundation. The Den-Hartog design criteria were used for the optimal design of the TMD parameters. The critical TMD design parameters are discussed, including ground motions with different frequency contents, site conditions, and the TMD system's stiffness, damping, and mass ratios. Furthermore, the effect of different main structure frequencies on the seismic reduction performance of the TMD is investigated. The two design frequencies are considered in this paper, the frequency of the fixed foundation structure and the fundamental frequency of the soil-structure system, respectively. The results show that the TMD reduction performance is decreased by considering SSI. The performance of TMD is benefited by considering the soil nonlinear. The obtained conclusion can provide experience for future works on the pre-tuning stage of TMD considering SSI effects.

In the future, the seismic performance analysis of nonlinear structures equipped with TMDs considering nonlinear SSI effects should be considered. The Den-Hartog design criteria have been developed for an SDOF system with a fixed base under the white noise load. The applicability design criteria of the TMD in multi-degree-of-freedom systems considering SSI needs to be studied. In addition, the model experiment investigation should be carried out. The effect of SSI on TMD performance should be clarified from the experimental perspective for future research.

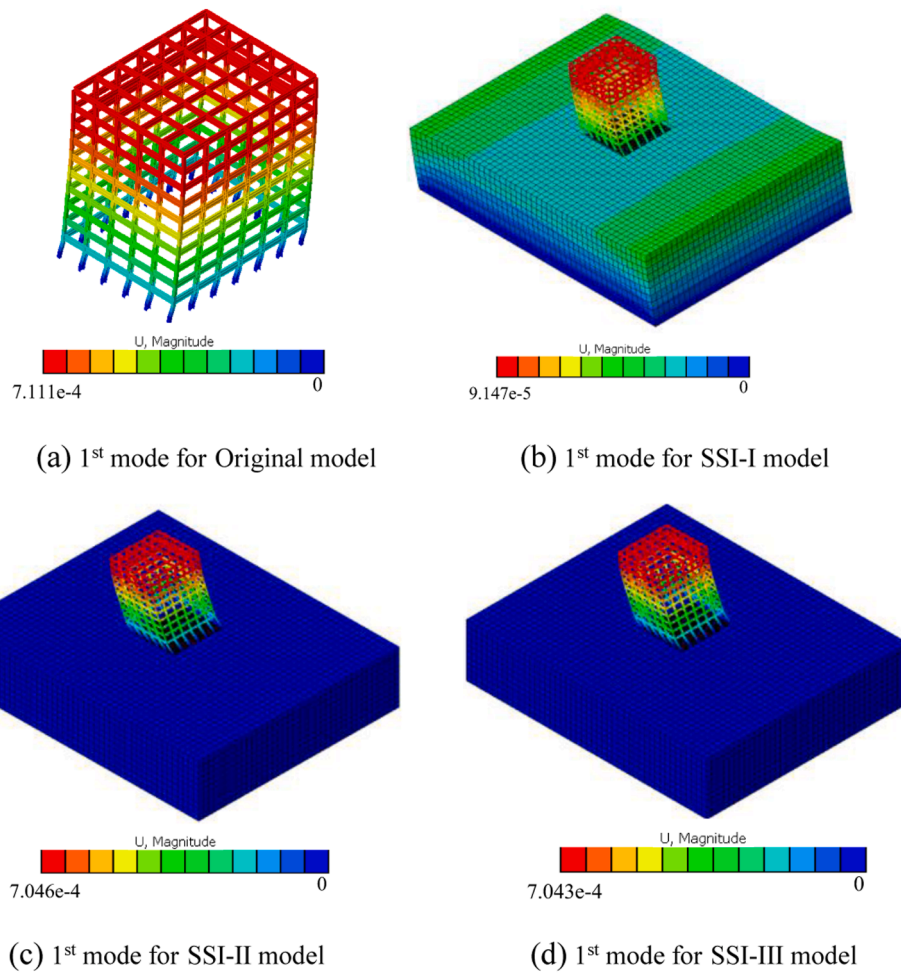


Fig. 15. 1st modes for the Original model and three SSI models.

Table 6

TMD parameters under different site conditions.

Models	Mass (kg)	Stiffness (kN/m)	Damping (kN.s/m)
SSI-I	165930	2178691	125061
SSI-II	165930	3641848	161691
SSI-III	165930	3700665	112707

6. Conclusion

In this paper, four 3D finite element models including the Original, Original+TMD, Original+SSI, and SSI+TMD are first established. The nonlinear soil-structure interaction effects on the seismic performance of

TMD are investigated. The effects of design parametric on the seismic performance of TMD are investigated, including different site conditions and ground motions. The stiffness, damping, and mass ratio of the TMD system are also considered. The TMD design is closely related to the dynamic characteristics of the main structure. The effect of different main structure frequencies on the seismic reduction performance of the TMD is carried out. Some conclusions are summarized as follows.

- (1) The TMD can provide better-tuned vibration mitigation for controlled structures. The TMD can reduce the seismic response of controlled structures with a maximum of 50 %. When the SSI effect is considered, the TMD reduces the seismic response of the

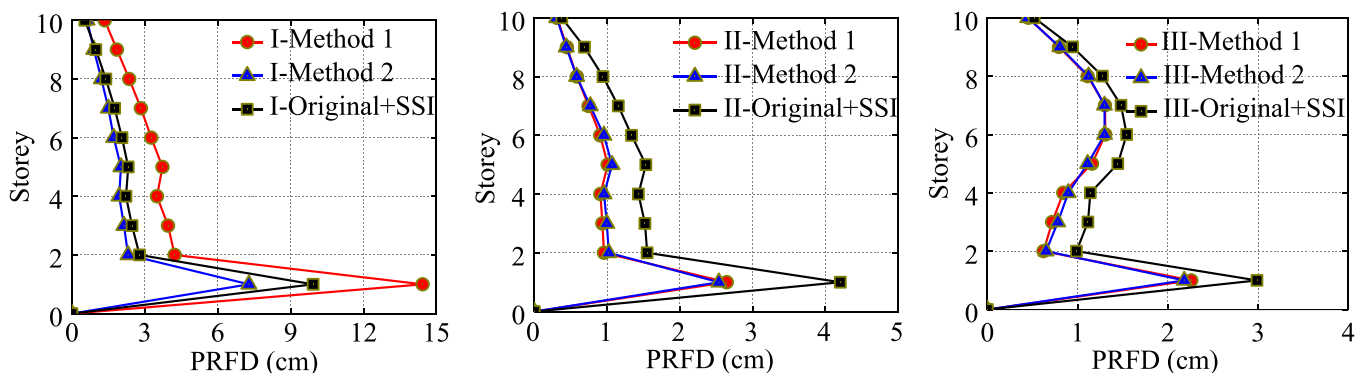


Fig. 16. The PRFD under different TMD design methods.

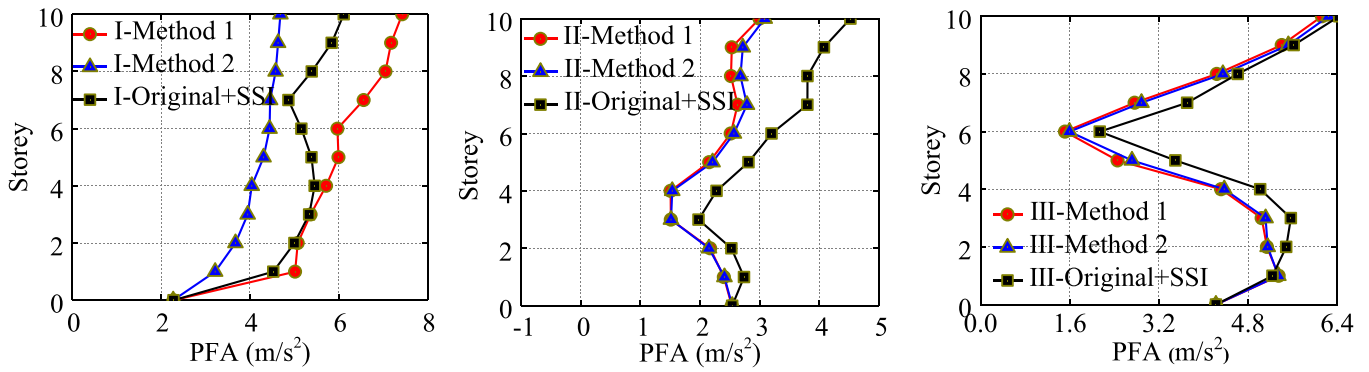


Fig. 17. The PFA under different TMD design methods.

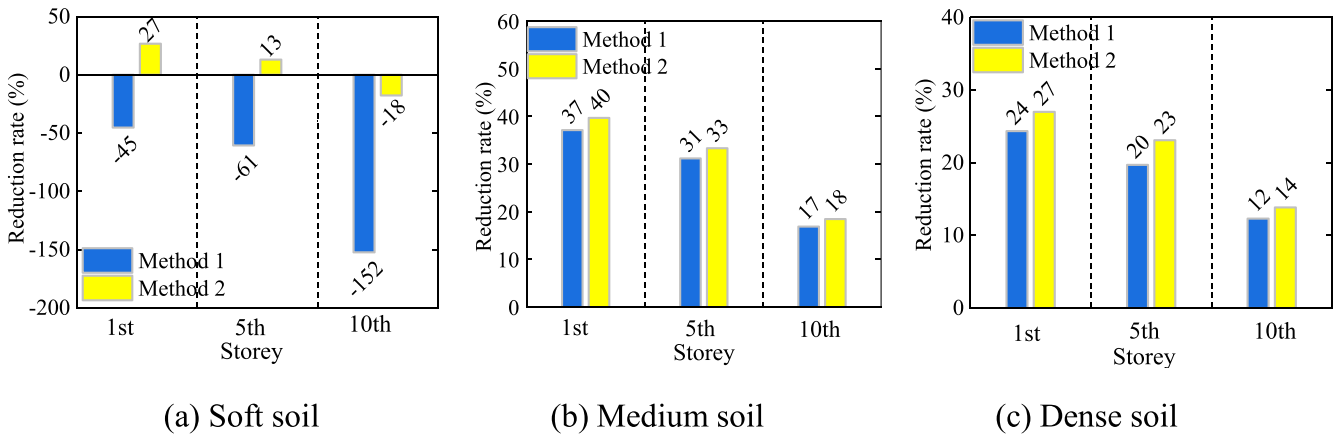


Fig. 18. The reduction rates for PRFD under different TMD design methods.

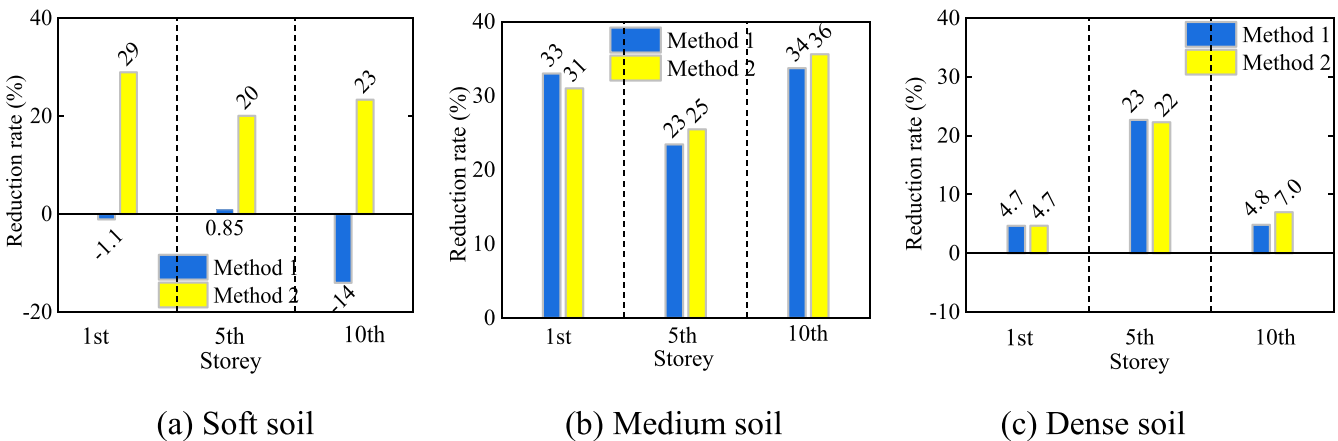


Fig. 19. The reduction rates for PFA under different TMD design methods.

controlled structures by a maximum of 37 %. The SSI effects can degrade the effectiveness of TMD. The TMD is favored for reducing the structural seismic response after considering the soil nonlinear. The performance of TMD is affected by the different spectral characteristic earthquakes. The dampers' stiffness and damping of the TMD system are specified according to the TMD design criteria, and the TMD provides better effectiveness performance. When the damping and stiffness of the TMD system deviate from the optimal design parameter by 50 %, the TMD still provides good reduction performance.

- (2) The dynamic properties of the main structure are changed when considering the SSI effect. The fundamental frequency reduction rate of the SSI model in soft soil is 19.16 % compared with a fixed foundation model. The TMD was designed based on the frequency of a fixed foundation structure detuned in soft soil, amplifying the structural response. The traditional TMD design based on the assumption of a fixed foundation should not be adopted when the SSI effects are strong. The effect of SSI on the frequency of the structure should be considered when designing TMD.
- (3) The TMD is designed according to the natural frequencies of the soil-structure system and a good reduced performance is

obtained. The TMD design is performed by using the fundamental frequencies of the soil-structure system. When the SSI effect is significant, the soil will be involved in the modal shape of the soil-structure system. The fundamental frequency of the soil-structure system is not the same as the fundamental frequency of the structure. The effectiveness of reducing the seismic response of structures may be degraded when the TMD is designed for soil-structure system frequencies. Therefore, effectively identifying the dynamic properties of the structure from the soil-structure system for TMD design is very important in future research.

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Ethical Statement

We declare that we have no conflict of interest with other people or organizations.

CRediT authorship contribution statement

Yangzhou Wu: Data curation, Writing-Original draft preparation, Program. **Mi Zhao:** Proofread the English grammar, Writing-Reviewing. **Zhidong Gao** (corresponding author): Conceptualization, Writing-Reviewing. **Xiuli Du:** Resources, Fund support.

Declaration of Competing Interest

We declare that we have no conflict of interest with other people or organizations.

Data Availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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