Seismic Monitoring of a Slope to Investigate Topographic Amplification

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Abstract: Some earthquakes with a magnitude lower than Ms 7.0, such as Ludian earthquake in Yunnan in 2013, have triggered strong secondary geo-hazards in the form of slope failures. Topographic amplification is generally considered to be the main causal factor for these slope failures. However, until recently, this idea is not supported by appropriate seismic monitoring data. The Kangding Ms 6.3 earthquake on November 22nd, 2014 was monitored in Lengzhuguan, Sichuan Province, located 56 km from the earthquake epicenter. Six monitoring instruments have recorded this earthquake. The horizontal and vertical component Peak Ground Acceleration (PGA), the site response directivity, the directional variation of the Arias intensity, and the acceleration response spectrum were determined from the data obtained. Conclusions could be drawn that the topographic amplification effect of the isolated ridge on the right bank was stronger than that of nearly linear slope on the left bank and the topographic amplification effect at a slope break was stronger than on a linear slope.

Keywords: Kangding Ms 6.3 earthquake, topographic amplification, slope seismic response, PGA, Lengzhuguan creek

1 Introduction

Based on geological studies and theoretical modeling, many authors have reported that topographic amplification effects occur at convex topography and slope breaks during earthquakes leading to more slope failures at those locations than at other parts of the slopes. The seismic response data analysis of the Central Chile earthquake in 1985 (Celebi 1987) revealed that the frequency range of the ground motion amplification could be obtained by the frequency ratio method and that an amplification effect was obvious at special topographical features and along a mountain ridge. Geli et al (1988) revealed that topographic amplification effects were obvious at hilltops where the slope width was approximately equal to the incident wavelength. The amplification effect was lower for incident P-waves than for the incident S-waves; the topographic amplification effect of the primary wave and the vertical component of the secondary wave are slightly stronger than that of the horizontal component of the secondary wave, and the topographic amplification effect increased near adjacent ridges. Field surveys after Wenchuan Ms 8.0 earthquake on 12th May, 2008 (Luo and Wang 2013) revealed that the horizontal components of the seismic waves were significantly enlarged when the slope width was close to the incident seismic wavelength: the amplification effect was distinct along narrow mountain ridges and spurs, at slope breaks, and on convex slopes. The Lushan Ms 7.0 earthquake on 20th April, 2013 (Huang et al 2013) showed that the source of rock fall was usually near the top of steep slopes and near prominent changes in slope angle. Analysis of the seismic response of the Lengzhuguan slope during the Lushan earthquake revealed that the topographic
amplification effect along the thin ridge of the right bank was significantly stronger than on the slopes of the left bank (Luo et al 2013). The highest peak ground acceleration (PGA) records during the Wenchuan earthquake were also caused by local topographic effects (Wen et al 2013). Qi et al (2003) simulated three components of the acceleration distribution and carried out slope dynamic stability analysis on the right bank of Jinping hydropower station. Over 2000 secondary slope failures caused by the Lushan earthquake and large scale landslides triggered by the Ludian earthquake were assumed to be associated with topographic amplification effects, but real monitoring data of seismic response on various locations on slopes are still lacking.

With the support of the China Geological Survey Bureau and the National Science Foundation of China, we set up a monitoring section in Lengzhuguan in 2011. At 16:55 hours of November 22, 2014, a magnitude Ms 6.3 earthquake occurred in Kangding County, Sichuan, located 56 km in northwestern (315º) direction from the monitoring section. The six seismic instruments in the section (stations 1, 2, 3, 4 and 5) were triggered by the earthquake, and a series of data were obtained to study the topographic amplification factors.

2 The Monitoring Profile

The Lengzhuguan earthquake monitoring stations are located on both sides of Lengzhuguan river valley where it flows into Dadu River on the right bank (Figure 1). Two stations are located on the right bank and three stations on the left bank of Lengzhuguan river valley (Figure 2). One seismic monitoring instrument was set in each station from 1 to 4, and two monitoring instruments were set in station 5 (the outer one is 57 m from the portal and the inner one is 135 m from the portal). The ridge on the right bank reaches an elevation of 1520 m, while the left bank is 1000 m high sloping terrain which is connected with the right concave bank of Dadu River. Station 1 is on the top of the ridge on the right bank and station 2 is half way up the ridge; station 3 is situated at a slope break, and station 4 and station 5 are located at different levels on the nearly linear slope. So we can study the different topographic amplification effects at the two banks of the canyon from station 1, 2 and 3, and the topographic amplification on the nearly linear slope at station 4 and 5. Earthquake motions were measured by the E-catcher strong motion seismographs (Application of Japan, Saitama city), with basic sensitivity parameters 1 V/G. A meter full scale is 2000 gal (1 gal = 1 cm·s⁻²), and the range of cycle frequency is DC~20 Hz (-3 dB).

3 The Seismic Response Data

The location parameters of the monitoring stations are shown in Table 1, the recorded waveforms are shown in Figure 3 and the ground motion parameter characteristics of each monitoring station are listed in Table 2. The data reveal that the PGA of station 1 is 188.1 gal in EW direction on the right bank while the station 3 is 49.8 gal, so the PGA on the right bank is about three times as large as that on the left bank. The PGA of outer point (57 m from the portal) at station 5 is 1.15 times larger than the inner one (135 m from the portal).

The site response directivity can be effectively analyzed by examining the directional variation of the Arias Intensity (Ia) (Arias 1970). The Ia values in three directions for each monitoring station are shown in Table 2. The maximum horizontal Ia on the right bank is about 15 times as large as that on the left bank and the vertical Ia about 7.5 times. The horizontal and vertical Ia values of station 1 are 2.7 and 3.1 times, respectively, as much as those of station 2, and for station 4 are 1.4 and 2.0 times larger than those of station 5. The outer and inner Ia values at station 5 are at the same level. Therefore, the seismic energy at the right bank is larger than that at the left bank.

4 The Acceleration Response Spectrum

The concept of the acceleration response spectrum is based on Elastic System Dynamics (Biot 1941). A series of response spectrum curves were derived from a number of typical strong earthquake accelerations (Housner 1959). A
Figure 1 Location of the Lengzhuguan seismic monitoring section (a. the regional tectonic map; b. the monitoring station distribution plan)
Table 1 Location parameters of the monitoring stations

<table>
<thead>
<tr>
<th>Monitoring station no.</th>
<th>Elevation (m)</th>
<th>Epicentral distance (km)</th>
<th>Distance to Guza station (km)</th>
<th>Type of bed rock</th>
<th>Degree of weathering</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1516</td>
<td>56.2563</td>
<td>7.9045</td>
<td>granite</td>
<td>moderate weathered</td>
</tr>
<tr>
<td>2</td>
<td>1478</td>
<td>56.2331</td>
<td>7.8201</td>
<td>granite</td>
<td>moderate weathered</td>
</tr>
<tr>
<td>3</td>
<td>1518</td>
<td>56.0337</td>
<td>7.6618</td>
<td>granite</td>
<td>moderate weathered</td>
</tr>
<tr>
<td>4</td>
<td>1520</td>
<td>55.9515</td>
<td>7.3536</td>
<td>granite</td>
<td>moderate weathered</td>
</tr>
<tr>
<td>5 (Outer)</td>
<td>1686</td>
<td>55.7189</td>
<td>7.1986</td>
<td>granite</td>
<td>slightly weathered</td>
</tr>
<tr>
<td>5 (Inner)</td>
<td>1686</td>
<td>55.7189</td>
<td>7.1986</td>
<td>granite</td>
<td>slightly weathered</td>
</tr>
</tbody>
</table>

Table 2 The ground motion parameter characteristics in East-West (EW), North-South (SN) and Vertical Direction (VD)

<table>
<thead>
<tr>
<th>Number of monitoring stations</th>
<th>PGA (gal)</th>
<th>Arias intensity (cm·s⁻¹)</th>
<th>Dominant frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EW</td>
<td>SN</td>
<td>VD</td>
</tr>
<tr>
<td>1</td>
<td>188.1</td>
<td>147.6</td>
<td>111.8</td>
</tr>
<tr>
<td>2</td>
<td>70.4</td>
<td>69.9</td>
<td>36.5</td>
</tr>
<tr>
<td>3</td>
<td>49.9</td>
<td>62.4</td>
<td>36.6</td>
</tr>
<tr>
<td>4</td>
<td>35.0</td>
<td>26.4</td>
<td>27.6</td>
</tr>
<tr>
<td>5 (Outer)</td>
<td>24.9</td>
<td>22.7</td>
<td>14.0</td>
</tr>
<tr>
<td>5 (Inner)</td>
<td>22.5</td>
<td>19.8</td>
<td>12.0</td>
</tr>
</tbody>
</table>
The acceleration amplitude decreases with the increase of the damping ratio, and is at the maximum with a damping ratio of 0.05 (Figure 4). The upward and downward trends of the horizontal and vertical acceleration response spectrum curves for each monitoring point are consistent, i.e., they reach the maximum and minimum values for the acceleration amplitude for different damping ratios at the same time. These results show that the seismic amplitude value is affected by the damping characteristics of the ground while the ground motion characteristics are not affected significantly. The horizontal acceleration amplitude at each monitoring point is larger than the vertical one at the different damping ratios, which is consistent with the waveform at the monitoring stations. The acceleration response spectrum curve of station 1 is about 3.1 times as large as the station 2 with the same damping ratio, and the vertical is 4.5 times large. The acceleration amplitude at station 1 with the damping ratio of 0.2 is also larger than at the station 2 with a damping ratio of 0.05. It is also larger than those at each monitoring station at the left bank with a damping ratio of 0.05. So the acceleration amplitude of the response spectrum on the right bank is bigger than that on the left bank.
The acceleration response spectra at the monitoring stations: (a) station 1, (b) station 2, (c) station 3, (d) station 4, (e) station 5 outer and (f) station 5 inner.

Figure 4 The acceleration response spectra at the monitoring stations: (a) station 1, (b) station 2, (c) station 3, (d) station 4, (e) station 5 outer and (f) station 5 inner.
5 Topographic Amplification Effect

At the Guza earthquake monitoring station (at a distance of 7 km from the Lengzhuguan monitoring section and with a position at the bottom of the valley) the horizontal and vertical components of PGA of the main shock records were 16.4 and 15.7 gal, respectively. We used these values as reference values for the Lengzhuguan section as the two stations, designed to record the reference values at the bottom of the valley in the Lengzhuguan section, unfortunately were not triggered by the Kangding earthquake. The PGA amplification coefficients for each monitoring station at Lengzhuguan are shown in Figure 5.

The ridge on the right bank of Lengzhuguan is shaped peninsular and the left bank is nearly linear (Figure 6). The amplification effect of the ridge on the right bank is stronger than that on the left nearly linear slope (Figure 5).

Station 3 is at a slope break while station 4 is at the middle of a linear slope, and both are at the same level. The magnification coefficients at station 3 in three directions are larger than those at station 4 (Figures 7 and 8), so we conclude that the topographic amplification effect at a slope break is stronger than on a linear slope. We can also conclude that the outer magnification coefficients at station 5 closer to the terrain surface are larger than that deep inside the rock mass. These conclusions are also consistent with the indoor model test reached by Wang and Wang (1987) and numerical results reached by Qi et al (2003) and Qi (2006).

The topographic amplification effect is scarcely affected by the lithology as the five stations are of the same lithology (granite), and their weathering degrees are similar.

6 Conclusions

Reference to Guza station of the main shock record of Kangding earthquake (its horizontal and vertical component PGA was 16.4 and 15.7 gal, respectively), the monitoring data on the two banks of Lengzhuguan section reveal obvious topography amplification effects: (1) the amplification effect is strongest on the peninsular ridge on the right bank and weaker on the left nearly linear slope; (2) the amplification effect at the slope break is stronger than that at the linear slope from the monitoring data of station 3 and station 4; (3) the amplification factor near the surface of the slope is larger than deeper into the rock mass from two motoring instruments at
station 5. It is clear that the characteristics of topography are important factors for slope stability, and that varying degrees of earthquake damage will be occur in different parts of slopes because of topographic amplification effects. What’s more, we could study the mechanism of seismic landslide and slope failure with the monitoring data in different view.

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