Field survey around strong motion stations and its implications on the seismic intensity in the Lushan earthquake on April 20, 2013

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Abstract The $M_s7.0$ Lushan earthquake on April 20, 2013 is another destructive event in China since the $M_s8.0$ Wenchuan earthquake in 2008 and $M_s7.1$ Yushu earthquake in 2010. A large number of strong motion recordings were accumulated by the National Strong Motion Observation Network System of China. The maximum peak ground acceleration (PGA) at Station 51BXD in Baoxing Country is recorded as $-1,005.3 \text{ cm/s}^2$, which is even larger than the maximum one in the Wenchuan earthquake. A field survey around three typical strong motion stations confirms that the earthquake damage is consistent with the issued map of macroseismic intensity. For the oscillation period 0.3–1.0 s which is the common natural period range of the Chinese civil building, a comparison shows that the observed response spectrums are considerably smaller than the designed values in the Chinese code and this could be one of the reasons that the macroseismic intensity is lower than what we expected despite the high amplitude of PGAs. The Housner spectral intensities from 16 stations are also basically correlated with their macroseismic intensities, and the empirical distribution of spectral intensities from Lushan and Wenchuan Earthquakes under the Chinese scale is almost identical with those under the European scale.

Keywords Lushan earthquake · Strong motion recording · Macroseismic intensity · Field survey · Earthquake damage · Spectral intensity

1 Introduction

At 8:02, April 20, 2013, a destructive earthquake occurred in Lushan Country, Sichuan Province. The magnitude is $M_s7.0$ and hypocenter depth is 13 km. Up to April 26, 2013, the earthquake had caused 196 dead, 21 missing, and 11,470 injured. It is another destructive shallow earthquake since $M_s8.0$ Wenchuan earthquake in 2008 and $M_s7.1$ Yushu earthquake in 2010 in China mainland.

During the main shock, a large number of strong motion recordings were accumulated by the National Strong Motion Observation Network System of China, and the maximum peak ground acceleration (PGA) of $-1,005.3 \text{ cm/s}^2$ was obtained in the station coded 51BXD in Baoxing Country (Wen et al. 2013a). The PGA between 708 and $1,414 \text{ cm/s}^2$ is one of the criteria to define the macro intensity X in Chinese national code “Chinese seismic intensity scale” (IEM and IGP, CEA 2008). However, the seismic intensity in Baoxing Country is in fact assessed as VII by the post-earthquake investigation. In some other near-field strong motion stations, large PGAs were also observed, such as the stations coded 51BXZ and 51YAD, that are 583.2, 316.4, -387.2 cm/s^2 and -524.4 , 398.6, 196.3 cm/s^2 in the East–West (EW), North–South (NS), and Up–Down (UD) components, respectively (Wen et al. 2013b). Also both are located in the area of seismic intensity VII. The amplitude of the observed PGAs seems higher but the macroseismic intensity is a little bit lower. It is better to check the running status of the instruments of these stations during the earthquake.

Of course, the ground motion parameters are not the only metrics for measuring the intensity of an earthquake which quantifies the effects of the earthquake on the Earth’s surface, human beings, objects of nature, and man-made structures. The strong motion observation network

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intensity, defined as I_M , but the maximum $I_M = VIII$ at the station 51LSF is highly different with the I_I . Furthermore, the I_I for the stations in the Wenchuan earthquake is also calculated as shown in Fig. 2. There are eight stations of which the I_I is larger than the maximum in the Lushan earthquake, which means that the PGVs are also larger because the high I_I is predominantly dependent on PGV. Figure 2 also shows that the I_M mostly corresponds to the range of $I_I \pm 1$ unit of intensity, except the $I_M = VI$ in the Wenchuan earthquake which corresponds to the wide variation from 4 to 7 of I_I .

3 Ground motion and field survey of strong motion stations

Under the support of the scientific investigation project of the China Earthquake Administration (CEA), we surveyed the earthquake damage of the nearby buildings around the stations 51BXD, 51LSF, and 51YAD. All these three stations obtained the recordings in the main shock. Some parameters are listed in Table 1, including the site condition, epicenter distance, rupture distance, PGA, and PGV.

3.1 Station 51BXD

The station 51BXD is located beside the Baoxing Earthquake Disaster Mitigation Board Office where the

elevation is 1,022 m. It is also located on a steep hillside which is in the center of the first terrace of the left bank of Dong River, 35 m from the leading edge. There is a V-shaped valley landscape around the station in terms of a 1,500 m-elevation mountain and 300 m-width valley. The accelerometers are installed on the granite outcrop site, 12 m above the flat terrace.

The observed PGAs and PGVs of 51BXD are $-1,005.3$, 823.6 , 478.1 cm/s^2 and 24.5 , 24.2 , 11.7 cm/s in the EW, NS, and UD components, respectively, as shown in Fig. 3. It is the first strong motion recording with more than 1 g PGA obtained at free field site in China, thus it is a milestone event in strong motion observation history of China (Wen et al. 2013a). However, it should be noticed that the PGVs are not simultaneously as a large level as the PGAs.

The observed acceleration response spectrum of each horizontal component is compared with the predicted values calculated by Huo (1989), as shown in Fig. 4. It represents that the observed values at short-period part (below 0.2 s) are remarkably larger than the predicted values, and at long-period part (above 0.5 s) are remarkably smaller. It is possible that the fault rupture releases a majority of high-frequency energy since the rupture lasted only about 10 s (Wang et al. 2013).

Furthermore, the observed horizontal acceleration response spectrum is also compared with the design spectrum stipulated by the “Code for seismic design of building (GB 50011-2010)” of China (MOHURD 2010), as shown

Table 1 The ground motion parameters of three surveyed stations

Station code	Site condition	Epicentral distance (km)	Rupture distance (km)	PGA (cm/s^2)			PGV (cm/s)		
				EW	NS	UD	EW	NS	UD
51BXD	Rock	9.7	16.6	$-1,005.3$	823.6	478.1	24.5	24.2	11.7
51LSF	Soil	31.9	4.1	387.4	357.0	-267.4	13.8	-13.0	13.7
51YAD	Soil	38.4	9.4	-524.4	398.6	196.3	13.6	-16.3	7.0

Fig. 3 Acceleration and velocity time-histories observed in the Lushan earthquake for the station 51BXD

Fig. 4 Comparison of the observed and predicted acceleration response spectrums for the station 51BXD. The predicted values are calculated by Huo (1989) which is commonly used in China

Fig. 5 Comparison of the observed acceleration response spectrum and the designed spectrum for the station 51BXD. The designed spectrum is calculated under the case of rare earthquake

in Fig. 5. The observed spectrum is vectorially synthesized by two orthogonal horizontal components. The design spectrum is considered under the case of rare earthquake. In Fig. 5, the observed values are remarkably larger than the designed values when the spectral period is smaller than 0.3 s. However, for the oscillation period from 0.3 to 1.0 s, which is the natural period range of the common civil buildings in China, the observed values are smaller than the designed values; that is, indicating that those seismic-designed civil buildings in Baoxing Country could not suffer from the Lushan earthquake.

In addition, at the long-period part (>1 s) the observed spectrum is much smaller than the design spectrum. Thus, the structures with the long natural period, such as the dams, long-span bridges, power-transmission towers and other lifeline facilities, large gymnasiums, and high-rise buildings cannot be heavily damaged while being suffered from this recording.

Fig. 6 Schematic view of the plane location of six surveyed buildings around the station 51BXD and their structure type, construction year, number of story, and damage description

Fig. 7 Spatial locations of the six surveyed buildings around the station 51BXD

Figure 6 shows a schematic view of the plane location, structure type, construction year, number of story, and damage description of six surveyed buildings around the station 51BXD and Fig. 7 shows their spatial locations. There are three six-story masonry structures (Nos. ①, ②, and ③) and one four-story masonry structure (No. ④) built in 1990s among which the three ones are intact, and the other one is seriously damaged. A two-story masonry structure of the Baoxing Earthquake Disaster Mitigation Board Office (No. ⑥), which is located just beside the housing of the station, has the serious damage. However, the housing of the station is intact. There is a possibility that the building of No. ⑥ is not constructed under the specification of the design code since it was built in 1970. Figure 8 indicates that the instruments of 51BXD are

Fig. 8 Two cases of the field survey results for the station 51BXD. The *left picture* indicates that the instruments of 51BXD are running correctly. The *right picture* shows a *horizontal crack* penetrating the gable wall of the No. ⑤ building

Fig. 9 Acceleration and velocity time-histories observed in the Lushan earthquake for the station 51YAD

running correctly and shows a horizontal crack that penetrates the gable wall of the No. ⑤ building. The gable wall bears the load of above structure so that the penetrating crack makes the building nonfunctional.

The above-described survey results show that the macroseismic intensity is appropriate as VII around the station 51BXD.

3.2 Station 51YAD

The 51YAD station is located in Ya'an city where the elevation is 595 m. The station is also located in the trailing edge of the second terrace of the right bank of Qingyi River, 300 m away from the leading edge. The terrain is flat and its average uppermost-20 m shear wave velocity V_{s20} is 190 m/s, classified as the soft soil site.

Its observed PGAs and PGVs are -524.4 , 398.6 , 196.3 cm/s^2 and 13.6 , -16.3 , 7.0 cm/s in the EW, NS, and UD components, respectively, as shown in Fig. 9. As same as the station 51BXD, the PGVs of 51YAD are also not as a large level as the PGAs. It is also found that the observed

Fig. 10 Comparison of the observed and predicted acceleration response spectra for the station 51YAD. The predicted values are calculated by Huo (1989) which is commonly used in China

horizontal acceleration response spectrum at long-period part (above 0.5 s) is remarkably smaller than the predicted value calculated by Huo (1989), as shown in Fig. 10. The

short-period parts (below 0.2 s) of the observed values are kept in the range of the mean predicted values plus or minus one standard deviation. The comparison between the observed and designed horizontal response spectrum for the station 51YAD has the same results as the station

Fig. 11 Comparison of the observed acceleration response spectrum and the designed spectrum for the station 51YAD. The designed spectrum is calculated under the case of rare earthquake

Fig. 12 Schematic view of the plane location of four surveyed buildings around the station 51YAD and their structure type, number of story, and damage description

51BXD that deduces the same conclusions, as shown in Fig. 11.

Figure 12 shows a schematic view of the plane location, structure type, number of story, and damage description of four surveyed buildings around the station 51YAD. No. ① is the station housing which is located on the flat site. It was not damaged in the earthquake and its instruments are running correctly. Also no damage is found on the masonry buildings of Nos. ②, ③, and ④. Figure 13 shows their exterior view and the interior view of the station housing.

3.3 Station 51LSF

The 51LSF station is located in the Feixian Town of Lushan Country where the elevation is 643 m. The station is also located on the second terrace of the right bank of Baoxing River, 20 m away from the leading edge. The average uppermost-20 m shear wave velocity V_{s20} of the observed site is 242 m/s, and the thickness of overlying soil is 6.90 m, classified as the soft soil site.

Its observed PGAs and PGVs are 387.4, 357.0, -267.4 cm/s^2 and 13.8, -13.0 , 13.7 cm/s in the EW, NS, and UD components, respectively, as shown in Fig. 14. As same as both the stations 51BXD and 51YAD, the PGVs are also not very large. Like the station 51YAD whose observed horizontal acceleration response spectrum at long-period part (above 0.5 s) is remarkably smaller than the predicted value calculated by Huo (1989), and the short-period parts (below 0.2 s) are within the range of the mean predicted values plus or minus one standard deviation, as shown in Fig. 15.

The comparison between the observed and designed horizontal response spectrum (Fig. 16) shows that at the period below 0.1 s the observed values are identical as the designed values, at the period between 0.1 and 0.3 s the observed values are larger than the designed values, and at the period above 0.3 s the observed values are remarkably smaller than the designed values as same as both the stations 51BXD and 51YAD.

Fig. 13 Photos of the interior view of the station housing (left one), exterior view of the surveyed No. ② building (middle one) and Nos. ③ and ④ buildings (right one)

Fig. 14 Acceleration and velocity time-histories observed in the Lushan earthquake for the station 51LSF

Fig. 15 Comparison of the observed and predicted acceleration response spectra for the station 51LSF. The predicted values are calculated by Huo (1989) which is commonly used in China

Fig. 16 Comparison of the observed acceleration response spectrum and the designed spectrum for the station 51LSF. The designed spectrum is calculated under the case of rare earthquake

Figure 17 shows a schematic view of the plane location, structure type, number of story, and damage description of four surveyed buildings around the station 51LSF. No. ① is

Fig. 17 Schematic view of the plane location of four surveyed buildings around the station 51LSF and their structure type, number of story, and damage description

the station housing which is a masonry structure built in earlier years. The transverse cracks can be found inside and the exterior wall tiles drop out. It is classified as a moderate damage. The instruments are running correctly. The other three buildings are also masonry structures and moderately or seriously damaged. It can be found that the horizontal cracks penetrate the bottom of No. ③ building and the diagonal cracks appear on the corner of the window. Also some horizontal and diagonal cracks can be found inside the No. ④ building in Fig. 18.

According to the above-described survey results, it is clear that the station 51LSF is located inside the area of macroseismic intensity VIII.

3.4 Discussion

The above-mentioned survey results show that there is no collapsed building around the strong motion stations

Fig. 18 Photos of the exterior view of the station housing (*left one*) and surveyed No. ③ (*middle one*) and No. ④ (*right one*) buildings

51BXD, 51YAD, and 51LSF, the extent of earthquake damage surrounding the station 51LSF is the most serious, 51BXD is moderate, and 51YAD is slighter. Those are basically consistent with the published map of macroseismic intensity. The analysis of the observed ground motion shows that the high-frequency motion is predominant for each station and the low-frequency motion is remarkably smaller than the empirical predicted values. It is noticed that the station 51BXD is located on a steep hillside; therefore, the observed ground motion will be probably affected by the local site topography. Taking a measurement of ambient vibration along the different elevations of the hillside, Wen et al. (2013a) calculated their H/V spectral ratio and verified the site amplification by the steep slope in the 3–20 Hz frequency bands.

4 Comparison of macroseismic and spectral intensities

The definition of the spectral intensity was initially proposed in 1952 by Housner (1952), known as Housner intensity, and it has been confirmed that the spectral intensity has a good correlation with the earthquake damage. It is represented as follows:

$$I_H = \int_{T_1}^{T_2} S_v(T, \xi) dT, \quad (1)$$

where I_H is the spectral intensity, S_v means the velocity response spectrum, T is the spectral period, ξ is the damping ratio of the single degree of freedom system, usually taking 5 %, and T_1 and T_2 are the used lower and

Fig. 19 Relationship of the macroseismic intensity versus Housner spectral intensity I_H [0.1–2.5 s] and I_H [0.2–2.0 s] calculated in the range of period 0.1–2.5 and 0.2–2.0 s, respectively, for each strong motion station in the Lushan earthquake. For each macroseismic intensity, the 95 % confidence interval of I_H is estimated as their empirical distribution; it is compared with the empirical relationship of the European Macroseismic Scale (EMS) given by Masi et al. (2011). Hereby for keeping uniform with the spectral intensity, the *Arabic numerals* are indicated for the macroseismic intensity instead of the *Roman numerals*

upper limit of the spectral period, generally taking 0.1 and 2.5 s, respectively.

The Housner intensities of 16 stations within the area of macro intensity above VI as shown in Fig. 1 are calculated. The geometric mean of two orthogonal horizontal components is calculated. The computed interval with respect to the spectral period controlled by T_1 and T_2 is 0.1–2.5 and 0.2–2.0 s, as I_H [0.1–2.5 s] and I_H [0.2–2.0 s], respectively.

Figure 19 shows the calculated results for each station and the 95 % confidence interval is estimated as an empirical distribution range for both grades of macro intensities VI and VII. The Arabic numerals are indicated for the macroseismic intensity instead of the commonly Roman numerals in order to keep it uniform with the spectral intensity. It is represented that: two distributions are well separated which preliminarily yields a verification that the spectral intensity has a good correlation with the macroseismic intensity. The computed empirical distribution in the case of I_H [0.2–2.0 s] is compared with the empirical one of the European Macroseismic Scale (EMS) (Grünthal 1998) given by Masi et al. (2011). It is noted that the EMS has the nearly approximate criteria with the Chinese seismic intensity scale (IEM and IGP, CEA 2008) for each grade of macroseismic intensity. The comparison result shown in Fig. 19 represents that the empirical distribution of spectral intensity with respect to the macroseismic intensity under the EMS scale is almost identical to the one under the Chinese scale. In addition, both for the macro intensities VI and VII, the average value of the spectral intensity under the Chinese scale is a little bit smaller than the average value under the EMS.

5 Conclusions

A field survey around three strong motion stations coded 51BXD, 51YAD, and 51LSF has been taken immediately after the Lushan earthquake occurred. The characteristics of strong ground motion recorded by these stations are analyzed. The correlation between the macroseismic intensity and spectral intensity are researched. The following conclusions can be drawn:

- (1) It has been confirmed that the earthquake damage surrounding the surveyed three stations is consistent with the issued macroseismic intensity, though their recorded PGAs are unexpectedly large. All the instruments of three stations are running correctly.
- (2) The comparison of the observed response spectrum and the designed spectrum stipulated by the “Code for seismic design of building (GB 50011-2010)” shows that at the period from 0.3 to 1.0 s, which is the natural period range of the common civil buildings in

China, the observed values are considerably smaller than the designed values. That is probably one of the primary causes why the macroseismic intensity in the Lushan earthquake is not as high as we expected, although high amplitude of PGAs are observed.

- (3) The Housner spectral intensities for sixteen stations are calculated and correlated with their macroseismic intensities. The results show that it has a good correlation, and the average distribution range of the Housner spectral intensity is also separated for the different macroseismic intensities. The empirical distribution of spectral intensity with respect to the macro intensity under the Chinese scale is almost identical to that under the European scale.

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