Influence of crustal layering and thickness on co-seismic effects of Wenchuan earthquake

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Abstract: Using the PSGRN/PSCMP software and the fault model offered by USGS and on the basis of finite rectangular dislocation theory and the local layered wave velocity structures of the crust-upper-mantle, the influences of crustal layering and thickness on co-seismic gravity changes and deformation of Wenchuan earthquake have been simulated. The results indicate that; the influences have a relationship with the attitude of faults and the relative position between calculated points and fault. The difference distribution form of simulated results between the two models is similar to that of co-seismic effect. For the per centum distribution, its positive is far away from the zero line. For the crustal thickness, the effect is about 10% -20%. The negative and the effect over 30% focus around the zero line. The average influences of crustal layering and thickness for the E-W displacement, N-S displacement, and vertical displacement and gravity changes are 18.4%, 18.0%, 15.8% and 16.2% respectively, When the crustal thickness is 40 km, they are 4.6%, 5.3%, 3.8% and 3.8%. Then the crustal thickness is 70 km, the average influences are 3.5%, 4.6%, 3.0% and 2.5% respectively.

Key words: Wenchuan earthquake; co-seismic effects; crustal layering; crustal thickness; finite rectangular dislocation theory

1 Introduction

Wenchuan Ms8.0 earthquake took place at Longmenshan fault zone, which is the secondary fault zone in the middle of the most active N-S seismic belt in China1. The Longmenshan fault zone is located at the joint of Songpan-Ganzi orogenic zone and Yangzi block, which is the composition of the east borderline of the Qinghai-Tibet plateau together with Minshan uplift. It’s quite different in the structure of crustal layering and thickness of different areas because of the nappe structure environment2-5. In the northwest, the crustal density of the Qinghai-Tibet plateau is smaller and the crustal thickness can reach to 70 km, which is thinning eastwardly. While in the southeast, crustal thickness of Sichuan basin is about 40 km. The local crustal structure of Longmenshan fault zone provides the basis for simulation study by using dislocation theory.

Many scientists have researches on co-seismic effects by using dislocation theory at present6-9. Their studies show that the influence of layered structure is larger than other factors of medium parameters in dislocation simulation, but their conclusions are not identical, and don’t have specific description about the influence distribution. They also don’t consider the factor of crustal
thickness and the influence on co-seismic gravity changes caused by every factor. In layered elastic-viscoelastic half space, the surface deformation and gravity changes caused by Wenchuan earthquake have been simulated by Tan Hongbo\cite{10}. The results between measuring and simulating are different, which may be related to the crust medium parameter selecting. Based on that, the influence of Wenchuan co-seismic deformation and gravity changes caused by crustal layering and thickness will be simulated by using the PSGRN/PSCMP software\cite{11}. And the distribution of percentage will be elaborated too. It may offer some gists for explaining the mechanism of Wenchuan earthquake preparation.

2 Fault model and layered medium model

This model is inversed by Chen Ji (USGS), of which the fault plane is inconsistent with the slip direction (Fig. 1). Red star represents the epicenter, the color represents slippage value, and the arrowhead represents the moving direction of top-wall opposite to the footwall. Isoline is the rupture start time. The optimum fault parameters are as follows: strike is 229°, dip angle is 33°, 21 × 8 blocks along strike and dip, every sub-fault is 15 km × 5 km.

There are lots of results about deep seismic sounding tomography, natural and artificial earthquake in the area of Sichuan and Yunnan province\cite{5,13-15}. Their results indicate that the crust-upper mantle appears to be layered. But the parameters of the wave velocity layered model are different from each other by dissimilar way and data. Overall consideration, we choose the model as table 1, where the density is gained from the Nafe-Drake density-velocity experience transform formula\cite{16}, and the viscosity modulus is from the result of Tan Kai\cite{17}.

For better analyzing the influence of crustal layering, we design a homogeneous crust model (Tab. 2) based on the weighted average of crust parameters in each layer thickness. Obviously, the difference between simulant results of the two models can reflect the influence of crustal layering\cite{18}. We choose two models as examples, one is 70 km crustal thickness of the northwest Qinghai-Tibet plateau and the other is 40 km crustal thickness of the southeast Sichuan basin. Comparing with the homogeneous crust model of which the crustal thickness is 57 km, co-seismic influence caused by different crustal thickness will be quantitatively simulated and analyzed.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Layered structure of the crust-upper-mantle based on the average velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>h (km)</td>
<td>( V_p ) (km/s)</td>
</tr>
<tr>
<td>0 – 20</td>
<td>5.98</td>
</tr>
<tr>
<td>20 – 40</td>
<td>6.55</td>
</tr>
<tr>
<td>40 – 57</td>
<td>6.83</td>
</tr>
<tr>
<td>57 – ( \infty )</td>
<td>7.75</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Homogeneous structure of the crust-upper-mantle</th>
</tr>
</thead>
<tbody>
<tr>
<td>h (km)</td>
<td>( V_p ) (km/s)</td>
</tr>
<tr>
<td>0.0 – 57.0</td>
<td>6.4335</td>
</tr>
<tr>
<td>57.0 – ( \infty )</td>
<td>7.7500</td>
</tr>
</tbody>
</table>

Notes: Where h is the depth, \( V_p \) is the P wave velocity, \( V_s \) is the S wave velocity, \( \rho \) is density, \( \eta \) is the viscosity modulus, \( \alpha \) is the relax ratio, \( \alpha = 0 \) means complete elastic medium, \( \alpha = 1 \) means Maxwell viscoelastic medium.
3 The influence of surface deformation and gravity changes caused by crustal layering

The pictures of the co-seismic deformation and gravity changes are similar between the homogeneous crust model and layered crust model. For the homogeneous model, the radiation range of the pictures is larger. As shown in Figure 2(a), we can see that; the outline is similar to the picture of co-seismic E-W horizontal displacement, which are divided into northwestern and southeastern parts against the rupture zone. The isolines are antisymmetric; maximum positive difference can reach to 55 mm; maximum negative difference can reach to $-85 \text{ mm}$. Most of the difference focus on the fault around, and decays in the far field. The difference of N-S horizontal displacement (Fig. 2(c)) is similar to the N-S horizontal displacement in outline, but present to be negative in the southwest. So, the picture comes to be four quadrants positive and negative distribution; the maximum positive difference can reach to 25 mm; the maximum negative difference can reach to $-45 \text{ mm}$. The difference of vertical displacement (Fig. 2(e)) and gravity changes (Fig. 2(g)) focus on the fault around. It's not obvious in four quadrants distribution comparing with vertical displacement and gravity changes, but presents a positive and negative distribution along fault, and decays fast in the near field.
Figure 2 Co-seismic effect difference and its percentage between the layered crust model and the homogenous crust model (gravity unit: $10^{-8}$ ms$^{-2}$; deformation unit: mm; percentage unit: %)

Percentage of co-seismic effect difference between homogeneous crust model and layered crust model is the ratio of the co-seismic effect difference and the simulation results of homogeneous crust model (wipe off a few ratio which are bigger than 1). The right in Figure 2 shows that co-seismic effect difference and its percentage are closely related to each other. Most of the percentage is positive and the value is between 10% and 20%. While negative and big one are near the positive and negative transforming area. The More close to the zero line, the larger the difference percentage is. Based on the close relationship between co-seismic effect and fault attitude, or the relative position between the simulated points and fault$^{[19,20]}$, we can infer that the influence of co-seismic effect caused by crustal layering has a relationship with fault attitude, and the relative position between the simulate points and fault.

By comprehensive consideration, using absolute value and taking an average of the difference percentage, we can get that; the influence of the E-W horizontal displacement caused by crustal layering is 18.4%; for the N-S horizontal displacement, E-W and N-S vertical displacement and gravity changes, they are 18.0%, 15.8% and 16.2% respectively.
4 The influence of surface deformation and gravity changes caused by crustal thickness

Difference distribution of surface deformation and gravity changes among the 40 km, 70 km, and 57 km crustal thickness is showed in Figure 3. For co-seismic effect difference of 40–57 km crust model (left in Fig. 3), the pictures of E-W horizontal displacement are similar to the difference of E-W displacement; the isolines are left-right two quadrants antisymmetric distribution. The maximum positive change is 26 mm, while the maximum negative change is -20 mm. The extremum appears 0.2° beside the fault, and decays against the fault. The difference of N-S horizontal displacement is four quadrants distribution; on the left, it’s positive difference, and the extremum is 12 mm; on the right, it’s negative difference, and the extremum is -11 mm. The difference of vertical displacement and gravity changes focus on the rupture area, decaying against the fault, and the maximum positive difference can reach to 18 mm and $3.5 \times 10^{-8} \text{ms}^{-2}$; while the maximum negative difference can reach to -30 mm and $-7 \times 10^{-8} \text{ms}^{-2}$. For co-seismic effect difference of 70–57 km crust model (right in Fig. 3), it’s similar in outline, but smaller in the radiation range, and reverse in the change value.

For better understanding the influence of surface deformation and gravity changes caused by crustal thickness, difference per centum has been calculated by using the similar way which Figure 2 has used. The distribution has similar characteristics with Figure 2; difference per centum is restricted by the co-seismic zero line, where negative and large value focus on. Using absolute value and taking an average of the difference percentage, we can get that; for the difference pictures of 40–57 km crustal thickness model, difference per centum of the E-W displacement, N-S displacement, vertical displacement and gravity changes are 4.6%, 5.3%, 3.8% and 3.8% respectively; while for 70–57 km crustal thickness model, they are 3.5%, 4.6%, 3.0% and 2.5% respectively.

Conclusively, co-seismic effect difference of the 40–57 km model is bigger than that of the 70–57 km model. The radiation range of the E-W and N-S displacement difference is wider, and decays slowly against the fault. The radiation range of the vertical displacement difference and gravity changes difference is smaller, and decays fast. Surface deformation and gravity changes caused by Wenchuan earthquake are increasing when the crustal thickness increases. The influence caused by crustal thickness is biggest on the N-S displacement, then the vertical displacement and E-W displacement, smallest on the gravity changes.

5 Discussion and conclusions

1) Crustal layering has great influences to the co-seismic deformation and gravity changes; for Wenchuan earthquake, the influences to E-W displacement, N-S displacement, vertical displacement and gravity changes
Figure 3  Co-seismic effect difference among crustal thickness of 40 km, 70 km and 57 km

(gravity unit: $10^{-8}\text{ms}^{-2}$; deformation unit: mm)
are 18.4%, 18.0%, 15.8% and 16.2% respectively, which are bigger than the results analyzed by Deng Mingpian [51]. She got the per centum by comparing the maximum co-seismic difference of the two models with the maximum co-seismic effects. That is not comprehensive, because the maximum influence per centum is around the fault. Our results are more similar to Pollitz [6], Sun and Okubo’s [27], but with some value over 100%, because the position of the co-seismic effect zero lines simulated by different models are not the same. So, the difference per centum is singular when closing to the zero line. Generally speaking, the influence distribution caused by crustal layering is reliable.

2) The influences of co-seismic deformation and gravity changes caused by crustal layering have a relationship to the attitude of fault and the relative position between calculated points and fault. Results of homogeneous crust model and crustal layering model have the biggest difference in the near field, which decays against the fault with similar outline to co-seismic effects. The per centum distribution is restricted by the zero line of the co-seismic effects obviously; most of the percentage is positive and the value is between 10% and 20%; while negative and big one are near the positive and negative transforming area.

3) Crustal thickness has a little effect on co-seismic deformation and gravity changes; in the case of 40 km crustal thickness, the influences of E-W displacement, N-S displacement, vertical displacement and gravity changes caused by Wenchuan earthquake are 4.6%, 5.3%, 3.8% and 3.8% respectively; while in the case of 70 km crustal thickness, they are 3.5%, 4.6%, 3.0% and 2.5% respectively.

4) Comparison between simulated and measured results
As an example of comparison between simulated and measured results, we get the results of 3 GPS continuous observation stations which are Pixian (103.76° E, 31.91° N), Mianyang (104.73° E, 31.44° N) and Qionglai (103.31° E, 30.35° N) (Tab. 3) [21]. Mianyang and Pixian stations are in the east of the surface rapture zone. The shortest distances between these two stations and Yingxiu-Beichuan fault are 47 km and 28 km respectively. Qionglai station is in the southeast of the surface rapture zone. Only judging on vertical direction, Qionglai simulated results is consistent with Pixian’s, but reverse for Mianyang station, because the precision of GPS vertical displacement is too low. To horizontal displacement, Pixian simulated and measured results are consistent in terms of direction, but great different on magnitude. The differences between Mianyang simulated and measured results are 7% and 49% on E-W and N-S displacement. Taking account of crustal layering and thickness influence, the E-W displacement simulated result is credible, but the difference is biggest on the N-S displacement. For Qionglai station, the direction is reverse on N-S displacement, and consistent on E-W displacement with 34% difference which is over the range of crustal layering and thickness influence.

Generally speaking, some station’s simulated and measured results can be inoscilated in error range of analyzed crustal layering and thickness. But in most cases, it’s not reasonable. Back to the original question, there are two factors which cause the difference between simulated and measured value: medium model difference and fault model difference. Since two main factors (crustal layering and crustal thickness) in medium model can not explain the difference, the reason might be the fault mode difference. The fault model inversed by far field earthquake wave is too simple, and has big difference with the actual situation. Joint inverting Wenchuan earthquake fault model by using gravity, leveling and GPS data will be the best way to solve the difference between simulated and measured data.

Table 3 Comparison between simulated and measured results (unit: mm)

<table>
<thead>
<tr>
<th>displacement</th>
<th>Pixian measured</th>
<th>Pixian simulated</th>
<th>Mianyang measured</th>
<th>Mianyang simulated</th>
<th>Qionglai measured</th>
<th>Qionglai simulated</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-W</td>
<td>-563</td>
<td>-189.5</td>
<td>-305</td>
<td>-285</td>
<td>-15</td>
<td>-26</td>
</tr>
<tr>
<td>N-S</td>
<td>426</td>
<td>64.5</td>
<td>66</td>
<td>131</td>
<td>-3</td>
<td>10.4</td>
</tr>
<tr>
<td>vertical</td>
<td>81</td>
<td>43.9</td>
<td>14</td>
<td>-9.4</td>
<td>28</td>
<td>27</td>
</tr>
</tbody>
</table>
References


