Wenchuan Ms8.0 earthquake coseismic slip distribution inversion

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\textbf{A B S T R A C T}

By using GPS and gravity data before and after the Wenchuan Ms8.0 earthquake and combining data from geological surveys and geophysical inversion studies, an initial coseismic fault model is constructed. The dip angle changes of the fault slip distribution on the fault plane are inversed, and the inversion results show that the shape of the fault resembles a double-shovel. The Yingxiu–Beichuan Fault is approximately 330 km long, the surface fault dip angle is 65.1\textdegree, which gradually reduces with increasing depth to 0\textdegree at the detachment layer at a depth of 19.62 km. The Guanxian–Jiangyou Fault is approximately 90 km long, and its dip angle at the surface is 55.3\textdegree, which gradually reduces with increasing depth; the fault joins the Yingxiu–Beichuan Fault at 13.75 km. Coseismic slip mainly occurs above a depth of 19 km. There are five concentrated rupture areas, Yingxiu, Wenchuan, Hanwang, Beichuan, and Pingwu, which are consistent with geological survey results and analyses of the aftershock distribution. The rupture mainly has a thrust component with a small dextral strike-slip component. The maximum slip was more than 10 m, which occurred near Beichuan and Hanwang. The seismic moment is $7.84 \times 10^{20}$ Nm ($M_w$7.9), which is consistent with the seismological results.

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1. Introduction

As an important physical quantity in seismic source research, coseismic slip distribution is receiving significant attention in the study of earthquake mechanisms and source rupture processes [1]. The source rupture process of the Wenchuan earthquake is very complex, and it has been determined through individual inversion or joint inversion of seismic waves, Global Positioning System (GPS), leveling, and Interferometric Synthetic Aperture Radar (InSAR) data [2–6] in different studies with different results. Different sets of data contain different source information. As the most direct and quickly obtained data, far-field seismic waves have a predominant in rupture process inversion and disaster assessment. However, uncertain path effects from the source to seismic stations caused by lateral heterogeneity can lead to uncertainty in determining the fault slip distribution. This may be the reason why fault slip distributions inversed by seismic waves have large differences. Surface coseismic deformation data have high precision and high resolution, which can guarantee more details of slip distribution. The data mainly contain surface position change information; however, the coseismic gravity change data include not only information of surface vertical deformation changes but also information of mass changes caused by earthquakes. Therefore, it is a useful complement for other data sources for the inversion of fault slip distribution.

Measurements to aid in emergency planning and scientific investigation of earthquakes have been conducted by the Institute of Seismology, China Earthquake Administration immediately after the Wenchuan Ms8.0 earthquake, and valuable coseismic deformation and gravity data were obtained. In this study, horizontal GNSS data from 160 stations obtained from references [6] and [8] and gravity data from 24 stations near the rupture area were used for inversion (Fig.1).

2. Coseismic deformation and gravity changes

Repeated Global Navigation Satellite System (GNSS) and gravity measurements around the Longmenshan fault zone have been conducted by the China Earthquake Administration after the Wenchuan Ms8.0 earthquake, and valuable coseismic deformation and gravity data were obtained. In this study, horizontal GNSS data from 160 stations obtained from references [6] and [8] and gravity data from 24 stations near the rupture area were used for inversion (Fig.1).

3. Genetic algorithm based on dislocation theory in rheological stratified medium

The forward modeling software PSGRN/PSCMP developed by Wang et al. [7] can calculate coseismic and post-seismic effects. On the basis of the classical dislocation theory, the software considers the elastic–viscoelastic layered medium and self-weight to make the medium of the model more realistic [14,15]. The inversion algorithm is based on a genetic algorithm in which the basic idea is to imitate...
biological genetic processes. The algorithm optimizes the result of nonlinear complex problems by searching effectively and evolving dynamically. By using the features of global search with no derivation and high efficiency, we built an inversion model in which 3-D dislocation can be inversed in an elastic-viscoelastic layered medium. For stable and reliable results, the objective function in evaluation includes three items: the correction residuals (the first and second item, which represent “reasonableness”) and the mixed error function of the total abnormal mass (the last items represent “smoothness”). The formula is expressed as follows.

\[
F(m_k) = (g^{obs} - g)^T E^{-1} (g^{obs} - g) + \alpha \left[ (u_x^{obs} - u_x) E_x^{-1} (u_x^{obs} - u_x) + (u_y^{obs} - u_y) E_y^{-1} (u_y^{obs} - u_y) \right] + \beta m_k^T C_m m_k
\]

where \( g^{obs} \) and \( u^{obs} \) are the matrices comprising observational data; \( g \) and \( u \) are the matrices comprising forward calculation data; \( E_x, E_y \) are the error matrices of observational data; \( m_k \) is the unknown parameter matrix; \( C_m \) is the unknown parameter weight matrix; and \( \beta \) is the regularization parameter.

4. Regional medium layered model

Previous studies have shown that the Longmenshan Fault is located at the area of collision between the Tibetan Plateau and Sichuan Basin and there are clear differences in the crustal layering and crustal thickness on the two sides of the fault [16,17]. To understand the greater influence of crustal layering on coseismic effects [18], a model of the layered structure of the crust—upper mantle was produced considering the average velocity obtained in different research [17,19,20], as presented in Table 1. The lower crust and upper mantle’s viscosity are also considered in this model, in which the coefficient of viscosity was taken from Tan et al. [21] and the density was obtained through the Nafe—Drake density—velocity empirical conversion formula [22].

5. Fault model

Referring to the focal mechanism solution of the Wenchuan mainshock [5], surface rupture distribution [9–11], and the results of aftershock locations [12,13], a simple initial fault model was designed and used in this study (presented in Table 2). With a double-shovel-type structure, the Yingxiu–Beichuan Fault is 330 km long and 60 km wide. Six layers were set in the dip direction, and the dip angles were reduced from top to bottom. The Guanxian–Jiangyou Fault is 90 km long, and 32 km wide. Four layers were set in the dip direction, and the dip angles were also reduced from top to bottom.

5.1. Fault dip angle

The above fault dip angles were obtained by surface geological surveys and precise positioning of aftershocks. Because of the significant influence of fault dip variations on surface deformation and gravity changes [23,24], it is necessary to correct the fault dip angle of each layer in the initial fault model. Hence, the fault model was simplified appropriately, wherein the orientations remained the same along the strike direction; the Yingxiu–Beichuan Fault was divided into five sections (5 × 66 km = 330 km) and the Guanxian–Jiangyou Fault was divided into three segments (5 × 30 km = 90 km). As shown in Fig.2, the dip angles and sub-fault slips were inversed using surface gravity data and GPS data. Dip angles of the Yingxiu–Beichuan Fault are 65.1°, 50.8°, 28.9°, 13.1°, 3.5°, and 0° from top to bottom, and 55.3°, 38.6°, 15.8°, and 5.7° from top to bottom for the Guanxian–Jiangyou Fault. The faults join at a depth of 13.75 km, which is consistent with the depth of hypocenter. The depth of the detachment layer is 19.62 km, which is consistent with the depth of the low-velocity layer under the Songpan Plateau [13,25].

5.2. Precise fault model

The inversion results are affected by the amount of surface observation data and fault’s parameters for inverting, and different influences of the shallow and deep portions of the fault to the surface deformation. Thus, the fault’s shape \( M \) (length, width, depth, dip, strike, and flat position), is fixed and the orientation of the layers remains the same. The Yingxiu–Beichuan Fault is divided into 66 sections (66 × 5 km = 330 km) in the strike direction, and the Guanxian–Jiangyou fault is divided into 18 segments (18 × 5 km = 90 km). There are 468 sub-faults in total (Fig.3).

6. Coseismic fault slip distribution of the Wenchuan Ms8.0 earthquake

On basis of the above medium model and fault model, strike slip and dip slip of every sub-fault was inversed using the genetic algorithm with gravity change data obtained from 24 stations and GPS data obtained from 160 stations [6,8]. Before joint inversion, each model was tested using single data. The results indicate that each data type has its own advantages and disadvantages for fault slip inversion. GPS data have higher precision in the horizontal direction but lower precision in the vertical direction. Therefore, only horizontal displacement was used for inversion. There are data from 160 GPS points, and each of them contains two horizontal displacement components; therefore, the GPS data better constrain the fault slip distribution. There are 24 points
around the Yingxiu–Beichuan Fault from which gravity data with a vertical component were used, and the results are more accurate in the vicinity of the Yingxiu–Beichuan Fault. To prevent the inversion results from being biased because of the significantly larger amount of GPS data, the weight of the gravity data was increased. After repeated debugging, the weight of the gravity data was set at 3, while that of the GPS data was set at 1. The final result is shown in Fig.4.

The earthquake was a unilateral rupture event, rupturing from southwest to northeast. The rupture occurred mainly along the Yingxiu–Beichuan Fault, primarily on the fault plane in the range from 0 to 40 km, with a small amount of slip at the detachment layer. The rupture mainly comprised thrust motion with a small amount of dextral strike slip movement. The dislocation was focused in five areas, Yinxiu, Dabao, Beichuan, Hanwang, and Pinwu. The slippage in Beichuan and Hanwang was over 10 m and occurred near the Earth’s surface, which is consistent with the surface rupture and seismic intensity distribution [9,10]. The maximum slip was 6–8 m in Wenchuan, Dabao, and Yinxiu, and 6 m in Pinwu. There was a

<table>
<thead>
<tr>
<th>Fault</th>
<th>Fault starting position</th>
<th>Strike (°)</th>
<th>Dip angle (°)</th>
<th>Width (km)</th>
<th>Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yelping–Beichuan Fault</td>
<td>1 32.84396 105.6321</td>
<td>0</td>
<td>65</td>
<td>8</td>
<td>330</td>
</tr>
<tr>
<td></td>
<td>2 32.85691 105.6122</td>
<td>7.25045</td>
<td>229</td>
<td>8</td>
<td>330</td>
</tr>
<tr>
<td></td>
<td>3 32.90181 105.5818</td>
<td>13.37882</td>
<td>229</td>
<td>8</td>
<td>330</td>
</tr>
<tr>
<td></td>
<td>4 32.94629 105.5431</td>
<td>17.96743</td>
<td>229</td>
<td>8</td>
<td>330</td>
</tr>
<tr>
<td></td>
<td>5 32.99731 105.4988</td>
<td>20.70359</td>
<td>229</td>
<td>8</td>
<td>330</td>
</tr>
<tr>
<td>Guanxian–Jiangyou Fault</td>
<td>6 33.05078 105.4523</td>
<td>22.09277</td>
<td>229</td>
<td>20</td>
<td>330</td>
</tr>
<tr>
<td></td>
<td>1 31.61000 104.3760</td>
<td>0</td>
<td>231</td>
<td>8</td>
<td>90</td>
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<td></td>
<td>2 31.64207 104.3500</td>
<td>6.55322</td>
<td>231</td>
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<tr>
<td></td>
<td>3 31.68490 104.3153</td>
<td>11.69552</td>
<td>231</td>
<td>8</td>
<td>90</td>
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<tr>
<td></td>
<td>4 31.73744 104.2728</td>
<td>14.43168</td>
<td>231</td>
<td>8</td>
<td>90</td>
</tr>
</tbody>
</table>
small amount of slip near the surface in Qinchuan, but it reached 5–6 m at a depth of 10 km. This is consistent with the fact that no surface rupture occurred in this area. The slip was smaller on the Guanxian–Jiangyou Fault, and the accumulation characteristic is not obviously which maybe caused by small surface data constraint. The seismic moment was $7.84 \times 10^{20}$ Nm ($M_w 7.9$), which is consistent with seismological results.

7. Discussion

(1) Comparison between inversion values and observed values

The surface displacement and gravity changes were simulated using the inverted fault slips and compared with the observed values (shown in Figs. 5 and 6). The results show that the far field GPS observation values are smaller, which are consistent with the inversion values; the near field GPS observation values are larger, correlating well with the magnitude of the inversion values, but they have a certain bias toward some directions. The gravity observation data were from sites in the vicinity of the Longmenshan Fault. The simplified fault model and actual fault are not fully consistent, resulting in a few observation and inversion value shaving opposite direction, but the greater magnitude changes are consistent with each other.

(2) Comparison between the distribution of fault slip and surface rupture

Fig. 7 shows the inversion result of the surface displacement along the Yingxiu–Beichuan Fault, and also shows a comparison between the fault slip and surface rupture distribution. The fault slip mainly occurred near
Yingxiu, Wenchuan, Hanwang, Beichuan, and Pingwu. The inversion results are clearly consistent with the surface rupture date obtained by surface geological surveys conducted after the Ms8.0 earthquake, which illustrates that the coseismic slip inversion generally reflects the main features of the earthquake.

(3) Comparison with other inversion results

Zhang et al. [5] used seismic waves to inverse the seismic moment released along the fault and found that approximately 70% of the seismic moment was released within a distance of 150 km from the epicenter to the fault, which is equivalent to the distance between Yingxiu and Beichuan and correlates well with the area of fault slip distribution in this study. However, the static slip distribution of the bilateral rupture mode is different from the inversion results in this study, which may be because of the different data sources used. Far field seismic wave inversion can provide the source parameters and fracture information quickly but cannot precisely predict the slip on the fault. In this study, we used a larger number of near field gravity and GPS data, which better constrains the distribution of fault slip. The fault slip magnitude determined by Zhang et al. [2] is comparable to our results; the maximum sliding amount was approximately 10 m in their results, and the shape of the fault slip distribution is similar. However, the results of this study correlate better with the distribution of the surface rupture. This may be because of the use of gravity data from near the fault and the larger amount of GNSS data used for inversion in this study. More data will provide better inversion results. The slip distribution also correlates well with the results of Shen et al. [6], which focused on Yingxiu and Beichuan, but the maximum slip in this study reached 10 m, which is greater than the 7 m obtained by the reference [6]. This may be related to the modeling of the detachment layer and double-shovel structure of the fault and the use of near fault gravity data.

8. Conclusions

In this study, by combining the respective strengths of gravity and GPS data, a more reliable coseismic rupture slip distribution model of the Ms8.0 Wenchuan earthquake was obtained through joint inversion of the gravity and GPS data.
The inversion results show that the earthquake was a unilateral rupture event, which mainly comprised a thrust component with a small dextral strike slip component. The rupture mainly occurred on the fault surface above 40 km and was concentrated in five areas, Yingxiu, Wenchuan, Hanwang, Beichuan, and Pingwu, which is consistent with the results of geological surface surveys. The moment tensor obtained by the joint inversion was $7.84 \times 10^{20}$ Nm (Mw7.9), which is consistent with seismological results.

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