CHARACTERISTICS OF NEAR-FAULT VERTICAL AND HORIZONTAL GROUND MOTION FROM THE 2008 WENCHUAN EARTHQUAKE

XIE Jun-Ju1, WEN Zeng-Ping1*, GAO Meng-Tan1, HU Yu-Xian1, HE Shao-Lin2

1 Institute of Geophysics, China Earthquake Administration, Beijing 100081, China
2 Institute of Earthquake Science (Lanzhou), China Earthquake Administration, Lanzhou 730000, China

Abstract Characteristics of near-fault vertical and horizontal ground motion from 2008 Wenchuan earthquake are investigated in this paper. Records from 40 strong motion stations along the Beichuan-Yingxiu fault with fault distance smaller than 120km are used as database. Based on the analysis of peak ground acceleration, peak velocity, spectra acceleration and spectra ratio of vertical to horizontal ground motion, the following conclusions can be made: (1) Hanging wall effects are shown in PGA for near-fault ground motions within 60 km to the surface rupture, the empirical model results in up to a 30% ∼ 40% increase in peak horizontal and vertical accelerations on the hanging wall over the distance range of 3 to 60 km relative to the median attenuation for the Wenchuan earthquake. The peak acceleration residuals on the hanging wall appear to be biased to positive values whereas the residuals of footwall sites are negative. The EW component of horizontal accelerations is larger than the NS component and attenuates more slowly. (2) There is a lack of long period component in near-fault ground motion of Wenchuan earthquake, the value of spectrum acceleration decreases rapidly in the long period range. The maximum spectrum acceleration is only 0.5 g even at locations very close to the main causative fault at period 1.0 s. Large distinctions are shown in the distribution of acceleration spectrum ratio (Vertical/Horizontal) for near-source ground motion at longer periods (T=0.2 s, 0.5 s, 1.0 s) with respect to short periods (T=0.05 s, 0.1 s). (3) High intensity of UD component is shown for near-fault ground motion, the PGA ratio (Vertical/Horizontal) can be as large as 1.4. High intensity of UD component is more obvious on the hanging wall, and the PGA ratios on the hanging wall are much larger compared with the footwall. For some near-fault records, the acceleration spectral ratio (Vertical/Horizontal) can even be larger than 1.5. It can also be concluded that the spectral ratio decreases with the increasing of fault distance at short periods (<0.1 s).

Key words Ground motion, Spectra ratio, Wenchuan earthquake, Hanging wall effects, Near-source, Fault distance

1 INTRODUCTION

On 12 May 2008, a great earthquake with magnitude of $M_{w}8.0$ struck Wenchuan, Western China, which provides lots of strong motion records. The National Strong Motion Observation Network System (NSMONS) have obtained a total of 420 three-component intact acceleration records from the main shock[1]. More than 50 motion stations had acquired acceleration records with PGA larger than 100 Gal, and 46 three-component acceleration records with fault distance less than 100 km[2-3].

Strong motion records from the Wenchuan earthquake makes it possible for further studies on the relationships between the vertical and horizontal acceleration response spectra for an inland earthquake with high-angle thrust mechanism. It is commonly acknowledged that the statistical average of the ratio of vertical to horizontal acceleration response spectra is between 1/2 and 2/3. However, there are many other factors affect the average statistical results, especially in the near-fault region. The 1989 Loma Prieta earthquake, the 1994 Northridge earthquake and the Chi-Chi earthquake provide a large number of near-field strong motion records, which makes it possible to carry out the research on the relationship of vertical to horizontal acceleration response spectra. Zhou et al.[4] have done detailed studies on characteristics of the spectral ratio between the vertical and horizontal acceleration response spectrum for near-fault ground motion from the Chi-Chi earthquake, and the effects...
of hanging wall, site conditions and fault distance on the spectral ratio are analyzed. Zhou et al.\cite{5} have done statistical analysis on acceleration records from about 10 earthquake events, they focused on the characteristics of vertical acceleration response spectra from Chi-Chi earthquake. The results show that the PGA ratio of vertical to horizontal ground motion decreases with increasing fault distance, and the spectral ratio of the vertical to horizontal response spectra is influenced by the fault distance, site condition and the period. Many foreign scholars have investigated the characteristics of vertical acceleration records from worldwide, and the statistical relationships between vertical and horizontal acceleration response spectra are also analyzed\cite{6∼12}. Campbell and Bozorgnia\cite{13,14} have studied the spectral ratio of vertical to horizontal ground motion with periods between 0.04~3 s, and the results show that the spectral ratio can exceed 1.0 in the short period range (<0.1 s), or even reach as high as 1.8, which is much higher than 2/3, while in the period range of 0.3~1.0 s, the spectral ratio is much less than 1/2. Therefore, the rationality of the current seismic design which fixes the vertical response spectra by multiplying a fixed proportional coefficient according to the horizontal acceleration response spectra is yet to be verified by the study of strong motion records from the Wenchuan earthquake and other major earthquake events.

In this paper, 40 groups of three component (EW, NS and UD) acceleration records with fault distance smaller than 120 km are selected from the main shock of Wenchuan earthquake, the PGAs, response spectra and spectral ratio of vertical to horizontal ground motion are statistically analyzed in order to investigate the characteristics of strong motions during Wenchuan earthquake and provide a reference for further study on damage pattern and mechanism of engineering structures when subjected to earthquake ground motions.

2 CHARACTERISTICS OF THE AMPLITUDE FOR VERTICAL AND HORIZONTAL GROUND MOTIONS

The 2008 Wenchuan earthquake was caused by dynamic rupture along two major faults (i.e. Beichuan-Yingxiu fault and Guanxian-Jiangyou fault) within the northeast trending Longmenshan thrust belt, one of the intra-plate thrust faulting systems along the eastern margin of the Tibetan Plateau. The surface rupture along the Beichuan-Yingxiu fault extends for some 240 km while the surface rupture along the Guanxian-Jiangyou fault extends for some 72 km\cite{15}. Fig. 1 shows the distribution of selected 40 strong motion stations along the causative fault used in this study. Based on the seismic design code used in China (GB50011-2001), the site conditions can be classified into four kinds according to the equivalent shear wave velocity and thickness of the covered soil layers (see Table 1). Among the 40 strong motion stations used in this paper, the number of strong motion stations is 5, 21 and 14 for bedrock (Class I), medium-hard soil (Class II), medium-soft soil (Class III), respectively.

2.1 PGA Attenuation of Strong Ground Motions

40 groups of near-fault strong motion records within 120 km to the rupture fault are used to analyze the attenuation of PGA for the Wenchuan earthquake, and the attenuation relationships of PGA are derived by statistical regression methods. Table 2 shows the regression formula and the obtained regression coefficients

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**Table 2**

<table>
<thead>
<tr>
<th>Period (s)</th>
<th>Regression Formula</th>
<th>Obtained Regression Coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.04~3 s</td>
<td>$\text{PGA} = \text{a} \times \text{period}^\text{b}$</td>
<td>$\text{a} = \text{c}$, $\text{b} = \text{d}$</td>
</tr>
<tr>
<td>0.3~1.0 s</td>
<td>$\text{PGA} = \text{e} \times \text{period}^\text{f}$</td>
<td>$\text{e} = \text{g}$, $\text{f} = \text{h}$</td>
</tr>
</tbody>
</table>

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**Fig. 1** The distribution of 40 strong motion stations along the causative fault used in this study
Table 1 Site classification system used in seismic design code (GB 50011-2001)

<table>
<thead>
<tr>
<th>Equivalent shear wave velocity $V_{se}$/(m·s$^{-1}$)</th>
<th>Class I</th>
<th>Class II</th>
<th>Class III</th>
<th>Class IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{se} &gt; 500$</td>
<td>0</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$250 &lt; V_{se} \leq 500$</td>
<td>$&lt; 5$</td>
<td>$\geq 5$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$140 &lt; V_{se} \leq 250$</td>
<td>$&lt; 3$</td>
<td>3~50</td>
<td>$&gt; 50$</td>
<td>–</td>
</tr>
<tr>
<td>$V_{se} \leq 140$</td>
<td>$&lt; 3$</td>
<td>3~15</td>
<td>15~80</td>
<td>$&gt; 80$</td>
</tr>
</tbody>
</table>

for the attenuation of PGA with fault distance $R$ for three-component acceleration records of this earthquake, including the regression coefficients for horizontal ground motion obtained from EW and NS component data. PGA in the table stands for peak ground acceleration, the unit is cm/s$^2$; $R$ is the fault distance, which is defined as the closest distance from the strong motion station to the surface rupture fault, and its unit is km; $C_1, C_2$ and $C_3$ are the regression coefficients.

Figure 2 shows the attenuation curves of PGA for EW, NS and UD component acceleration records. It shows that the recorded PGAs for vertical (UD) component are obviously lower than the horizontal component, while the variations of PGAs for EW and NS component are relatively small. The recorded PGAs for EW component are a little higher than the NS component within 60 km to the rupture fault, while the differences between the two horizontal components are unobvious when the fault distance is larger than 60 km.

Table 3 lists the obtained statistical average values of PGA and PGV ratio (EW component/NS component) in different fault distance ranges. As shown in Fig. 3, the average PGA and PGV ratio is larger than 1 when the fault distance is smaller than 60 km, that is, the recorded PGA and PGV of EW component is higher than the NS component within 60 km to the causative fault. In particular, when the fault distance is smaller than 30 km, the average value of PGA and PGV ratio is 1.19 and 2.25 respectively. Large distinctions are shown between EW and NS component for near-fault strong motions, and the PGA and PGV in E-W direction is larger than the N-S direction on the whole, this may be related to the thrust faulting mechanism of Wenchuan earthquake[16-20].

Abrahamson et al. and Yu et al.[21,22] have investigated the hanging wall effects during the Northridge and Chi-Chi earthquake, respectively. Using the residual analysis method suggested by Abrahamson et al. and Yu et al.[21,22], logarithmic residuals of PGA for both horizontal and vertical ground motion recorded

\[ \lg(PGA) = C_1 + C_2\lg(R + C_3) + \sigma \]

<table>
<thead>
<tr>
<th>Fault distance (km)</th>
<th>Number of records</th>
<th>PGA: EW/NS</th>
<th>PGV: EW/NS</th>
</tr>
</thead>
<tbody>
<tr>
<td>0~30</td>
<td>8</td>
<td>1.19</td>
<td>1.25</td>
</tr>
<tr>
<td>30~60</td>
<td>7</td>
<td>1.02</td>
<td>1.04</td>
</tr>
<tr>
<td>60~90</td>
<td>14</td>
<td>1.05</td>
<td>0.96</td>
</tr>
<tr>
<td>90~120</td>
<td>11</td>
<td>0.96</td>
<td>1.18</td>
</tr>
</tbody>
</table>
on hanging wall and footwall of the causative fault were compared. Fig. 3 shows the distribution of logarithmic PGA residual with fault distance. In the figure, the solid circle denotes the PGA residual data on the hanging wall, while the empty circle shows the PGA residual data on the footwall. The fault distances for hanging wall records are denoted by positive values, whereas the fault distances for footwall records are shown as negative values. From Fig. 3, most PGA residuals for both vertical and horizontal ground motion on the hanging wall are positive when the fault distance is smaller than 60 km, and the recorded PGAs are about 30%–40% larger than the predicted values by the median attenuation curve. In contrary, the PGA residuals of vertical and horizontal ground motion are mostly negative values, and the recorded PGAs are lower than the predicted values. It can be concluded that the effects of hanging wall on the distribution of PGAs are obvious for this inland thrust faulting earthquake, and the study shows that this effect is restricted in the near-fault zone with fault distance smaller than 60 km.

Comparing the residuals for PGA recorded on different sites, Fig. 4 shows the distribution of PGA residual on bedrock site (Class I), medium-hard soil site (Class II) and medium-soft soil site (Class III). The PGA residuals on bedrock site, medium-hard soil site and medium-soft soil site are denoted by solid circles, hollow circles and triangles, respectively. The fault distances for hanging wall records are indicated by positive values, whereas the fault distances for footwall records are shown as negative values. Clearly, the PGA residual on the rock site is smaller than the soil site both on the hanging wall and the footwall, and the PGA residuals on the rock site are mostly negative, it means that on the observed PGAs on rock sites are larger than the predicted

![Fig. 3 Calculated PGA residuals on the hanging wall (solid circle) and footwall (open circle)](image1)
(a) Horizontal; (b) Vertical.

![Fig. 4 Calculated PGA residuals on rock sites (solid circle) and soil sites (open circle)](image2)
(a) Horizontal; (b) Vertical.
values. The distribution of PGA residuals on medium-hard soil site and medium-soft soil site with fault distance is relatively dispersive.

2.2 Distribution of the PGA Ratio of Vertical to Horizontal Ground Motion

In order to investigate the distribution characteristics of near-fault vertical ground motion along the Longmenshan fault, an analysis is conducted for the PGA ratio of vertical to horizontal component. Fig. 5 shows the contour map of PGA ratio, as shown in the figure, the vertical to horizontal ratio of PGA is much larger in the areas near the causative fault and the ratio can reach 1.5 for some records, while the PGA ratio is relatively small in the areas far away from the causative fault. In addition, the PGA ratio on the hanging wall is significantly larger than that on the footwall, indicating that the vertical ground motions on the hanging wall are much more intense.

![Fig. 5 The distribution of PGA ratio along the causative fault](image)

(a) Vertical/EW; (b) Vertical/NS.

2.3 Variation of the PGA Ratio with Fault Distance

40 groups of strong motion records are divided into hanging wall records and footwall records according to the location of strong motion stations relative to the causative fault. Fig. 6 shows the variation of PGA ratio (vertical/horizontal) with fault distance, it can be seen that most of the records with PGA ratio (vertical/horizontal) larger than 1.0 are observed within 60km to the causative fault. The PGA ratio gradually decreases with the increasing of fault distance and the ratio is clearly higher on the hanging wall than on the footwall. Using the PGA ratio of vertical/EW and vertical/NS for the same station as an independent data point, the relationships of PGA ratio with fault distance are obtained for the hanging wall and the footwall, respectively.

Table 4 lists the obtained regression coefficients of the PGA ratio with fault distance on the hanging wall and the footwall based on least-squares method. Fig. 7 shows the fitted regression curve of PGA ratio (Vertical/Horizontal) with fault distance on the hanging wall and footwall, the PGA ratios on bedrock sites, medium-hard soil sites and medium-soft soil sites are denoted by solid circles, the empty circles and triangles. As shown in Fig. 7, the vertical PGAs are relatively higher within 60km to causative fault, for some near-fault records, the vertical PGAs are even 1.5 times as high as the horizontal components, and the PGA ratios (Vertical/Horizontal) decrease with the increasing of fault distance. It can be concluded from Fig. 7a and 7b...
that the PGA ratios on the hanging wall are significantly higher than those on the footwall. For fault distance less than 30 km, the average PGA ratio on the hanging wall is about 0.9 to 1.1, whereas the PGA ratio on the footwall is only 0.7 to 0.8.

3 CHARACTERISTICS OF THE ACCELERATION RESPONSE SPECTRA FOR VERTICAL AND HORIZONTAL STRONG MOTIONS

3.1 Distribution of the Spectral Accelerations Along the Causative Fault

The spatial distribution of the 5% damped response spectral accelerations with periods of 0.2 s and 1.0 s along the Longmenshan fault zone are investigated, in order to study the characteristics of frequency contents for the near-fault strong motions of this event. Fig. 8 is the isopleths map of spectral accelerations for east-west, south-north and vertical ground motion, respectively. As shown in the figure, the maximum spectral
Accelerations are mainly distributed near the Beichuan-Yingxiu fault. The spectral accelerations attenuate rapidly with the increasing of the fault distance, especially for the period of 0.2 s. On the whole, the spectral accelerations for vertical component are lower than the horizontal component. It can also be concluded that the spectral accelerations decrease rapidly with the increasing of periods by comparing the spectral accelerations for 0.2 s and 1.0 s. The spectral accelerations for period 0.2 s can reach as high as 1.6 g in the near-fault zone, while for the period 1.0 s, the maximum spectral accelerations are only 0.5 g. This indicates that near-fault strong motion in Wenchuan earthquake is not very rich in long period component, which may be related to the fault mechanism of several discontinuous ruptures.

![Fig. 8 The distribution of spectrum accelerations (Unit: g) along the causative fault](image)

Fig. 8 The distribution of spectrum accelerations (Unit: g) along the causative fault (A) $T=0.2$ s; (B) $T=1.0$ s. (a1,b1) EW component; (a2,b2) NS component; (a3,b3) Vertical component.

Figure 9 shows the contour map of the spectral ratio of the vertical to horizontal response spectra. In this figure, (a), (b), (c), (d) and (e) are the spectral ratio for periods of 0.05, 0.1, 0.2, 0.5 s and 1.0 s, respectively. As shown in the figure, the maximum spectral ratio for periods of 0.05 s and 0.1 s is distributed near the causative fault region, and the spectral ratio diminishes with the increasing of fault distance. For the periods of 0.2, 0.5 s and 1.0 s, the maximum spectral ratios are not near the surface rupture, but on the hanging wall of the Beichuan-Yingxiu fault, and the spectral ratio on the hanging wall is obviously higher than that on the footwall. This indicates that there are large distinctions in the distribution of spectral ratio for near-fault strong motions along the causative fault between the short periods and the long periods. It can also be seen that the spectral ratio for periods of 0.2 s and 0.5 s is generally lower, while the spectral ratio for the short period of 0.05 s and longer period of 1.0 s is relatively higher.
Fig. 9 The distribution of acceleration spectrum ratio (Vertical/Horizontal) along the causative fault
(A) T=0.05 s; (B) T=0.1 s; (C) T=0.2 s; (D) T=0.5 s; (E) T=1.0 s; (a1∼e1) Vertical/EW; (a2∼e2) Vertical/NS.

3.2 Spectral Ratio Curves of the Vertical to Horizontal Ground Motions

The acceleration records are grouped according to fault distance and the 0.01∼4.0 s spectral ratio curves of vertical and horizontal response spectra for different distance range are obtained based on statistic analysis. Fig. 10 shows the average spectral ratio curves for fault distance $R < 30\text{ km}$, $30\text{ km} < R < 60\text{ km}$, $60\text{ km} < R < 904\text{ km}$ and $90\text{ km} < R < 120\text{ km}$. It can be seen that the average acceleration spectral ratio curves (vertical and horizontal) are characterized by lower values in the middle period range, while the spectral ratios are much higher in the longer period range of 1.0∼4.0 s and shorter period range ($< 0.1\text{ s}$). In the short period range ($< 0.1\text{ s}$), the average spectral ratio can reach as high as 1.3 near the causative fault ($R < 30\text{ km}$). In the middle period range of 0.2∼1 s, the spectral ratio is less than 2/3. In the longer period range of 1.0∼4.0 s, the spectral ratio shows a trend of increasing with periods.

The results of this study are similar with the results from the Chi-Chi earthquake given by Zhou et al. [4]. Comparing the spectral ratio curves for different fault distance, it can be concluded that in the short period range ($< 0.2\text{ s}$), the average spectral ratio decreases with increasing fault distance, and the average spectral ratios for two groups of acceleration records with fault distance smaller than 60 km are much higher than the two groups of records with fault distance larger than 60 km. Besides, in longer period range ($> 1.0\text{ s}$), the average spectral ratio of the records with fault distance smaller than 30 km is much lower than the other three groups.

4 CONCLUSION

(1) Significant hanging wall effects are shown in the distribution of PGA for vertical and horizontal ground motion, the results of regression analysis show that the recorded PGAs on the hanging wall are about 30%∼40% larger than the predicted values for vertical and horizontal ground motion in the fault distance range of 3 to 60 km. The PGA residuals on the hanging wall are mostly positive, while the PGA residuals on the footwall
are mostly negative. The recorded PGAs and PGVs for EW component are generally higher than the NS component for the records with fault distance smaller than 60 km, and the PGA of EW component attenuates much more slowly compared with NS component, while the differences between the EW and NS component are unobvious when the fault distance is above 60 km.

(2) There is a lack of long period component in near-fault ground motion of Wenchuan earthquake. The distribution of spectral acceleration is mainly controlled by the causative fault, the maximum spectral accelerations are observed along near the Beichuan-Yingxiu fault, and the spectral accelerations attenuate rapidly with the increasing of fault distance to the causative fault. It can also be concluded that the spectral accelerations diminish rapidly with the increasing of periods, the maximum spectral accelerations are only 0.5 g when the period is equal to 1.0 s. Large distinctions are shown in the distribution of spectral ratio along the causative fault between the short periods and the long periods. The maximum spectral ratio for periods of 0.05 s and 0.1 s is distributed near the causative fault region, and the spectral ratio diminishes with the increasing of fault distance. For the periods of 0.2 s, 0.5 s and 1.0 s, the maximum spectral ratios are not near the surface rupture, but on the hanging wall of the Beichuan-Yingxiu fault, and the spectral ratio on the hanging wall is obviously higher than that on the footwall.

(3) High intensity of vertical component is shown for near-fault strong motions, the PGA ratio (Vertical/Horizontal) can be as high as 1.4. High intensity of UD component is more obvious on the hanging wall, and the PGA ratios on the hanging wall are much larger compared with those on the footwall. In the short period range (< 0.1 s), the acceleration spectral ratio (Vertical/Horizontal) is much larger than 2/3, and the spectral ratio can even be larger than 1.5 for some near-fault records. The spectral ratio curve is influenced by the period and fault distance, it can be seen that the average acceleration spectral ratio curves (Vertical/Horizontal) are characterized by lower values in the middle period range, while the spectral ratios are much higher in the longer period range of 1.0~4.0 s and shorter period range (< 0.1 s), and the spectral ratio decreases with the increasing of fault distance at short periods (< 0.1 s).

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