Research Article

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Ground motion of the *Ms*7.0 Jiuzhaigou earthquake

<https://doi.org/10.1515/geo-2020-0319>

received February 20, 2021; accepted November 16, 2021

Abstract: Eighty-eight free-field strong ground motion observation datasets obtained by the National Strong Motion Observation Network System of China for the Jiuzhaigou *Ms*7.0 earthquake were used to study the characteristics of the strong ground motion and the site response. In this study, we calculated the VS30 of the near field station and compared the observed values of the horizontal peak acceleration and peak velocity with the CB2014 ground motion prediction models developed by Campbell et al. (2014). The results indicate that the observed values of the horizontal peak acceleration and peak velocity of the Jiuzhaigou earthquake are both smaller than the predicted values obtained from the ground motion prediction equations. By regressing the spatial variation curves of the D_{SR} (5–95%) and D_{SR} (5–75%) ground motion durations, and comparing them with Bommer's (2009) ground motion duration prediction curve, it was found that the duration of the Jiuzhaigou earthquake was greater than that obtained from the global empirical prediction equation. The scope of the source duration corresponding to the D_{SR} (5–75%) duration is 2.76–4.28 s, and the scope of the source duration corresponding to the D_{SR} (5–95%) duration is 8.88–10.36 s, which are close to the peak time and completion time of the seismic moment release during the

source rupture process. The linear elastic acceleration response spectra of 11 stations within 100 km of the fault were calculated for comparison with the design spectrum. It was concluded that the range of the predominant period of the response spectrum was 0.05–0.26 s, which is less than the natural vibration period of the local multi-story building. However, the response spectrum value recorded by station 51JZZ is greater than the design spectrum of the 8° rare earthquake and the observation values of the nearby strong ground motion stations. Through analysis of the *H/V* spectrum ratio and the case of station 51JZZ, which is closest to the epicenter, this phenomenon was concluded to be related to the magnification effect of the near-surface soil layer and the nonlinear response of the site under the action of strong earthquakes.

Keywords: Jiuzhaigou earthquake, strong ground motion, amplitude, duration, spectrum, site response, nonlinear

1 Introduction

At 21:19 (Beijing time) on August 8, 2017, an *Ms*7.0 earthquake occurred in Jiuzhaigou County (33.20°N, 103.82°E), Aba Prefecture, Sichuan Province, western China, with a focal depth of 20 km. The earthquake resulted in 29 deaths and 525 injuries, affected 19,768 households, and damaged 73,671 houses to varying degrees (76 of them collapsed). It also induced many natural disasters such as landslides, collapses, and mudslides in the source area and caused serious damage in the famous Jiuzhaigou scenic area [1]. The earthquake occurred near the Minjiang fault, the Tazang fault, and the Huya fault. It was another devastating earthquake that occurred on the boundary of the Bayankala massif following the *Ms*8.0 Wenchuan earthquake in 2008 and the *Ms*7.0 Lushan earthquake in 2013 [2]. According to the precise location results of the earthquake and the distribution of the aftershocks, institutions and scholars such as the China Earthquake Network Center, Fang et al., and Liang et al. concluded that the seismogenic fault on which this earthquake

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occurred is the northern line of the Huya fault, which is a hidden fault [3–5]. The Global CMT project inverted the focal mechanism of the Jiuzhaigou earthquake and obtained the strike/dip/slip angles of the two planes as $150^\circ/78^\circ/-13^\circ$ and $243^\circ/82^\circ/-168^\circ$ and the moment magnitude M_w as 6.5, making it a high-angle strike-slip earthquake.

The National Strong Motion Observation Network System (NSMONS) captured 88 sets of three component strong motion records for this earthquake. Thus far, several researchers [6–9] have used the Jiuzhaigou strong earthquake data to investigate the characteristics of the ground motions. However, these studies mostly focused on the peak acceleration and intensity attenuation, while few studies have been conducted on the earthquake duration, source duration, response spectrum, and site response. As a structure's seismic response is a dynamic process, when the predominant frequency of the ground motion is the same or close to the natural frequency of the structure, the vibration of the structure is strongest. This is also the major reason for the destruction of structures under the action of earthquakes. Therefore, ground motions with different frequency spectrums will produce different seismic-induced damages to structures with different natural vibration periods [10]. For a specific structure, when it yields and undergoes plastic deformation under the action of a strong earthquake, the longer the duration of the earthquake, the more significant the structural stiffness and the strength degradation and the more serious the damage to the structure [11]. Thus, those involved in seismic fortification and post-disaster reconstruction not only need to consider the amplitude of the ground motion but also need to fully consider the impact of the duration and spectrum composition. In addition, because the Jiuzhaigou earthquake occurred in the western region of China, which has a complex geomorphology and drastic topographical fluctuations [12], the abnormal intensity of the earthquake aggravated the earthquake-induced damage and the induced landslides, collapses, and other phenomena that were directly related to local site conditions [13]. Numerous strong motion records were obtained for the Jiuzhaigou earthquake, and these provide a good opportunity for the study of the differences in the ground motion parameters in adjacent regions caused by differences in the site conditions, such as the local topography and ground cover soil layer.

In this study, the strong ground motion characteristics of the Jiuzhaigou earthquake were investigated from the perspectives of the ground motion amplitude, duration, attenuation relationship, response spectrum, and design spectrum. Based on the strong ground motion

records of the main shock and aftershocks, the site effect of four soil stations near the fault was studied using the horizontal-to-vertical spectral ratio method, and the non-linear response was identified. The reason why the peak ground acceleration (PGA) of station 51JZZ exceeded 1.5 g was investigated.

2 Strong-motion dataset

There are 88 NSMONS free-field strong earthquake stations in Sichuan, Gansu, Shaanxi, and Ningxia provinces, which recorded the Jiuzhaigou *Ms*7.0 earthquake, capturing a total of 264 three-component acceleration records. The stations are mainly distributed in the Joyner–Boore distance (R_{JB}) range of 0–600 km (Figure 1) [14]. Among them, there are 44 sets of strong motion records in the near field ($R_{JB} < 200$ km) and 44 sets of strong motion records in the far field ($R_{JB} > 200$ km), which have a good potential engineering application value. The Boore method [15] was applied to all 264 acceleration records for baseline correction, and a Butterworth band-pass filter with a bandwidth of 0.05–30 Hz was used to obtain the ground motion parameters of this earthquake. Table 1 only gives the ground motion parameters recorded by a few typical stations in the near field. The Code for the Seismic Design of Buildings (CSDB) of China adopts the equivalent shear wave velocity (V_{s20}) and overburden thickness (H_m) of 20 m as important indicators of site classification [16]. Therefore, most of the strong ground motion stations in this area only have shear wave velocity data with borehole depths of less than 20 m. To study the attenuation relationship of the ground motion amplitude and the duration of this earthquake and compare them with the global empirical model, it was necessary to calculate the equivalent shear wave velocity within a depth of 30 m below the surface (V_{s30}) according to the principle of equivalent shear wave velocity propagation time. The calculation method is shown in equations (1) and (2) [17]. The calculation results are presented in Table 1:

$$V_{s30\text{profile}} = 30/t(30), \quad (1)$$

$$t(30) = \int_0^{30} \frac{dz}{V_s(z)}. \quad (2)$$

In the equations, $V_{s30\text{profile}}$ and $t(30)$ are the equivalent shear wave velocity and propagation time at a depth of 30 m below the surface, respectively, and $V_s(z)$ is the shear wave velocity at depth z .

Figure 1: Location of the *Ms*7.0 Jiuzhaigou earthquake and locations of the strong motion recording stations.

The maximum peak acceleration of this earthquake was obtained from station 51JZZ in macrointensity zone IX. Its PGAs in the East and West (EW), North and South (NS), Up and Down (UD) directions were 1525.9, −1237.4, and 1229.5 cm/s/s, respectively; the peak ground velocities (PGVs) were −52.8, −38.9, and −19.8 cm/s, respectively. To describe the intensity more accurately, the *Chinese Seismic Intensity Scale* (GB/T 17742-2008) emphasizes that when

there are free-field strong ground motion records, the horizontal PGA and PGV can be used as reference indicators for the comprehensive evaluation of the intensity. The PGA recorded at station 51JZZ is much larger than the parameter range (354–707 cm/s/s) given by the specification, but the recorded PGV conforms to the reference range of the degree zone IX (36–71 cm/s). The reason for this phenomenon is not only that station 51JZZ is closest to the epicenter but also related

Table 1: Typical near fault station information and acquired ground motion parameters

Station name	Code	V_{S30} (m/s)	R_{JB} (km)	R_{rup} (km)	PGA (cm/s/s)			PGV (cm/s)		
					EW	NS	UD	EW	NS	UD
Jiuzhai Zhangzha	51JZZ	—	0.00	6.590	1525.9	1237.4	1229.5	−52.8	−38.83	−19.8
Jiuzhai Baihe	51JZB	344.1	21.48	26.07	−115.1	−178.1	105.5	−3.71	6.62	2.41
Jiuzhai Wujiao	51JZW	454.1	19.08	23.25	−73.80	−91.7	43.30	−3.99	4.51	−3.9
Jiuzhai Yongfeng	51JZY	330.4	28.48	32.92	−45.80	66.7	−67.7	2.47	−4.2	2.44
Songpan Chuanz	51SPC	406.9	47.54	47.85	−50.23	−46.3	−22.9	3.05	2.94	−2.7
Wenxian	62WEX	500.0	63.34	66.60	5.70	−8.4	5.2	0.73	0.48	1.08
Pingwu Muzuo	51PWM	401.5	69.14	70.88	−18.6	20.9	13.7	−1.09	−1.6	1.41
Zhouqu	62ZHQ	500.0	71.71	75.24	10.2	−9.0	−8.0	0.66	0.75	−0.4
Sha Wan	62SHW	411.3	74.25	77.76	−18.6	20.5	16.8	0.89	−1.5	0.55
Pingwu Diban	51PWD	338.7	86.88	87.90	17.8	16.9	−8.5	−0.94	1.74	1.28
Diebu	62DIB	300.2	92.86	93.02	13.6	−8.1	−13.2	1.66	0.68	−1.7

to the local site conditions. We will analyze this in detail in Chapter 3.4. The next highest values were for Jiuzhai Baihe Station (51JZB), which had PGAs in the EW, NS, and UD directions of -115.1 , -178.1 , and 105.5 cm/s/s, respec-

tively. The PGAs of the other stations gradually decreased with the increasing fault distance. The acceleration and velocity time history curves of stations 51JZZ and 51JZB are shown in Figure 2.

Figure 2: Three-component acceleration time history and velocity time history recorded at stations 51JZZ and 51JZB: (a) the acceleration time history of station 51JZZ; (b) the velocity time history of station 51JZZ; (c) the acceleration time history of station 51JZB; and (d) the velocity time history of station 51JZB.

3 Methods and results

3.1 Ground motion amplitudes

Since the energy of a seismic wave decreases as the distance increases during the propagation process, the ground motion recorded by the station also tends to attenuate. To analyze the attenuation laws of the ground motion amplitudes, the horizontal PGA and PGV of the *Ms*7.0 Jiuzhaigou earthquake records were calculated and compared with the Next Generation Attenuation-West2 (NGA-West2) ground motion prediction models. The comparison results and the within-event residuals are shown in Figure 3. Among them,

model CB2014 was established by Campbell *et al.* [18]. The V_{s30} required to calculate the predicted ground motion value was calculated using equations (1) and (2). The observation data for the *Ms*7.0 Jiuzhaigou earthquake used in this study were mostly obtained from the medium hard soil site. According to Zhao *et al.* [19], the medium hard soil site corresponds to the equivalent shear wave velocity 30 m underground in the NEHPR site classification in the United States ($200 \text{ m/s} < V_{s30} \leq 600 \text{ m/s}$), and the minimum equivalent shear wave velocity of the bedrock site is $V_{s30} \geq 760 \text{ m/s}$. In Figure 3, $V_{s30} = 760 \text{ m/s}$ is the equivalent shear wave velocity of the bedrock site station.

As can be seen from Figure 3(a), except for the PGA observation value for station 51JZZ being larger than the

Figure 3: Comparison of the observed horizontal PGA and PGV values of the *Ms*7.0 Jiuzhaigou earthquake with the predicted values of the NGA-West2 CB2014 model in the United States: the observed PGA and PGV values of one station with $R_{JB} = 0 \text{ km}$ for the Jiuzhaigou earthquake are plotted on the vertical axis at $R_{JB} = 1 \text{ km}$. (a) The comparison of the observed horizontal PGA values and the predicted values. (b) The residuals between the observed PGA values and the predicted values. (c) The comparison of the observed horizontal PGV values and the predicted values. (d) The residuals between the observed PGV values and the predicted values.

predicted value, the discrete PGA observation points of the other stations are all less than the predicted values. Figure 3(c) shows that the observed PGV value for station 51JZZ is slightly smaller than the predicted value from the CB2014 model, and the remaining discrete points of the PGV observations are significantly smaller than the predicted values. The actual observed PGA and PGV values are generally evenly distributed below the predicted values of the CB2014 model at the bedrock site ($V_{S30} = 760$ m/s). Since most of the stations that recorded the Jiuzhaigou earthquake are soil stations, the ground cover layer has a certain amplifying effect on the ground motions. Even so, the observed values for the Jiuzhaigou earthquake are still generally smaller than the predicted values of the ground motion for the bedrock site, indicating that the ground motion level of the Ms7.0 Jiuzhaigou earthquake was significantly lower than that for other earthquakes of the same magnitude. This conclusion is consistent with the results of Ren et al. [9] who compared the observed values for the Jiuzhaigou and Lushan earthquakes with the predicted values of the ASK2014 and BSSA2014 models.

Figure 3(b) and (d) show the within-event residual between the observed values and the CB2014 empirical prediction model values. It can be seen that as R_{JB} increases, the residual between the observed value and the predicted model generally decreases. However, when R_{JB} is less than 50 km, the rate of decrease of the residual is relatively slow, and when R_{JB} is greater than 50 km, the rate of change of the residual between the observed and predicted values increases.

3.2 Significant duration

Duration is an important ground motion parameter in the seismic design of engineering structures. When the structure yields and enters the plastic deformation phase, the duration directly affects the accumulated plastic energy consumption of the structure, which has a great effect on the damage and collapse of the structure. Due to different research and application purposes, definitions, and classification standards, there are currently more than 30 durations, but they are mainly divided into two categories: the absolute duration and relative duration. In this study, the commonly used relative durations of D_{SR} (5–95%) and D_{SR} (5–75%) were taken as the research objects. They are defined by Trifunac et al. [20] as the time interval from 5 to 95% and from 5 to 75% of the Arias intensity, respectively. As the fault distance (the closest

distance from the rupture surface of the fault to the station, R_{rup}) is used in the global earthquake duration prediction equation, to facilitate the comparison with the durations recorded at the strong motion stations, in this study, the fault distance was also used to express the spatial distance relationship of the duration in the analysis. Earthquake duration prediction equation of Bommer et al. [21] was used, which is based on the statistics of the new generation of the earthquake attenuation relationship (NGA) developed in the United States:

$$\ln D_{SR}(x) = c_0 + m_1 M_w + (r_1 + r_2 M_w) \ln \sqrt{R_{rup}^2 + h_1^2} + v_1 \ln V_{S30} + z_1 Z_{tor}, \quad (3)$$

where c_0 , m_1 , r_1 , r_2 , h_1 , v_1 , and z_1 are regression coefficients. For their specific values, see Bommer et al. [21]. M_w , R_{rup} , V_{S30} , and Z_{tor} are the moment magnitude, fault distance, site shear wave velocity, and the upper boundary depth of the fault rupture, respectively. According to equations (1) and (2), the V_{S30} of the station a distance of 200 km from this earthquake was calculated to be 300–760 m/s. Taking into account the characteristics of the engineering geology in the Jiuzhaigou area, a V_{S30} value of 350 m/s was used [22,23]. According to the inversion results of the focal mechanism of Li et al. [24], the moment magnitude M_w and the upper fault depth Z_{tor} were taken as 6.5 and 5.4 km, respectively. Figure 4 shows that the durations of the three components D_{SR} (5–95%) and D_{SR} (5–75%) of ground motions recorded are generally higher than the prediction results of Bommer et al. [21]. To better describe the spatial variation in the duration of the Jiuzhaigou earthquake, curve regression was performed according to equation (4) based on the seismic duration recorded by the station.

$$D_{SR} = c_1 + c_2 R_{rup} + \sigma, \quad (4)$$

where D_{SR} is the relative duration, and R_{rup} is the fault distance. R_{rup} represents the shortest distance between the station and the fault rupture plane. The fault distance of each station was calculated based on the geometric parameters of the fault rupture plane inverted by Shen et al. [25]. The regression coefficients c_1 and c_2 were obtained using the least square method, and the standard deviation is presented in Table 2.

As can be seen from the regression curve in Figure 4, as the fault distance increases, the durations of the three components of the ground motions increase. In the near field where the fault distance is less than 30 km, the regression curve is approximately parallel to the prediction curve of Bommer et al. [21]. The duration decay rate of the observation value is similar to that of the prediction values, and the duration of the up–down seismic motion is also similar to the horizontal duration time. The

Figure 4: Observed duration values of the Jiuzhaigou regression curve and Bommer's prediction equation: (a) the comparison of the D_{SR} (5–95%) duration observed values and the prediction equation and (b) the comparison of the observed D_{SR} (5–75%) duration values and the prediction equation.

characteristic of UD component duration $\approx$ EW component duration $>$ NS component duration can be seen. This is because in the near field, close to the seismic source, the ground motion parameters are mainly controlled by the seismogenic fault, whereas the vertical ground motion parameters and the horizontal direction are similar to the characteristics of the near field motion. In addition, according to the source parameter inversion results, the main rupture plane of this earthquake was the NNW-trending nodal plane, and the angle was about $N30^\circ W$. Therefore, the duration of the EW component was larger than the duration of the NS component, which is consistent with the fact that the near-field ground motion perpendicular to the fault's strike was greater than the ground motion parallel to the fault's strike. When the fault distance was greater than 30 km, the dispersion of the observed and predicted values of D_{SR} (5–95%) and D_{SR} (5–75%) gradually increased. The rate of change of the regression curve is significantly faster than that predicted by Bommer et al. [21], indicating that the ground motion parameters of the Jiuzhaigou earthquake decayed rapidly for the fault distance of greater than 30 km. In addition, as the fault

distance increased, the influence of the seismogenic fault (seismic source) on the ground motion continued to decrease. The two horizontal regression curves gradually become closer, with a tendency to intersect. At this time, the horizontal ground motion is more susceptible to the influence of the propagation path and site conditions, whereas the vertical ground motion is gentler. Therefore, when the relative duration is adopted, the duration of the vertical ground motion is relatively large.

When the fault distance is zero, the duration corresponding to the intercept of the curve in Figure 4 with the vertical axis is the source duration. According to the fitting parameters presented in Table 3, the D_{SR} (5–95%) source durations in the EW, NS, and UD directions were calculated to be 10.36, 8.88, and 9.73 s, respectively, using equation (4). The source durations of D_{SR} (5–75%) in the EW, NS, and UD directions were 4.28, 2.76, and 4.16 s, respectively. According to the inversion results of the source rupture process obtained by Zhen et al. [26], the seismic moment gradually increased after the rupture began, reaching a peak value at 4–6 s, and all of the seismic moment was basically released within 8–10 s after

Table 2: Regression coefficients of the relationship between the duration and spatial variation of the fault distance

Coefficient	D_{SR} (5–95%)			D_{SR} (5–75%)		
	EW	NS	UD	EW	NS	UD
c_1	1.1072	−0.5175	−0.3028	−1.8874	−3.6787	−2.8284
c_2	0.1624	0.1680	0.1854	0.1257	0.1317	0.1466
σ	9.251	9.393	10.035	6.165	6.436	6.992

Table 3: Basic information about the research stations

Station code	Site	R_{rup} (km)	V_{S30} (m/s)	PGA (cm/s/s) of main shock recording			f_s (Hz)	Number of aftershocks with PGA < 30 cm/s/s	f_w (Hz)
				EW	NS	UD			
51JZZ	Soil	6.59	—	1525.9	−1237.4	1229.5	2.5	25	6.5
51JZB	Soil	23.25	344.1	−129.5	−185	−124.7	2.8	17	3.3
51JZW	Soil	26.07	454.1	−73.8	−91.7	43.3	3.9	10	4.1
51JZY	Soil	32.92	330.4	−45.8	66.7	−67.7	4.5	6	4.7

the rupture began. It can be seen that the duration of the ground motion at the seismic source fitted in this study is basically the same as the duration of the rupture process of the main shock source, which is consistent with the actual source rupture process. Among them, the source duration calculated using the D_{SR} (5–95%) duration fitting curve reflects the moment required to complete the source rupture well. The source duration fitted using the D_{SR} (5–75%) duration can predict the moment when the peak of seismic moment energy is released better. According to Bommer's et al. [21] sustained prediction results, the source durations of D_{SR} (5–95%) and D_{SR} (5–75%) where the fault distance is zero were 6.71 and 2.52 s, respectively. Both are smaller than the inversion result of the main shock rupture process. Therefore, the ground motion duration curve fitted using equation (4) in this study is more consistent with the actual rupture process of the Jiuzhaigou earthquake.

3.3 Ground motion response spectra

The linear elastic acceleration response spectra of the five stations (51JZZ, 51JZB, 51JZW, 51JZY, and 51SPC) with large amplitudes near the fault were calculated, and the damping ratio was 5%. The results were compared with the design spectra of the Chinese CSDB (GB 50011-2010; Figure 5) [16]. Among them, the level of the earthquake-resistant intensity in the area where stations 51JZZ, 51JZB, 51JZW, and 51JZY are located is 8°, and the grouping of the designed earthquake is the third group. The level of the earthquake-resistant intensity of the area where station 51SPC is located is 8°, and the grouping of the designed earthquake is the second group. The classification of the site conditions is class II.

Figure 5(a) shows the comparison results of the response spectrum recorded at station 51JZZ during the *Ms*7.0 Jiuzhaigou earthquake and the seismic design spectrum of the area. As station 51JZZ was closest to the epicenter, the spectral accelerations of the EW, NS, and UD components all exceeded the design spectrum of the 8° rare earthquake to varying degrees during the

platform period. The response spectra of the EW and NS components are much larger than the design spectrum of the 8° fortification earthquake even in the period of 0.45–1 s. As the maximum intensity of this earthquake was IX, and station 51JZZ is located in zone IX, according to the previous analysis, the earthquake-resistant intensity of the area is 8°. Therefore, no matter from the magnitude of the response spectrum recorded by 51JZZ station, or from the period of action, the earthquake may cause serious damage to the buildings in the area near station 51JZZ. This is consistent with the serious damage to a group of 136 houses in Zhangzha Village, Zhangzha Town [1]. Figure 5(b) shows the three components of the acceleration response spectrum recorded at station 51JZB. Among them, the response spectrum value of the NS component is greater than the response spectrum values of the EW and UD components, and it is also higher than the design spectrum of the 8° earthquake fortification. However, the predominant plateau is relatively narrow, with a peak period of about 0.18 s, and the amplitude of the response spectrum decays rapidly after a period of 0.2 s, which is lower than the design spectrum for an 8° earthquake. Figure 5(c–e) shows the response spectra recorded at stations 51JZW, 51JZY, and 51SPC and the seismic fortification design spectrum of the area. Although the peak response spectra recorded at these three stations exceeded the design spectrum of the 8° frequent earthquakes within a certain period, the peak response spectrum was always lower than the 8° earthquake fortification throughout the entire platform period.

Since the natural frequency of the main building structures in China's small and medium-sized cities and towns is 1–3 Hz [22,27], the corresponding natural vibration period is 0.3–1 s. Within this range, except that the response spectrum value of station 51JZZ is higher than the design spectrum of the earthquake fortification, the acceleration response spectra recorded by the other four stations are far less than the design spectrum of the earthquake fortification. Therefore, this earthquake was less destructive to the buildings in this area within the natural vibration period. The on-site investigation results

Figure 5: Comparison of the observed and recorded response spectra of five typical stations with the design spectrum. Among them, the design spectrum value of the 8° rare earthquake is the largest, followed by the 8° fortification earthquake, and the design spectrum value of the 8° frequent earthquake is the smallest. (a–e) represent the comparison of response spectrum of stations 51JZZ, 51JZB, 51JZW, 51JZY, and 51SPC, respectively, and the Chinese design spectrum.

also show that the earthquake caused serious damage to buildings in Zhangzha Town, Jiuzhaigou County (where station 51JZZ is located). However, the damage to the buildings in Baihe Township, Wujiao Township, and Yongfeng Township in Jiuzhaigou County and the Chuanzhusi Area in Songpan County (where stations 51JZB, 51JZW, 51JZY, and 51SPC are located, respectively) was relatively mild, and some were not even damaged or only a small number of buildings in some areas were destroyed. In addition, for medium and long periods of greater than 1 s, although the amplitude of the response spectrum at station 51JZZ is larger, it is lower than the fortification spectrum. The response spectrum values recorded by the remaining four stations are only a dozen gal or even close to zero. As a result, it had less of an effect on dams, bridges, transmission towers, and super-high buildings with long natural vibration periods near the station.

The acceleration response spectra of 11 stations within a fault distance of 100 km were calculated, and the horizontal geometric average was determined and plotted in Figure 6. Figure 6a shows the response spectra of nine soil stations, and Figure 6b shows the response spectra of two bedrock stations and two soil stations with similar fault distances. As can be seen from Figure 6a, as the fault distance increases in the near field, the response spectrum value recorded at each station gradually decreases. However, the predominant period of the response spectrum does not change significantly and is concentrated in the range of 0.05–0.3 s. This indicates that the high-frequency (short-period) components of this earthquake are dominant as the peak period of the response spectrum is mostly lower than the natural vibration period (0.2–1.2 s) of the general multistory houses in the *Chinese Code for Residential*

Design (GB50096-2011) [28]. This may be another reason why the damage to the houses caused by the Jiuzhaigou earthquake was relatively lighter than that caused by other earthquakes of the same magnitude. Figure 6b shows that for periods of 0.05–1 s, the response spectra of the two soil stations (51PWM and 62SHW) have different degrees of amplification than the response spectra of the two bedrock stations (62WEX and 62ZHQ). This shows that although the fault distances and the propagation paths are similar, the recorded response spectra are very different due to the local site conditions of the stations. In addition, for the two soil stations, the response spectrum of station 62SHW, which has a larger fault distance, is significantly higher than that of station 51PWM, which has a shorter fault distance, for periods of 0.08–0.7 s. The two bedrock stations also have similar results; that is, the response spectrum of station 62ZHQ, which has a larger fault distance, is higher than that of station 62WEX, which has a smaller fault distance, in most frequency bands. This shows that even if the local site conditions, such as the lithology, are the same and the fault distances are similar, the response spectra recorded at the stations are different due to factors such as the anisotropy of the medium along the different propagation paths.

3.4 Site response

3.4.1 H/V spectral ratio

The attenuation laws of the ground motion amplitude show that the peak acceleration value at station 51JZZ was much greater than that at the surrounding stations

Figure 6: Comparison of response spectra observed at different stations: (a) the response spectra of nine soil stations with different fault distances and (b) the response spectra of two soil stations and two bedrock stations with similar fault distances.

(51JZB, 51JZW, and 51JZY). This may be due to differences in the site conditions such as the local topography and ground cover. To analyze the site amplification effect, the H/V single-station spectral ratio method proposed by Nakamura [29] was used. First, the shear wave data were intercepted from the three-component acceleration time-history records, and the normalized Fourier amplitude spectrum was calculated (Figure 7). Then, equation (5) was used to calculate the H/V spectral ratio curve of the station site, and a Hanning window with a window width of 0.1 Hz was used for the smoothing. In equation (5), S_{EW} , S_{NS} , and S_{UD} are the three components of the normalized Fourier amplitude spectrum. The calculated H/V spectral ratio curve is shown in Figure 8. Because the H/V spectral ratio method can eliminate the influence of the seismic source and path, it can reflect the characteristics of the site and has been widely used:

$$H/V = \frac{\sqrt{S_{EW}^2 + S_{NS}^2}}{S_{UD}}. \quad (5)$$

Four near-fault stations (51JZZ, 51JZB, 51JZW, and 51JZY) recorded a large amount of strong ground motion data from the main and aftershocks of the $M_s7.0$ Jiuzhaigou earthquake, which provides an opportunity to study the site effect on ground motions and the nonlinear response of

the site. Figure 9 shows the H/V spectral ratio curves of these four stations, in which the shaded area represents the site's spectral ratio curve calculated using multiple sets of Jiuzhaigou aftershock data with a $PGA < 30$ cm/s/s. The bold black line represents the spectral ratio curve of the station site calculated using the Jiuzhaigou main shock record. As can be seen from Figure 9, the H/V spectrum ratio curves calculated from the acceleration waveforms of multiple aftershocks are similar, and the curves tend to be consistent. The predominant frequencies of the four stations are stable, that is, around 5, 3.3, 4.1, and 4.7 Hz, respectively. Stations 51JZZ, 51JZB, 51JZW, and 51JZY had a significant amplification effect on the ground motion in the frequency bands of 4–9, 1.5–6, 2–6, and 1–6 Hz, respectively. In addition, the amplitude of station 51JZZ's spectrum ratio curve at its predominant frequency is greater than the amplitudes of the other three stations' spectrum ratio curves at the predominant frequency. Since the peak acceleration value is mainly determined by the high frequency part of the ground motion, the peak acceleration value of station 51JZZ is much larger than those of the surrounding stations (51JZB, 51JZW, and 51JZY). This may be due to the significant amplification of the medium- and the high-frequency components of the ground motion at station site 51JZZ.

Figure 7: (a) Intercepted S-wave data from the three component acceleration time history and (b) the calculated Fourier amplitude spectrum.

Figure 8: *H/V* spectral ratio curve calculated using the method of Nakamura et al.

3.4.2 Nonlinear site response

Compared with the predominant frequency of the *H/V* spectral ratio curve calculated using a large number of aftershock records, the predominant frequency of station 51JZZ's *H/V* spectral ratio curve calculated using the Jiuzhaigou main shock record (Figure 9) is significantly shifted in the low-frequency direction. The predominant frequency of the main shock *H/V* spectral ratio curve of station 51JZB is also shifted in the low-frequency direction relative to the predominant frequency of the aftershock *H/V* spectral ratio curve, whereas the deviations of the predominant frequency of the spectral ratio curves of stations 51JZW and 51JZY are not obvious. In addition, the PGAs recorded at these four stations during the main shock are much larger than the PGA recorded for the

Figure 9: Comparison of the *H/V* spectral curves of stations (a) 51JZZ, (b) 51JZB, (c) 51JZW, and (d) 51JZY for the weak aftershocks with PGA < 30 cm/s/s (the shaded area) and strong earthquakes such as the mainshock of the *M*_s7.0 Jiuzhaigou earthquake (bold black line).

aftershocks ($\text{PGA} < 30 \text{ cm/s/s}$). However, the amplitude of the H/V spectral ratio curve calculated using the main shock data is not much larger than the amplitude of the H/V spectral ratio curve calculated using the aftershock data, and there is even a decreasing trend. This phenomenon has also been observed for several destructive earthquakes. For example, the ground motion records of sites under many strong earthquakes are much smaller than those simulated based on linear elastic theory. Researchers have generally concluded that this is caused by the nonlinear characteristics of the site's soil [30,31]. A large number of soil dynamic test results have revealed that due to the increase in the strain amplitude of the soil under strong ground motions, the shear modulus decreases and the damping ratio increases. When the strain exceeds a certain range, the soil will exhibit a nonlinear response [32–34].

The difference between the H/V spectrum ratio of a strong earthquake and the H/V spectrum ratio of a weak earthquake was used to reveal the difference between linear and nonlinear soil responses and has been demonstrated to be more convenient for identifying the nonlinear response of the site [35–37]. Since stations 51JZZ, 51JZB, 51JZW, and 51JZY were closest to the epicenter, the peak unidirectional acceleration of the main earthquake of the Jiuzhaigou earthquake far exceeded or approached 100 cm/s/s . There is a possibility of nonlinear site reaction. In addition, these stations also recorded a large number of acceleration records for the aftershocks of the Jiuzhaigou earthquake, which provides a good opportunity to study the differences in the site responses under strong and weak earthquakes at the same site. The station information is presented in Table 3.

Considering the requirements of the data processing for the signal-to-noise ratio, the Jiuzhaigou aftershock acceleration records with $3 \text{ cm/s/s} < \text{PGA} < 30 \text{ cm/s/s}$ from stations 51JZZ, 51JZB, 51JZW, and 51JZY were selected. Table 3 lists the number of aftershock records that meet this condition. The H/V spectrum ratio curves of each aftershock record were calculated, and then, the average spectrum ratio curve was used as a reference for the linear response of the site. The nonlinear response of the site was identified by comparing the spectral ratio curves of the main shocks, and the predominant frequency comparison chart of the strong and weak spectral ratio curves of each station was drawn (Figure 10).

As can be seen from Figure 10, under the action of strong earthquakes (main shocks), all four stations exhibited different degrees of predominant frequency shift toward lower frequencies, and their offsets Δf were in the following order: $51\text{JZZ} > 51\text{JZB} > 51\text{JZW} > 51\text{JZY}$. Dimitriu

et al. [38] concluded that under the action of strong earthquakes, the shift in the predominant frequency of the H/V spectrum ratio curve to the lower frequencies was caused by the reduction of the equivalent shear wave velocity of the soil and the reduction of the shear modulus of the soil. Beresnev and Wen [39] estimated the shear modulus changes of a site under strong and weak earthquakes based on the shift in the predominant frequency and proposed a formula (equation (6)). The deviation of the H/V spectrum ratio curve from the predominant frequency is regarded as one of the important characteristics of the nonlinear response of a site [40].

$$\Delta f = f_w [1 - (G_s/G_w)^{1/2}]. \quad (6)$$

In equation (6), Δf is the deviation of the predominant frequency. G_s , G_w , and f_w are the shear modulus and the predominant frequencies of the soil layer under strong and weak earthquakes. To further explain the difference between the site responses of the station under the action of strong earthquakes and weak earthquakes, plots of the ratio of the average spectral ratio of weak earthquakes to the main shock spectral ratio curve versus the frequency were drawn (Figure 11).

As can be seen from Figure 11a–c, the ratios of the weak to strong spectrum ratio curves from stations 51JZZ, 51JZB, and 51JZW are located near 1 when the frequency is less than f_{NL} . This is because the wavelength of the low-frequency seismic waves far exceeds the thickness of the surface soil, and the cover soil on the surface is not the main factor affecting the site amplification. Therefore, there is not much difference between the linear response and the nonlinear response. However, the spectrum ratio

Figure 10: Comparison of the predominant frequency of the main shock spectrum ratio curve and the weak earthquake spectrum ratio curve.

Figure 11: The ratio of site response curves under the action of the weak aftershocks and main shock. The ratio of site response curves at stations (a) 51JZZ, (b) 51JZB, (c) 51JZW, and (d) 51JZY under the action of the weak aftershocks and main shock.

curve of the weak earthquakes is obviously larger than that of the strong earthquakes when the frequency is greater than f_{NL} . This is because the radiation energy is concentrated in the middle frequency band ($f > f_{NL}$) under the action of strong vibration, and the scattering damping effect is obvious, which leads to the reduction of the spectral ratio amplitude under strong earthquakes in this frequency band. Thus, the nonlinear response of the site begins to appear. Beresnev and Wen [39,40] defined the critical frequency as f_{NL} . Based on this, it is concluded that stations 51JZZ, 51JZB, and 51JZW exhibited nonlinear site responses in the middle and high frequency bands, that is, at greater than 3.6, 2.9, and 5 Hz, respectively. (2) As can be seen from Figure 11d, since the peak acceleration of station 51JZY is smaller than that of stations 51JZZ, 51JZB, 51JZW in the Jiuzhaigou main shock, the predominant frequencies of the soil layer at

station 51JZY under strong (main shock) and weak earthquakes (aftershocks) are not significantly different. The amplitudes of the spectral ratio curves of the weak earthquakes and strong earthquakes are approximately equal, the ratio is slightly greater than 1, and the amplitude of the change is not large. It always fluctuates between 1 and 1.5, and there is no obvious trend. Therefore, it is concluded that station site 51JZY is in the linear range.

4 Discussion and conclusions

Based on high-quality main shock and aftershock acceleration data collected by the National Strong Motion Observation Network System of China for the *Ms*7.0 Jiuzhaigou earthquake, the strong ground motion

characteristic and site response were studied in terms of the amplitude, duration, acceleration response spectrum, attenuation law, site effects, and nonlinear site identification. The following conclusions were drawn:

(1) Regardless of the amplitude of the PGA and PGV, for the soil layer sites, the observed values of the Ms7.0 Jiuzhaigou earthquake are generally lower than the predicted values obtained using ground motion prediction equations established by the NGA project. This shows that the ground motion caused by the Jiuzhaigou earthquake was much smaller than that caused by other earthquakes of the same magnitude.

(2) The empirical relationship between D_{SR} (5–95%), D_{SR} (5–75%), and the fault distance R_{rup} was determined through regression and was compared with the global prediction model of Bommer *et al.* It was found that the D_{SR} (5–95%) and D_{SR} (5–75%) durations of the Jiuzhaigou earthquake are generally greater than the predicted values of the model of Bommer *et al.* The duration regression curves recorded at the stations near the fault (within 30 km of the fault) are approximately parallel to the prediction curve obtained using the model of Bommer *et al.* The rates of change of the two curves are similar, and the EW direction lasts longer than the NS direction. When the fault distance is greater than 30 km, the difference between the observed duration and the predicted duration increases, and the rate of change of the regression curve accelerates. This shows that the seismic energy of the Jiuzhaigou earthquake decays rapidly at fault distances of >30 km, which is faster than the average rate for earthquakes of the same magnitude obtained using Bommer *et al.*'s statistics and regression equation. When fitted using the D_{SR} (5–95%) duration regression curve, the source duration was 8.88–10.36 s; when fitted using the D_{SR} (5–75%) duration regression curve, the source duration was 2.76–4.28 s. This is basically consistent with the inversion results of the source rupture process obtained by Zheng *et al.* That is, the release process of the Jiuzhaigou seismic moment gradually increased after the rupture began, reaching a peak at 4–6 s, and all of the seismic moment was basically released within 8–10 s after the rupture began. Thus, by choosing different durations, the curve fitting can better predict the time required for the completion of the seismic source rupture and the peak moment of the seismic moment energy release to provide a reference for the calculation of the seismic source parameters.

(3) The period of the peak acceleration response spectrum of the 5% damping ratio recorded at 11 stations in the near field area of the Jiuzhaigou earthquake is within 0.05–0.26 s, which is generally shorter than the natural vibration period (0.2–1.2 s) of general multistory

buildings. This indicates that the high-frequency (short-period) component of this earthquake was dominant, which is another reason why the damage to houses caused by the earthquake was relatively light. The horizontal acceleration response spectrum of station 51JZZ is higher than the response spectrum of the rare earthquakes throughout the platform period. Even in the range of 0.45–1 s, which is greater than the characteristic period, it was higher than the local 8° seismic fortification response spectrum value. As the natural frequency of most of the buildings in the small and medium cities and towns in the epicenter area is 1–3 Hz, the corresponding period is 0.3–1 s. Therefore, regardless of the response spectrum amplitude and the action period, the earthquake may cause serious damage to the buildings near station 51JZZ. This is consistent with the post-earthquake investigation results; that is, that a group of 136 houses in Zhangzha Village, Zhangzha Town, were seriously damaged. The response spectra of the other stations are slightly higher than the response spectrum for earthquake fortification and the design spectrum for frequent earthquakes within a small range. However, due to the narrow plateau period and rapid attenuation, it was less destructive to the buildings near the station that met the seismic fortification standards.

(4) By calculating the H/V spectrum ratio curve of the Jiuzhaigou aftershock records with $PGA < 30$ cm/s/s recorded by stations 51JZZ, 51JZB, 51JZW, and 51JZY, it was found that the predominant frequency of station 51JZZ was higher than those of the other three stations, which had a significant amplification effect on the high-frequency components of the ground motions. By comparing the H/V spectrum ratio curves of the strong earthquake (main shock) recorded by four strong earthquake stations with the H/V spectrum ratio curves of the weak earthquakes record, it was found that the predominant frequency of the H/V spectrum ratio curves of the strong earthquake exhibits a certain degree of deviation toward low frequencies compared with the weak earthquake curves. In addition, the amplitude of the H/V spectrum ratio curves of the strong earthquake in the middle- and high-frequency bands is lower than that of the weak earthquake spectrum ratio curves to a certain extent. This shows that the four stations that recorded the Jiuzhaigou main shock experienced different degrees of nonlinear soil site response. Since the peak acceleration is mainly determined by the high-frequency components of the ground motion, the site effect and nonlinear site response at station 51JZZ may be the main reason that the high-frequency components of the ground motion were significantly amplified. This is also the main reason that the PGA of the main shock recorded

by station 51JZZ was much larger than those recorded by the surrounding stations. In addition, since station 51JZZ is located on the hanging wall of the fault, and although the Jiuzhaigou earthquake was a high-angle strike-slip earthquake, station 51JZZ was closest to the rupture plane of the fault ($R_{JB} = 0$ km, $R_{rup} = 6.59$ km). The hanging wall effect may still have had a greater impact on the PGA recorded by station 51JZZ.

Acknowledgements: We thank the NSMONS of the Institute of Engineering Mechanics, China Earthquake Administration for providing data support for this study, and we thank the Earthquake Science and Technology Spark Program Project of China Earthquake Administration (XH19043), the Scientific and Technological Achievements Funding Scheme for Young Talents of Gansu Earthquake Agency (2019YC-03-20), the Earthquake Science and Technology Development Fund of Lanzhou Institute of Seismology, China Earthquake Administration (KY1903017, 2018Y02), and the Gansu Youth Science and Technology Fund Project (21JR7RA793, 20JR10RA503) for funding the research reported in this article. We thank LetPub (www.letpub.com) for its linguistic assistance during the preparation of this manuscript.

Author contributions: The research idea proposed was by WWC. The research procedures were conducted by CJF. The data collection and sorting were conducted by SXY and CLJ. The calculated code was conducted by WLN and JZJ. The seismic hazard investigation was conducted by SWB, LHM, and WY. The original draft was prepared by WWC.

Conflict of interest: Authors state no conflict of interest.

References

- [1] Dai JW, Sun BT, Li SY, Tao ZR, Ma Q, Zhang LX, et al. Engineering damage in Jiuzhaigou M7.0 Earthquake; Beijing, China: Seismological Press; 2018. p. 18 (In Chinese).
- [2] Shan XJ, Qu CY, Gong WY, Zhao DZ, Zhang YF, Zhang GH, et al. Coseismic deformation field of the Jiuzhaigou MS7.0 earthquake from Sentinel-1A InSAR data and fault slip inversion. *Chin J Geophys.* 2017;60(12):4527–36 (In Chinese).
- [3] Fang LH, Wu JP, Su JR, Wang MM, Jiang C, Fan LP, et al. Relocation of mainshock and aftershock sequence of the Ms7.0 Sichuan Jiuzhaigou earthquake. *Chin Sci Bull.* 2018;63(7):649–62 (In Chinese).
- [4] Liang SS, Lei JS, Xu ZG, Xu XW, Zou LY, Liu JG, et al. Relocation of aftershocks of the 2017 Jiuzhaigou, Sichuan, MS7.0 earthquake and inversion for focal mechanism of the main-shock. *Chin J Geophys.* 2018;61(5):2163–75 (In Chinese).
- [5] Guo Z, Chen LC, Li T, Gao X. Focal mechanism of the August 8, M7.0 Sichuan Jiuzhaigou and August 9, M6.6 Xinjiang Jinghe earthquakes of 2017. *Seismol Geol.* 2018;40(6):1294–1304 (In Chinese).
- [6] Wang HW, Ren YF, Wen RZ. Source spectrum of the August 8, 2017 Jiuzhaigou Ms7.0 earthquake and quality factor in the epicenter area. *Chin J Geophys.* 2017;60(11):4421–30 (In Chinese).
- [7] Li M, Li XJ. Comparison of different methods used to calculate instrumental intensities of the Jiuzhaigou Ms7.0 earthquake. *Technol Earthq Disaster Prev.* 2017;12(4):803–14 (In Chinese).
- [8] Hu JJ, Sun J, Liu J. Preliminary analysis of distribution characteristics of ground motion and attenuation relation of the Jiuzhaigou Ms 7.0 earthquake on August 8, 2017. *Sichuan Province Technol Earthq Disaster Prev.* 2017;12(4):796–802 (In Chinese).
- [9] Ren YF, Wang HW, Xu PB, Dhakal YP, Wen RZ, Ma Q, et al. Strong-motion observations of the 2017 Ms7.0 Jiuzhaigou earthquake: comparison with the 2013 Ms7.0 Lushan earthquake. *Seismolog Res Lett.* 2018;89(4):1354–65.
- [10] Alford JL, Housner GW, Martel RR. Spectrum analysis of strong motion earthquakes. *Bull Seismolog Soc Am.* 1953;43(2):97–119.
- [11] Hancock J, Bommer JJ. Using spectral matched records to explore the influence of strong-motion duration on inelastic structural response. *Soil Dyn Earthq Eng.* 2007;27(4):291–9.
- [12] Rong MS, Wang ZM, Woolery EW, Lu YJ, Li XJ, Li SY. Nonlinear site response from the strong ground-motion recordings in western China. *Soil Dyn Earthq Eng.* 2016;82:99–110.
- [13] Wen RZ, Ren YF, Huang XT, Lu T, Qi WH. Strong motion records and their engineering damage implications for Lushan earthquake April 20, 2013. *J Earthq Eng Eng Vib.* 2013;33(4):1–14 (In Chinese).
- [14] Joyner WB, Boore DM. Peak horizontal acceleration and velocity from strong-motion records including records from the 1979 Imperial Valley, California, earthquake. *Bull Seism Soc Am.* 1981;71(2):2011–38.
- [15] Boore DM. Effect of baseline corrections on displacements and response spectra for several recordings of the 1999 Chi-Chi, Taiwan, earthquake. *Bull Seism Soc Amer.* 2001;91(5):1199–211.
- [16] Ministry of Housing and Urban-Rural Development of the People's Republic of China, General Administration of Quality Supervision, Inspection and Quarantine of the people's Republic of China. Code for Seismic Design of Buildings: GB50011-2010. Beijing: China Architecture & Building Press; 2010.
- [17] Yu Y. Empirical estimate model for ground motion of Wenchuan earthquake zone. Harbin, China: Institute of Engineering Mechanics, China Earthquake Administration; 2012. p. 9–12 (In Chinese).
- [18] Campbell KW, Bozorgnia Y. NGA-West2 Campbell-Bozorgnia ground motion model for the horizontal components of PGA, PGV, and 5%-damped elastic pseudo-acceleration response spectra for periods ranging from 0.01 to 10 sec. *Earthq Spectra.* 2014;30(4):1087–115.
- [19] Zhao JX, Irikura K, Zhang J, Fukushima Y, Somerville PG, Asano A, et al. An empirical site-classification method for

- strong-motion stations in Japan using H/V response spectral ratio. *Bull Seismolog Soc Am.* 2006;96(3):914–25.
- [20] Trifunac MD, Brady AG. A study on the duration of strong earthquake ground motion. *Bull Seismolog Soc Am.* 1975;65(3):581–626.
- [21] Bommer JJ, Stafford PJ, Alarcón JE. Empirical equations for the prediction of the significant, bracketed, and uniform duration of earthquake ground motion. *Bull Seismolog Soc Am.* 2009;99(6):3217–33.
- [22] Ren YF, Wen RZ, Zhou BF, Huang XT. The characteristics of strong ground motion of Lushan Earthquake on April 20, 2013. *Chin J Geophys.* 2014;57(6):1836–46 (In Chinese).
- [23] Bindi D, Luzi L, Massa M, Pacor F. Horizontal and vertical ground motion prediction equations derived from the Italian Accelerometric Archive (ITACA). *Bull Earthq Eng.* 2010;8(5):1209–30.
- [24] Li Y, Wang WM, Shao CJ, Li FY, Zhou RJ, Liu YF, et al. Left-lateral strike-slip effect and dynamic mechanism of the Jiuzhaigou Ms 7.0 earthquake in the eastern margin of Tibetan Plateau, China. *J Chengdu Univ Technol (Sci & Technol Ed).* 2017;44(6):641–8 (In Chinese).
- [25] Shen WH, Li YS, Jiao QS. Joint inversion of strong motion and InSAR/GPS data for fault slip distribution of the Jiuzhaigou 7.0 earthquake and its application in seismology. *Chin J Geophys.* 2019;62(1):115–29 (In Chinese).
- [26] Zhen XJ, Zhang Y, Wang RJ. Estimating the rupture process of the 8 August 2017 Jiuzhaigou earthquake by inverting strong-motion data with IDS method. *Chin J Geophys.* 2017;60(11):4421–30.
- [27] Wen RZ, Ren YF, Qi WH. Maximum acceleration recording from Lushan earthquake on April 20, 2013. *J Southwest Jiaotong Univ.* 2013;48(5):783–91 (In Chinese).
- [28] Ministry of Housing and Urban-Rural Development of the People's Republic of China. Code for Design of Dwelling Houses:GB50096-2011. Beijing: China Architecture & Building Press; 2011.
- [29] Nakamura Y. A method for dynamic characteristics estimation of subsurface using microtremor on ground surface. *Q Rep Rtri.* 1989;30(1):25–33.
- [30] Chin BH, Aki K. Simultaneous study of the source, path, and site effects on strong ground motion during the 1989 Loma Prieta earthquake: a preliminary result on pervasive nonlinear site effects. *Bull Seismolog Soc Am.* 1991;81(5):1859–84.
- [31] Kamiyama M, Matsukawa T. Dynamic variation of soil rigidity based on down-hole array observation. *12WCEE*; 2000. p. 1–8.
- [32] Seed HB, Idriss IM. Soil moduli and damping factors for dynamic response analysis. Berkeley: Earthquake Engineering Research Center, University of California; December 1970. p. 48.
- [33] Zeghal M, Elgamal AW. Analysis of site liquefaction using earthquake records. *J Geotech Eng.* 1994;120(6):996–1017.
- [34] Assimaki D, Li W, Steidl J, Schmedes J. Quantifying nonlinearity susceptibility via site-response modeling uncertainty at three sites in the Los Angeles basin. *Bull Seismolog Soc Am.* 2008;98(5):2364–90.
- [35] Kordowicz AGR, Gough MJ. Nonlinear behavior of soil sediments identified by using borehole records observed at the Ashigara Valley, Japan T Satoh, T. Sato, H. Kawase. *Bulletin-Seismolog Soc Am.* 1995;85(6):1821–34. *International Journal of Rock Mechanics & Mining Sciences & Geomechanics Abstracts.* 2014;33(5):441–3.
- [36] Wen KL, Chang TM, Lin CM, Chang HJ. Identification of nonlinear site response using the H/V spectral ratio method. *Terrestrial Atmos Ocean Sci.* 2006;17(3):533–49.
- [37] Noguchi S, Sasatani T. Quantification of degree of nonlinear site response. In: *14 World Conference on Earthquake Engineering*. Beijing, China; 2008.
- [38] Dimitriu P, Kalogeras I, Theodulidis N. Evidence of nonlinear site response in horizontal-to-vertical spectral ratio from near-field earthquakes. *Soil Dyn Earthq Eng.* 1999;18:423–35.
- [39] Beresnev IA, Wen KL. Nonlinear soil response-A reality? *Bull Seismolog Soc Am.* 1996;86(6):1964–78.
- [40] Regnier J, Cadet H, Bonilla LF, Bertrand E, Semblat JF. Assessing nonlinear behavior of soils in seismic site response: Statistical analysis on KIK-net strong motion data. *Bull Seismolog Soc Am.* 2013;103(3):1750–70.