Earthq Eng & Eng Vib (2016) 15: 435-444 **DOI**:10.1007/s11803-016-0334-0

Site amplification effects as an explanation for the intensity anomaly in the Hanyuan Town during the Wenchuan M_w 7.9 earthquake

Liu Hongshuai[1†], Bo Jingshan[2, 3‡], Li Ping[2§], Qi Wenhao[3†] and Zhang Yudong[2§]

1. *National Earthquake Infrastructure Service, Beijing 100036, China*
2. *Institute of Disaster Prevention, Sanhe 065201, China*
3. *Key Laboratory of Earthquake Engineering and Engineering Vibration, Institute of Engineering Mechanics, China Earthquake Administration, Harbin 150080, China*

Abstract: The Hanyuan Town is located approximately 200 km from the macro-epicenter of the great Wenchuan earthquake. However, it is within the only Intensity VIII zone, surrounded by a region of Intensity VI. The objective of this study was to investigate this high-intensity anomaly with respect to the site amplifications in the Hanyuan Town. The base inputs were derived from the records at a nearby strong-motion station because no records were available from the town. The characteristics of the subsurface formations and their dynamic properties at a typical site in the town were obtained by drilling, field tests and laboratory tests. Seismic response and parametric sensitivity analyses of the site were conducted using Shake 91, and the results were compared with the provisions for rare earthquakes from the Chinese Code for Seismic Design of Buildings (GBJ11-89). The results showed that the average peak acceleration at the site during the Wenchuan earthquake is similar to the code-specified value under rare earthquakes, that the corresponding spectral accelerations for periods between approximately 0.35 and 0.75 s are significantly stronger than those specified by the code and that the average amplification factor at the site is significantly higher than the mean value of the site class. These findings indicate that the high-intensity anomaly in the town was primarily caused by site amplification effects from the unique structure of the soil strata.

Keywords: Wenchuan earthquake; Hanyuan Town; high-intensity anomaly; site amplification; rare earthquake

1 Introduction

A catastrophic M_w 7.9 earthquake struck Sichuan Province in southwest China on May 12, 2008. Its epicenter was located in the Yingxiu Town (31.0°N, 103.4°E) in Wenchuan County, and the focal depth was nearly 14 km. An isoseismal map (Fig. 1) of the Wenchuan earthquake (Yuan, 2008) was developed based on field surveys and the China Seismic Scale (1999), which is similar to the modified Mercalli intensity scale.

Figure 1 shows that the shaking intensity at the epicenter reached XI. The Hanyuan Town, approximately 200 km from the macro-epicenter, is within the only area of intensity VIII that is surrounded by a zone of intensity VI. It is regarded as an abnormal high-intensity tele-seismic area (Bo *et al.*, 2009). Both the mechanisms of the abnormal intensity in the Hanyuan Town and countermeasures for mitigating damaging effects are of great interest in the field of earthquake engineering.

Abnormal intensities are typically induced by local site conditions. Qualitative and quantitative methods are used to investigate the amplification effects of shaking from various site conditions. Such qualitative methods usually examine the effects of soil stiffness,

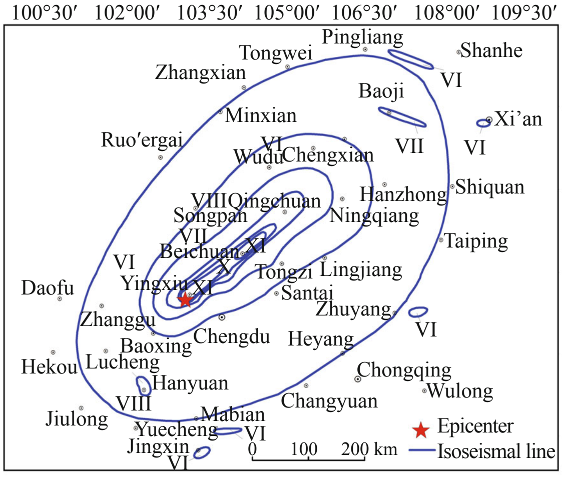

Fig. 1 Isoseismal map of the Wenchuan M_w 7.9 earthquake (Yuan, 2008)

Correspondence to: Bo Jingshan, Institute of Disaster Prevention, Sanhe 065201, China
Tel: 86-10-61596002
E-mail: bojingshan@163.com
†Associate Researcher; ‡Professor; §Lecturer

Supported by: National Natural Science Foundation of China under Grant Nos. 50978237 and 41172293
Received March 15, 2013; **Accepted** August 25, 2015

strata structure, geological structure, topography, and groundwater on ground motions (Liu *et al*., 1982; Bakir *et al*., 2002; Gao *et al*., 2008; Meslem *et al*., 2012; Assimaka *et al*., 2012). Such quantitative methods primarily include horizontal-to- vertical (H/V) spectral ratios from single-station ambient-noise records (Paudyal *et al*., 2012) and earthquake records (Lovati *et al*., 2011), standard spectral ratios from a reference site (Lovati *et al*., 2011) and numerical analyses (frequency and time-domain methods, including finite difference, finite element, and boundary element methods (Raptakis *et al*., 2004) and spectral element methods (Puglia *et al*., 2013)), which are employed to demonstrate the amplification effects of a site on a damage zone. The H/V and standard spectral ratios are the most commonly used method because of their simplicity.

The mechanisms of the intensity anomaly in the Hanyuan Town have been studied by several researchers. Gao *et al.* (2008) indicated that the hypocentral mechanism of the M_w 7.9 Wenchuan earthquake, its spatial energy distribution, and the site conditions, caused the intensity anomaly. Bo *et al.* (2009) proposed that the reactivation of the Beihou Mountain landslide and the amplification effects originating from the unique structure of the soil layer were the primary reasons for the anomaly. Lei *et al.* (2011) noted that the topography was also an important factor. Li *et al.* (2012) analyzed the responses of typical sites using numerical simulations and verified the results of Bo *et al.* (2009). Most of these studies qualitatively described the potential influencing factors for the intensity abnormality. Li *et al.* (2012) quantitatively analyzed the cause but did not consider the effects of the inhomogeneities of the soil formation.

This paper briefly describes the characteristics of the distribution of seismic damage in the Hanyuan Town, quantitatively discusses the causes of the intensity abnormality, systematically analyzes the site amplification effects in the town, and demonstrates the cause of the intensity abnormality in view of the site amplification effects.

2 Damage distribution and causes of the intensity anomaly

2.1 Damage distribution

The results of the damage survey performed during the earthquake emergency period after the Wenchuan earthquake showed that the damage in the Hanyuan Town was the most serious and concentrated in the area of the anomaly (Gao *et al*., 2008). The town contains mostly multi-type buildings (Lu *et al*., 2009), whereas the other towns and rural areas in the anomaly area contain one- and two-story brick buildings and adobe structures that were not designed to withstand seismic loads. Detailed surveys of the earthquake damage in the town were only conducted during the scientific survey period. The results are described below.

Based on the distribution of streets in the town, 42 sample points were chosen across an area of approximately 42 km^2 (Fig. 2). The distribution of the points was approximately uniform, and the damage to 86 typical buildings was surveyed. The damage grade and damage index (DI) of each building were determined using the *Chinese National Code for Post-earthquake Field Works* (part 3) (GB/T 18208.3-2000). Contours of the damage indexes were compiled (Fig. 2). Buildings within the DI = 0.5 isoline were seriously damaged or collapsed, and the intensity in this area was greater than or equal to VIII. The buildings outside the DI = 0.5 isoline and within the DI = 0.2 isoline were slightly to moderately damaged, and the intensity in this area was between VII and VIII (Bo *et al*., 2009). Therefore, the seismic intensity in the town was comprehensively considered to be VIII.

2.2 Causes of the intensity anomaly

Intensity anomalies are caused by a variety of factors, but the local site conditions are the dominant factor. Quaternary and Holocene deposits primarily cover the town and the surrounding area, including the area along the Dadu and Liusha Rivers. The fluvial sediments consist primarily of gravel, sand and cohesive soil. The distribution of Quaternary sediments is not uniform; the formations are spatially discontinuous, and the thickness of each formation is multivariate. The town is located on the north shore of the Liusha River. Along the northern part of the river valley, the Quaternary sediments are up to 80 m thick. The thickness decreases rapidly away from the river valley. The Quaternary sediments are approximately 10 m thick along the southern bank of the river.

Borehole data from the second middle school have shown that moderately coarse sand and silty clay layers directly overlie a gravel layer, which is an uncommon soil structure in China. Preliminary seismic response analyses have shown that the soil structure can magnify peak accelerations up to three times. This unique soil structure is the cause of the abnormal intensity (Bo

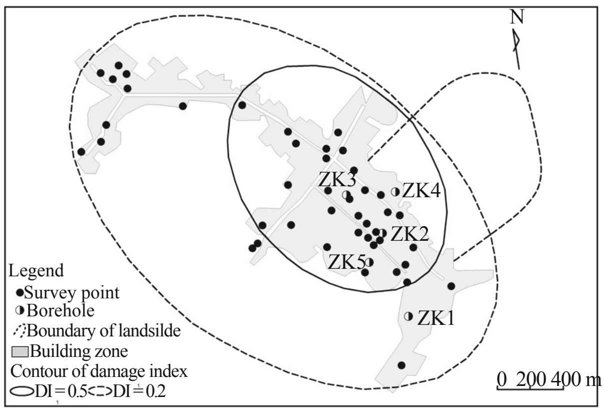

Fig. 2 Damage index contours in the Hanyuan Town during the Wenchuan earthquake

et al., 2009).

Hanyuan Town is located on the second and third terraces of the Liusha River, the convergence zone of the alluvial fans, and the piedmont of the Hanyuan River valley basin (Gao *et al.*, 2008). Historically, many landslides have occurred in the area and have deposited thick layers of loose soil, which are similar to those deposited in a weak basin. In addition, the river valley basin is wedge shaped; it is narrow in the east-west (EW) direction and wide in the north-south (NS) direction. Moderately high mountains with elevations of 2000−2500 m and hills with a maximum elevation of 1000 m are located to the northeast and southwest of the basin, respectively. This topography is likely to cause multiple reflections of seismic waves, which is an important cause of amplification.

The town is located to the southeast of the intersection of the Xianshui River, the Longmen Mountains and the Anning River fault belts, which form a Y-shaped seismotectonic zone. The Xianshui and Anning River faults may have reflected the ground motions from the focal fault, which would have enhanced the ground motions at the town (Gao *et al.*, 2008). This is also one of the causes of the intensity anomaly.

In summary, the intensity anomaly at the Hanyuan Town is the result of a combination of the seismic wave propagation path (influences of the Y-shaped structure), the soil conditions (unique soil structures) and the topographic conditions (focusing effects of the basin). The first and last conditions are secondary factors that affected the intensity anomaly, and the soil conditions are the primary cause of the anomaly.

The Fourth Session of the Ninth National People's Congress declared the Pubugou Hydropower Project to be the national project of the Tenth Five-Year Plan on March 15, 2001. Subsequently, the Sichuan Provincial People's Government issued a command to stop all building construction in the submerged area of the Pubugou Hydropower Project on April 28, 2001 (*http://baike.baidu.com/view/949413.htm*). The Hanyuan Town is in the submerged area of the project. The buildings in the town were constructed prior to 2001, and most were designed according to the *Chinese Code for Seismic Design of Buildings* (GBJ11-89). Therefore, this study selected this code as the reference rather than the current code.

The subsequent sections of this paper focus on the site magnification effects at the Hanyuan Town as an explanation of the intensity anomaly during the M_w 7.9 Wenchuan earthquake.

3 Input bedrock ground motions

In engineering practice, there are two primary methods used to determine the input bedrock ground motion: the artificial ground motion, whose response spectra matches the spectra that are obtained by seismic hazard analysis, or those specified by the relevant codes and strong motion records selected directly from cases with similar conditions (Liu *et al.*, 2013). For the Hanyuan Town, the former cannot consider the effects of the focal mechanisms, media and propagation path from the Wenchuan earthquake, and the latter was unsuitable because the strong motion records from the area adjacent to the town were recorded at a soil site, which can significantly alter the frequency spectra of the bedrock ground motion (Cai *et al.*, 2000). In this section, the strong motion records from the soil site near the Hanyuan Town were utilized to back-calculate the bedrock ground motions.

3.1 Strong-motion station and ground motion characteristics

The Jiuxiang, Qingxi, Wusihe and Yidong stations are located approximately 17, 23, 20 and 38 km from the Hanyuan Town, respectively (Fig. 3). They recorded the complete acceleration time histories of the main shock of the Wenchuan earthquake (Li *et al.*, 2008). The records at the four stations were documented at the ground surface (Earthquake Disaster Prevention and Mitigation Division of CEA, 2008). No strong motion station was located in the Hanyuan Town, and thus no records of the main shock were obtained in the town.

Jiuxiang station is the closest to Hanyuan and is located in the same anomaly zone as the town. Their epicentral distances are similar, and they suffered similar bedrock ground motions. Therefore, the inverted bedrock ground motions, calculated from the records of the Jiuxiang station, accurately reflect the characteristics of the focal mechanism and propagation path during the Wenchuan earthquake. These values are used as the bedrock inputs for the town.

The acceleration time histories and the dynamic

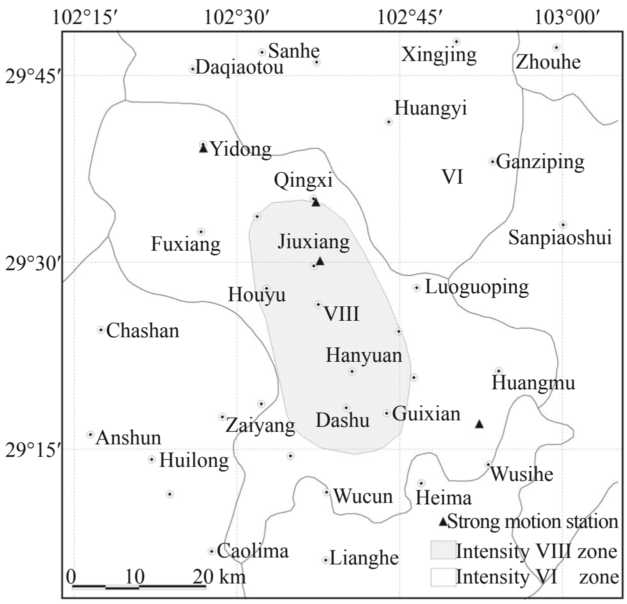

Fig. 3 Distribution of strong motion stations around the Hanyuan Town

amplification factors of the Jiuxiang station are shown in Fig. 4. The EW and NS peak accelerations of the Jiuxiang station are 74.9 and 80.4 Gal respectively, and the amplification factors are approximately 2.5−4.0 for the periods between 0.2 and 0.7 s, which are higher than the average amplification factor of 2.5.

3.2 Site conditions at the Jiuxiang station

The Jiuxiang station is located approximately 190 km from the epicenter of the Wenchuan earthquake. It lies in the rear area of the Jiuxiangshan piedmont alluvial-proluvial fan. A borehole at the station revealed the presence of Quaternary miscellaneous fill, breakstone, gravel and cailloutis (Fig. 5). The thickness and shear wave velocity of each soil layer at the Jiuxiang station are shown in Fig. 5.

The dynamic soil parameters are required for the analysis of site response. Liu *et al.* (2005) found that the dynamic shear modulus ratios and damping ratios of the soil do not greatly affect the ground motion if the peak acceleration of the input ground motion is less than 90 Gal. Because the peak accelerations at the Jiuxiang station during the Wenchuan earthquake were below this limit, the dynamic parameters of the soils from Shi (1989) were employed.

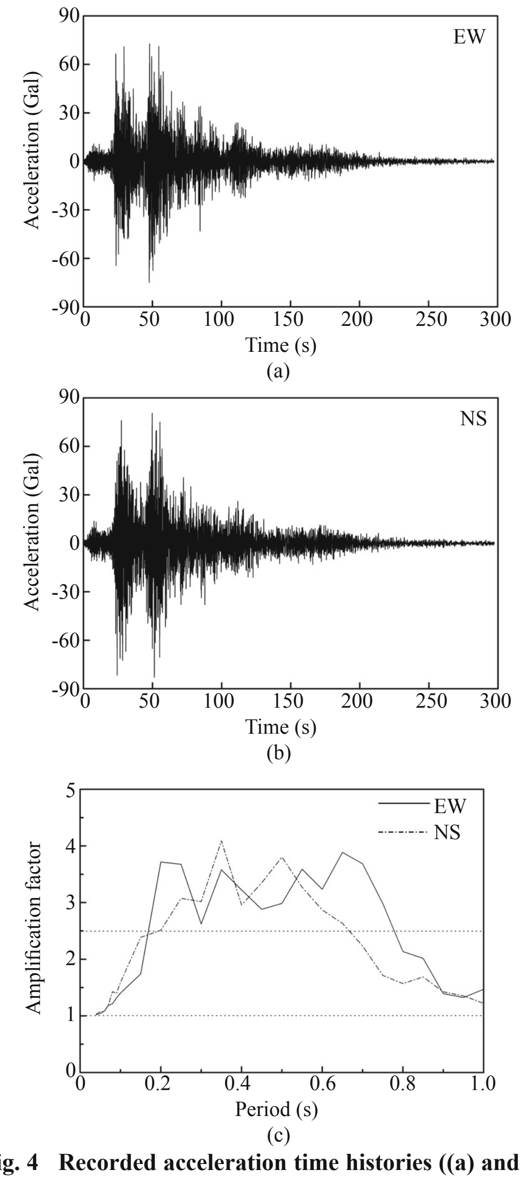

Fig. 4 Recorded acceleration time histories ((a) and (b)) and their amplification factors (c) at the Jiuxiang station during the Wenchuan earthquake

3.3 Determination and verification of bedrock seismic motion

The one-dimensional equivalent linearization frequency-domain wave propagation method is commonly used for the forward and reverse modeling of ground motions (Krammer, 1996). The method is implemented in the Shake91 program (Idriss and Sun, 1992), which is considered to be the most representative program currently available. The site response model was developed based on the site conditions presented in Section 3.2. The acceleration time histories in Fig. 4 (A and B) were used as the surface inputs for the inverse modeling of the bedrock ground motions. The resulting bedrock ground motions are shown in Fig. 6.

The acceleration time histories of the ground surface, which were computed from the bedrock ground motions (Fig. 6), were compared with those of the strong motion records. To demonstrate the differences, only the results of the EW direction for the time interval from 45−50 s are presented in Fig. 7. The computed acceleration time histories are nearly identical to those of the records on the soil surface. Therefore, the inverted bedrock ground motions are highly reliable.

4 Site conditions at the Hanyuan Town

The site conditions are the basis for estimating the ground motion parameters. Five boreholes were drilled at sampling points that experienced relatively heavy damage, and their shear wave velocities were tested using the single-hole method. Typical soil samples were tested in the lab using the resonant column method. These

Depth (m)	Layer thickness (m)	Notation	Soil description	Shear wave velocity (m/s)
0.5	0.5		Miscellaneous fill	151
3.6	3.1		Breakstone	340
11.67	8.07		Gravel	450
22.3	10.63		Cailloutis	515

Fig. 5 Comprehensive stratigraphic column at the Jiuxiang station

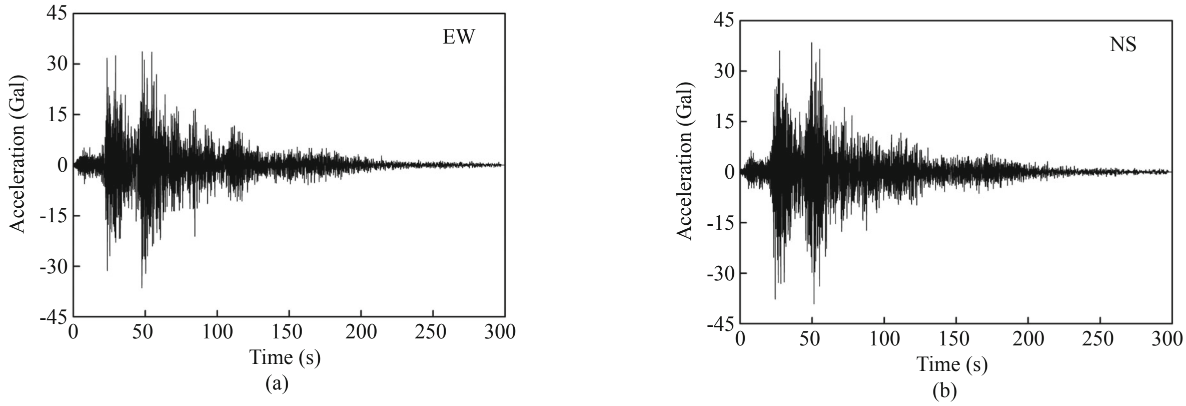

Fig. 6 Acceleration time histories for the bedrock from the surface records of the Wenchuan main shock at the Jiuxiang station

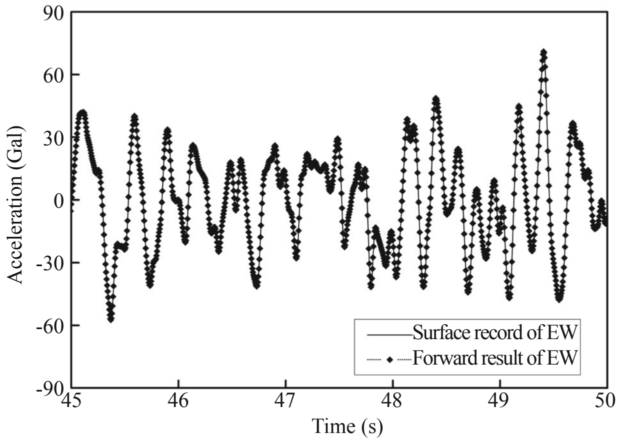

Fig. 7 Comparison between the recorded and computed acceleration time histories of the surface at the Jiuxiang station during the Wenchuan main shock

techniques were used to find the soil type, soil thickness, shear wave velocity and dynamic nonlinear parameters of the main soil layer at the sites, which are the basic data required to develop seismic response models.

4.1 Characteristics and shear wave velocities of the subsoil

Based on the results of the earthquake damage surveys described in Section 2.1, five boreholes were drilled at relatively severely damaged sites; their locations are shown in Fig. 2. According to the *Chinese Standard for Seismic Safety Evaluation of Engineering Sites* (GB17741-2005), the earthquake input interface at an important construction site should be located at the top of the soil layer with a shear wave velocity of no less than 500 m/s. Only borehole ZK1 matched the requirements of GB17741-2005; therefore, this paper explicitly describes the results obtained using this borehole. The lithological description, the division of the lithological layers, and the undisturbed samples of borehole ZK1 were obtained according to the *Chinese Code for Investigation of Geotechnical Engineering* (GB50021-2001). The shear wave velocities of borehole ZK1 were tested in situ using the downhole method according to the *Chinese Code for Measurement Method of Dynamic Properties of Subsoil* (GB/T 50269-97). The soil properties for a typical site in the town were thus obtained and are shown in Fig. 8.

4.2 Dynamic parameters of the subsoil

Based on the *Chinese Code for Measurement Method of Dynamic Properties of Subsoil* (GB/T 50269-97), the dynamic parameters for seven groups of soil samples (Fig. 8, S1-S7) from the town of Hanyuan were tested using a DGZ-1 resonant column, which was developed by the Institute of Engineering Mechanics,

Depth (m)	Layer thickness (m)	Notation	Soil description	Shear wave velocity (m/s)	Sample depth (m)
1.2	1.2		Miscellaneous fill	111	
3.7	2.5		Silt clay	110	S1: 3.0−3.2
8.5	4.8		Silt clay	132	S2: 7.4−7.6
13.6	5.1		Medium sand	217	S3: 12.5−12.7
21.9	8.3		Silt clay	269	S4: 17.2−17.4
26.7	4.8		Cobble	354	
32.2	5.5		Silt clay	324	
36.3	4.1		Silt clay	306	S5: 35.4−35.6
40.8	4.5		Silt clay	291	
46.2	5.4		Silt clay	362	S6: 45.3−45.5
50.9	4.7		Silt clay	439	
54.2	3.3		Fine sand	441	S7: 52.5−52.7
56.2	2.0		Mudstone	478	
58.0	1.8		Mudstone	552	

Fig. 8 Comprehensive stratigraphic column of borehole ZK1

China Earthquake Administration. The Hardin model was employed to fit the variations of the dynamic shear modulus ratio and damping ratio with the shear strain and to obtain their corresponding values.

Each sample was consolidated under a confining stress that represented its depth, and the dynamic parameters of the soil samples (Fig. 8) were obtained. Because samples of the miscellaneous fill (S8) and the cobble (S9) were unavailable, their parameters were taken from Shi (1989). The dynamic shear modulus ratios and damping ratios used are shown in Fig. 9.

5 Seismic response analysis of the town site

As described in Section 2.2, the layered structure of the subsoil is complex. According to the five boreholes, the most prominent features are that the thickness of the surface fill varies from 1.3 to 6.3 m, the depth of the cobble layer ranges from 6.3 to 26.5 m, the thickness of the cobble varies from 0.6 to 6.9 m, and the shear wave velocity of the cobble ranges from 179 to 354 m/s (Qi, 2011). Because of the variability in these parameters, the effects of the fill thickness, cobble depth, cobble thickness and cobble shear wave velocity on the ground seismic parameters were studied to explain the anomaly by using the parametric sensitivity method to determine the seismic response at the town sites.

5.1 Effect of thickness of the fill

In the models, the thickness of the fill was varied from 1 to 6 m in increments of 1 m. If the modeled fill was less than 1.2 m thick, the redundant fill was replaced by the underlying silty clay. If the modeled fill was more than 1.2 m thick, the fill replaced the other strata at the modeled depths. Figure 10 shows the ground response spectra for different thicknesses of the fill. The thickness of the fill has little effect on the shape of the ground response spectra but has a significant influence on the spectral magnitude. The peak acceleration increases with the thickness of the fill and has a maximum variation of 19%, whereas the magnitudes of the spectral acceleration increase significantly for periods between approximately 0.35 and 0.75 s with increasing fill thickness. The maximum variations in the EW and NS directions are 41% and 40% and occur at periods of 0.48 and 0.42 s, respectively. Thus, the thickness of the miscellaneous fill

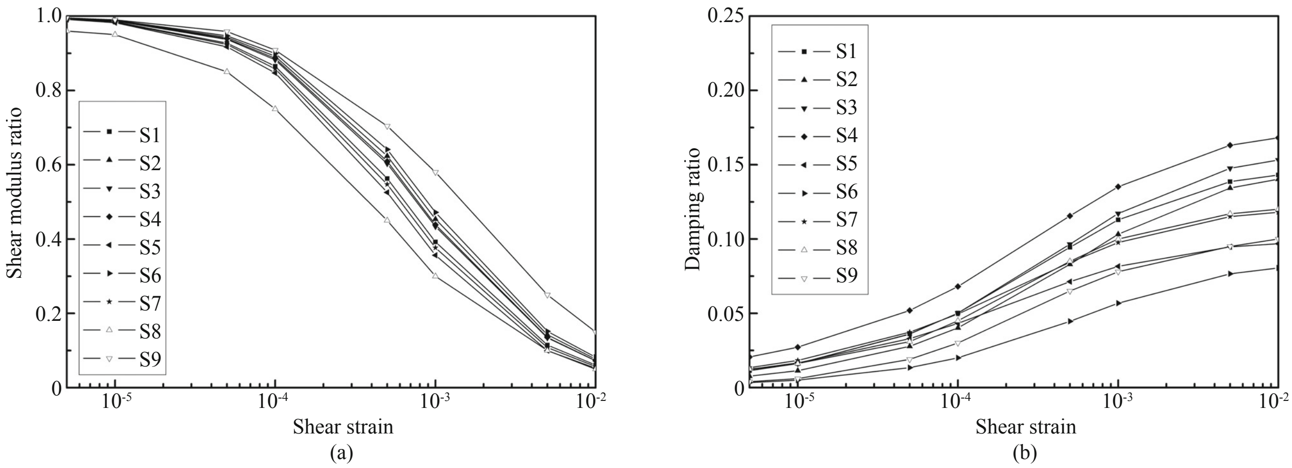

Fig. 9 Shear modulus ratios and damping ratios of the subsoils

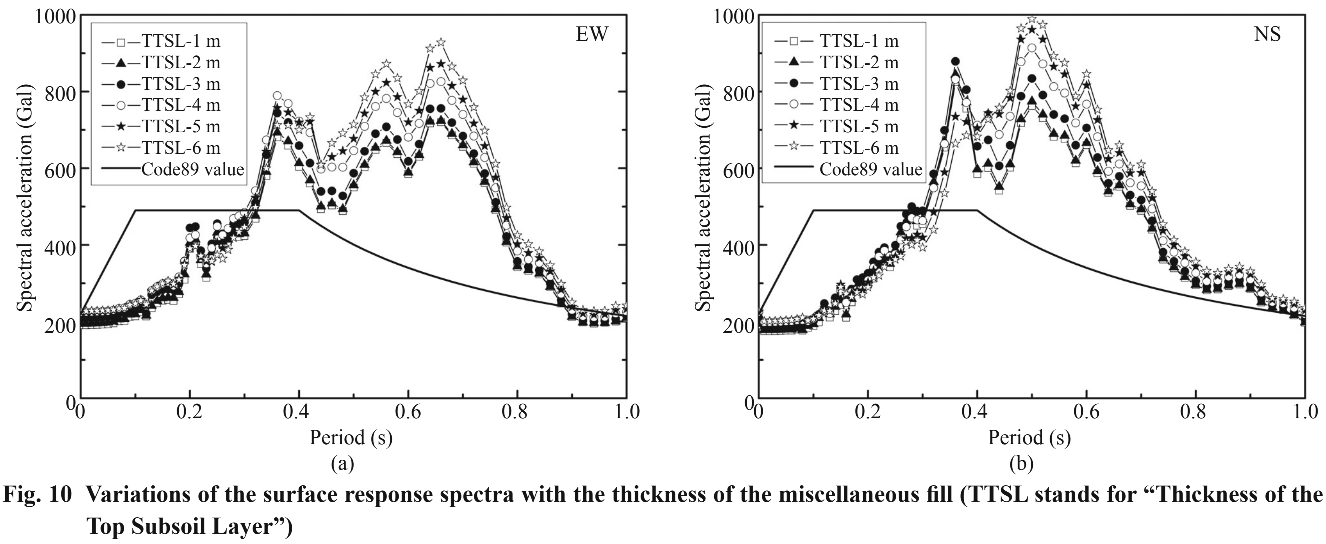

Fig. 10 Variations of the surface response spectra with the thickness of the miscellaneous fill (TTSL stands for "Thickness of the Top Subsoil Layer")

has significant effects on the ground response spectral acceleration for periods between approximately 0.35 and 0.75 s.

5.2 Effect of depth of the cobble layer

The cobble layer in borehole ZK1 is 4.8 m thick. To investigate the effect of the depth of the cobble layer, the middle 3 m of the layer was considered, and the upper and lower 0.9 m of the layer were replaced by the adjacent silty clay. The thickness of the modeled 3-m-thick cobble layer was expected to be constant, and its depth was varied from 6 to 26 m in increments of 4 m to replace the actual strata at the corresponding depth. The surface response spectra for the different cobble depths are shown in Fig. 11. The peak surface spectral acceleration increases with the depth of the cobble layer and has a maximum variation of 19%, and the response spectra increases slightly at periods between 0.3 and 0.7 s with a maximum variation of 17%. These results demonstrate that the depth of the cobble layer has a limited effect on the surface response spectra.

5.3 Effect of thickness of the cobble layer

To examine the effect of the thickness of the cobble layer, the overall depth of borehole ZK1 was fixed, and the thickness of the cobble layer was increased from 1 to 6 m in increments of 1 m. If the actual cobble thickness of ZK1 was greater than the modeled thickness, the redundant cobbles were replaced by silty clay. If the actual thickness of the cobble layer was less than that of the model, the lacking section was modeled as cobble. Figure 12 shows the surface response spectra for different cobble thicknesses. The ground response spectra of sites with different cobble thicknesses are approximately identical; therefore, the effects of the cobble layer thickness can be neglected.

5.4 Effect of shear wave velocity of the cobble layer

The shear wave velocity of the cobble layer was increased from 200 to 400 m/s in 50 m/s increments. The surface response spectra for the different shear wave velocities of the cobble layer are shown in Fig. 13. The

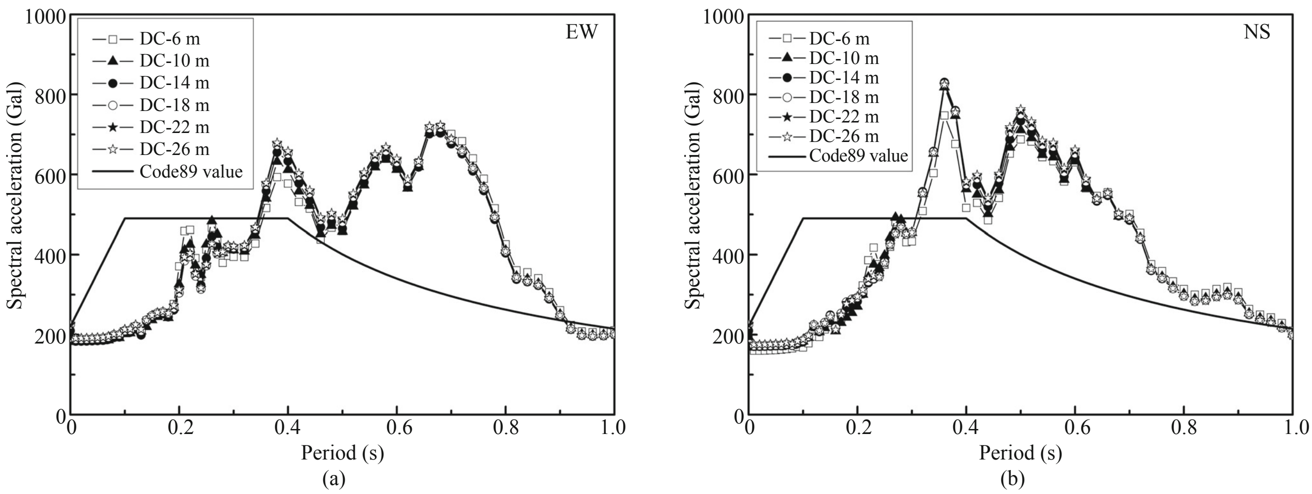

Fig. 11 Variation of the surface response spectra with the depth of the cobble layer (DC stands for "Depth of the Cobble")

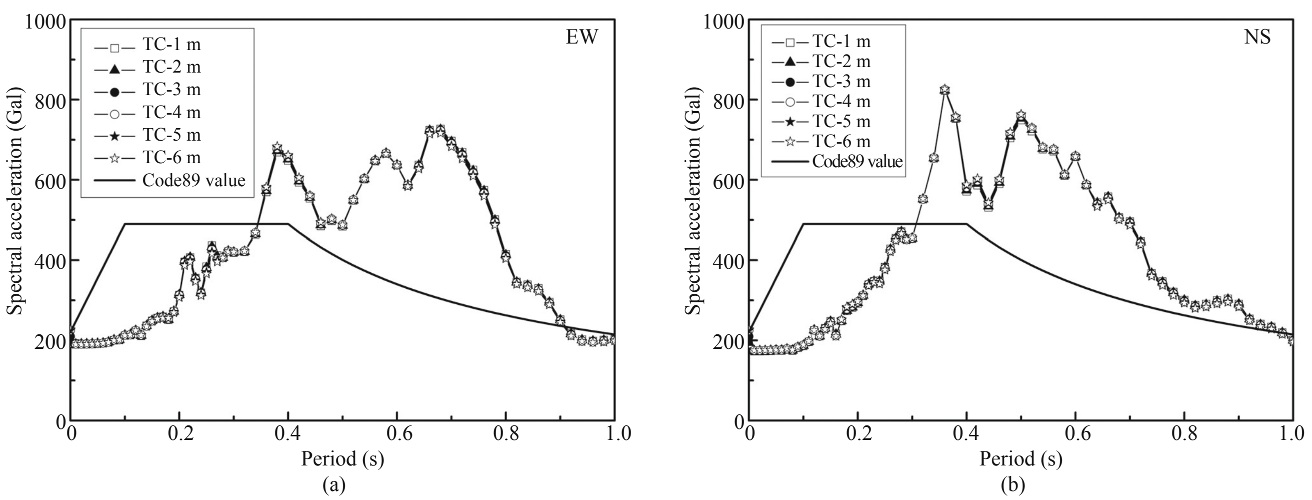

Fig. 12 Variations of the surface response spectra with the thickness of the cobble layer (TC stands for "Thickness of the Cobble")

ground response spectra increase slightly with increasing shear wave velocity of the cobble layer at periods from 0.3–0.7 s, but the maximum variation is less than 10%. Therefore, the shear wave velocity of the cobble layer has a minor effect.

6 Discussion

According to the seismic intensity zoning map of China (1990), the precautionary seismic intensity for the Hanyuan Town is VII, and the corresponding peak acceleration for the rare earthquake is 220 Gal. According to the stratigraphic column of borehole ZK1 (Fig. 8), the overburden thickness and equivalent shear velocity are 56.2 m and 171 m/s, respectively. The site is classified as a class II site by the code GBJ11-89, and the maximum horizontal seismic influence coefficient and characteristic period are 0.5 and 0.4 s, respectively. The design spectra for the town for a rare earthquake are shown in Figs. 10 – 13.

The surface response spectra induced by the Wenchuan earthquake differ substantially from that of the rare earthquake in the Hanyuan Town. The values of the surface response spectra are significantly higher than the design spectra for the periods between approximately 0.3 to 0.9 s and are lower at other periods.

To quantitatively analyze these differences, the ratios of the ground response spectra from the Wenchuan earthquake (Fig. 14) to the design spectra for a rare earthquake under typical conditions of 6 m of miscellaneous fill and a 14-m-deep, 4.8-m-thick cobble layer with a shear wave velocity of 250 m/s are shown in Fig. 15.

Figure 14 shows that the EW and NS peak ground accelerations are 225 and 197 Gal, respectively, and the average value is 211 Gal, which approximates the conditions in the town for a rare earthquake in the code GBJ11-89. A comparison of Fig. 14 and Fig. 6 shows that the peak ground acceleration amplifications (the ratio of the peak ground acceleration to the peak outcrop bedrock acceleration) in the EW and NS directions are 3.3 and 2.6, respectively. The peak ground acceleration amplifications at the sites in the town are significantly higher than the average value of 2.1 in the same site category that were obtained by Lü *et al.* (2007); this effect is primarily caused by the rare and unique soil structure, consisting of fine silt and silty clay above the layers of large cobble (Bo *et al.*, 2009).

The data shown in Fig. 15 show that the ratios are greater than 1 during approximately 0.3−1.0 s. In

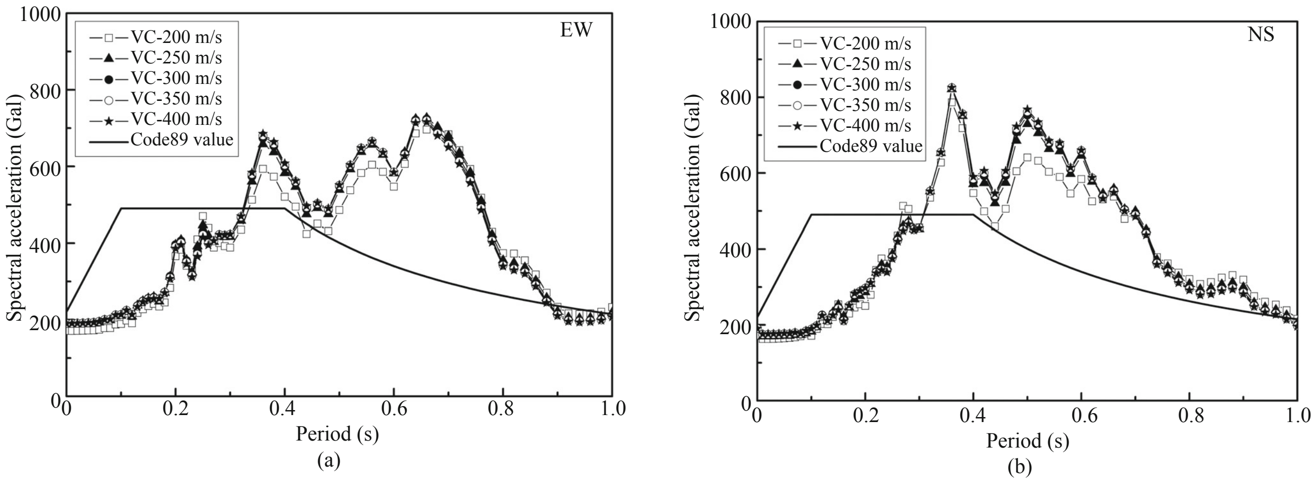

Fig. 13 Variation of the surface response spectra with the shear wave velocity of the cobble layer (VC stands for "Velocity of the Cobble")

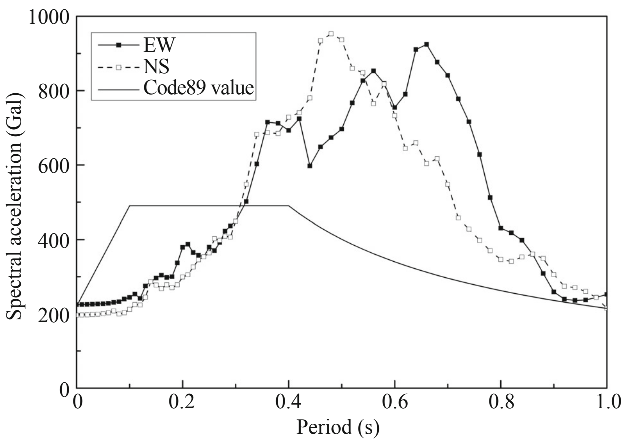

Fig. 14 Ground response spectra for typical site conditions

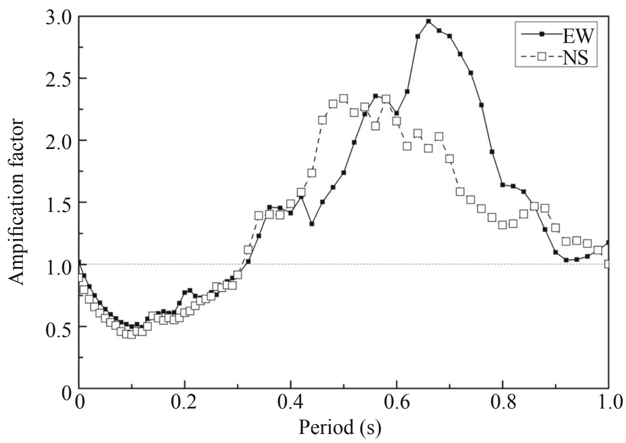

Fig. 15 Ratios of the ground response spectra for the Wenchuan earthquake to the design spectra for the rare earthquake

particular, they are greater than 1.5 during 0.4−0.8 s. The maximum ratio is approximately 3. It is less than 1 at the other periods.

The natural vibration periods of the buildings in the town are approximately 0.1−0.85 s, and those of the 2−6F masonry and frame buildings are approximately 0.3 s−0.85 s (Qi, 2011). Previous results showed that the buildings with natural vibration periods of 0.3−0.85 s in the town suffered from inertia loads, which were much higher than the code values for rare earthquakes, and also from significant resonance effects; thus, these buildings experienced loads that were at least as high as those of the design rare earthquake. These combined effects of the two factors directly caused severe damage to the buildings in the town. The seismic damage surveys indicated that the 1F buildings, which have natural vibration periods of approximately 0.1−0.2 s, suffered less seismic damage than did the multi-floor buildings (Lu *et al.*, 2009) because the spectra induced by the Wenchuan earthquake in their natural vibration periods are lower than the design spectra.

From the results of the seismic response analysis of the town site, the effects of the thickness of the fill on the spectra values are the most noticeable. Figure 2 shows that the buildings at the center of the town were the most damaged, potentially from the thicker fill provided by human activities that contributed to the phenomenon.

This study analyzed the causes of the intensity anomaly in the Hanyuan Town only from the perspective of site amplification effects. However, the Hanyuan Town is located on the valley terrace of the Liusha River and in front of the Beihou Mountain. Therefore, the effects of the geomorphic conditions and landslides on the ground motion should not be neglected. The effects of the terrain and landslides on the intensity anomaly should be further analyzed using two-dimensional (2D) or three-dimensional (3D) numerical simulations, which may provide more scientific explanations for the Hanyuan intensity anomaly.

7 Conclusions

The results of the seismic response analysis of the site in the Hanyuan Town led to the following conclusions:

(1) The amplification effect of the unique soil structure is the root cause of the high-intensity anomaly in the Hanyuan Town because the site magnification factors in the town were significantly higher than the average value of the same site category.

(2) The direct causes of the intensity anomaly in the Hanyuan Town are the combined effects of the following: the inertia loads were greater than the level of the rare earthquake defined in the code, and there was significant resonance between the buildings and the ground motions.

(3) The buildings at the center of the town were the most damaged, potentially from the thicker fill provided by human activities that contributed to the phenomenon.

References

Assimaki D, Ledezma C, Montalva GA, *et al*. (2012), "Site Effect and Damage Patterns," *Earthquake Spectra*, **28**(S1): S55–S74.

Bakir BS, Scuologu H and Yilmaz (2002), "An Overview of Local Site Effects and the Associated Building Damage in Adapazarı during the 17 August 1999 Izmit Earthquake," *Bulletin of the Seismological Society of America*, **92**(1): 509–526.

Bo Jingshan, Qi Wenhao, Liu Hongshuai, *et al.* (2009), "Abnormality of Seismic Intensity in Hanyuan during Wenchuan Earthquake," *Journal of Earthquake Engineering and Engineering Vibration*, **29**(6): 53–64. (in Chinese)

Cai Yuanqiang, Ling Daosheng, Zhou Diyong and QianLei (2000), "Inverse Calculational Analysis of Ground Motion in Nonlinear Layered Soil," *Journal of Vibration Engineering*, **13**(3): 426–432. (in Chinese)

China Earthquake Administration (2005), *Seismic Safety Evaluation of Engineering Site* (*GB17741-2005*), Beijing: China Standard Press. (in Chinese)

Chinese National Standard (1999), *The Chinese Seismic Intensity Scale* (*GB/T17742-1999*), Beijing: China Standard Press, 1999. (in Chinese)

Construction Ministry of PRC (1989), *Code for Seismic Design of Buildings* (*GBJ11-89*), Beijing: China Architecture & Building Press. (in Chinese)

Construction Ministry of PRC (1998), *Code for Measurement Method of Dynamic Properites of Subsoil* (*GB/T50269-97*), Beijing: China Planning Press. (in Chinese)

Construction Ministry of PRC (2001), *Code for Investigation of Geotechnical Engineering* (*GB50021-2001*), Beijing: China Architecture & Building Press. (in Chinese)

Earthquake Disaster Prevention and Mitigation Division of CEA (2008), *Uncorrected Acceleration Recordings of Wenchuan Earthquake*, Beijing: Seismological Press. (in Chinese)

Gao Mengtan, Chen Xueliang, Yu Yanxiang, *et al.* (2008), "Preliminary Discussion on Intensity Anomalous Mechanism of Hanyuan Town in 5.12 Wenchuan Earthquake," *Technology for Earthquake Disaster Prevention*, **3**(3): 216–223. (in Chinese)

Idriss MI and Sun J (1992), *User's Manual for HAKE91*,Structures Division of Building and Fire Research Laboratory, National Institute of Standards and Technology and Center for Geotechnical Modeling of Department of Civil & Environmental Engineering, University of Califora.

Krammer SL (1996), *Geotechnical Earthquake Engineering*, New Jersey: Prentice-Hall, Inc., Englewood Cliffs, N.J. Lei.

Lei Dongning, Cai Yongjian, Li Heng and Chen shujun(2011), "The Earthquake Disaster Characteristic and Cause Discussion about Hanyuan Abnormal Intensity from the 2008 Wenchuan *M*8.0 Earthquake," *Earthquake Research in Sichuan*, (4): 35–40.(in Chinese)

Li Ping, Bo Jingshan, Qi Wenhao, Liu Dedong and Xiao Ruijie (2012), "Effects of Soil Structure on Abnormal Intensity in Hanyuan Old Town," *Acta Seismological Sinica*, **34**(6): 851–857. (in Chinese)

Li Xiaojun, Zhou Zhenghua, Yu Haiying, *et al.* (2008), "Strong Motion Observations and Recordings from the Great Wenchuan Earthquake," *Earthquake Engineering and Engineering Vibration*, 2008, **7**(3): 235–246.

Liu Hongshuai, Bo Jingshan, Wu Zhaoying *et al.* (2005), "Effects of Soil Parameters on Ground Surface Acceleration Peak and Response Spectra," *Journal of Seismological Research*, **28**(2): 167–171. (in Chinese)

Liu Hongshuai, Yang Junbo, Bo Jingshan, *et al.* (2013), "Bedrock Ground Motion Input to High-intensity Abnormality Area in Hanyuan County Town during Wenchuan *M*s 8.0 Earthquake," *Earthquake Engineering and Engineering Vibration*, **32**(2): 27–36. (in Chinese)

Liu Zengwu, Kou Dianqin, Lu Genshcng, *et al.* (1982), "On the Cause of Low Intensity Anomaly in Yutian During the Tangshan Earthquake," *Earthquake Engineering and Engineering Vibration*, **2**(2): 11–25. (in Chinese)

Lovati S, Bakavoli MKH, Massa M, *et al.* (2011), "Estimation of Topographical Effects at Narni Ridge(Central Italy): Comparisons between Experimental Results and Numerical Modelling," *Bulletin of Earthquake Engineering*, **9**(6): 1987–2005.

Lü Hongshan, Zhao Fengxin (2007), "Site Coefficients Suitable to China Site Category," *Acta Seismologica Sinica*, **29**(1): 67–76. (in Chinese)

Lu Tao, Bo Jingshan, Li Juwen, Liu Xiaoyang and Liu Qifang(2009), "Damage to Buildings in Hanyuan County Town during 2008 M_s8.0 Wenchuan Earthquake," *Earthquake Engineering and Engineering Vibration*, **29**(6): 88–95. (in Chinese)

Meslem A, Yamazaki F, Maruyama Y, *et al.* (2012), "The Effects of Building Characteristics and Site Conditions on the Damage Distribution in Boumerdes after the 2003 Algeria Earthquake," *Earthquake Spectra*, **28**(1): 185–216.

Paudyal YR, Yatabe R, Bhandary NP, *et al.* (2012), "A Study of Local Amplification Effect of Soil Layers on Ground Motion in the Kathmandu Valley Using Microtremor Analysis," *Earthquake Engineering and Engineering Vibration*,**11**(2): 257–268.

Puglia R, Vona M, Klin P, *et al.* (2013), "Analysis of Site Response and Building Damage Distribution Induced by the 31 October 2002 Earthquake at San Giuliano Di Puglia(Italy)," *Earthquake Spectra*, **29**(2): 497–526.

Qi Wenhao (2011), *Postdoctoral Report on the Site Characteristics of Abnormal Intensity Area in Hanyuan Town due to Wenchuan Earthquake*, Harbin: Harbin Engineering University.

Raptakis D, Makra K, Anastaslandis A, *et al.* (2004), "Complex Site Effects in Thessaloniki (Greece): I. Soil Structure and Comparison of Observations with 1D Analysis," *Bulletin of Earthquake Engineering*, **2**(3): 271–300.

Shi Zhaoji (1989), "Dynamic Shear Modulus and Damp Ratio of Soil," In Liao Zhenpeng, ed., *Seismic Microzonation: Theory and Practice*, Chapter 11, Beijing: Seismological Press. (in Chinese)

Yuan Yifan (2008), "Impact of Intensity and Loss Assessment Following the Great Wenchuan Earthquake," *Earthquake Engineering and Engineering Vibration*, **7**(3): 247–254.