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Comparison of the earthquake responses of super-high-rise building structures based on different seismic design spectra

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ABSTRACT

To evaluate the reliability of the long-period segments of seismic design spectra, two super-high-rise buildings with long-period vibration periods are analyzed. The response spectrum method and dynamic time-history method are employed to investigate the maximum displacement of the building's top and the maximum earthquake shear of the building's base. Based on the long-period segments stipulated in the Japanese and Chinese design codes, the displacement spectra increase significantly as the vibrational period increases, which is not consistent with the statistical attenuation characteristics. The maximum earthquake shear force calculated in accordance with the response spectrum method in the proposed design spectrum is consistent with the average results calculated by the dynamic time-history method as well as with the results calculated according to the Chinese design spectrum and the design spectrum utilized in the US. However, the proposed design spectrum better characterizes the shear response of the long-period building with high-order modes. For large long-period buildings, the maximum displacement calculated in accordance with the Chinese design spectrum increases with the damping ratio. The variation of the maximum shear force of the building's base is very small. This indicates that the long-period segment in the Chinese design spectrum is not reasonable. For large long-period buildings, the increasing ratio of the damping force to the structural system's internal force as the damping ratio increases cannot be ignored. Therefore, the reduction ratio of the damping force in the long-period segments of the response spectrum should be appropriately selected.

Keywords: Long-period ground motion; design spectra; modal decomposition response spectrum method; dynamic time-history analysis method; damping ratio.

INTRODUCTION

Since the 1985 Ms 8.0 Mexico earthquake, engineers have paid increasing attention to the risks of long-period ground motions in the far field (Yu *et al*., 1997 & Takewakii *et al*., 2011). The May 12, 2008, Ms 8.0 Wenchuan earthquake was one of the most disastrous earthquakes in China, and strong shaking was detected in high-rise buildings in the cities of Baoji and Xi'an, China, which were located 520 kilometers and 700 kilometers, respectively, from the earthquake epicenter (Liang *et al.*, 2009). When the Ms 9.0 earthquake hit Tohoku-Oki, Japan, in 2011, strong shaking was detected in super-high-rise government office buildings in Osaka, which was located 770 kilometers from the epicenter. The seismic response of high-rise buildings in Osaka was nearly the same as that of buildings in Sendai, which was only 100 kilometers from the epicenter (Zhou *et al*., 2012 & Takewakii *et al*., 2011). Therefore, studying the dynamic behavior of super-high-rise building structures under long-period ground motions and proposing safe and practical seismic design methods are important topics that structural engineers working in seismic regions must undertake. The *Code for Seismic Design of Buildings* (GB50011, 2010) and *Technical Specification for Concrete Structures of Tall Buildings* (JGJ 3, 2010) in China incorporate the design of seismic isolation and seismic energy-dissipating buildings into the code and also provide specific values for the design spectra of different damping ratios.

However, with the extensive construction of high-rise reinforced concrete (RC) buildings and energy-dissipating high-rise RC buildings with added damping devices, new requirements and challenges have emerged concerning the applicability of the long-period segment of the design spectrum in the seismic design of high-rise RC buildings. Over the past decade, many studies in China (Chen & Yu, 2007; Cao *et al.*, 2011; Luo *et al.*, 2011; Li *et al.*, 2012; Fang *et al.*, 2014) have focused on the selection of the long-period segment values in the design spectrum stipulated in the *Technical Specification for Concrete Structures of Tall Buildings* (JGJ 3, 2010). The seismic design spectrum's long-period segment should be evaluated and verified by several ground motions with rich long-period components and high-rise RC buildings. Numerous factors affect the attenuation of the earthquake response spectrum (Chandler *et al.*, 2003) and its damping reduction factor spectrum (Zhou *et al.*, 2014), including the structural system's internal factors, such as the structure's damping and vibration period, and external factors, such as the earthquake magnitude, source rupture mechanism, epicentral distance, ground motion duration, and site conditions. The design spectrum stipulated in the Chinese seismic design codes for buildings has many shortcomings, which must be improved (Fang *et al.*, 2014; Luo *et al.*, 2011; Chen *et al.*, 2007). For example, during the design process, due to the artificial adjustment of the long periods, the statistical characteristics of the ground motion change, which causes an anomaly in the long periods of the power spectrum that corresponds to the acceleration response spectrum. The relative displacement spectrum obtained based on the quasi-spectral relation increases linearly with the extension of the structural self-vibration period under any site and damping ratio conditions. This results in an unreasonably large calculated displacement of the long-period building structure due to the effect of an earthquake, which is not consistent with the statistical characteristics of the relative displacement spectrum. In addition, the earthquake influence coefficient curves of different damping ratios bifurcate after they intersect at the long period segment. The attenuation rate of the earthquake influence coefficient of larger damping ratios is significantly lower than that of smaller damping coefficients. This is not consistent with the vibration attenuation relationships of building structures with different damping ratios in practical engineering. In this paper, two super-high-rise building structures are analyzed using the design spectrum stipulated in the seismic design codes of China, the US, and Japan as well as the design response spectrum proposed by the authors in a previous study (hereinafter referred to as the proposed design spectrum (Zhou *et al.*, 2017)). The differences between the calculated results obtained based on the different seismic design spectra are compared. The calculated results are also compared with those calculated based on dynamic time-history analysis. The results obtained in this paper can be used as a reference for the seismic design of long-period building structures.

SEISMIC ACTION AND STRUCTURAL MODEL

Seismic design spectrum

The Chinese seismic design code (GB 50011, 2010) defines the seismic precautionary intensity as having a greater than 10% probability of occurring during the 50-year design reference period. The maximum earthquake considered in the US seismic design code (ASCE, 2010) is defined as having a greater than 2% probability of occurring over the 50-year design reference period, and 2/3 of the seismic acceleration of the maximum earthquake considered is used as the design earthquake magnitude. The Japanese seismic design code (Mistumasa *et al.*, 2003 & Sun *et al.*, 2011) does not specify the precautionary intensity. The precautionary criterion is based on the standard horizontal seismic shear coefficient C_0 and the seismic partition coefficient Z. In Japan's seismic design code, the standard seismic shear coefficient C_0=0.2, and the design acceleration is approximately 80 gal (0.2×9.81×100/2.5=78.48 gal). This is slightly higher than the acceleration of frequent earthquakes in the 8-degree zone of Chinese seismic design code. The maximum seismic design acceleration in the second stage is approximately 400 gal, which is equivalent to the acceleration of rare earthquakes encountered in the 8-degree zone of the Chinese seismic design code. The most significant difference between the Japanese seismic design code and other countries' seismic design codes is the expression of the seismic action. In the allowable stress method, the seismic action is represented by horizontal shear in the floor caused by an earthquake. However, the ultimate strength design method uses the ground surface acceleration spectrum method, which is similar to the earthquake influence coefficient spectrum method utilized in Chinese seismic design codes. To compare the response spectra of different seismic designs with similar on-site conditions, the spectral curves of the building base's earthquake influence coefficient of the elastic seismic design in the first stage are given. The corresponding displacement coefficient spectrum is given based on the quasi-spectral relation. The damping ratio of the structural system is selected as 5%.

In the Chinese seismic design code (GB 50011, 2010), the design spectrum curves are based on the frequent earthquake in an 8-degree zone. The maximum earthquake influence coefficient is α=0.16, the site is Class III, the group is 3, the site's characteristic period T_g=0.65 s, and the transition period of the long period's starting point $T_D=5T_g$. The spectrum curve is extended along a straight line for segments longer than 6.0 s.

$$\alpha(T)=\begin{cases}\alpha_{\max}(5.5T+0.45) & (0<T\le 0.1)\\ \eta_2\alpha_{\max} & (0.1<T\le T_g)\\ \left(\dfrac{T_g}{T}\right)^r\eta_2\alpha_{\max} & (T_g<T\le 5T_g)\\ \left[\eta_2 0.2^r-\eta_1(T-5T_g)\right]\alpha_{\max} & (5T_g<T\le 10\text{s})\end{cases} \tag{1}$$

where $\alpha(T)$ is the earthquake influence coefficient; $\alpha_{\max}$ is the maximum earthquake influence coefficient at the site; $r=0.9+\dfrac{0.05-\xi}{0.3+6\xi}$, which is the curve's attenuation index in the descending section; $\eta_1=0.02+\dfrac{0.05-\xi}{4+32\xi}$, which is no less than 0; $\eta_2=1+\dfrac{0.05-\xi}{0.08+1.6\xi}$, which is the damping adjustment coefficient and is no less than 0.55; and ξ is the damping ratio of the structural system.

Classes D and E sites in the US seismic design codes (ASCE, 2010) are roughly equivalent to a Class III site in the Chinese seismic design codes. Compared to the results of a Class D site, the calculated displacement and the base earthquake shear force are smaller. The risk level of the design earthquake (2/3 of the maximum acceleration of the earthquake ground motion is considered) is equivalent to that of the strengthened intensity in the Chinese standard. In the Chinese standard, to determine the precautionary intensity of an 8-degree zone, the earthquake's peak acceleration is taken as 0.2 g. Using an iterative calculation process and based on the design spectrum in the US seismic design code that corresponds to a Class III site, the maximum acceleration in the response spectrum platform is approximately S_S=1.04 g. At a period of 1 s, the maximum acceleration is S_1=0.5 g (Luo *et al*., 2006). For a Type E site, the minimum acceleration is S_1=0.75 g. Therefore, the intermediate value S_1=0.625 g is used in the following analysis. During the first stage of seismic design, the strength reduction factor R is used to adjust the design of the seismic action. R is dependent on the specific structural system. For an RC frame-core tube building structure, R=4.5.

$$\alpha(T)=\begin{cases}\dfrac{S_{DS}}{R}\left(0.4+0.6\dfrac{T}{T_0}\right) & (0<T\le T_0)\\ \eta_\xi\dfrac{S_{DS}}{R} & (T_0<T\le T_s)\\ \eta_\xi\dfrac{S_{D1}}{T\cdot R} & (T_s<T\le T_L)\\ \eta_\xi\dfrac{S_{D1}T_L}{T^2\cdot R} & (T_L<T\le 10\text{s})\end{cases} \tag{2}$$

$$\eta_\xi=\begin{cases}1.514\text{-}0.321\cdot\ln(100\xi) & (T_0<T\le T_s)\\ 1.400\text{-}0.248\cdot\ln(100\xi) & (T_s<T\le T_L)\\ 1.309\text{-}0.194\cdot\ln(100\xi) & (T_L<T\le 10\text{s})\end{cases} \tag{3}$$

where F_a=1.084; F_v=1.5; $S_{DS}=\frac{2}{3}F_aS_s$=0.7516 g; $S_{D1}=\frac{2}{3}F_vS_1$= 0.625 g; $T_0=0.2\frac{S_{D1}}{S_{DS}}$=0.1663 s; $T_s=\frac{S_{D1}}{S_{DS}}$=0.8316 s; T_L is the transition period of the long-period starting point (usually, T_L=6.0 s); and η_ξ is the damping correction factor.

In the design spectrum curve of the Japanese seismic design code (Mistumasa *et al*., 2003), the earthquake partition coefficient is Z=0.9 (Z=0.9 and Z=1.0 are two major seismic zones in Japan). The standard seismic shear coefficient is C_0=0.2, and the seismic design's maximum acceleration in the first stage is approximately 70.6 gal, which is equivalent to that of the 8-degree zone frequent earthquake in the Chinese seismic design code. A Class II site in the Japanese seismic design code is roughly equivalent to a Class III site in the Chinese seismic design code.

$$\alpha(T)=\begin{cases} Z\dfrac{1.5}{g}(0.64+6T) & (0<T\le 0.16) \\ \eta_\xi Z\dfrac{2.4}{g} & \left(0.16<T\le 0.64\dfrac{G_v}{1.5}=0.864\right) \\ \eta_\xi Z\dfrac{1.024G_v}{T\cdot g} & (0.864<T\le 10) \end{cases} \tag{4}$$

where G_v is the magnification factor for a Class II site in the Japanese seismic design code, and G_v=2.03; $\eta_\xi=\frac{1.5}{1+10\xi}\ge 0.4$; and g is the gravitational acceleration.

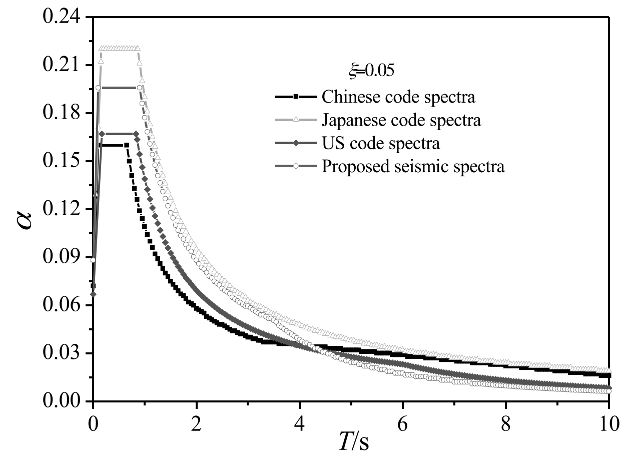
The seismic design spectra in the Chinese seismic design code (GB 50011, 2010) only specify standard spectra up to 6.0 s, and the spectrum curve is generally extended in a straight line for segments longer than 6.0 s. The spectra are not sufficiently long, and the values are often not reliable, which means that the seismic design code cannot accurately define the seismic design requirements for long-period building structures. Taking into account the actual conditions of Chinese seismic design, Zhou *et al.* (2015 & 2017) developed attenuation relationships of acceleration response spectra for periods up to 10.0 s based on digital recordings with rich long-period components from destructive shallow crustal strong earthquakes. A total of 4209 acceleration recordings from 109 earthquake events within 800 km of the causative fault were selected, and the average elastic spectrum was used to study the spectrum's characteristic period as well as the attenuation index and damping adjustment factors. The influences of the distance and site conditions on the long-period response spectrum were discussed, and the shapes of the amplification spectra were compared with the standard spectra specified in the Chinese seismic design code. The proposed long-period spectrum has several distinct characteristics; for example, the spectrum's platform segment is affected by the type of site, and the characteristic period of the site has a larger variation. In this paper, the proposed design spectrum curve (Zhou *et al*., 2017) is selected based on the frequent earthquake in the 8-degree zone. The maximum earthquake influence coefficient is given as $\alpha_{\max}$=0.178 (70×2.5/100×9.81=0.178), which corresponds to the third group in a Class III site, T_g=0.9 s, and T_D=3.5 s. The site effect coefficient is $S_i=S_{III}$=1.1. Compared with the seismic design spectrum in the Chinese seismic design code, attenuation coefficients of -1 and -2, which are consistent with steeper descending slopes, have been suggested to be used in the descending section of the designed spectrum. This selection takes into account the influence of the site classification. The site's characteristic period increases by 0.25 s.

$$\alpha(T)=\begin{cases} S_i\alpha_{\max}(5.5T+0.45) & (0<T\le 0.1) \\ \eta_\xi S_i\alpha_{\max} & (0.1<T\le T_g) \\ \eta_\xi S_i\dfrac{T_g}{T}\alpha_{\max} & (T_g<T\le T_D) \\ \eta_\xi S_i\dfrac{T_gT_D}{T^2}\alpha_{\max} & (T_D<T\le 10\text{s}) \end{cases} \tag{5}$$

where T_g is the site's characteristic period; T_D is the transition period of the long period; and the damping adjustment coefficient is $\eta_\xi=1+\frac{0.05-\xi}{0.1+1.3\xi}$, which is no less than 0.5.

A comparison of four seismic design spectra is shown in Figure 1a. When the damping ratio is ξ=0.05 (Figure 1a), the earthquake influence coefficients of the long period (approximately T>4.5 s) are different. The Japanese seismic design code gives the largest spectrum, followed by the spectra given by the Chinese and US seismic design codes, whereas the proposed design spectrum is the smallest. After approximately 7 s, the spectra given by the Japanese and Chinese seismic design codes are similar to each other, whereas the proposed seismic spectrum (Zhou *et al.*, 2017) is similar to that given by the US seismic design codes. The overall trend is that the spectra attenuate with an increase of the vibration period. However, the attenuation indexes are different. The displacement coefficient spectrum (Figure 1b) obtained based on the quasi-spectral relationship ($S_d=S_\alpha/\omega^2$) shows significant differences in the long-period segment. The displacement coefficient spectrum given by the US seismic design code (T>6 s) and the proposed design spectrum (T>3.5 s) remained unchanged with an increase of the vibration period. In contrast, the displacement coefficient spectra given by the Japanese and Chinese seismic design codes increase significantly as the vibration period increases. In the long-period segment, the displacement spectrum's increase with increasing period is not consistent with the statistical characteristics of the displacement spectrum's attenuation. In reality, when the structure's self-vibration period reaches a certain value, its relative displacement spectrum does not increase as its self-vibration period increases. The displacement at extremely long periods should be equal to the maximum displacement of the ground motion.

When the damping ratio is ξ=0.10 or 0.20 (Figure 1c and Figure 1d, respectively), the Chinese seismic design code gives the largest spectrum value in the long-period segment, which is even larger than that given by the Japanese seismic design code. The difference increases with increasing damping ratio. Research has shown that the long-period section of the response spectrum in the Chinese seismic design code is artificially adjusted. This changes the statistical characteristics of the ground motion, which results in anomalies in the displacement spectrum and the power spectrum in the long-period segment. These spectra correspond to the acceleration spectrum in the long-period segment. The seismic design spectrum is extracted from the absolute acceleration spectrum based on the seismic inertia force, and the damping adjustment coefficient is not set appropriately. As a result, the spectrum value of the design spectrum in the long-period segment increases as the damping ratio increases. This is inconsistent with the actual attenuation pattern in damped building structures.



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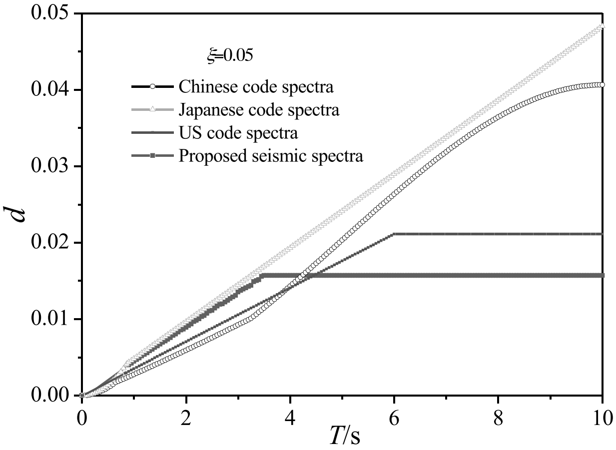

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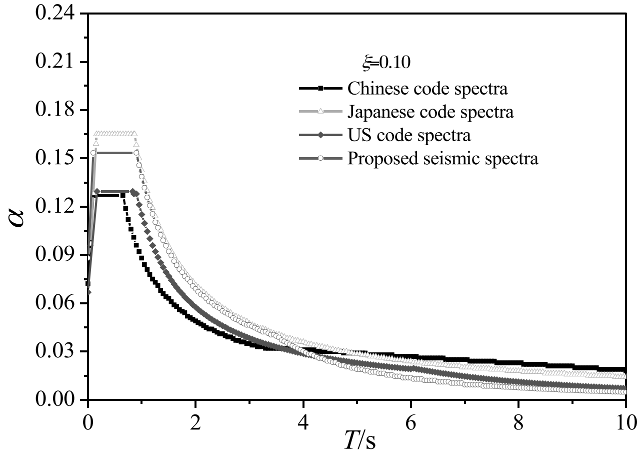
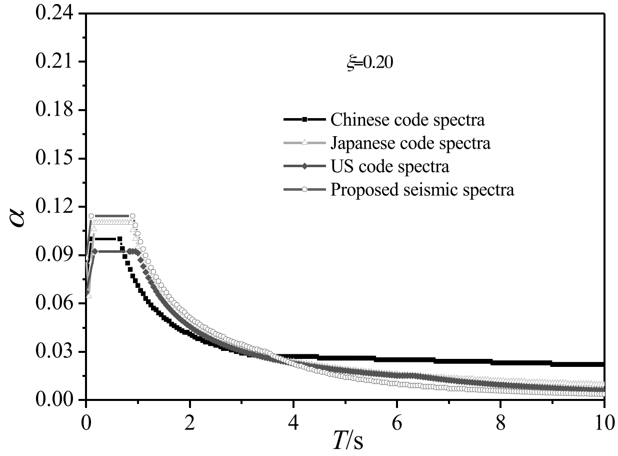


(c)



(d)

Figure 1. Comparison of seismic design spectra: (a) earthquake influence coefficient curves (ξ=0.05); (b) displacement coefficient curves (ξ=0.05); (c) earthquake influence coefficient curves (ξ=0.1); and (d) earthquake influence coefficient curves (ξ=0.2).

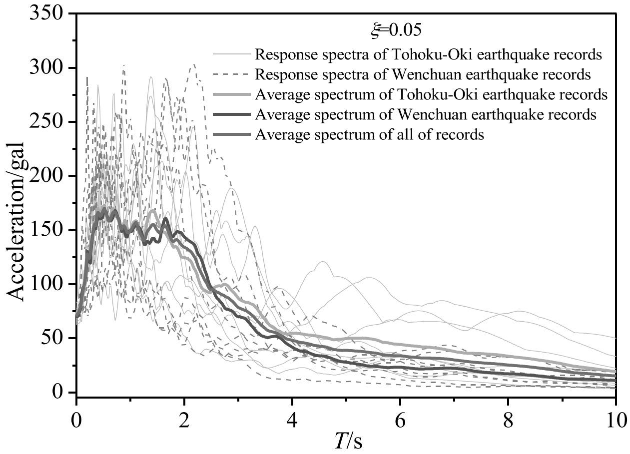
Ground motion records

The seismic design spectrum is the most representative statistical mean curve that can be extracted from a large number of seismic response spectra under the same basic conditions. Therefore, the structural response based on the design response spectrum analysis may be larger than the actual response. To assess the reliability of the results provided by the response spectrum analysis method, the results of the time-history analysis based on two sets of ground motion are compared. Eight records from ground motions in the Wenchuan earthquake and the Tohoku-Oki earthquake are selected. The two groups of records both contain significant amounts of information specific to the long-period segment. It is important to select proper ground motions to estimate seismic demands using linear response history analyses. Current seismic design provisions such as GB 50011-2010 provide criteria for selecting ground motions. In this study, to evaluate the reliability of the seismic design spectra in the long-period segment, far-field ground motions with long-period components are selected. The selection criteria are as follows: earthquake magnitude $M_s \geq 8.0$ (large magnitude), source depth ≤45 km (destructive shallow earthquake), epicentral distance 300 km≤R≤700 km (long distance), and the station has detailed geological survey data.

An elastic dynamic time-history analysis is conducted under the conditions of the 8-degree zone seismic acceleration (a=70 gal) in accordance with the Chinese seismic design code (GB 50011, 2010). The original seismic record information is shown in Table 1. After applying a zero line correction and bandpass filtering, the low frequency cutoff frequency is 0.05 Hz. The site conditions in the Tohoku-Oki ground motion record are determined in accordance with the site classification criteria of the Chinese seismic design code. To preserve the spectral characteristics, only the acceleration peak is scaled (amplitude modulation). Based on the response spectrum analysis, the average acceleration response spectra and the displacement response spectra of the two sets of seismic records are shown in Figure 2. The average displacement response spectra show that the selected ground motion records have many long-period components.

Table 1. Ground motion records used in the dynamic time-history analysis.

Record group	Sequence	Station	Component	Distance to epicenter (km)	PGA (gal)	Delay (s)	Site Classification
Wenchuan Earthquake records	E1	61FEX	NS	540	21.6	127	Medium-soft soil
	E2	61HXI	NS	597	90.3	439	Medium-soft soil
	E3	61LOX	NS	537	89.3	173	Medium-soft soil
	E4	61QIS	NS	552	37.3	306	Medium-soft soil
	E5	62HEP	NS	557	43.2	434	Medium-soft soil
	E6	62KLE	NS	489	13.1	223	Medium-soft soil
	E7	62LJB	NS	566	14.7	251	Medium-soft soil
	E8	62ZXX	NS	588	13.6	147	Medium-soft soil
Tohoku-Oki Earthquake records	E9	ABSH11	EW2	655	13.117	300	Type III
	E10	AICH06	EW2	650	8.107	285	Type III
	E11	IBRH20	EW2	316	187.623	300	Type III
	E12	NMRH03	EW2	630	21.010	300	Type III
	E13	SBSH07	EW2	546	10.804	300	Type III
	E14	TKCH07	EW2	526	32.3	300	Type III
	E15	SZOH35	EW2	487	48.5	300	Type III
	E16	SZOH42	EW2	495	61.038	300	Type III



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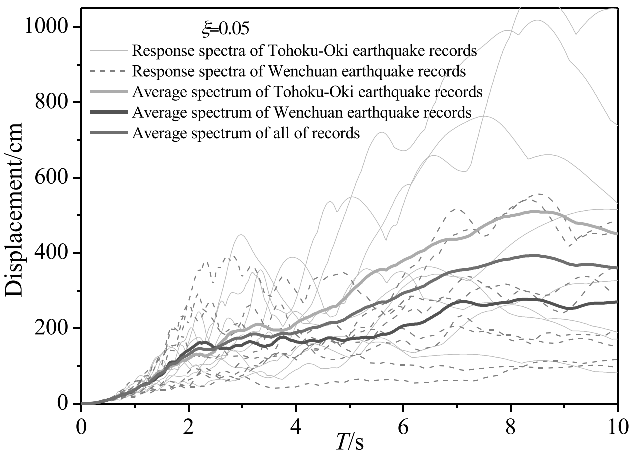


(b)

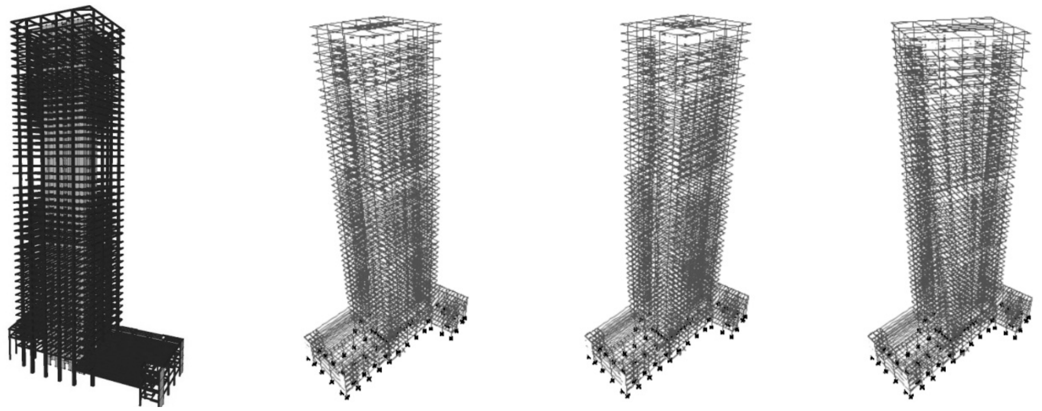
Figure 2. Response spectra in the ground motion records: (a) acceleration response spectra; (b) displacement response spectra.

Structural model

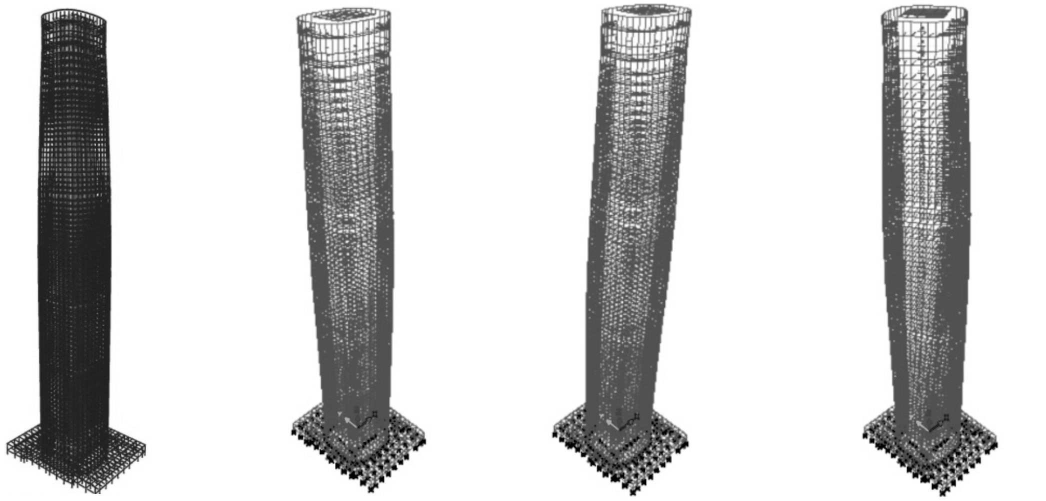
Taking two actual projects as examples, the differences between the results obtained from the response spectrum analysis and the elastic dynamic time-history analysis in accordance with the Chinese seismic design code, the Japanese seismic design code, the design spectrum in the US seismic design code, and the proposed design spectrum are compared in Figure 1. The square root of the sum of the squares (SRSS) combination is used to analyze the mode-superposition response spectra. Three-dimensional views of the structures are shown in Figure 3.

Structural model No. 1 represents the Olympic Park International Center in Shenzheng, China. The height of the building structure above the ground is 200.5 m, and it has 48 floors. The structural system is basically a core-supported structure, and its structural members are beams, columns, and the shear wall core, which are generally RC elements. Structural model No. 2 represents the International Financial Center in Guizhou, China, which has a structural height of 380 m above the ground and 80 floors. The structural system is also a core-supported structure, and its structural members are beams, columns, and the shear wall core. The columns are concrete-filled circular hollow section (CHS) members. The beams are generally RC elements, and the shear wall cores are typical steel RC walls. This composite wall core is designed because the structural core is the main element that withstands horizontal loads.

Fully three-dimensional finite element models with SAP2000 are utilized to perform the structural analyses and design. All of the primary controlling parameters are in accordance with China's current code. In structural model No. 1, 30 vibrational modes are included in the calculations, and the mass participation coefficient is 96% (>90%). In structural model No. 2, 60 vibrational modes are included in the calculations, and the mass participation coefficient is 92% (>90%). The periods of the first six modes of the two structural models are shown in Table 2. The internal forces and deformations of the building structures under the frequent earthquake (Level 1) are analyzed. The horizontal seismic actions are considered and checked separately in the two orthogonal major axial directions of the building structures. The design criteria (Level 1) is that the members will remain within the elastic range and that the maximum elastic story drift angle will not exceed 1/650. High seismic performance is required for this type of high-rise building structure. Therefore, design criteria (Level 2) are set for the seismic performance that when the building is subjected to extremely rare earthquakes (Level 2), the response story drift angle will not exceed 1/100. Dynamic time-history analyses via the response spectrum method are performed on the three-dimensional models to confirm the safety of the members under each level of earthquake and to confirm the failure mechanism. Figure 3 shows the shapes of the first vibration modes.



(a)



(b)

Figure 3. Actual projects: (a) structural model No.1 and its first 3 modes shapes, and (b) structural model No.2 and its first 3 modes shapes.

Table 2. The vibrational periods of the first 6 modes in the structural models.

Vibrational Mode	Structural model No. 1		Structural model No. 2	
	Vibrational Period (s)	Vibrational Direction	Vibrational Period (s)	Vibrational Direction
1st mode	5.994	Mainly horizontal motion in the Y direction	9.557	Mainly horizontal motion in the X direction
2nd mode	5.503	Mainly horizontal motion in the X direction	8.976	Mainly horizontal motion in the Y direction
3rd mode	4.118	Mainly torsion	5.724	Mainly torsion
4th mode	1.559	Mainly torsion	3.258	Mainly horizontal motion in the X direction
5th mode	1.493	Mainly horizontal motion in the X direction	2.755	Mainly horizontal motion in the Y direction
6th mode	1.341	Mainly horizontal motion in the Y direction	2.185	Mainly torsion

RESULTS AND DISCUSSION

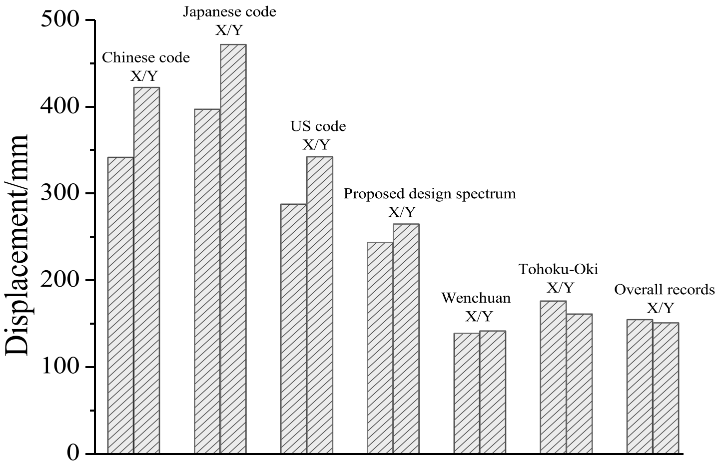
The damping ratio of the structural system is considered to be 5%. The maximum displacement (D_T) response at the top of the building structure and the maximum base earthquake shear force (V_S) are taken as reference parameters, and the seismic responses in the X and Y directions are recorded. The displacement response obtained from the dynamic time-history analysis and the seismic shear responses are highly discrete. Eight seismic records from the Wenchuan earthquake and eight seismic records from the Tohoku-Oki earthquake are selected, and the average values (μ) of all 16 seismic records are selected for comparison (Tables 3 and 4).

Maximum displacement response at the top

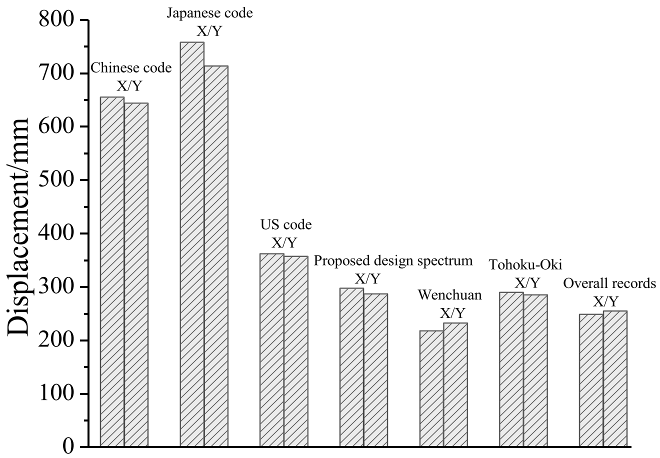
The maximum displacement response (Table 3 and Figure 4) calculated based on the response spectrum method is large, which is consistent with the sequence of the displacement spectrum (Figure 1b) obtained from the quasi-spectral relationship. The spectrum in the Japanese seismic design codes gives the largest result, followed by those in the Chinese and US seismic design codes. The proposed design spectrum gives the smallest result. The basic vibrational period of structural model No. 2 is larger. The displacement responses calculated based on the US seismic design code and the proposed design spectrum are significantly different from those calculated based on the Japanese and Chinese seismic design codes (Figure 4b). This observation reflects the characteristics of the displacement response spectrum (Figure 1b). The maximum displacement responses calculated based on the four seismic design spectra are all larger than the maximum average displacement response (μ_1, μ_2, μ_3) calculated based on the time-history analysis. For structural model No. 2 (Figure 4b), which has a longer vibration period, the maximum displacement response calculated based on the spectrum in the Japanese seismic design code is more than 2.8 times the maximum average displacement response μ_3 calculated based on the time-history analysis. If calculated based on the spectrum in the Chinese and US seismic design codes, this ratio will be more than 2.5 and 1.4 times greater, respectively. However, the maximum displacement response calculated based on the proposed design spectrum is only approximately 1.1 times the maximum average displacement response μ_3 calculated based on the time-history analysis, which means that these two results are more similar to each other. A comparison of the calculated results based on structural model No. 1 (Figure 4a) shows that the overall trends are similar, although the difference between the displacement responses is distinct due to the model's short vibration period. In the US seismic design code, the transition period of the long-period segment's starting point is longer, and the displacement response spectrum is larger. The difference is more pronounced than in the displacement response calculated based on the time-history analysis. The two engineering examples also show that, for the long-period building structures, the displacement responses calculated based on the design spectrum in the Japanese and Chinese seismic design codes are too conservative. These results are not consistent with the actual seismic response of the building structure, which may lead to a conservative seismic design. However, the proposed design spectrum reflects the real ground motion characteristics, which are characterized by a rapidly descending earthquake velocity due to the effect of the long period response spectrum. The difference between the maximum calculated displacement response and the maximum calculated average displacement response based on the time-history analysis decreases significantly. Therefore, the proposed design spectrum is highly reliable.

Table 3. Comparison of the different calculation methods (ξ=0.05).

Dynamic calculation method			Structural model No. 1				Structural model No. 2			
			D_T (mm)		V_S (kN)		D_T (mm)		V_S (kN)	
			X	Y	X	Y	X	Y	X	Y
Response spectrum method		Spectra of Chinese code	341.5	422.2	36,961	35,848	655.3	643.8	39,365	43,359
		Spectra of Japanese code	397.0	471.6	49,725	47,682	757.7	713.6	52,858	57,649
		Spectra of US code	287.5	342.2	36,673	35,301	361.8	357.1	33,076	37,764
		Proposed design spectrum	243.4	264.8	39,834	38,679	297.2	287.1	38,189	43,939
Time-history analysis method	Seismic records of Wenchuan earthquake	E1	72.8	82.6	35,615	29,570	140.0	191.6	22,042	37,376
		E2	211.3	191.2	37,548	34,453	148.2	192.9	18,254	37,450
		E3	104.0	110.7	33,595	31,072	181.3	210.4	30,436	34,008
		E4	145.2	145.9	46,698	38,751	98.0	146.7	22,506	37,468
		E5	84.1	77.5	32,007	29,642	92.4	90.7	22,030	34,018
		E6	231.8	240.2	53,834	52,509	687.5	615.7	76,685	65,398
		E7	127.3	124.6	21,396	14,061	200.3	198.7	22,647	24,005
		E8	131.4	159.6	37,690	47,526	194.4	209.1	35,066	35,156
		Average μ_1	138.5	141.5	37,298	34,698	217.8	232.0	31,208	38,110
		Standard deviation σ_1	56.9	55.2	9079	11,120	194.1	160.2	17,919	11,109
	Seismic records of Tohoku-Oki earthquake	E9	115.2	141.4	40,735	45,436	250.4	192.7	41,992	52,624
		E10	307.7	267.7	62,174	55,197	300.9	325.8	32,952	66,852
		E11	233.7	222.2	36,478	35,888	685.3	684.4	17,693	21,788
		E12	94.0	89.0	23,449	29,343	82.7	103.1	16,522	23,596
		E13	188.6	195.2	51,491	44,503	196.1	186.9	46,148	38,737
		E14	75.4	84.1	30,635	35,959	97.5	117.9	19,114	21,794
		E15	81.1	86.6	35,784	41,241	167.0	154.8	24,180	38,360
		E16	115.7	124.8	31,192	27,660	222.0	216.7	24,645	35,386
		Average μ_2	175.8	161.0	38,992	39,403	289.6	284.9	27,906	37,392
		Standard deviation σ_2	83.5	69.2	12,453	9091	207.1	208.4	11,290	15,963
	Overall average μ_3		154.5	150.6	38,145	37,051	248.5	254.7	29,557	37,751
	Overall standard deviation σ_3		69.3	60.6	10,821	10,508	195.3	176.8	15,286	13,597
Spectra of Chinese code /μ_3			2.21	2.80	0.97	0.97	2.64	2.53	1.33	1.15
Spectra of Japanese code /μ_3			2.57	3.13	1.30	1.29	3.05	2.80	1.79	1.53
Spectra of US code /μ_3			1.86	2.27	0.96	0.95	1.46	1.40	1.12	1.00
Proposed design spectrum /μ_3			1.58	1.76	1.04	1.04	1.20	1.13	1.29	1.16



(a)

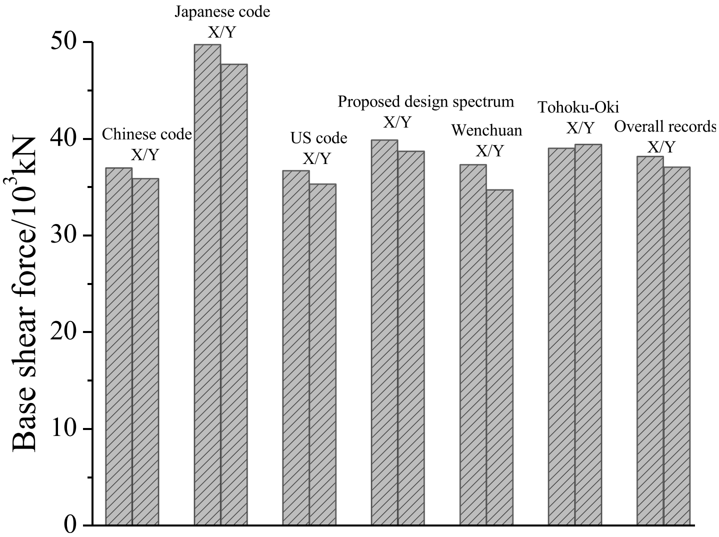


(b)

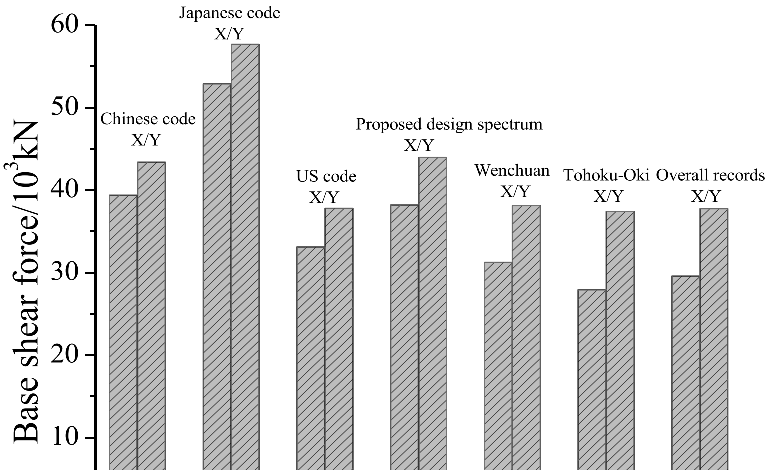
Figure 4. Maximum displacement of the top: (a) structural model No.1 (ξ=0.05), and (b) structural model No.2 (ξ=0.05).

Maximum seismic response of the base shear force

The differences in the maximum base shear force (Figure 5) calculated based on the mode-superposition response spectrum method are not as significant as the differences in the maximum displacement response at the top. The difference between the results calculated in accordance with the spectra stipulated in the Chinese and US seismic design codes and the proposed design spectrum is less than 16%. The spectrum stipulated in the Japanese seismic design code gives the largest maximum shear force. This is because, in the full period spectrum of the earthquake influence coefficient spectrum, the spectrum values in the Japanese seismic design codes are always the largest. For the earthquake effect coefficient that corresponds to the basic vibrational period (T_1=5.994 s) in structural model No. 1 (Figure 1a), the spectrum value in the Chinese seismic design code is 1.65 times that given by the proposed design spectrum. For the earthquake effect coefficient that corresponds to the basic vibrational period (T_1=9.557 s) in structural model No. 2, the spectrum value in the Chinese seismic design code is 2.65 times that given by the proposed design spectrum. However, the differences between the maximum base shear forces (Figure 5) are small. In structural model No. 1 (Figure 5a), the result given by the proposed design spectrum is approximately 8% larger than the results calculated based on the spectrum in the Chinese seismic design code. The main reason for this result is that, in the acceleration-sensitive section (platform section) and the velocity-sensitive section (T_g<T<3.5 s), the proposed design spectrum value is larger than the spectrum values in the Chinese seismic design code. When the vibration model's mass participation coefficient is greater than 90%, most of the high-order vibration modes studied are located in the short-period segment. Therefore, the complex maximum base shear force after the SRSS complex vibration analysis does not decrease. This shows that, compared with the Chinese seismic design code spectrum, the analysis based on the proposed design spectrum can better characterize the effect of high-order vibration modes on long-period building structures and the dynamic responses of the ultra-high and long-period building structures.



(a)



(b)

Figure 5. Maximum base shear force: (a) structural model No. 1 (ξ=0.05); (b) structural model No. 2 (ξ=0.05).

Comparison of the responses for high damping ratios

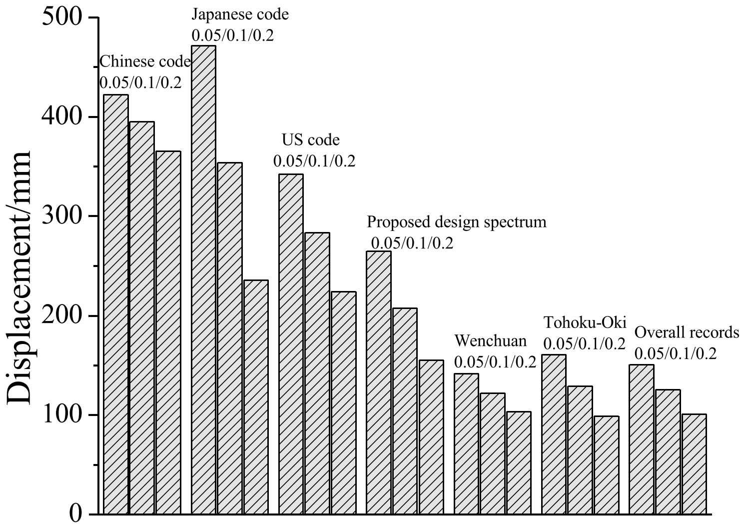
The response spectra for the high damping ratios (ξ=0.1 and ξ=0.2; Figures 1c and 1d, respectively) are used to perform the modal decomposition response analysis, and the time-history analysis is conducted simultaneously. The maximum displacement at the top and the maximum base shear force in the Y direction are taken as reference parameters, and the results are compared in Table 4 and Figures 6 and 7. Except for the results calculated based on the design spectrum in the Chinese seismic design code, the results calculated based on the design spectra and the average results calculated based on the time-history analysis show the same trends. The maximum displacement responses at the top and the maximum base shear force decrease as the damping ratio increases. The results calculated based on the design spectrum in the Japanese seismic design code change the most.

For structural model No. 1 (T_1=5.994 s), the maximum displacement response and the maximum base shear force calculated based on the design spectrum in the Chinese seismic design code also decrease as the damping ratio increases, although the decreases are limited. However, for structural model No. 2 (T_1=9.557 s), the maximum displacement response increases as the damping ratio increases, whereas the maximum base shear force does not change significantly. The design spectrum in the Chinese seismic design code (Figure 1) shows that, in the long period, the design spectrum value in the Chinese seismic design code increases as the damping ratio increases. This phenomenon becomes more pronounced as the vibrational period increases. Therefore, for structural model No. 2 in the long period, this is demonstrated by the anomaly in the displacement variation. In addition, the base shear force, which decreases as the damping ratio increases, may be essentially the same as the shearing force generated by the increase of the response spectrum's value. Therefore, the base shear force does not change significantly.

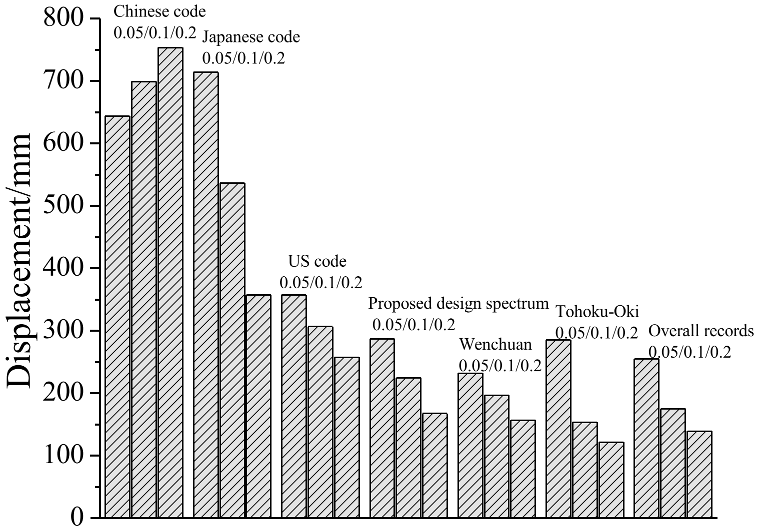
The results of the displacement responses calculated based on the four design spectra are all larger than the average results calculated based on the time-history analysis. All of the cases have large safety margins. However, as the damping ratio increases, the maximum base shear forces calculated in accordance with the spectra in the Japanese and US seismic design codes, as well as the proposed design spectra, are all smaller than the average results calculated based on the time-history analysis. The main reason is that the design spectra in the Japanese and US seismic design codes and the proposed design spectrum use the damping adjustment ratio, which does not change with the vibrational period. Several previous analyses have demonstrated that, for both the absolute acceleration spectrum values calculated based on the earthquake's inertial forces and the quasi-acceleration spectrum calculated based on the hysteresis restoring force, the increasing proportion of the damping force in the internal force of the structural system as the damping increases in the long-period segment cannot be neglected. Therefore, for the design spectrum in the long period, the damping adjustment should be appropriately reduced.

Table 4. Comparison of the different calculation methods (responses in the Y direction).

Dynamic calculation method			Structural model No.1				Structural model No.2			
			D_T (mm)		V_S (kN)		D_T (mm)		V_S (kN)	
			ξ=0.1	ξ=0.2	ξ=0.1	ξ=0.2	ξ=0.1	ξ=0.2	ξ=0.1	ξ=0.2
Response spectrum method	Spectra of Chinese code		395.0	365.4	31,083	27,021	698.7	753.4	42,576	42,681
	Spectra of Japanese code		353.7	235.8	35,784	23,853	536.6	356.8	43,303	28,825
	Spectra of US code		283.3	224.3	28,494	21,753	306.6	257.6	31,328	24,879
	Proposed design spectrum		207.6	154.9	30,291	22,565	224.7	167.4	34,419	25,621
Time-history analysis method	Seismic records of Wenchuan earthquake	E1	75.5	66.7	25,415	21,193	152.0	117.4	29,212	24,607
		E2	168.5	132.3	30,186	22,032	152.8	171.1	26,943	21,583
		E3	104.3	94.5	36,673	31,551	170.0	112.8	37,165	38,590
		E4	120.0	86.4	28,897	23,160	118.9	91.1	27,847	22,064
		E5	66.7	54.6	25,232	21,044	79.6	64.7	27,334	21,916
		E6	189.0	198.8	29,768	29,708	547.2	417.5	53,146	36,465
		E7	118.9	101.7	14,575	15,177	171.0	137.1	20,091	18,174
		E8	131.3	93.9	34,247	26,980	181.9	145.9	29,585	25,804
		Average μ_1	121.8	103.6	28,124	23,856	196.7	157.2	31,415	26,150
		Standard deviation σ_1	41.9	44.9	6734	5310	145.5	110.2	9936	7394
	Seismic records of Tohoku-Oki earthquake	E9	119.2	92.4	34,652	26,568	177.6	138.3	46,177	34,535
		E10	212.6	159.6	45,283	38,452	250.2	189.3	46,206	38,546
		E11	180.8	138.7	31,636	25,757	120.0	96.4	21,846	21,156
		E12	78.1	66.7	23,287	21,436	96.2	86.6	22,828	21,319
		E13	180.5	115.9	39,027	30,987	149.5	100.8	34,316	30,625
		E14	68.2	50.6	28,468	23,037	102.2	80.8	22,169	19,846
		E15	77.5	65.4	31,753	25,692	136.6	124.0	34,479	29,367
		E16	115.2	99.3	26,084	24,859	193.3	158.6	29,547	23,879
		Average μ_2	129.0	98.6	32,524	27,099	153.2	121.9	32,196	27,409
		Standard deviation σ_2	55.5	38.0	7114	5367	51.9	38.2	10,028	6916
	Overall average μ_3		125.4	101.1	30,324	25,477	174.9	139.5	31,806	26,780
	Overall standard deviation σ_3		47.6	40.3	7067	5423	107.9	81.7	9652	6947
Spectra of Chinese seismic code /μ_3			3.15	3.61	1.03	1.06	3.99	5.40	1.34	1.59
Spectra of Japanese seismic code /μ_3			2.82	2.33	1.18	0.94	3.07	2.56	1.36	1.08
Spectra of US seismic code /μ_3			2.26	2.22	0.94	0.85	1.75	1.85	0.98	0.93
Proposed design spectrum /μ_3			1.66	1.53	1.01	0.89	1.28	1.20	1.08	0.96



(a)



(b)

Figure 6. Maximum displacement at the top: (a) structural model No. 1 (Y direction), and (b) structural model No. 2 (Y direction).

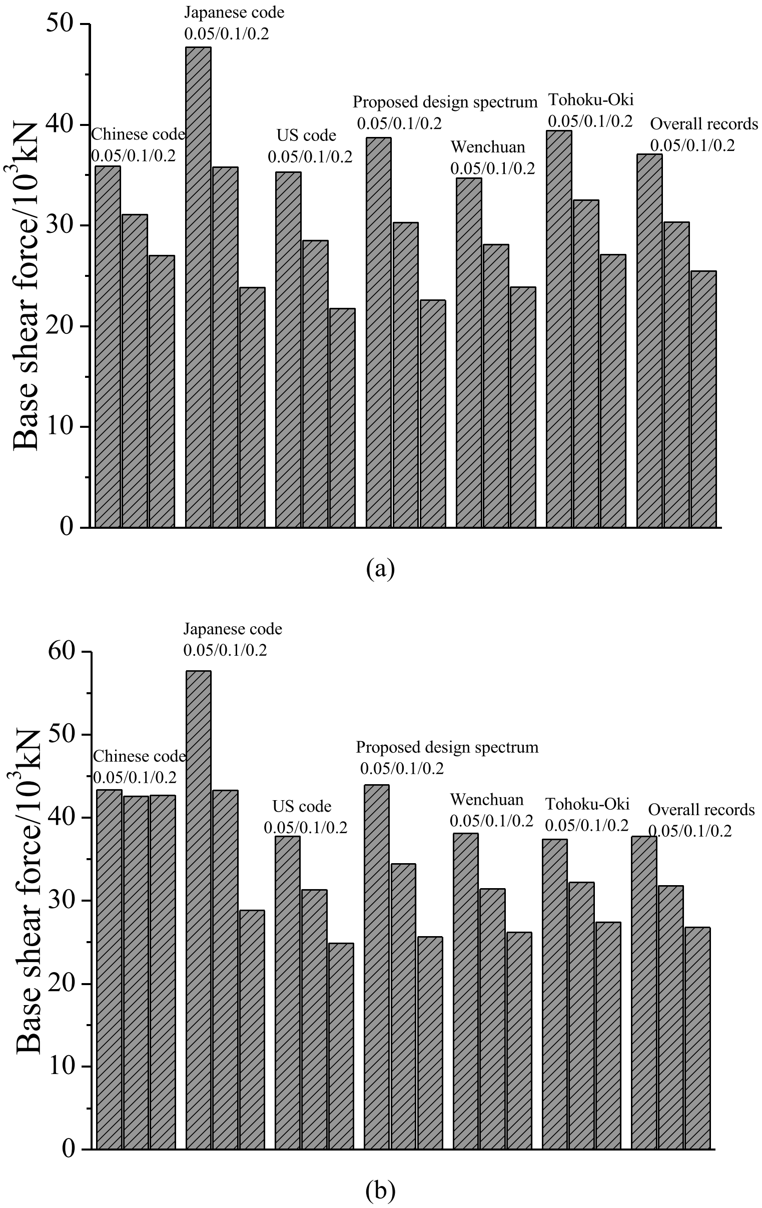
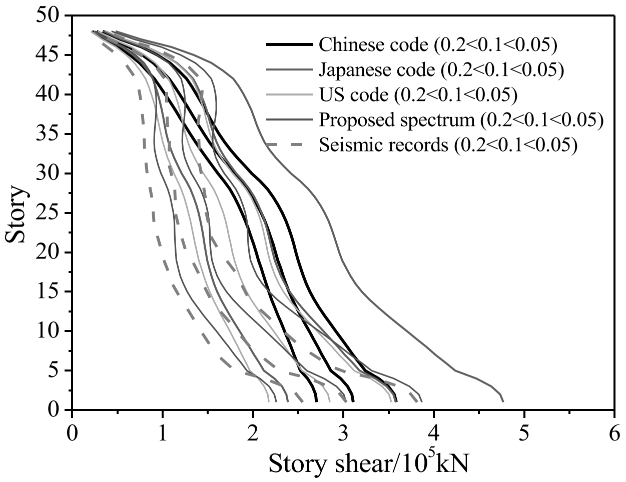
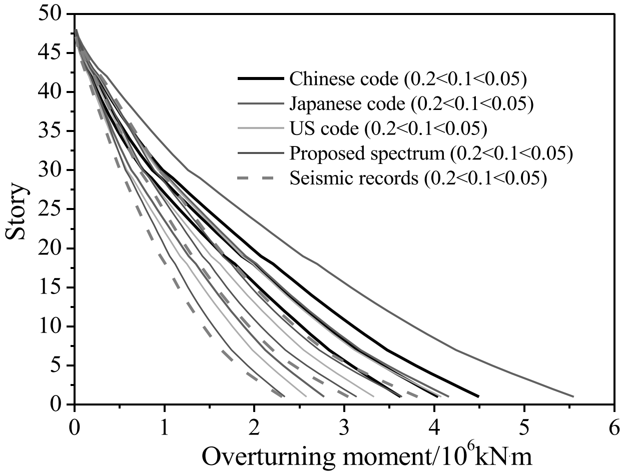


Figure 7. Maximum base shear force: (a) structural model No.1 (Y direction), and (b) structural model No. 2 (Y direction).

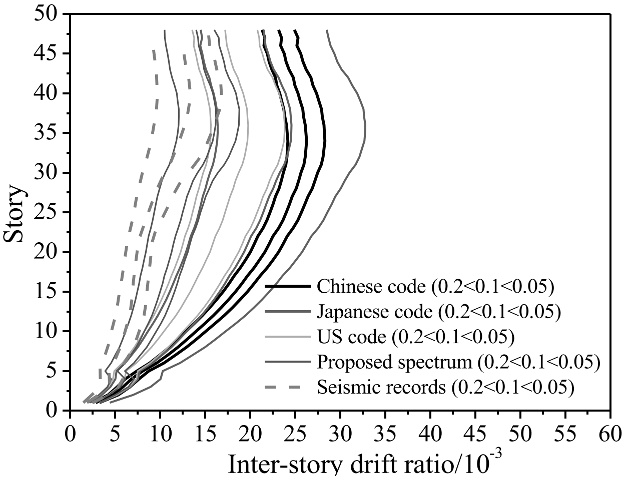
In the structural seismic response analysis, these data shown in Figures 8 and 9, such as the story shear and overturning moment, inter-story drift ratio, and story drift profile along the height of building structures, have been extracted and analyzed. The results are similar to the change trend of the top displacement and base seismic shear force. However, for structural model No.2 (T_1=9.557 s), the change trend of the results calculated based on the Chinese seismic design spectrum is different from that of the results calculated based on the other design spectra and the average results calculated based on the time-history analysis. In particular, the curves of story shear and overturning moment along the height of building structure with different damping ratio occur at the intersection in the middle-story. In general, the design spectrum in the long-period segment of the Chinese seismic design code needs to be modified and improved.


Chinese code (0.2<0.1<0.05)
Japanese code (0.2<0.1<0.05)
US code (0.2<0.1<0.05)
Proposed spectrum (0.2<0.1<0.05)
Seismic records (0.2<0.1<0.05)
Story
Story shear/10^5kN

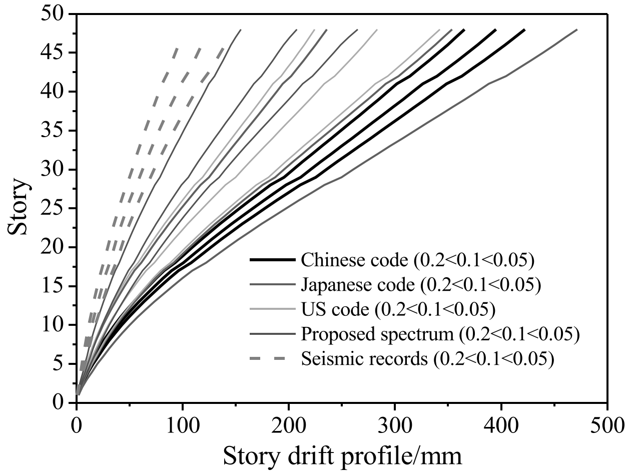
(a)


Chinese code (0.2<0.1<0.05)
Japanese code (0.2<0.1<0.05)
US code (0.2<0.1<0.05)
Proposed spectrum (0.2<0.1<0.05)
Seismic records (0.2<0.1<0.05)
Story
Overturning moment/10^6kN·m

(b)

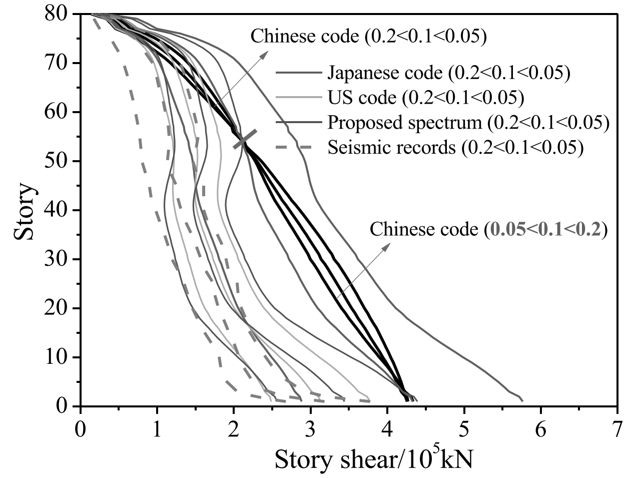

Chinese code (0.2<0.1<0.05)
Japanese code (0.2<0.1<0.05)
US code (0.2<0.1<0.05)
Proposed spectrum (0.2<0.1<0.05)
Seismic records (0.2<0.1<0.05)
Story
Inter-story drift ratio/10^-3

(c)

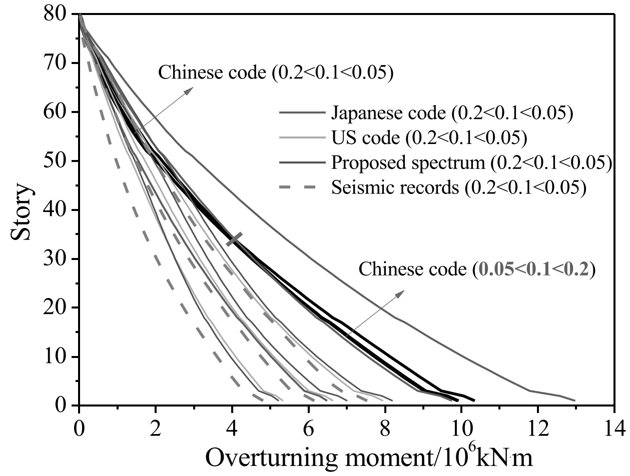


(d)

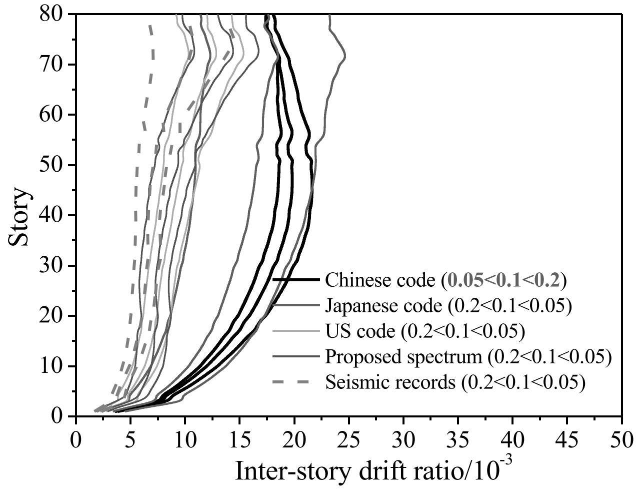
Figure 8. Structural model No.1 (Y direction): (a) story shear, (b) overturning moment, (c) inter-story drift ratio, and (d) story drift profile.



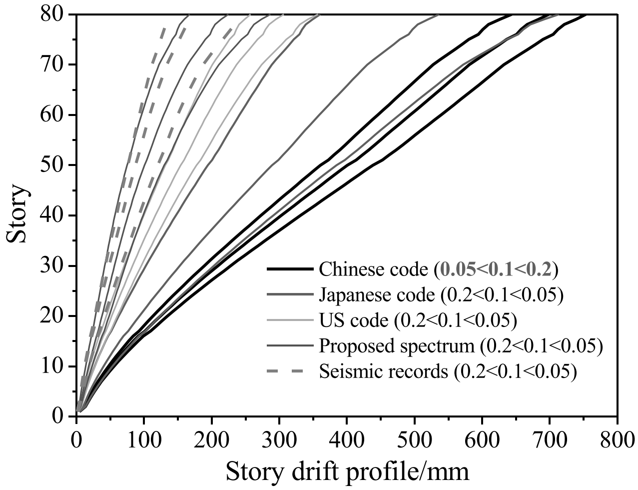
(a)



(b)



(c)



(d)

Figure 9. Structural model No.2 (Y direction): (a) story shear, (b) overturning moment, (c) inter-story drift ratio, and (d) story drift profile.

CONCLUSIONS

In the long period segments of the design spectra in the Japanese and Chinese seismic design codes, the displacement spectra increase significantly as the vibrational period increases. This is not consistent with the statistical attenuation characteristics and the physical meaning of the displacement response spectrum.

The maximum displacement responses at the top of long-period building structures, which are calculated using the mode-superposition response spectrum method in the design spectra stipulated in the Japanese and Chinese seismic design codes, are significantly larger than the average result calculated based on the dynamic time-history analysis method. The Japanese and Chinese seismic design codes are too conservative in this regard. The differences between the displacements calculated based on the design spectrum stipulated in the US seismic design code or the proposed design spectrum and the results calculated based on the time-history analysis are relatively small. Therefore, the US seismic design code and the proposed design spectrum are highly reliable in this regard.

When the damping ratio is 0.05, the maximum base earthquake shear force of the long-period building structure calculated using the mode-superposition response spectrum method in the proposed design spectrum is larger than the average results calculated based on the time-history analysis. Therefore, the proposed design spectrum is highly reliable in this regard. Taking into account the site conditions, by increasing the maximum value of the acceleration-sensitive segment in the short-period segment and increasing the site's characteristic period, the proposed design spectrum can better characterize the influence of the higher-order vibrational modes in the long-period building structure.

For the large long-period building structures, the maximum displacement responses calculated based on the design spectrum in the Chinese seismic design code increase as the damping ratio increases, whereas the maximum base shear forces do not change significantly. This indicates that the long period segment of the design spectrum in the Chinese seismic design code must be modified and improved. For large long-period building structures, as the damping ratio increases, the proportion of the damping force in the internal force of the structural system increases and thus cannot be neglected. Therefore, the damping force reduction ratio in the long period section of the response spectrum must be reduced appropriately.

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مقارنة ردود فعل هياكل المباني الشاهقة جداً للزلازل بناءً على تصاميم قياسية مختلفة لمقاومة الزلازل

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الخلاصة

لتقييم موثوقية الأجزاء طويلة الأجل من أطياف التصميم الزلزالي، تم تحليل مبنيين شاهقين الارتفاع بفترات اهتزاز طويلة المدى. ومن خلال رصد وتحليل رد فعل تفكك وتوزيع أنماط الأحمال الزلزالية وتحليل أوقات وتواريخ القوى الدافعة، تم مقارنة رد الفعل الانتقالي الأقصى عند السطح ورد فعل قوة القص القصوى للأحمال الزلزالية عند الأساسات. بالنسبة للتصاميم القياسية طويلة الأجل المنصوص عليها في رموز التصميم اليابانية والصينية، تزداد أطياف الإزاحة بشكل كبير مع زيادة فترة الاهتزاز، وهو ما لا يتماشى مع الخصائص الإحصائية لتخفيف رد الفعل الانتقالي. تتوافق أقصى قوة قص للزلزال تم حسابها وفقاً لطريقة الاستجابة في طيف التصميم المُقترح مع متوسط النتائج المحسوبة بطريقة التاريخ والوقت الديناميكي وكذلك مع النتائج المحسوبة وفقاً للتصاميم القياسية الصينية والأمريكية. ومع ذلك، فإن طيف التصميم المُقترح يميز بشكل أفضل رد فعل قوة قص الهياكل طويلة الأجل للهزات المرتفعة بشكل أكبر. بالنسبة للهياكل طويلة الأجل نسبياً، يزداد رد الفعل الانتقالي الأقصى المحسوب وفقاً للتصاميم القياسية الصينية مع ازدياد معدل الاضمحلال. بينما تكون درجة التغيير في قوة القص عند الأساسات صغيرة جداً. الأمر الذي يبين أن الإعدادات طويلة الأجل للتصاميم القياسية الصينية مازالت غير موثوقة. بالنسبة للهياكل الكبيرة طويلة الأجل؛ وبسبب ازدياد معدل الاضمحلال، لا يمكن تجاهل ازدياد نسبة قوة الاضمحلال وسط القوى الداخلية للنظام الهيكلى. لذلك، يجب التقليل من قوة الاضمحلال الناتجة عن تقليل رد الفعل مع طول الوقت بشكل مناسب.