

RECENT ADVANCES IN ENGINEERING CHARACTERISTICS OF NEAR-FAULT GROUND MOTIONS AND SEISMIC EFFECTS OF BUILDING STRUCTURES

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ABSTRACT

Severe damages of civil infrastructures under near-fault ground motions have impelled the community of earthquake engineering to pay intensive attention and investigation to their engineering characteristics and structural seismic effects. This paper reviews the recent research advances of authors in the engineering characteristics of near-fault ground motions and seismic responses and base-isolated performance analysis of building structures. Firstly, two non-structure-specific intensity measures, such as improved effective peak acceleration and velocity (*IEPA*, *IEPV*) were proposed. Two frequency content parameters were also suggested, namely the mean period of Hilbert marginal spectrum T_{mh} , and coefficient of variance of dominant instantaneous frequency of Hilbert spectrum H_{cov} which reflects the frequency nonstationary degree of ground motions. Meanwhile, a new stochastic model to synthesize near-fault impulsive ground motions with the feature of the strongest pulse was established. Then, the chaotic and fractal/multifractal characteristics of strong earthquake ground motions were analyzed deeply to explore their complexity from a novel perspective of nonlinear dynamics, and the inherent relation between fractal dimensions and period parameters of near-fault motions was exposed. Moreover, the mechanism of interstory deformation of tall building was illustrated based on engineering properties of pulse-like ground motions and generalized drift spectral analysis. Finally, the influence of ground motion properties on the seismic responses and performance of tall structures and base-isolated buildings was revealed.

KEYWORDS

Near-fault ground motions, intensity measures, frequency content parameters, chaotic and fractal characteristics, seismic performance of buildings.

INTRODUCTION

The engineering characteristics and structural seismic effects of near-fault ground motions have drawn much attention of many earthquake engineers since several destructive near-fault earthquakes, such as Northridge earthquake in 1994, Kobe earthquake in 1995, Chi-Chi earthquake, Taiwan in 1999, and Wen-Chuan earthquake in 2008 etc (Anderson and Bertero 1987; Hall *et al.* 1995; Somerville *et al.* 1997; Wang *et al.* 2002; Mavroeidis and Papageorgiou 2003; Bray and Rodriguez-Marek 2004; Liu *et al.* 2006; Tian *et al.* 2007; Zhai *et al.* 2008; Zhai *et al.* 2013). Generally speaking, near-fault ground motions are referred to the earthquake ground motions which are close to the rupture surface with the fault distance smaller than 20 km, and strongly depend on the rupture mechanism and obviously involve rupture forward directivity and fling-step effect. At present, there are numerous of theoretical and experimental studies on the analysis of seismic responses and dynamic performance in building and bridge engineering, including the base-isolated structures and energy dissipation structures subjected to near-fault ground motions (Alavi and Krawinkler 2004; Kalkan and Kunnath 2006; Yi and Zhang 2007; Tang *et al.* 2007; Zhao *et al.* 2008; Rupakhety and Sigurdsson 2011; Zamora and Riddell 2011; Ma *et al.* 2012; Li *et al.* 2012; Psycharis *et al.* 2013).

One of the most significant characteristics of great earthquake events is that the epicenters of earthquakes were close to the urban areas and the near-fault ground motions have distinct long-duration velocity and displacement pulses, which result in the high seismic intensity of downtown area. For example, in the Kobe earthquake in 1995, almost 90% of buildings located within the 5 km distance to the rupturing fault were collapsed or seriously damaged. In recent twenty years, engineering properties and structural effects of near-fault ground motions as well as the earthquake-resistant and vibration-reduction design of engineering structures have become important research topics in the field of engineering seismology and earthquake engineering. Meanwhile, the objective of these researches is to clarify the mechanism of structural seismic damage, and seek for effective strategies of structural seismic protection and thus develop relevant seismic design codes of civil

infrastructures. Seismic isolation of structure is a rapid developing technology for seismic protection, which has been applied widely in civil engineering. The base-isolated building presents a good performance of vibration-reduction in far-field region, but for the near-fault ground motions, the distinct long-duration velocity pulses may impose adverse influence on the seismic behavior and design of base-isolated buildings and other long-period structures. Moreover, note that the existing seismic design codes in many countries are developed based on the earthquake records not enough close to destructive faults, and the associated studies and understandings on damage potentials of near-fault ground motions with long-duration impulses are still insufficient.

This paper reviews the recent research developments of authors in the engineering characteristics of near-fault ground motions (Yang *et al.* 2009; Yang and Wang 2012; Yang *et al.* 2012; Yang and Zhang 2013; Yang and Long 2014; Yang *et al.* 2015, Yang and Zhou 2015) and seismic performance analysis of building structures (Yang *et al.* 2005; Yang *et al.* 2006; Yang *et al.* 2007; Yang *et al.* 2008; Yang *et al.* 2010; Jiang *et al.* 2010; Yang and Zhao 2010). In particular, two non-structure-specific intensity measures, i.e. improved effective peak acceleration and velocity (*IEPA*, *IEPV*) were proposed. Meanwhile, two frequency content parameters were advised, namely the mean period of Hilbert marginal spectrum T_{mh} and variance coefficient of dominant instantaneous frequency of Hilbert spectrum H_{cov} , and the nonlocal period parameters of near-fault ground motions were scrutinized. The stochastic modeling and synthesizing of near-fault pulse-like motions with forward directivity effect taking the orientation of the strongest pulses into account was addressed. Further, the chaotic and fractal properties of near-fault motions were explored from a new perspective of nonlinear dynamics. Moreover, it was shown that the velocity pulses of forward directivity and fling-step effect can excite different modal response of structures, and the mechanism of deformation distribution of tall building was illustrated as well. Finally, the influence of ground motion properties on seismic responses and performance of tall structures and base-isolated buildings was revealed.

INTENSITY AND PERIOD PARAMETERS OF NEAR-FAULT GROUND MOTIONS

The topic of engineering characteristics and structural effects of near-fault ground motions is becoming a research hotspot and important area in earthquake engineering, which plays a significant role in forming new field of this discipline and developing innovational technology of earthquake resistance and disaster mitigation. However, previous studies mainly focused on the characteristics of far-fault ground motions, and lacked the works examining deeply the properties of near-fault ground motions and seismic effects of structures.

Intensity measures of near-fault ground motions

Considering the frequency property of near-fault ground motions with rich long-period contents, Yang *et al.* (2009) proposed two improved intensity measures, namely, improved effective peak acceleration (*IEPA*) and improved effective peak velocity (*IEPV*). They are expressed as:

$$IEPA = \frac{S_a(T_{PA} - 0.2s, T_{PA} + 0.2s)}{2.5} \quad (1)$$

$$IEPV = \frac{S_v(T_{PV} - 0.2s, T_{PV} + 0.2s)}{2.5} \quad (2)$$

in which $S_a(T_{PA}-0.2s, T_{PA}+0.2s)$ represents the mean 5%-damped spectral acceleration in the period range of $T_{PA}-0.2s$ and $T_{PA}+0.2s$, and the length of interval is 0.4 s as the same as the definition in ATC-3 code; $S_v(T_{PA}-0.2s, T_{PA}+0.2s)$ denotes the mean 5%-damped spectral velocity in the period range of T_{PV} .

Then, 150 near-fault earthquake records including pulse-like ground motions from two different earthquake events, Chi-Chi earthquake and Northridge earthquake were chosen. The correlation between 30 intensity indices of the near-fault ground motions and dynamic responses (i.e., maximum displacement, input and hysteretic energy) of bilinear single degree of freedom (SDOF) systems were examined. The numerical results indicate that the correlation between intensity indices of near-fault ground motions and structural responses are related to the fundamental period of structures. Generally speaking, the acceleration-related intensity parameters (*PGA*/Peak Ground Acceleration, *IEPA* and I_a) have a strong correlation with demand parameters or dynamic responses of short-period SDOF systems, and the velocity-related parameters (*IEPV*, I_F and *PGV*/Peak Ground Velocity) present good correlation with demand parameters of SDOF systems with the medium-period and medium-long-period. For the long-period systems, displacement-related parameters (I_d , d_{sq} and P_d) are fairly correlated with demand parameters. Moreover, the *IEPA* and *IEPV* of near-fault ground motions improve the performance of intensity measure of conventional parameters, i.e., *EPA* and *EPV*, respectively. Compared with the Northridge earthquake the long-period impulsive feature of Chi-Chi earthquake is more remarkable due to

the different source mechanism. There are considerable differences in the correlation curves of intensity measures of impulsive and non-pulse ground motions, especially for Chi-Chi records.

Nonlocal period parameters of near-fault ground motions

Hilbert-Huang transformation is a new time-frequency signal analysis method, which can be applied to investigate the time-variant non-stationary frequency property of near-fault ground motions. Using HHT to analyze the representative near-fault records, the variance coefficient of predominant instantaneous frequency of Hilbert spectrum (H_{cov}) was suggested to reflect the non-stationary degree of frequency contents of ground motion (Yang and Wang 2012):

$$H_{cov} = \frac{\sigma(\omega(t))}{\mu(\omega(t))} \quad (3)$$

Eq. 3 means that H_{cov} equals the ratio of standard deviation to mean value of time history of predominant instantaneous frequency of Hilbert spectrum $\omega(t)$ in the whole duration of ground motion. It can be seen from the definition that the non-stationary degree of ground motion's frequency increases with the variance coefficient H_{cov} .

Meanwhile, considering that the Hilbert marginal spectrum can describe the frequency content of strong ground motions better than Fourier amplitude spectrum, we defined similarly the mean period of Hilbert marginal spectrum (T_{mh}) by Hilbert marginal spectrum (Yang and Wang 2012), namely,

$$T_{mh} = \frac{\sum_i H_i^2 (1/f_i)}{\sum_i H_i^2} \quad 0.2\text{Hz} \leq f_i \leq 25\text{Hz} \quad (4)$$

where H_i stands for the Hilbert marginal spectrum coefficient, and f_i is the discrete frequency.

Subsequently, 46 near-fault ground motion records from Chi-Chi earthquake are grouped into several categories with different motion characteristics, and 7 period parameters characterizing frequency contents of ground motion are calculated, including the mean period of Fourier amplitude spectrum T_m , mean period of Hilbert marginal spectrum T_{mh} , characteristic period of acceleration response spectrum T_c , the predominant period T_{PA} and T_{PV} of 5%-damped acceleration and velocity response spectrum, etc. Furthermore, the variance coefficient of predominant instantaneous frequency of Hilbert spectrum is also obtained. It is demonstrated that the non-stationary characteristic of near-fault ground motions is significant, and the variance coefficient H_{cov} of predominant instantaneous frequency of Hilbert spectrum clearly reflects the non-stationary property and degree of ground motion's frequency. In addition, the influence of motion characteristics of near-fault records on their frequency content parameters and non-stationary property is analyzed.

A stochastic model and synthesis of near-fault impulsive ground motions

When considering the pulse-like motions and their seismic responses, the orientation of ground motions are paramount (Zamora and Riddell 2011; Shahi 2013). The combination of continuous wavelet transform coefficients from two horizontal and orthogonal components of a ground motion record is utilized to yield the orientation of its strongest pulse. According to the statistical parametric analysis of velocity time histories in the orientation of the strongest pulse, a new stochastic pulse model (Yang and Zhou 2015) with a specified magnitude and various fault distances R was established as follows

$$V_p(t) = PGV \cdot \exp \left[\sigma_{\ln PGV} - \frac{\pi^2}{4} \left(\frac{t - T_{pk}}{N_c T_p} \right)^2 \right] \cdot \cos \left(2\pi \frac{t - T_{pk}}{T_p} - \varphi \right) \quad (5)$$

$$\ln(PGV) = 4.39 - 0.14 \ln R \quad (6)$$

where T_p , V_p , N_c , T_{pk} and φ represent the pulse period, peak pulse velocity, number of circles in the pulse, the location and phase of the pulse, respectively, which have a clear physical interpretation. These pulse parameters are estimated by nonlinear least-square fit of the single Gabor wavelet in Eq. 5 to the velocity time history with the strongest pulse. Meanwhile, the correlations between pulse parameters and seismological parameters are analyzed, and different regression models are adopted to fit those correlated parameters. The standard deviations together with those uncorrelated parameters are regarded as random variables, which follow well the normal or lognormal distributions based on the statistical analysis.

Finally, acceleration time histories of ground motions with high- and low-frequency components are generated by the superposition of the stochastic pulse and the stochastic high-frequency accelerogram modulated by an

intensity envelope function. The synthesized ground motions indicate that the proposed stochastic model can reflect the pulse characteristic of near-fault ground motions. Additionally, the dynamical reliability of frame building under random near-fault pulse-like excitations generated from the stochastic model is addressed.

CHAOTIC AND FRACTAL PROPERTIES OF NEAR-FAULT GROUND MOTIONS

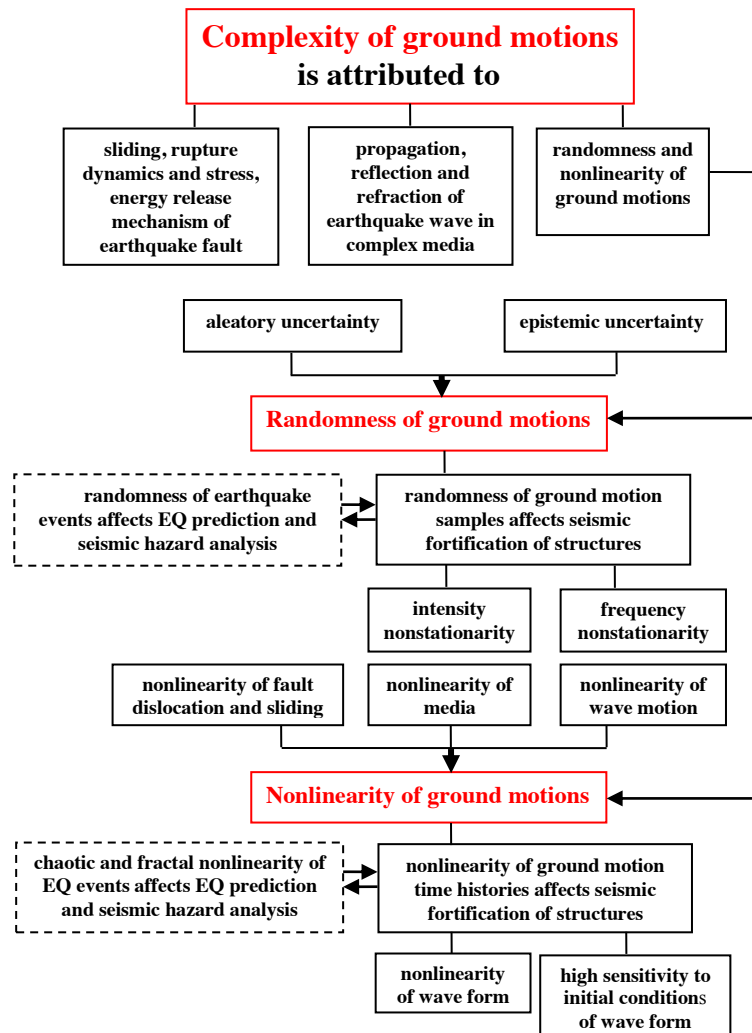


Figure 1 Complexity of earthquake ground motions

In fact, at present the two issues of earthquake engineering in near-fault region are closely connected with the two difficulties or challenges emerged in the development of earthquake engineering. One difficulty is the complexity of earthquake ground motions, and another is the complexity of damage failure of engineering structure. The complexity of structural failure is shown as diverse failure modes and failure behaviors, in which the reasons contain the plastic deformation of materials and components, the degradation of strength or stiffness, hysteretic energy dissipation, damage accumulation, low-cycle fatigue, crack extension, frictional contact, buckling instability, etc. The complexity of earthquake ground motions is attributed to various factors, such as sliding, rupture dynamics and stress and energy release mechanism of earthquake fault, propagation, reflection and refraction of earthquake wave in complex media, and the randomness and nonlinearity of ground motions at engineering site, etc. A number of ground motion samples recorded in single or multiple earthquake events generally exhibit the randomness. Also, the multiple earthquake events occurred at the same or different sites present the stochasticity. The randomness of ground motion samples and earthquake events is mutually affected and correlated. The randomness of earthquake events incurs a great difficulty to earthquake prediction and seismic hazard analysis, while the randomness of ground motion samples produces a challenge to seismic fortification of engineering structures. Generally, the randomness of ground motion samples refers to the nonstationarity of intensity and frequency content of ground motions as stochastic processes. The power

spectrum model of ground motions suitable to random vibration analysis of structures can characterize well the intensity nonstationarity of ground motions, but it is still necessary to further develop a fully time-frequency non-stationary model of ground motions for random vibration analysis. The randomness of ground motions is originated from the aleatory and epistemic uncertainty. Since Housner established the white-noise stochastic model of earthquake ground motions in 1947, the researchers usually regard the ground motions as a kind of stochastic process, which is related to that the probability and statistics theory dealing with the random uncertainty issues was developed quite maturely in 1940s.

Nevertheless, another aspect of complexity of earthquake ground motions, namely nonlinearity, has been ignored for a long time in earthquake engineering, which is associated with a fact that nonlinear dynamics theory was developed until 1980s. Many ground motions recorded in single or multiple earthquake events present the nonlinearity. Meanwhile, the multiple earthquake events occurred at the same or different sites exhibit the nonlinearity. The nonlinearity of ground motions and earthquake events is also mutually affected and correlated. The nonlinearity of chaotic and fractal properties of earthquake events imposes a great difficulty to earthquake prediction and seismic hazard analysis, while the nonlinearity of ground motions produces a challenge to seismic fortification of structure. The nonlinearity of time history of ground motions is shown in: (1) the waveform of time history of ground motions is nonlinear, which cannot be linearly superimposed by simple harmonic waves; (2) the waveform of time history of ground motions is highly sensitive to initial condition, and waveforms of ground motion records from different stations with the near distances in the same earthquake event and those from the same station in different earthquake events with short time interval present remarkable distinction. In practice, earthquake ground motions are the site output response of nonlinear dynamical system of geophysics, and their strong nonlinearity comes from the nonlinearity of initial condition of earthquake dynamic process and dynamic model, including the nonlinearity of fault dislocation and sliding, the nonlinearity of media and wave motion etc. Currently, the wavelet transform and Hilbert-Huang transform appropriate for nonlinear and non-stationary time series analysis are widely used in the characteristics analysis of ground motion time histories and structural seismic responses.

Recently, Yang *et al.* (2012) examined the nonlinear dynamical property of acceleration time histories of near-fault ground motions by introducing the method of chaotic time series analysis. Based on the approach of power spectrum analysis, principal component analysis and improved false nearest neighbor (FNN) method, it is qualitatively illustrated that the ground motion acceleration series possess the chaotic property. Then, the method of chaotic time series analysis is applied to quantitatively calculate the nonlinear characteristic parameters such as correlation dimension and maximal Lyapunov exponent. Computational results indicate that the strong earthquake ground motions have the chaotic characteristic, which are not the pure random signal. The high irregularity and complexity of ground motions are the reflection of strong nonlinearity of earthquake physical process.

On the other hand, Yang and Zhang (2013) investigated the complexity and irregularity of near-fault ground motions from the viewpoint of fractal geometry. The box-counting fractal dimensions of 30 acceleration time histories of near-fault ground motions from the Chi-Chi and Northridge earthquakes are calculated. It is shown that the acceleration time histories of ground motions exhibit the statistical fractal property, and the effect of characteristic of near-fault motions on their fractal dimensions is remarkable. The average fractal dimension of near-fault impulsive ground motions with forward directivity effect is middle, and that of impulsive ground motions with fling-step effect is the smallest, while the average fractal dimension of non-pulse ground motions is the largest and the corresponding irregular degree of waveforms is the highest. Moreover, the fractal dimension of ground motions reflects their frequency property, and can be regarded as an index to represent their period. The fractal dimension D of ground motions is negatively correlated with their characteristic period T_c . In addition, the fractal property of the seismic dynamic responses of SDOF systems under near-fault ground motions is examined. Finally, based on multifractal detrended fluctuation analysis, the multifractal characteristic parameters of acceleration time series for typical near-fault ground motions are calculated (Yang *et al.* 2015). It is illustrated that the scaling exponent $h(2)$ can be utilized to measure the frequency content and irregularity degree of strong earthquake ground motions, and the long-range correlation of small and large fluctuation is the major source of multifractality of near-fault ground motions.

SEISMIC PERFORMANCE ANALYSIS OF BUILDINGS UNDER NEAR-FAULT MOTIONS

Deformational distribution feature and mechanism analysis of buildings subjected to near-fault pulse-type ground motions

Based on the method of generalized interstory drift spectral analysis, the tall building is equivalently expressed as a shear-flexural beam shown in Figure 2, and the interstory drift ratios (IDR) of typical shear-flexural beams

are exhibited in Figure 3 (Yang *et al.* 2010). Ground inputs include the idealized simple pulses and three groups of near-fault records with forward directivity pulses, fling-step pulses and without pulse. The features of deformational distribution of buildings along height subjected to near-fault motions are acquired. It is illustrated that for moment-resisting frame buildings, the fling-step pulses excite primarily their contribution in the first mode and generate large deformation in the lower stories. The forward directivity pulses can activate the drift response of higher modes of frame buildings. Moreover, the mechanism for these deformational phenomena of building are revealed according to the distinct property of near-fault pulse-type ground motions and generalized drift spectral analysis. It is pointed out that the difference among the average interstory drift spectra of three groups of ground motions is remarkable in the whole range of fundamental period.

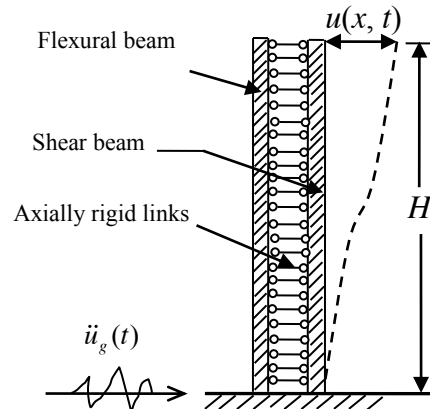


Figure 2 Shear-flexural beam model used in interstory drift spectrum analysis

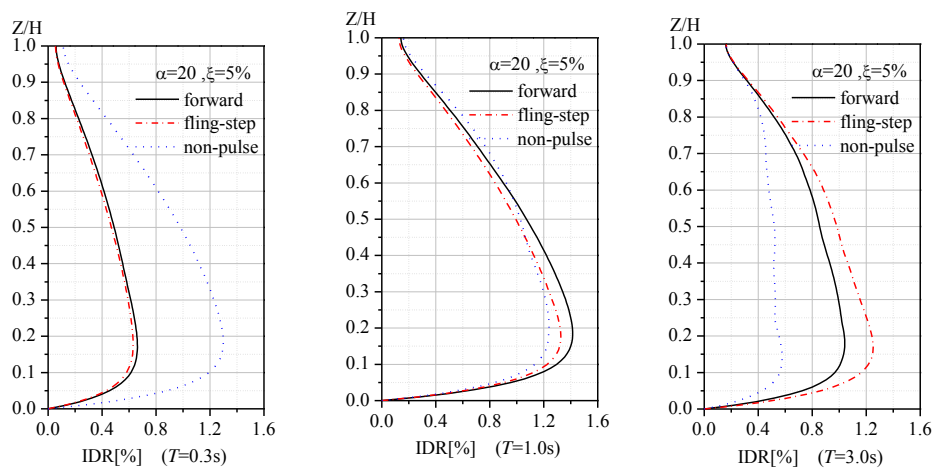


Figure 3 Mean IDR distribution of buildings under three groups of near-fault ground motions with fundamental periods $T=0.3$ s, 1.0 s, 3.0 s

Influence of near-fault ground motions on seismic responses of tall building with short-limb wall

Near-fault ground motions have the unique characteristics of hanging wall effect, rupture directivity effect, and large velocity pulse. The effect of ground motions with these features on the seismic responses of tall building with short-limb walls was examined in Yang *et al.* (2008). The near-fault recordings from Chi-Chi, Taiwan earthquake are selected as the input and the ANSYS software is used to establish a spatial bar-shell combined finite element model for one 12-story tall building with short-limb walls in Figure 4, then the elastoplastic time history analysis of this mode is implemented. The calculated results show that the hanging wall and rupture directivity effect can remarkably amplify the dynamic responses of structural system with short-limb walls, and the maximum drift ratio 0.98% occurs at the 5th story in the middle of building, which means that the building reaches medium damage state. Moreover, the effect of pulse-like ground motions highly depends on the structural period, and the pulse-like effect on the long-period structure is significant.

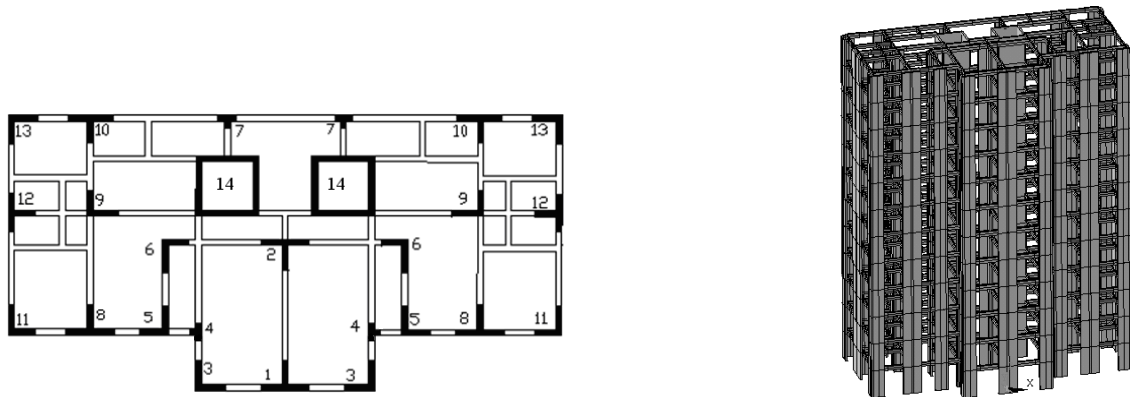


Figure 4 Plane and finite element model for dynamic analysis of tall building with short-limb wall

Effects of forward directivity and fling step of near-fault ground motions on seismic responses of high-rise steel structure and based-isolated building

Table 1 Basic parameters of three groups of near-fault ground motions

	station, component	d (km)	site	PGA (g)	PGV (cm/s)	PGD (cm)	PGV/PGA (s)	t_d (s)
Impulsive records with forward directivity effect	TCU051 EW	6.95	D	0.160	51.53	124.52	0.27	24.18
	TCU054 EW	4.64	D	0.146	45.69	121.47	0.32	23.98
	TCU082 EW	4.47	D	0.226	51.54	152.35	0.23	23.28
	TCU102 EW	1.19	D	0.304	87.16	163.13	0.29	14.93
	TCU120 EW	9.87	C	0.228	62.58	107.63	0.28	32.35
	JEN 022	5.43	D	0.424	106.22	43.06	0.26	12.42
	RRS 228	6.50	D	0.838	166.05	28.78	0.20	7.03
	SCE 288	5.19	D	0.493	74.58	28.69	0.15	7.53
	SCS 052	5.35	D	0.612	117.45	53.47	0.20	15.10
	SYL 360	5.30	D	0.843	129.71	32.68	0.16	5.32
Impulsive records with fling-step effect	TCU052 NS	1.84	D	0.448	220.64	723.27 (676.90)	0.50	15.92
	TCU052 EW	1.84	D	0.356	182.96	506.73 (-443.10)	0.52	16.78
	TCU065 EW	2.49	D	0.789	132.29	194.31 (134.20)	0.17	28.78
	TCU067 EW	1.11	D	0.499	97.26	186.16 (102.95)	0.20	21.71
	TCU068 NS	3.01	D	0.365	291.94	867.76 (619.30)	0.82	13.21
	TCU068 EW	3.01	D	0.505	279.88	709.11 (-567.30)	0.57	12.36
	TCU075 EW	3.38	D	0.332	116.05	171.07 (120.00)	0.36	26.92
	TCU076 EW	3.17	D	0.343	69.29	108.55 (87.56)	0.21	29.68
TCU087 NS	3.42	C	0.113	45.20	93.09 (-81.23)	0.41	24.10	
TCU128 EW	9.08	C	0.144	60.58	145.39 (118.80)	0.43	19.20	
Non-pulse records	TCU071 EW	4.88	D	0.528	69.83	170.60	0.08	24.56
	TCU072 EW	7.87	D	0.476	85.51	223.86	0.18	21.92
	TCU078 EW	8.27	D	0.442	42.14	98.88	0.10	25.95
	TCU079 EW	10.95	D	0.589	64.49	173.20	0.11	24.24
	TCU089 EW	8.33	C	0.354	45.43	194.62	0.13	24.11
	KAT 090	13.42	D	0.640	37.84	5.09	0.06	6.57
	PKC 360	7.26	D	0.433	51.49	7.21	0.12	9.82
	SPV 360	8.44	D	0.939	76.60	14.95	0.08	8.20
	STC 180	12.09	D	0.477	61.48	22.06	0.13	10.61
TAR 360	15.60	D	0.990	77.62	30.45	0.08	12.66	

Note: PGD stands for peak ground displacement, d is the fault distance, t_d is the 95% significant duration, and the data in the bracket represent static displacement of ground motions with fling-step pulses.

The influence of two kinds of near-fault ground motions with different velocity pulses due to forward directivity and fling-step effects on the seismic responses of high-rise steel frame structure was scrutinized in Jiang *et al.* (2010). Near-fault ground motions with forward directivity and fling-step pulses and without velocity pulse are chosen as seismic inputs as shown in Table 1, and the velocity and displacement time histories of near-fault ground motion RRS228 with forward directivity pulse and TCU052 NS with fling-step pulse are demonstrated in Figures 5 and 6, respectively. The SAP2000 software is applied to model a 20-story plane frame structure, and the elastoplastic time history analysis of structure are implemented. Computational results illustrate that the

ground motions with fling-step and forward directivity pulses mainly activate the fundamental modal response of the 20-story steel building, and thus lead to the larger IDR in the lower story and global collapse, while the non-pulse ground motions can excite the response of higher modes. Furthermore, the structural damage potential of impulsive ground motions is significantly greater than that of non-pulse ground motions. Numerical results of dynamic responses and damage state of steel frame structure are explained rationally from the perspective of energy dissipation of SDOF system.

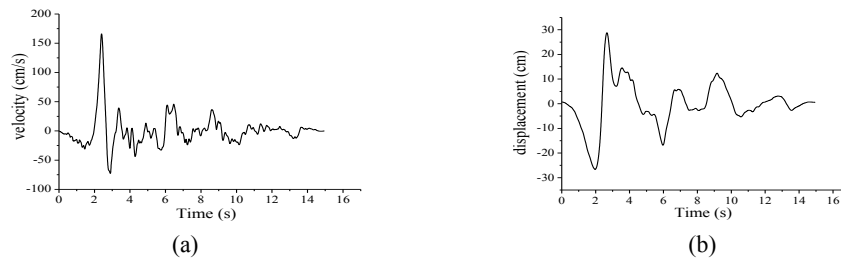


Figure 5 Velocity (a) and displacement (b) time histories of near-fault ground motion RRS228 with forward directivity pulse

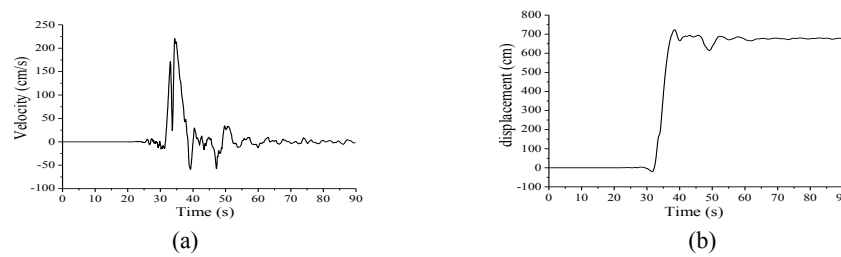


Figure 6 Velocity (a) and displacement (b) time histories of near-fault motion TCU052 NS with fling-step pulse

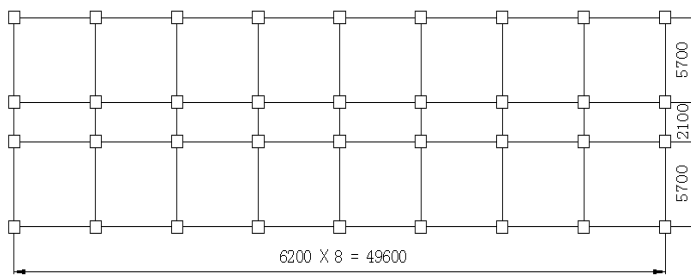


Figure 7 Plan of base-isolated building structure

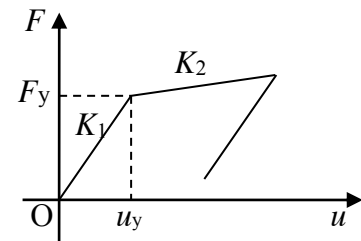


Figure 8 Bilinear hysteretic model of lead rubber bearings

In addition, near-fault ground motion records listed in Table 1 were also selected as seismic inputs, and the influences of forward directivity pulses and fling-step pulses on the seismic performance of SDOF system and base-isolated building with lead rubber bearings were examined in Yang and Zhao (2010). Six-story reinforced concrete base-isolated frame and bilinear hysteretic model of lead rubber bearings are shown in Figures 7 and 8, separately. The response spectrum analysis illustrates that the effects of rupture forward directivity and fling step of ground motions on the seismic responses of engineering structure are period-dependent. In the range of short and medium period, the spectral acceleration of ground motions with forward directivity effect is larger than that with fling step effect. In the long period range, the spectral acceleration of motions with fling step is generally larger than that with forward directivity. Furthermore, compared with the non-pulse ground motions, the dynamic responses of base-isolated buildings under the ground motions with rupture forward directivity and fling-step pulses are increased significantly. Moreover, the velocity pulses from fling-step effect remarkably amplify the interstory drift and shear force of base-isolated building at lower stories. This implies that the fling-step pulses cause more severe damage to long-period buildings than the forward directivity pulses.

CONCLUSIONS

This paper summarized the research advances of authors in engineering characteristics of near-fault ground motions as well as seismic performance of tall and base-isolated buildings under near-fault motions. Two non-structure-specific intensity measures, namely improved effective peak acceleration and velocity (*IEPA*, *IEPV*) were proposed. Meanwhile, two frequency content parameters were suggested, i.e., the mean period of Hilbert marginal spectrum T_{mh} , and coefficient of variance of dominant instantaneous frequency of Hilbert spectrum H_{cov} which reflects the frequency nonstationary degree of ground motions. Further, a new stochastic model to synthesize near-fault impulsive ground motions with the feature of the strongest pulse was constructed. Then, the chaotic and fractal/multifractal characteristics of strong earthquake ground motions were analyzed to explore their complexity from a novel viewpoint of nonlinear dynamics, and the inherent relation between fractal dimensions and period parameters of near-fault motions was exposed. Moreover, the mechanism of interstory deformation of tall building was illustrated based on engineering properties of impulsive ground motions and generalized drift spectral analysis.

However, the studies on seismic analysis and vibration-reduction design of high-rise building structures under stochastic excitations of near-fault ground motions are very scarce relatively, which hamper the development of performance-based earthquake engineering and seismic design code of structures. On the other hand, the improvement of the theories of seismic structures poses an urgent need to the profound research in this area. Therefore, conducting the research in seismic performance analysis and optimal vibration-reduction design of high-rise buildings under near-fault strong ground motions has important theoretical significance and potential of engineering application, and the further study on this line is worthy.

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