Near-Source Strong Motion Modeling of the 6.2 Magnitude Aftershock of June 9, 1976 in Longling, Yunnan

Xie Xiaobi and Yao Zhenxing

Institute of Geophysics, Academia Sinica, Beijing

The near-source strong ground motion data recorded from the June 9, 1976 Longling, Yunnan aftershock \( (M_s = 6.2) \) provided a good opportunity to investigate the faulting process of this event. By comparing the synthetic seismograms with the observed data, the characteristics of the faulting process, especially the rupture velocity, rupture length and slip distribution, were investigated. The results suggest a right-lateral faulting initiated from the northern end with a rupture velocity of nearly 0.9 shear velocity and a rupture length of about 20 km. Over the entire ruptured surface the average slip is 0.6 m; the average stress drop is about 23 bars, and the total moment is \( 3.0 \times 10^{18} \) N.m. The abundant high frequency content in the near-source data suggests that the distributions of slip and rise times on the ruptured surface are highly heterogeneous. From our model it is estimated that the maximum slip is 1.89 m and maximum stress drop is 200-300 bars, much higher than their average values.

INTRODUCTION

Near-source strong ground motion records can provide us with more information about the seismic source process than teleseismic data. Analysis of strong ground motion data has become one of the effective methods for investigating the faulting process. On the other hand, casualties and the destruction of building structures are directly caused by strong ground motions generated by great earthquakes. Analysis of the waveforms, decay laws and their relations to properties of the media can provide an important basis for seismic resistance design. For the above two reasons, the investigation and simulation of near-source strong ground motions have drawn the considerable
attention of both theoretical and engineering seismologists, and have developed rapidly in recent years.

Similar to other wave propagation problems in seismology, near-source ground motion can be expressed as a convolution of the source and the Green's function of the media. The near-source Green's function is composed of relatively broad wavenumbers as well as frequency bands, and usually needs to be calculated for various depths and epicentral distances, so it is very expensive calculation work. Various effective methods have been developed for computing the near-source Green's functions (e.g., Bouchon, 1979; Olson et al., 1984; Yao and Harkrider, 1983; Yao and Zheng, 1984; Li, 1985). To investigate near-source problems, the finite-size fault model must be considered. Generally, the fault is divided into many small elements with different slips, rise times and time delays assigned to these elements to simulate various types of fracture processes. Based on the above method, some authors have simulated the faulting processes for strong and moderate earthquakes (e.g., Hartzell, 1982; Liu and Melmberger, 1983; Olson and Apsel, 1982; Hartzell and Heaton, 1983; 1986). These results revealed the high complexity of the faulting process and indicated that the heterogeneities of the slip distribution and the fracture process may be caused by the heterogeneities of the stress field and strength along the fault. Larger dislocations or high stress drops may be concentrated at different sections of the fault. Such a complicated fault model will help to explain the abundant high frequency components in observed strong motion data.

In 1976, a strong earthquake sequence occurred in Longling, Yunnan, China. Among shocks of this sequence a strong aftershock with magnitude $M_s = 6.2$ occurred on June 6, 08:20 (Beijing ti-

![Various types of fault models and synthetic seismograms produced by the following models:](image)

- a) point source;
- b) homogeneous fault, fractured away from the observer;
- c) homogeneous fault, fractured bilaterally;
- d) homogeneous fault, fractured towards the observer;
- e) and f) inhomogeneous fault, fractured homogeneously, g) to i) inhomogeneous fault, fractured inhomogeneously.
me), near the north end of the aftershock area. The strong ground acceleration data from this even were recorded at three stations and provided us with a good opportunity to investigate the faulting process. Based on the computation method for the near-source Green's function (Yao and Harkrider, 1983; Yao and Zheng, 1984), these strong motion records are simulated. By comparing the synthetic seismograms with the observed data, the length of the fault, the fracture process and the slip distribution are investigated.

DISCUSSION ON VARIOUS TYPES OF FAULT MODELS

Along with the development of the seismic source theory, several types of fault models have been suggested. To discuss the differences of the seismic waves radiated from these fault models, we calculated the seismic waves radiated from a simple one-dimensional fault model for which different slip distributions, rise time distributions and fracture processes are specified. The model is a strike slip fault with a dip angle of 75°, a length of 6 km and buried at a depth of 10 km. The moment tensor is 2.5x10^18 N.m, the epicentral distance is 20 km and the angle between the strike of the fault and the direction of the receiver is 15°; the frequency band of the Green's function is 0-5 Hz. A sketch of the various types of fault models and the synthetic seismograms produced by these models is given in Fig. 1, in which the first column shows the slip distributions along the faults; the second column shows the space-time positions of the fracture front; and the last two columns are the synthetic ground velocities and displacements, respectively. The numbers show the maximum amplitudes. Model a is a point source with a rise time of 1 s. Models b-d are homogeneous faults fractured unilaterally away from the receiver, bilaterally from the middle point and unilaterally towards the receiver. Note that when the fault is fractured towards the receiver, the pulse width is narrower, the amplitude is larger and the waveform becomes simpler, as shown by the well known Doppler effect. The situation will be opposite when the fracture is directed away from the receiver. In practice, the homogeneous fault model is not reasonable. Seismic source theory and numerical experiments show that the slips are larger in the central part and smaller towards the ends. The stopping of the slip will also be affected by the edge effects. The rise times are relatively longer in the central part and become shorter near the edges. Model e is such a fault. Compared with d there is a greater high-frequency content in the synthetic seismograms of e and the amplitude is considerably larger, because of the shorter rise times at the edges.

In recent years, the studies of near-source strong ground motions show that the faulting processes are even more complicated for real earthquakes. The inhomogeneities of the slip, rise time and fracture velocity, even deceleration or a transient stop of the fracture may be caused by inhomogeneities in the stress field and strength along the fault. The stress drops are inhomogeneously distributed along the fractured fault. Local stress drops may reach several hundred bars, much higher than the commonly obtained average values. A large high frequency content is radiated from these parts. Several complicated fracture models, such as the barrier model and the asperity model, have been suggested to account for these phenomena. Some of them are tested here. In Fig. 1 f is a fault model with inhomogeneous slips and rise times but the fracture process is smooth. For models g-i, even the fracture process is heterogeneous. There are abundant high frequency components in the ground velocities radiated from models f-i which are similar to the observed data. For a highly inhomogeneous fault, the phases of the high frequency waves radiated from different parts of the fault are disorderly and will interfere with one another. This will decrease the high frequency radiations and reduce the directivity of a moving fracture front. By comparing the result of models f-i with that of e, it is shown that the amplitudes of the ground velocities, which contain more high frequency components, are decreased notably, but the changes in ground displace-
Fig. 2
Epicenters, intensity and the positions of seismic stations.

Fig. 3
Lower hemisphere equal area projects of P-wave first motion data. The open circles are compressions; solid circles are dilatations.

ments are not so evident. This is the result of interference. The above phenomena suggest that investigation of the high frequency accelerations and velocities can provide us with more detailed information about the source process. On the contrary, determination of the overall characteristics of the source, such as the total seismic moment, by making use of displacement, will be more reliable. Analysis of the characteristics of seismic waves radiated from the above fault models will help us to choose an appropriate model to simulate the observed data.
Table 1 The origin times, epicenter, focal depths and magnitudes given by various authors

<table>
<thead>
<tr>
<th>$T_o$ h min s</th>
<th>Latitude</th>
<th>Longitude</th>
<th>$d$ km</th>
<th>$M$</th>
<th>$m$</th>
<th>Source of data</th>
</tr>
</thead>
<tbody>
<tr>
<td>08-20-35.6</td>
<td>24.38</td>
<td>98.78</td>
<td>4.7</td>
<td>6.2</td>
<td></td>
<td>(1)</td>
</tr>
<tr>
<td>08-20-35.0</td>
<td>24.50</td>
<td>98.7</td>
<td>10</td>
<td>6.2</td>
<td></td>
<td>(2)</td>
</tr>
<tr>
<td>08-20</td>
<td>24.80</td>
<td>98.75</td>
<td>6.2</td>
<td></td>
<td></td>
<td>(3)</td>
</tr>
<tr>
<td>08-20-37.9</td>
<td>24.94</td>
<td>98.74</td>
<td>15 ± 2</td>
<td>5.6</td>
<td></td>
<td>(4)</td>
</tr>
<tr>
<td>08-20-39.5</td>
<td>24.89</td>
<td>98.75</td>
<td>33</td>
<td>5.9</td>
<td>5.7</td>
<td>(5)</td>
</tr>
<tr>
<td>08-20-37</td>
<td>24.10</td>
<td>98.9</td>
<td>20</td>
<td>5.9</td>
<td>6.0</td>
<td>(6)</td>
</tr>
<tr>
<td>08-20-35</td>
<td>24.83</td>
<td>98.75</td>
<td>10</td>
<td>6.2</td>
<td></td>
<td>(7)</td>
</tr>
</tbody>
</table>


Table 2 Seismic source parameters

<table>
<thead>
<tr>
<th></th>
<th>$l$</th>
<th>$d$</th>
<th>$h$</th>
<th>Pulse width</th>
<th>$m_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waveform simulation</td>
<td>190</td>
<td>3</td>
<td>75</td>
<td>10–20 km</td>
<td>3.0 × 10$^4$N · m</td>
</tr>
<tr>
<td>P-wave first motion</td>
<td>180</td>
<td>346</td>
<td>77</td>
<td>3–5 s</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 4
Comparison between the far field P-wave data (heavy lines) and synthetic seismograms (thin lines).

Fig. 5
Distribution of the final slip on the fault. In which the starting point is indicated with a cross and the isochrons of the fracture front are indicated by dashed lines.

THE SIMULATION TO THE MAGNITUDE 6.2 EVENT

Epicenter and Fault Plane Solution
The 6.2 magnitude event of 9 August 1976 occurred at the north end of the aftershock area. The origin time, epicenter, depth and magnitude obtained by various authors are given in Table 1 and Fig. 2. The lower hemisphere equal area projections of P-wave first motion data are shown in Fig. 3, along with the acceptable fault plane solution. For the first nodal plane the strike is 346° and the dip angle is 77°, and for the second nodal plane the strike is 75° and the dip angle is 90°. Also shown in Fig. 2 are the intensity distribution by Xie and Cai (1978), the aftershocks with magnitude
greater than three and the locations of strong motion stations. The highest rating in the epicentral area is intensity VIII, the shapes of isoseismals for intensity VII and VIII are ellipses with the ratio of major to minor axes of about 2:1 and the major axis in a nearly north-south direction. Most of the epicenters for the 6.2 magnitude event obtained by various authors are located near the isoseismal contour of intensity VIII. The aftershocks with magnitudes greater than three are located in the region between intensity VIII and intensity VII, and deviated slightly to the east of the center line of the meizoseismal area. The trend of the aftershock area is basically the same as that of the area of higher intensity. Combining the P-wave fault plane solution, the shapes of the areas of higher intensity, the trend of the aftershock area and the geological structures, it is suggested that the first nodal plane is the plane of a right lateral, nearly strike slip fault.

To further determine the source mechanism, the teleseismic P-wave data recorded by WWSSN at stations with epicentral distance between 17°-46° are simulated by the generalized ray method (Yao and Helmberger, 1985). The comparison between the synthetic seismograms and observed data are shown in Fig. 4. The source parameters obtained by simulation are listed in Table 2, along with the fault parameters obtained from first motion data. The two sets of data are compatible with each other. The seismic moment obtained by simulation is $3.0 \times 10^{18}$ N.m.

**Model of Crustal Structure**

Three P-wave velocity structures near the epicentral area were determined by the deep sounding technique (Hu et al., 1986). Since a horizontally layered media method is needed in the present research, we combine the three velocity models to construct a horizontally stratified model with seven layers. The S-wave velocity and density are evaluated by interpolating the velocity models from other regions. The layers of velocity models used to calculate the near-source synthetic seismograms are listed in Table 3.

**Observed Data of Strong Ground Motion**

For the 6.2 magnitude event, strong accelerograms were obtained at three stations, i.e., Longling, Luxi and Shidian. These stations were operated by the Institute of Engineering Mechanics. In Fig. 2, their locations are marked with crosses. The recorded ground acceleration data are digitized, filtered and corrected for instrument response. The frequency band of the filter is 0.35-

---

**Table 3** The velocity model used to calculate synthetic seismograms

<table>
<thead>
<tr>
<th>Depth (km)</th>
<th>Thickness (km)</th>
<th>$V_p$ (km/s)</th>
<th>$V_s$ (km/s)</th>
<th>$\rho$ (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.15</td>
<td>1.15</td>
<td>4.30</td>
<td>2.46</td>
<td>2.4</td>
</tr>
<tr>
<td>16.91</td>
<td>15.76</td>
<td>3.90</td>
<td>3.40</td>
<td>2.7</td>
</tr>
<tr>
<td>22.42</td>
<td>3.51</td>
<td>6.40</td>
<td>3.83</td>
<td>2.7</td>
</tr>
<tr>
<td>26.71</td>
<td>4.29</td>
<td>6.64</td>
<td>3.90</td>
<td>2.7</td>
</tr>
<tr>
<td>31.00</td>
<td>4.29</td>
<td>6.66</td>
<td>3.97</td>
<td>2.8</td>
</tr>
<tr>
<td>39.00</td>
<td>8.00</td>
<td>7.23</td>
<td>4.02</td>
<td>2.9</td>
</tr>
<tr>
<td>&gt;39.00</td>
<td></td>
<td>8.06</td>
<td>4.46</td>
<td>3.3</td>
</tr>
</tbody>
</table>
35 Hz. Because the instrument are triggered by the first motion, the first segments of the data are lost. In addition, all three stations are located near the P-wave nodal planes, the P-wave amplitude is relatively small, and the strong motion records are mainly composed S-waves. The particle traces synthesized by two horizontal components also indicate that the dominant phase is the SH-wave.

Considerations about the Source and the Results of Simulation

The strike and dip directions and dip angle of the fault can be drawn from teleseismic waveform simulation. The pulse width of the far field source time history and the length of the aftershock area suggest that the length of the fault is about 20 km. By investigating the near-source records, it can be seen that the waveforms are relatively narrower and the durations are shorter for the stations at Longling and Luxi, which are located near the extension line of the fault strike, but for Shidian station the duration is relatively longer. The above characteristics suggest that the source is a unilateral fault initiating from the north end. This is because in such a situation, the durations of vibration for Longling and Luxi stations are approximately proportional to \((L/v)-(L/\beta)\), but for Shidian station it is proportional to \(L/v\). Here \(L\) is the length of the fault, \(v\) fracture velocity and \(\beta\) is the shear wave velocity. This means that the durations of the vibration can provide us with some information about the length and the fracture velocity of the faulting process.

![Graphs showing velocity and displacement](image)

**Fig. 6**
Simulations of the near-source data
35 Hz. Because the instrument are triggered by the first motion, the first segments of the data are lost. In addition, all three stations are located near the P-wave nodal planes, the P-wave amplitude is relatively small, and the strong motion records are mainly composed S-waves. The particle traces synthesized by two horizontal components also indicate that the dominant phase is the SH-wave.

Considerations about the Source and the Results of Simulation

The strike and dip directions and dip angle of the fault can be drawn from teleseismic waveform simulation. The pulse width of the far field source time history and the length of the aftershock area suggest that the length of the fault is about 20 km. By investigating the near-source records, it can be seen that the waveforms are relatively narrower and the durations are shorter for the stations at Longling and Luxi, which are located near the extension line of the fault strike, but for Shidian station the duration is relatively longer. The above characteristics suggest that the source is a unilateral fault initiating from the north end. This is because in such a situation, the durations of vibration for Longling and Luxi stations are approximately proportional to \((L/v)-(L/\beta)\), but for Shidian station it is proportional to \(L/v\). Here \(L\) is the length of the fault, \(v\) fracture velocity and \(\beta\) is the shear wave velocity. This means that the durations of the vibration can provide us with some information about the length and the fracture velocity of the faulting process.

Fig. 6
Simulations of the near-source data
in Fig. 2 with a rectangle. The slip distribution on the fault is shown in Fig. 5 with solid lines, and the unit for slip is in meters. The rise time relating to the maximum slip is 1.2 sec. The fracture is initiated from the north end of the fault and the average fracture velocity is about 3 km/s (0.88 shear velocity), but deceleration and even a transient stop may happen in the faulting process. In Fig. 5, the starting point of the fracture is indicated by a cross and the isochrons of the fracture front are indicated by dashed lines. The numbers on the lines are time in seconds. The average Q of the media used to calculate the synthetic seismograms is 200. To be in accordance with the observed data, the synthetic seismograms are also filtered by a high pass filter with a cut-off frequency of 0.35 Hz. The final results for Longling, Luxi and Shidian stations are shown in Figs. 6a, b and c, respectively, in which the velocities and the displacements for both the vertical and transversal (EW components for Longling and Luxi but the NS component for Shidian) components are presented. The thick lines are observed data, the thin lines are synthetic seismograms, and the number on each line is the maximum amplitude. For Longling station, there is no vertical component record directly on the ground, so the vertical record on the first floor is given for comparison. The peak amplitudes of the observed and synthetic records as well as the ratios between them are listed in Table 4. By comparing both the waveforms and amplitudes, it is seen that the simulations are satisfactory for both ground displacements and velocities. To further examine the above results, the fault model is modified and tested repeatedly. The results show that the observed data cannot be modelled satisfactorily if the fault is either fractured bilaterally or initiated from the south end. Taking the transversal component of Longling station as an example, Fig. 7a is the observed data, b and c are theoretical seismograms.
synthesized for the fault models fractured from north to south and from south to north, respectively. Obviously, c is different from the observed data. In addition, various types of slip distributions have been tested and the results show that abundant high frequency components cannot be produced by homogeneous distributions.

DISCUSSION

The average slip $\bar{\Delta u}$ is about 0.6 m and the average stress drop obtained by the equation $\Delta \sigma = \Delta \sigma_{\text{ave}} \Delta \sigma_{\text{max}}$ for a rectangular fault is about 23 bars. These values are in accordance with the statistical results obtained by Zhou (1984) for some strong and moderate earthquakes in China. The maximum local slip on the fault is 1.89 m. Taking the fault segment where the slips are relatively concentrated roughly as a circular fault, and using the equation $\Delta \sigma = (7\pi/24)\mu \Delta \mu_{\text{ave}}/a$ for a circular fault, we find the local stress drop to be about 200-300 bars, much higher than the average values. The average slip velocity obtained from the final slips and the rise times is 1.6 m/s and the peak slip velocity is 3.2 m/s. The local values and slip velocities mentioned above are in accordance with the statistical values obtained by Aki (1983) for a number of earthquakes, and the peak slip velocity is similar to the dynamic numerical results by Day (1982), who used a slightly smaller fault model. The relations between the maximum slips and the intervals between the barriers obtained by Aki (1983) are shown in Fig. 8, taking the size of the areas concentrated with dislocations roughly as the space between the barriers. The value for the $M=6.2$ Longling event is also indicated in Fig. 8 with a star. It is in accordance with the results obtained by other methods.

From the above results, we can conclude that the near-source strong ground motion data can provide some strong constrains on the length, direction and velocity of the faulting process. To explain the complicated waveform and the high frequency content in the observed data, inhomogeneous distributions of the slip and the rise times are required. Under the above considerations an inhomogeneous fault model is designed to simulate the data. The theoretical seismograms synthesized with this model are well in accordance with the strong ground motion data. On the other hand, the overall values such as the average stress drop, average slip, fracture velocity and the local values such as the maximum slip, local stress drop, etc., are all in accordance with the available observed data and earthquake source theory. These results show that we could design a complicated inhomogeneous fault model to explain the observed waveforms. Conversely, by simulating the near-source ground motion data one can obtain much useful information about the faulting process.

In addition, starting from the fault models presented here, we can obtain the time histories for ground acceleration, velocity and displacement at various distances, as well as their decay law. This will be helpful in the design of earthquake resistant structures and seismic intensity regionalization.

ACKNOWLEDGEMENTS

The authors wish to thank Professor C. Y. Fu for his continuous encouragement throughout this research. They also thank Professor L. Xie for his kindly permitting the authors to use the strong motion data, and to Associate-professor T. Zheng for her interesting suggestions.

REFERENCES


