Evidence of hillslope directional amplification from accelerometer recordings at Qiaozhuang (Sichuan – China)

Yonghong Luo a,⁎, Vincenzo Del Gaudio b, Runqiu Huang a, Yunsheng Wang a, Janusz Wasowski c

a State Key Laboratory of Geo-Hazard Prevention and Geo-Environment Protection, Chengdu University of Technology, Chengdu 610059, China
b Dipartimento di Geologia e Geofisica, Universita degli Studi di Bari “Aldo Moro”, via E. Orabona, 4-70125 Bari, Italy
c Consiglio Nazionale delle Ricerche, Istituto di Ricerca per la Protezione Idrogeologica, Via G. Amendola, 122-70126 Bari, Italy

A R T I C L E   I N F O

Article history:
Received 14 April 2014
Received in revised form 6 October 2014
Accepted 9 October 2014
Available online 24 October 2014

Keywords:
2008 Wenchuan earthquake
Aftershocks
Directivity
Topographic amplification
Arias intensity
HVSR

A B S T R A C T

This work reports the results of an accelerometer monitoring aimed at revealing the seismic response of hillslopes in the town of Qiaozhuang, in Qingchuan County, near the north-eastern end of the fault ruptured during the 2008 Mw 7.9 Wenchuan earthquake in Sichuan Province. Serious damage and slope failures were induced by this earthquake in the town center and on the hills in the peri-urban zone. This suggested the possible occurrence of amplification phenomena. Five accelerometer stations were emplaced at two topographic reliefs to investigate their response to ground motion during the last part of the Wenchuan seismic sequence. About 50 aftershocks were recorded, whose magnitude (ML) varied between 1.2 and 5.5 and epicentral distance ranged from a few to 90 km. The accelerometer records provided evidence of directional amplification, which was investigated by analyzing the polar diagrams of normalized Arias intensity (Ia) and the horizontal to vertical spectral ratios (HVSR). Evidence of the anisotropic dynamic response and site specific resonance frequencies was obtained for both topographic reliefs. However, the ground shaking maxima orientations differed depending on the local geological setting: in one case they were transversal and in the other case sub-parallel to the relief elongation. No preferential direction of maximum shaking was observed at the site in the valley. Furthermore, evidence of resonance was derived from the calculation of spectral ratio between the sites on the slope and those at the foot of the hills. The resonance was more pronounced at higher elevations, which suggested a possible occurrence of topographic amplification. Resonance frequencies were lower (3–5 Hz) on the smaller hill consisting of sub-vertically layered phyllites and higher (up to 7 Hz) on the larger hill made mainly of limestones, whereas an opposite relation between resonance frequency and hill size could be expected from a purely topographic effect. This and the presence of amplification factors larger than 2 suggest that, in addition to topographic effects, local geology also played a significant role in differentiating the site response.

© 2014 Elsevier B.V. All rights reserved.

1. Introduction

At 14:28 of May 12th, 2008, a Ms 8.0 earthquake occurred in the Wenchuan county, Sichuan province, western China, with the epicenter located near Yingxiu town. This event led to tremendous casualties and property loss, a significant percentage of which were caused by the triggering of tens of thousands of landslides (Gorum et al., 2011). The interpretation of remote sensing data and field investigations showed that extensive rock slope failures and rock shattering often originated at the mountain tops or at slope convexities (Huang and Li, 2008; Xu and Huang, 2008; Wang et al., 2009). The concentration of source areas near the mountain ridge crests (Figure 1) suggests that seismically induced slope failures were favored by topographic amplification of ground shaking.

Several published case studies provided instrumental evidence of anisotropic amplifications affecting the top of the reliefs, often with shaking maxima oriented transversally to relief elongation. Such phenomena were observed on the Kegel Mountain and the Josephine Peak in California (Davis and West, 1973), in the mountains of the Appalachian chain in Tennessee and Virginia (Griffiths and Bollinger, 1979), on the hills in the area of Viña del Mar in Chile (Celebi, 1987), in the mountainous area hit by the 1989 Loma Prieta earthquake (Hartzell et al., 1994) and on the Wenxian hill (Gansu, China) where aftershocks of 2008 Wenchuan earthquake were recorded by a temporary array (Lu et al., 2011). The amplification phenomena were generally related to topographic effects and, in some cases, were invoked to explain the anomalous (high) concentration of slope failures observed near ridge crests (e.g. seismically triggered rock falls in Pacoima Canyon, Harp and Jibson, 2002; landslides triggered in the Pacoima Canyon, California...
by the 1994 Mw = 6.7 Northridge earthquake, Sepulveda et al., 2005). However, the numerical modeling of relief dynamic response, though capable to account for the observed resonance frequencies, generally resulted in a considerable underestimate of ground motion in comparison to instrumental observations (Chiu and Huang, 1992; Bouchon and Barker, 1996; Spudich et al., 1996; Fischiutta et al., 2010). Therefore, amplifications affecting the top of reliefs can hardly be attributed to a purely topographic effect, especially when amplification factors are larger than 2. In such cases, the local geological conditions could be responsible for a considerable enhancement of site amplification. This and the scarcity of accelerometer monitoring data from slope sites (Wasowski et al., 2011) indicates that further research efforts are needed to improve our understanding of slope dynamic response.

The area damaged by the 2008 Wenchuan event include the Qingchuan County which is located more than 300 km away from the epicenter, near the north-eastern tip of the fault that ruptured during the earthquake (Figure 2). Seismic ground motion not only induced extensive damage to infrastructure located on the alluvial terrace deposits in the Qiaozhuang River valley, but also slope failures on the hills in the urban periphery of Qiaozhuang town, which is the urban center of the Qingchuan County. In particular, field investigation revealed that the upper parts of the Weigan hill, Mount Dong and Mount Shizi were severely shattered (Figure 3) and locally gave rise to rock falls. Since these phenomena were mainly observed near the hilltops, the influence of topography amplification was suspected.
The Qingchuan County area was selected for an accelerometer monitoring study, because after the main shock many aftershocks occurred in the north-eastern section of the seismogenic fault, with epicenters close to Qiaozhuang town. Initially the focus was on Weigan hill where the main shock had caused significant damage and diffuse opening of cracks along the hill ridge crest or close to the hill top (Figure 4). This suggested that the failures might have been favored by the occurrence of topographic directional amplification of seismic ground motion, with maximum shaking transversal to the hill elongation. Therefore, the first two monitoring stations were temporarily emplaced at Weigan hill (Q1, Q2), together with a third station (Q0) installed in the valley, near the Qiaozhuang river (Figures 4, 5). The accelerometers were successively moved from Weigan hill to two sites at Mt. Dong (Q3, Q4) (Figure 5). From April to August 2009, these stations acquired 73 aftershocks whose local magnitude ($M_L$) and epicentral distances (to the monitoring sites) ranged, respectively, from 1.2 to 5.5 and from a few to 90 km ranging from only a few to 90 km.

In this paper we present and discuss the results of the accelerometer recordings at Qiaozhuang town. Data analysis is first conducted in terms of comparison of the mean levels of peak ground acceleration (PGA) observed at different sites. Then, in order to point out directional resonance phenomena, their frequencies and amplification factors, the directional variations in the shaking energy (expressed through Arias intensity — $I_a$) are examined together with the horizontal to the vertical spectral ratio (HVSR) and the standard spectral ratio (SSR). Finally, the implications of the detected site effects are discussed in the context of the ground and slope failures at Qiaozhuang triggered by the 2008 Wenchuan earthquake.

2. Geological setting and accelerometer station arrangement

The study area in the northeast of the Sichuan Province belongs to the north segment of the Longmen Mountains orogenic belt. The main lithologic units are represented by limestones (upper Sinian), phyllites
Fig. 4. Topographic map of Weigan hill showing series of extensive ground cracks formed during the main shock, Q1 and Q2 accelerometer stations deployed, respectively, on the hilltop and at the lower part of the hill.

Fig. 5. Distribution of accelerometer monitoring stations Q0–Q4 (red triangles) in the Qiaozhuang town area; red dashed lines indicate locations of main ground cracks developed on topographic reliefs during the Wenchuan earthquake and the yellow dashed line marks position of the profiles shown in Fig. 7.
The major tectonic structure is the Qingchuan–Pingwu fault, which is composed of three branches (Figure 6). The fault plane strikes approximately N70°E and dips steeply (about 60°) to NW. It has shown relatively strong tectonic activity from the late Pleistocene to early Holocene period, characterized mainly by thrusting mechanisms accompanied by strike-slip movement; the resultant average rate of diastrophism is about 0.6–1.2 mm/a (Liu et al., 2009). After the mainshock of the Wenchuan earthquake, a large number of aftershocks (more than 2000 with magnitude up to 6.3 until July 2009: see Liu et al., 2009) occurred in the proximity of the Qingchuan–Pingwu fault, likely as effect of its activity.

Qiaozhuang town is surrounded by low mountains and hills. In particular, the Weigan hill, located in the southwest periphery of Qiaozhuang, extends for about 650 m in NWW–SEE direction and in the orthogonal direction measures about 30 m, 230 m and 430 m, respectively at the top, middle and lower part of the relief (Figures 4, 5). The hill’s elevation is nearly 900 m above the sea level and the northern and the southern sides are steep while the eastern and the western ones are gentle. Further topographic and geologic details of Weigan hill are shown on the profile in Fig. 7.

At Weigan hilltop, the accelerometer data came from two monitoring sites distant only about 6 m from each other, named Q1a and Q1b: the former was set up in free field conditions, whereas the latter was installed inside a small building of 3 m in length, 5 m in width and 2 m in height. Another station (Q2) was deployed at the lower part of the hill (Figures 4, 7) on a cement floor with the underlying bedrock made of strongly weathered phyllites. The station at the valley bottom (Q0) was deployed on a concrete floor placed over the alluvial deposits (Figure 7). Two additional stations Q3 and Q4 were deployed at the foot and at the middle–upper part of Mt. Dong (Figure 5); the former was sited on moderately weathered phyllites and the latter on tectonically sheared limestones.

The sensors were connected by wire to a 24-channel G01 Universal data acquisition device produced by the Institute of Engineering Mechanics (China Earthquake Administration). Except for Q1a and b, all other stations consisted of single 3-component 941B accelerometers. These are broadband ultra-low frequency vibrometer measuring acceleration up to 2.0 g with a sensitivity of 0.3 V·s²/m.¹

3. Data analysis methodology

A preliminary analysis of differences in seismic response among the monitored sites was conducted in terms of peak ground acceleration (PGA). A comparison of PGA records for the same event at different stations can provide evidence of relative amplification. This kind of analysis was complicated by the variation of frequency at which PGA is observed, due to differences in spectral energy content depending on

¹ More information is available at http://www.iem.net.cn/gcy/yqc.htm.
event source magnitude and distance. Thus, relative amplification factors in terms of PGA can show variation with event magnitude, depending on the site resonance frequency.

The additional problem in analyzing the data acquired in the study area is that, with the exception of stations Q0 and Q2, the number of the same events simultaneously recorded at different stations was rather limited. To overcome this difficulty, we adopted a simplified approach based on correcting PGA values relative to different events by the effect of the wave geometric attenuation with distance and comparing the trends resulting for different sites as function of magnitude.

A regression model was used to determine PGA trends, based on simple formulation of attenuation relationship and assuming a linear dependence of log PGA against magnitude (cf. Joyner and Boore, 1981), according to the following formula

$$\log \text{PGA} = a + b \cdot M - \log \sqrt{D^2 + h^2}$$  \hspace{1cm} (1)$$

where $M$ is the event magnitude, $D$ is its epicentral distance and $h$ is its depth. The last term represents the geometric attenuation, which is independent of medium properties, and thus Eq. (1) can be rewritten in the form

$$\log \text{PGA}_r = \log \text{PGA} + \log \sqrt{D^2 + h^2} = a + b \cdot M$$  \hspace{1cm} (2)$$

where $\text{PGA}_r$ represents the peak acceleration reduced to unit distance. The values of $\log \text{PGA}_r$, plotted against magnitude, will show a scattering around a linear trend resulting from the anisotropy of the seismic energy radiation pattern and differences of anelastic attenuation along different source-station path. However, since the recording stations were very close to each other in comparison to source distances, and most events were aftershocks of the Wenchuan seismic sequence (presumably characterized by similar mechanisms), similar scattering properties could be expected for data relative to different recorded events. Therefore, differences in values of coefficients $a$ and $b$ obtained from the regression of Eq. (2) applied to data acquired at accelerometer stations, should reflect different characteristics of site response in terms of relative amplification at different magnitudes. This kind of analysis was carried out separately for each of the three components of the recordings to point out possible directional differences of amplification between vertical and horizontal ground motion.

PGA values do not reflect total shaking energy and, therefore, might not provide complete information on site amplification and on its directional variations. As indicated by Del Gaudio and Wasowski (2007, 2011), site response directivity can be effectively analyzed by examining directional variation of Arias intensity, a representative parameter of total shaking energy (Arias, 1970). Shaking energy can frequently show a pronounced directional maximum controlled by source properties and depending on site-epicenter azimuth. However, sites affected

Fig. 7. a) Geological profile across the Weigan hill showing the positions of Q0, Q1 and Q2 monitoring stations and main ground cracks (in red); b) Geological profile of Mt. Dong showing the positions of Q3 and Q4. See Fig. 5 for profiles location.
by directional resonance phenomena do show a systematic recurrence of shaking maximum along or close to a site specific direction, regardless of source properties or location.

The presence of a preferential orientation of ground shaking maximum does not necessarily imply the occurrence of resonance phenomena, because directivity could also be due to the directional deamplification (e.g., as effect of anisotropic attenuation) instead of amplification. Spectral analysis of recordings is needed to obtain evidence of resonance. For this purpose, two kinds of approaches could be used, either relying on a single station or on a comparison between a couple of stations.

The single station approach is based on the analysis of spectral ratios between horizontal and vertical components of accelerometer records, averaged over multiple events. This technique, known under the acronym HVSR (horizontal to vertical spectral ratio — Lermo and Chávez-García, 1993), is based on the assumption that pronounced peaks of H/V spectral ratios are found at frequencies for which S-waves are amplified by resonance phenomena. The amplitudes of such peaks are correlated to the amplification factors and spectral ratio maxima are considered significant if they are larger than 2 (Bard et al., 2004). However, H/V ratio amplitudes do not represent a reliable estimate of the actual amplification factors. A better assessment can be obtained from a “double station” technique based on the calculation of mean spectral ratios between homologous component recordings of several events acquired both at the study site and at a nearby reference site not affected by amplification phenomena (Borchert, 1970).

The “double station” technique, commonly known under the acronym SSR (standard spectral ratios), relies on a reference station site that should be characterized by a flat outcrop of a compact rocky formation. However, when a reference site is not close enough to the study area, the observed shaking at the reference may not be representative of that at the bedrock in the study area. In such a case a local station characterized by a lower level of shaking amplification can be chosen as common reference in order to obtain at least an estimate of relative levels of amplifications among the sites in the study area.

Both kind of spectral ratios (HVSR and SSR) can be analyzed in terms of directional variations to investigate the presence of directional resonance, its frequency and orientation. The discrepancies, however, can be found between the results of HVSR and SSR analysis, in relation to the presence of amplification affecting the ground motion vertical component (cf. Del Gaudio and Wasowski, 2007, 2011).

### 4. Data analysis results

From 1 April to 1 May, 2009, the Q1a, Q1b and Q0 stations recorded 6 events (Table 1), while from 10 May to 26 August, 2009, Q2 and Q0 recorded 59 events, 41 of which were recorded by both stations (Table 2). Additional 10 events were recorded by stations Q2, Q3 and Q4 from 10 August to 14 October (Table 3). Source parameters (focus coordinates and magnitude) were derived from the China Earthquake Data Center. Hypocenter depths of aftershocks ranged from 5 to 24 km and epicentral distance from 3 to about 90 km. Two seismogenic fault zones were recognized as responsible for these events: the Qingchuan–Pingwu fault that runs through the study area, and the Yingxiu–Beichuan fault, which represents the main surface rupture fault of Wenchuan earthquake; the latter is located 50–60 km south-west of the study area.

#### 4.1. PGA analysis

A preliminary comparative analysis of the amplification level in terms of PGA was conducted with the simplified approach as described in Section 3 (see Eq. (2)). Fig. 8 shows the results obtained for the different study sites. It can be preliminarily observed that the regression lines at sites Q0 and Q2 are characterized by a much larger scattering, quantified by the very low values of the determination coefficient R². This could be due to the larger dataset available for these stations (longer acquisition period), which implies more differentiated source types and source-site paths.

However, at the two sites, one located at the valley bottom (Q0) and the other near the foot of Weigan hill (Q2), similar PGA trends were found, with the regression lines being almost parallel for all the three components (Figure 8). Furthermore, for all the examined magnitudes, Q2 showed a similar relative amplification in comparison to Q0, i.e. by a factor of 2 on east and vertical components and by a 50% on the north component.

Regarding the other sites located on the hillslopes (Q1a, Q3, Q4), the analysis provided better R² values (from 65 to 89%) with steeper ascending regression lines (Figure 8). This suggests that, at least for the horizontal component, higher amplifications can be expected for larger magnitude events in comparison to the site located at the bottom of the valley. Moreover, at larger magnitudes, the sites on Mount Dong seemed to be characterized by a higher amplification on the east component in comparison to the site Q1 at Weigan hill, which, in turn, showed a clearly stronger amplification (by a 60%) on the vertical component. On the north component, the ground shaking appeared comparable for the three sites (Q1, Q3, Q4); therefore, the differences observed on the east component suggest a directional difference of amplification between the two hills.

#### 4.2. Analysis of Weigan hill monitoring data

To further investigate the possible presence of site response directivity at Weigan hill, we used polar diagrams of Arias intensity (Ia)
representing the shaking energy for each recorded event. In this case, the presence of a directional maximum exceeding an orthogonally directed minimum by a factor of not less than 2 could be considered indicative of the site response directivity, provided that this maximum is greater than 2. At Q2 the average direction of ground motion amplitude for each recorded event is characterized by the lowest level of ground motion amplitude for the half of the maximum found in orthogonal direction; this confers the polar diagram a typical “peanut” shape.

Figs. 9 and 10 show, respectively, the results obtained for the events recorded near the top (sites Q1a–Q1b) and the foot (site Q2) of Weigan hillside, compared with simultaneous records acquired at the site Q0. As indicated through the PGA analysis, Q0, located at the valley bottom, is characterized by the lowest level of ground motion amplitude for stronger earthquakes (Mw > 3–3.5). Weigan hill sites showed a systematic directivity of maximum shaking approximately oriented transversally to the hill elongation. Near the hill top the maximum shaking was almost constantly found in NE direction with a maximum/minimum ratio generally close to or larger than 2. At Q2 the average direction of ground

Table 2
Main source parameters of aftershocks from 11 May to 14 July, 2009. Legend as in Table 1.
shaking maxima appeared a bit rotated eastward, to an ENE direction, possibly in relation to a slight curvature of the hill shape, but directivity was still quite evident.

At Q0 there was no evidence of directional resonance. Even though, on the average, NE-SW oriented shaking maxima were more frequent, the cases of almost isotropic shaking or of maxima with a totally different direction were also relatively common. Therefore, the mean Ia values have maximum significantly less than 1 and a minimum of the order of three quarters of the maximum.

To evaluate whether the detected directivity was related to resonance phenomena, HVSR analysis was carried out first, exploiting all the recordings available for each site (Figure 11). The polar diagrams relative to the hilltop sites showed evidence of directional H/V peaks concentrated around NE orientation, in agreement with the directivity indicated by Ia polar diagrams. Such directivity was more clear for the free field station (Q1a) than for the one installed in a small building (Q1b), possibly as effect of the influence of the building response to shaking.

At Q1a major significant peaks (i.e. with H/V > 2 and directional maximum/minimum ratio larger than 1.5) are observed at frequencies between 0.8 and 9 Hz, whereas at Q1b the peaks are found between 0.4 Hz and 1.1 Hz. The amplitudes of these peaks are quite small (around 3 at most), but this could be due to the presence of a vertical component amplification (as suggested by the PGA data). At station Q2, H/V amplitude does not appear significant (value less than 2), and also the directional character is rather weak (minima mostly differing from maxima by no more than 50%). Thus, there is no clear evidence of directional resonance. Instead, the HVSR polar diagram of Q0 (Figure 11) shows a more pronounced peak at a relatively higher frequency (around 12 Hz), but with a scarcely directional character (ratio

---

**Table 3**

Main source parameters of aftershocks from 10 August to 19 September, 2009. Legend as in Table 1.

<table>
<thead>
<tr>
<th>Q2</th>
<th>Q3</th>
<th>Q4</th>
<th>Events</th>
<th>Time</th>
<th>Longitude (°)</th>
<th>Latitude (°)</th>
<th>Hypocenter depth (km)</th>
<th>Distance (km)</th>
<th>Azimuth (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>805 46</td>
<td>788 1</td>
<td>870 1</td>
<td>090810-ML2.5</td>
<td>06:40:06</td>
<td>32.62</td>
<td>105.38</td>
<td>5</td>
<td>14.25</td>
<td>72.3</td>
</tr>
<tr>
<td>805 49</td>
<td>788 2</td>
<td>870 2</td>
<td>090812-ML3.4</td>
<td>03:52:09</td>
<td>32.65</td>
<td>105.37</td>
<td>5</td>
<td>14.78</td>
<td>58.7</td>
</tr>
<tr>
<td>805 50</td>
<td>788 3</td>
<td>/</td>
<td>090812-ML1.3</td>
<td>16:54:23</td>
<td>32.52</td>
<td>105.22</td>
<td>5</td>
<td>6.92</td>
<td>191.7</td>
</tr>
<tr>
<td>/</td>
<td>788 4</td>
<td>870 3</td>
<td>090816-ML3.2</td>
<td>12:42:07</td>
<td>32.43</td>
<td>105.10</td>
<td>5</td>
<td>21.01</td>
<td>217.1</td>
</tr>
<tr>
<td>805 51</td>
<td>788 5</td>
<td>/</td>
<td>090820-ML2.3</td>
<td>08:01:33</td>
<td>32.52</td>
<td>105.26</td>
<td>13</td>
<td>7.17</td>
<td>160.9</td>
</tr>
<tr>
<td>805 52</td>
<td>788 6</td>
<td>870 4</td>
<td>090823-ML2.6</td>
<td>22:20:15</td>
<td>32.51</td>
<td>105.29</td>
<td>15</td>
<td>8.54</td>
<td>202.6</td>
</tr>
<tr>
<td>/</td>
<td>788 7</td>
<td>870 5</td>
<td>090903-ML2.7</td>
<td>02:09:45</td>
<td>32.57</td>
<td>105.34</td>
<td>11</td>
<td>9.76</td>
<td>101.8</td>
</tr>
<tr>
<td>805 53</td>
<td>788 8</td>
<td>870 6</td>
<td>090911-ML1.8</td>
<td>23:44:33</td>
<td>32.59</td>
<td>105.29</td>
<td>5</td>
<td>4.87</td>
<td>87.4</td>
</tr>
<tr>
<td>805 54</td>
<td>788 9</td>
<td>870 7</td>
<td>090919-Ms5.2</td>
<td>16:54:13</td>
<td>32.90</td>
<td>105.56</td>
<td>8</td>
<td>45.91</td>
<td>40.9</td>
</tr>
<tr>
<td>/</td>
<td>788 10</td>
<td>871 16</td>
<td>091014-ML4.1</td>
<td>16:03:04</td>
<td>32.58</td>
<td>105.37</td>
<td>23</td>
<td>12.39</td>
<td>72.0</td>
</tr>
</tbody>
</table>

**Fig. 8.** Linear trends of PGA reduced at unit distance as function of magnitude derived from linear regression of data relative to three component recordings acquired at the five monitored sites. Equation coefficients and determination coefficients $R^2$ are reported in the legend.
maximum/minimum equals to 1.3). One cannot exclude the possibility that such frequency reflects the resonance of the building that hosted the station. Nevertheless, below 11–12 Hz no resonance attributable to local soil properties could be recognized, and therefore this site can serve as the reference for frequencies not exceeding 10 Hz.

Using Q0 as reference, we also examined spectral ratio (SSR) of Q1a, Q1b and Q2. For the stations on the top of Weigan hill, the number of events simultaneously recorded at Q0 is small, but the results show similar amplification features consistent with the results of the previous analyses. Approximately NE–SW oriented directional maxima of spectral amplification were found with major peaks in the range of 2.5–5.0 Hz (Figure 12). However, the amplification factors (between 4.0 and 7.0) were much larger than the amplifications indicated by HVSR data. The latter were presumably biased by vertical ground motion amplification: indeed in the same frequency range, SSR calculated for the ground motion vertical component show an amplification by a factor varying from 4 to 6. In comparison, at Q2 the peak values of SSR amplification (frequency range 1.0–6.0 Hz) were lower by more than 50% (not larger than 2.5) (Figure 12). This observation is consistent with a decrease of the amplification effect at the base of the hill.

### 4.3. Analysis of Mount Dong monitoring data

Since 10 August 2009, stations Q3 and Q4 have recorded 10 events, some of which were also recorded by station Q2 at the foot of Weigan hill (Table. 3). The Ia polar diagrams relative to stations Q3 and Q4 show a systematic pronounced elongation oriented within a narrow azimuth around N77°E and N62.5°E, respectively, regardless of the azimuth and distance of the events (Figure 13). Besides, a similar preferential orientation (around N83°E) was found in station Q2 using the same after-shock data (Figure 13). The orientation of Ia maxima is approximately sub-parallel to the elongation of the Mt. Dong ridge, which again suggests a role of topography in generating the observed shaking anisotropy.

With regard to spectral ratios, the polar diagram of HVSR values showed some E–W directed peaks (Figure 14), however, while at the topographically higher site (Q4) the major peak frequency was at about 3 Hz, near the foot of the slope major peaks were found at high frequencies (12–14 Hz). Such frequencies suggested an influence of local scale site conditions rather than a topographic effect of the whole mountain. In general, the peaks did not show a clear correlation with the direction of maximum horizontal shaking revealed by Ia polar diagram, and this...
could be due to local peculiarity of ground motion vertical component (e.g. vertical ground motion deamplification causing an increase of H/V ratios).

SSR analysis was also carried out using station Q2 as reference (Figure 15). It should be taken into account that, in comparison to Q0, this station shows certain, not very pronounced amplification (see Figure 12); thus a possible effect of reduction of the actual amplification factors should be considered in any comparison with the results obtained for Weigan hill. Nevertheless, the SSR values can provide useful information for a comparison between the two stations (Q3, Q4).

Although based on a limited number of events, at Mt Dong the SSR results appeared consistent with the outcome of the Ia analysis, showing maxima in ENE directions (Figure 15). At Q4 the main peak is at 7 Hz, and a secondary one at 4–5 Hz; also Q3 shows one of the major peaks at 7 Hz, whereas other maxima are at 3 and 13 Hz (Figure 15). Amplification factors appear rather low (up to 1.5 and 3 for Q3 and Q4, respectively), but this could be due at least in part to the use of a slightly amplified site (Q2) as reference. However, in relative terms the topographically higher site (Q4) was more amplified than Q3 located at the slope base. This is consistent with the presence of an amplification related to the Mount Dong relief.

5. Discussion

The assessment of site amplification (characteristics) from an accelerometer monitoring conducted through a temporary array can encounter difficulties, because such a monitoring may not always record enough events representative of the site response to strong motions. However, the use of different kinds of analysis can provide useful insight into the dynamic response of a study site also when only “weak motion” data are available. This is particularly important in the study of the dynamic response of slopes potentially prone to failures under seismic shaking, where long term accelerometer monitoring is rarely feasible. We analyzed the data from an accelerometer monitoring conducted at five sites in Qiaozhuang (Sichuan, China) in a seven-month period (from April to October 2009), during a late stage of the 2008 Ms 8.0 Wenchuan earthquake seismic sequence. The monitoring effort was motivated by the observation of severe damages and slope failures on
some hills around the Qiaozhuang town, which suggested the possible influence of topographic amplification.

Dynamic response of different sites was analyzed comparing PGA values reduced to unit distance to correct wave geometric attenuation effect, and comparing directional variation of Arias intensity (Ia), horizontal-to-vertical spectral ratios (HVSR) and standard spectral ratios (SSR) relative to sites with lower shaking levels. Considering the outcomes of these different analyses, some results of HVSR were not completely consistent with those of the other methods. This could be related to the hilltop, convex slope terrain and geological structure affecting the site response and in particular the vertical ground motion: indeed, the common assumption that vertical component is not subject to amplification, adopted in “single station” spectral ratio techniques like HVSR, may not hold for slopes with complex geological structure.

In particular, at Weigan hill, PGA data indicated the presence of a significant vertical amplification, possibly related to the structural setting of the hill which can favor the transmission of a larger amount of energy by vertically polarized waves. We speculate that the simultaneous occurrence of vertical and horizontal amplifications, the latter approximately oriented in slope dip direction, may have favored the occurrence of slope failures at Qiaozhuang during the 2008 Wenchuan earthquake.

In general, numerous rock falls and other types of landslides induced by the 2008 Wenchuan earthquake originated in the steep mountain terrain which likely amplified the effect of the ground shaking (e.g., Xu and Huang, 2008; Yin et al., 2011). Furthermore, the remote sensing interpretation of post-earthquake imagery and field investigations showed that many slope and ground failures occurred on both sides of mountain ridges, at or near the top of the hillslopes and at sites with convex topography (Qi et al., 2010; Xu et al., 2011; Luo et al., 2013).

The above observations could be simply taken as clear evidence of topographic amplification if one overlooks the lack of consistent relation between the ridge morphology and the orientation of ground shaking maxima. However, the amplification factors observed at Qiaozhuang strongly suggest that geological–structural characteristics also play an important role, especially at Weigan hill, where spectral amplification at frequencies below 5 Hz is much larger than 2. We further speculate that the structural setting of Weigan hill, dominated by phyllites with sub-vertical layering roughly parallel to the hill elongation, can result in ground motions preferentially amplified in the direction transversal to the layering. This in turn can have important implications for local seismic hazard assessment.

Fig. 12. Polar diagrams of SSR (standard spectral ratio) values for Weigan hill sites Q1a, Q1b and Q2, with Q0 being the reference station. Vertical bars report spectral ratios for vertical component of ground motion.
Fig. 13. Polar diagrams of normalized Arias intensity (maximum made equal to 1) calculated for different azimuths at stations Q4, Q3 and Q2; event date, magnitude (ML or Ms) and epicentral distance are indicated at the top of the figure; arrows mark event source back-azimuth (station-epicenter directions); diagrams in the right-most column show mean values of normalized Arias intensities calculated along each direction from all the events recorded at each station.

Fig. 14. Polar diagrams of HVSR (horizontal-to-vertical spectral ratio) values for stations Q4 and Q3 at Mount Dong.
and SSR analyses, several conclusions can be drawn as follows: Based on PGA, polar diagrams of normalized Arias intensity, and HVSR number of aftershocks of the 2008 Wenchuan earthquake sequence. Dong in the Qiaozhuang town, Qingchuan County recorded a large on the local hills, should shed further light on their seismic response. this, together with the recent installation of new accelerometer stations actions. The monitoring efforts will continue at the Qiaozhuang area and it is believed that this case study represents a useful contribution aiming at improving the comprehension of the behavior of slopes under seismic. The monitoring efforts will continue at the Qiaozhuang area and this, together with the recent installation of new accelerometer stations on the local hills, should shed further light on their seismic response.

6. Conclusions

Five monitoring stations emplaced at the Weigan hill and Mount Dong in the Qiaozhuang town, Qingchuan County recorded a large number of aftershocks of the 2008 Wenchuan earthquake sequence. Based on PGA, polar diagrams of normalized Arias intensity, and HVSR and SSR analyses, several conclusions can be drawn as follows:

(1) Wenchuan earthquake generated slope failures and a large number of ground cracks in the Weigan hilltop, Mount Dong and other mountain tops in the Qiaozhuang study area. The cracks typically followed the ridge elongation.

(2) The analyses indicated the occurrence of amplification phenomena affecting Weigan hill and Mount Dong located, respectively, SW and NE of the Qiaozhuang town center. The amplifications had a pronounced directivity with shaking maxima oriented transversal (at Weigan) and sub-parallel (at Dong) to the relief elongation. In both cases the amplification factors were higher at sites close to the hilltop and lower near the foot of the slope.

(3) At Mount Dong the PGA values indicated slightly higher values of peak shaking than at Weigan hill, while spectral amplifications appeared smaller at lower frequencies (less than 5 Hz). This may be related to the differences in local lithology (mainly limestones), which, unlike the strongly weathered phyllites at Weigan, could afford greater strength to the Mount Dong slopes.

(4) There is evidence that in addition to the topographic features the geological structure and lithology also influence the observed site amplification and directivity phenomena.

Acknowledgments

This work has been supported by the National Natural Science Foundation of China (Grant No. 41072231, Grant No. 41202211), a talent fund provided by the State Key Laboratory of Geo-environment Protection and Geo-hazard Prevention (Grant No. 119-00002247), and the China Geological Survey Bureau (Grant Nos. 1212010914010 and 1212011220154). We would like to thank Wang Fuhai, Ma Xiao, Li Shun, Cheng Ning for their help and support in carrying out the field monitoring. We also particularly thank Th.W.J. van Asch for comments and suggestions on the earlier versions of the manuscript and Sandro Muscillo for assistance in data processing.

References


