

# Co- and post-seismic surface deformation and gravity changes of $M_S7.0$ Lushan, earthquake

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**Abstract** On April 20, 2013, an earthquake with magnitude 7.0 occurred in the southwest of the Longmenshan fault system in and around Lushan County, Sichuan Province, China. This devastating earthquake killed hundreds of people, injured 10 thousand others, and collapsed countless buildings. In order to analyze the potential risk of this big earthquake, we calculate the co- and post-seismic surface deformation and gravity changes of this event. In this work, a multilayered crustal model is designed, and the elastic dislocation theory is utilized to calculate the co- and post-seismic deformations and gravity changes. During the process, a rupture model obtained by seismic waveform inversion (Liu et al. *Sci China Earth Sci* 56(7):1187–1192, 2013) is applied. The time-dependent relaxation results show that the influences on Lushan and its surrounding areas caused by the  $M_S7.0$  Lushan earthquake will last as long as 10 years. The maximum horizontal displacement, vertical uplift, and settlement are about 5 cm, 21.24 cm, and 0.16 m, respectively; the maximal positive and negative values of gravity changes are 45 and  $-0.47 \mu\text{Gal}$ , respectively. These results may be applied to evaluate the long-term potential risk caused by this earthquake and to provide necessary information for post-earthquake reconstruction.

**Keywords** Lushan earthquake · Viscoelastic relaxation · Surface deformation · Gravity

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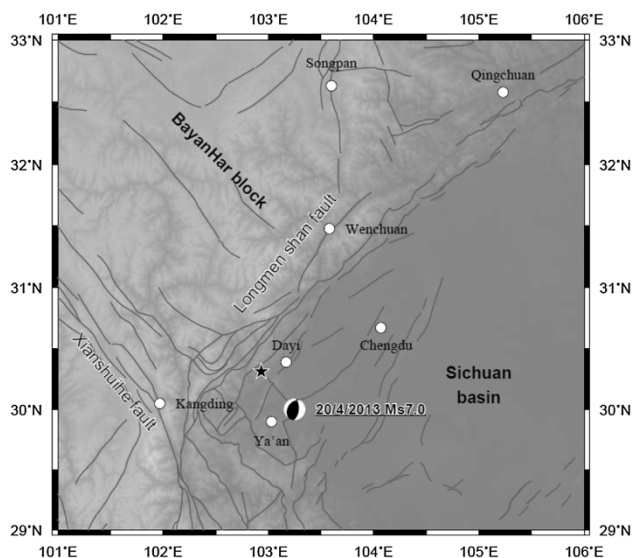
## 1 Introduction

At 8:02 on April 20, 2013, a magnitude 7.0 earthquake occurred in Lushan, Sichuan Province, China. The epicenter locates at  $30.284^\circ\text{N}$  and  $102.956^\circ\text{E}$ , and the focal depth is about 16 km (Xie et al. 2013). The rupture mainly occurred on the Longmenshan fault system (Fig. 1). The studies on the seismic activity of the Longmenshan fault system, the stress field impact on this thrust fault system, the deformation, and the gravity changes on the surrounding tectonic blocks caused by the Lushan earthquake, are critically significant for evaluating seismic hazards and studying the tectonic movement (Tapponnier et al. 1982), the crystal structure (Zhang et al. 2009, 2010; Zheng et al. 2013), and the evolution of process between Tibetan Plateau and Sichuan basin (Zhang et al. 2003; Wen et al. 2003).

Previous studies show that co- and post-seismic effects caused by earthquake dislocation may lead to the changes of various physical fields, such as deformation and gravity fields near the epicenter (Shen et al. 2008; Tan et al. 2009; Xu et al. 2010; Liu et al. 2011). Thus, the co- and post-seismic effects may disturb the observations on the long-term tectonic movement or inter-seismic deformation field so that they should be removed from the observations. In this paper, with the PSGRN/PSCMP software developed by Wang et al. (2006), we calculate and analyze the surface deformation and gravity changes of co- and post-seismic caused by the Lushan earthquake using a multiple sub-faults rupture model obtained by Liu et al. (2013) and a multi-layered crust model.

## 2 Theory and applied models

Wang (1999) proposed an orthogonal normalization method to calculate the Green function of seismic stress



**Fig. 1** Map of tectonic environment of the Longmenshan Fault system (Shan et al. 2013). The simplified active tectonic faults are shown in gray lines. The black star show the epicenter of Lushan earthquake, the beach ball shows the focal mechanism of the Lushan event (Xie et al. 2013), the white circles represent the main cities in this region

field. Based on this method and a viscoelastic multi-layered model, they established numerical methods for calculating the co- and post-seismic deformations (Wang et al. 2003; Wang and Kuempel 2003). With the PSGRN/PSCMP software developed by Wang et al. (2006), and the earthquake slip model inverted from seismic waveforms (Liu et al. 2013), we calculated the theoretical deformation and gravity changes caused by the Lushan Earthquake.

### 2.1 Crustal-layered model

With the increase of depth of the crust, high pressure and temperature prevent rock from failing in a brittle manner; instead, they flow viscously in response to stress (Kirby and Kronenberg 1987). Two kinds of phenomena result from this characteristic: 1. For the co-seismic deformation, the viscous regions behavior as elastic media; 2. For the long-term post-seismic period, these regions begin to relax and the stored elastic strains transfer upward to the seismogenic upper crust, leading to stress and strain changes in the upper crust. Based on the structure model provided by Crust2.0 (Bassin et al. 2000), considering the lower crust and mantle viscoelastic relaxation effects, we establish a multi-layered lithosphere model in Lushan area. The model parameters are listed in Table 1. In this study, we select Maxwell model to simulate the lower crust and upper mantle viscoelastic relaxation effect. Therefore, during the study of Lushan earthquake, we analyze the co-seismic effect under the elastic state, but for the analysis of

long-term deformation and gravity changes of post-earthquake, we focus on the viscoelastic relaxation effects of lower crust and upper mantle.

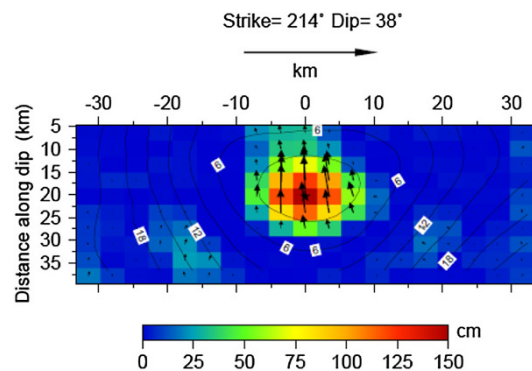
### 2.2 Finite fault rupture model

Following the inversion method (Ji et al. 2002), Liu et al. (2013) inverted the rupture model of Lushan earthquake (Fig. 2) with broadband seismograms recorded by Global Seismic Network broadband seismographs with the strike and dip angles of  $214^\circ$  and  $38^\circ$ , respectively. In order to get a high resolution image of the rupture process, the fault plane is divided into 190 subfaults with spatial dimension of 3.5 by 3.5 km. Inversion result shows that the rupture starts from hypocenter gradually expands around the hypocenter with the peak slip of about 1.5 m.

Based on the finite fault rupture model (Fig. 2) and a multi-layered structure model (Table 1), we further calculated the co- and post- seismic surface deformation and gravity field changes induced by the Lushan  $M_S7.0$  earthquake With the PSGRN/PSCMP software (Wang et al. 2006), and obtained the temporal evolution of these physical fields.

**Table 1** Multi-layered structure model for Lushan earthquake

Serial no.	Depth (km)	$V_P$ ( $\text{km s}^{-1}$ )	$V_S$ ( $\text{km s}^{-1}$ )	Density ( $\text{kg m}^{-3}$ )
1	0.0–1.0	2.50	1.20	2,100.0
2	1.0–2.0	4.00	2.10	2,400.0
3	2.0–22.0	6.10	3.50	2,750.0
4	22.0–42.0	6.30	3.60	2,800.0
5	42.0–46.0	7.20	4.00	3,100.0
6	$\geq 46.0$	8.08	4.47	3,750.0



**Fig. 2** The co-seismic slip model of Lushan  $M_S7.0$  earthquake. The black arrows represent the direction of the rupture slip, the contour represents the rupture initiation time in second

### 3 Results of co- and post-seismic deformation and gravity changes on the surface

#### 3.1 The relaxation time of viscoelastic relaxation model and stability testing

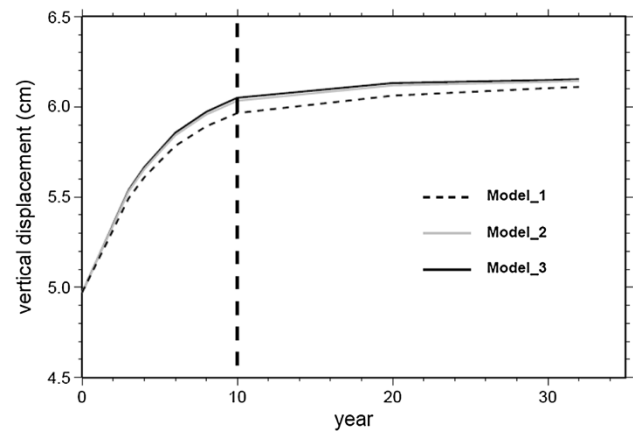
The relaxation time of lower crust and mantle has strong relationship to the scale of spatial and temporal effects of an earthquake, it is critical important to understand the seismicity pattern and the tectonic movement. So, we analyzed the duration of the post-seismic effect of Lushan earthquake at first.

Since the earthquake occurred in the Lushan County, and caused lots of damage, we calculated the theoretical co- and post-seismic vertical changes on this location induced by viscoelastic relaxation effect of the lower crust and mantle in 30 years (Fig. 3). The simulation shows the co-seismic vertical displacement changes induced by Lushan earthquake is 4.96 cm at this site. Since a warm and viscous lower crust and upper mantle cannot sustain such kind of stress and strain, they will migrate to the upper crust and further affect the deformation and gravity field at the surface. Therefore, during the first 10 years after earthquake the viscoelastic relaxation effect is obvious, and the magnitude of vertical displacement increases up to 6.0 cm from 4.96 cm caused by Lushan earthquake, and then tends to get stable gradually after 10–30 years.

Furthermore, we test different viscosity coefficients of lower crust and mantle to check the stability of our results. Taking the results of Ryder et al. (2007), Shao et al. (2008) and Wen et al. (2012) into consideration, we set the viscosity of the lower crust as  $1.0 \times 10^{18}$  Pa s, but as for the upper mantle, we set the viscosity are  $2.0 \times 10^{19}$ ,  $1.0 \times 10^{20}$  and  $1.0 \times 10^{21}$  Pa s respectively. The results with different viscosity coefficients indicate that the smaller the coefficient of viscosity is, the shorter the viscoelastic relaxation lasts. However, even though we employ different coefficients of viscosity, the final vertical displacement changes are almost identical at the same site, which shows that the viscoelastic coefficient rather control the time of relaxation than change the amplitude of the gravity. Consequently, using multi-layered structure model and viscosity model\_2, we calculate the theoretical value of surface deformation field and gravity field of co-seismic and the snapshot of 30 years after earthquake induced by Lushan  $M_S7.0$  earthquake.

#### 3.2 Simulation of co- and post-seismic surface deformation

Based on the multi-layered structure model, we calculate the surface deformation of co- and post-seismic by

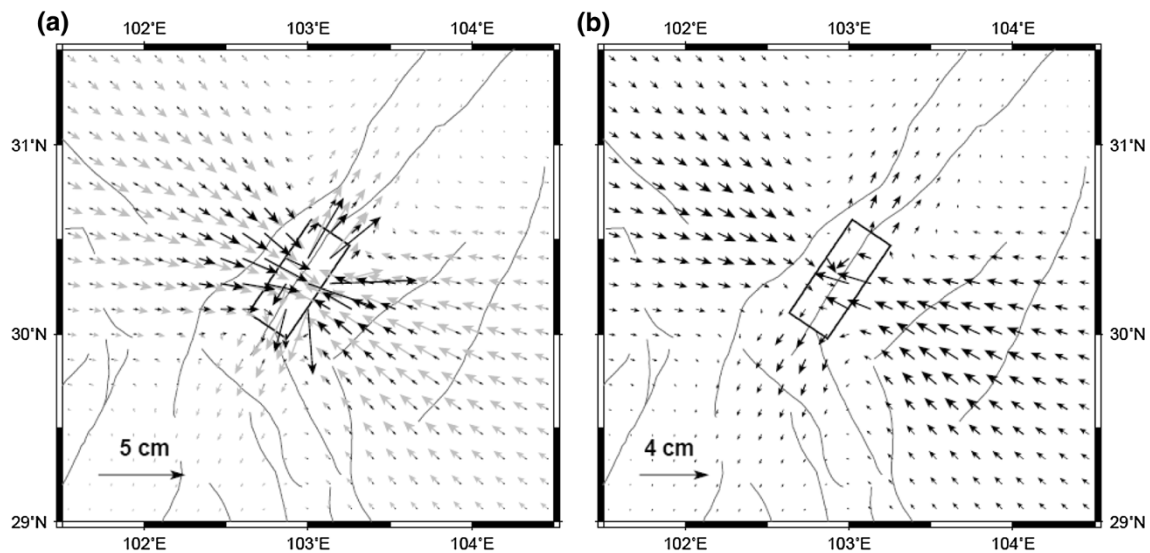


**Fig. 3** The co- and post-seismic vertical displacement of Lushan (30.17°N,102.91°E) with different viscous models

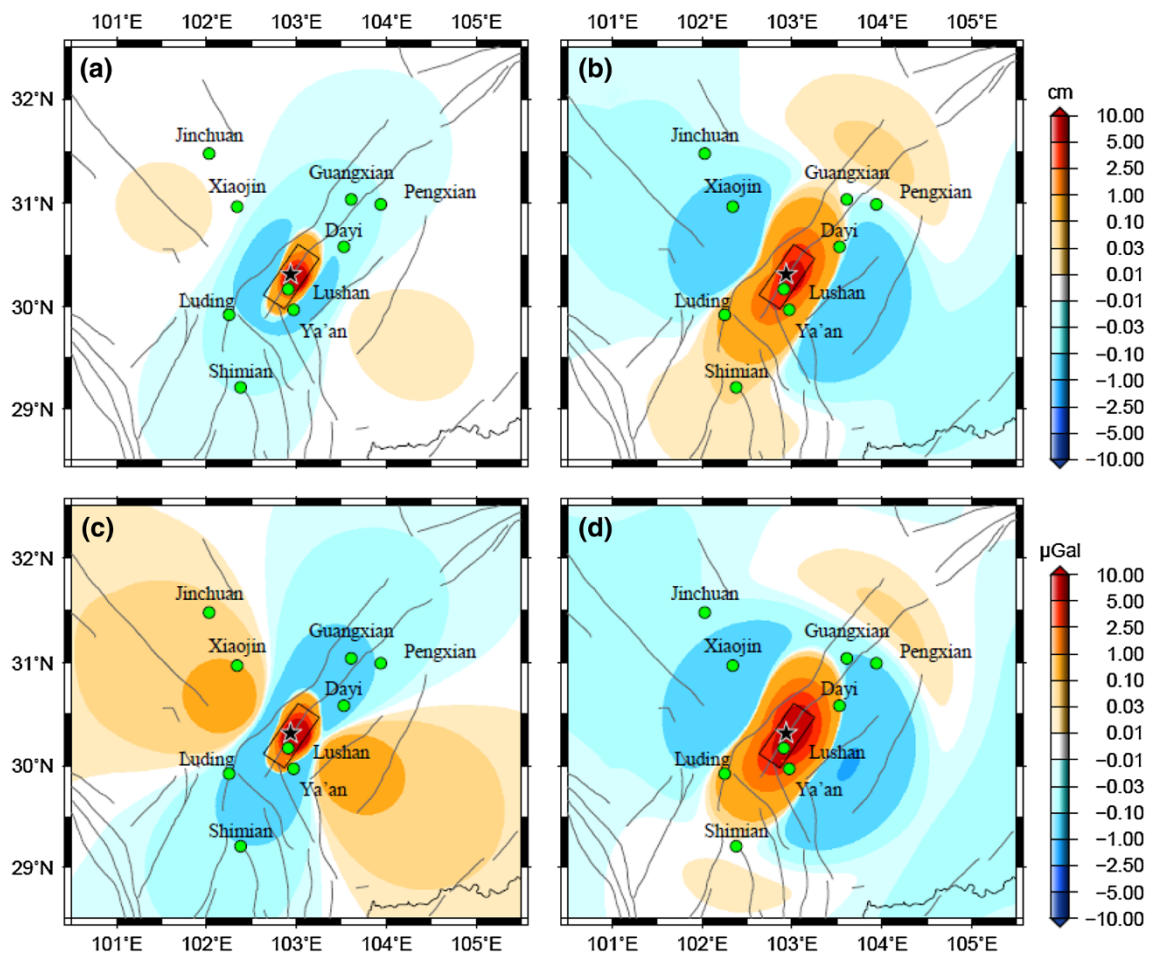
employing the program PSGRN/PSCMP, simulation results are shown in Figs. 4 and 5.

The horizontal displacement caused by Lushan earthquake is shown in Fig. 4. The motion of co-seismic surface deformation is dominated by a thrust fault mechanism with a largest horizontal co-seismic displacement near the epicenter about 5 cm, and the displacement caused by Lushan earthquake decreases with the distance from the epicenter. In order to make clear the influence of viscoelastic relaxation effect, we calculate the difference between the surface horizontal co-seismic displacement and the displacement after 30 years caused by the relaxation effect of the Lushan earthquake (Fig. 4b). 30 years later, the largest horizontal post-seismic displacement near the epicenter only decreases from 5 to 3 cm, which means that the Lushan earthquake will lead to 1–2 mm/a horizontal displacement for GPS observations in future 30 years. This kind of displacement change also means that the viscoelastic relaxation plays little effect on the near field of the rupture fault. The relaxation effects have spatial variations, in the northwest and the southeast parts of the studied region, the viscoelastic relaxation effects are stronger than those in the southwest and the northeast parts (Fig 4b).

The vertical displacement caused by Lushan earthquake is shown in Fig. 5a, b. The Lushan earthquake is mainly dominated by thrust dislocations, so the distribution of co- and post- seismic vertical displacement is relative lager than horizontal displacement. The co-seismic maximal vertical uplift and decline are 21.24 and  $-0.64$  cm, respectively, and the majority of vertical uplifts concentrates in a relatively compact area, mainly locates on the hanging wall of the fault, but the vertical displacement on both sides of fault is relative small. The decline area is just around the uplift region with peak movement of less than 1 cm. However, soon after the occurrence of the main-shock, owing to the influence of viscoelastic relaxation



**Fig. 4** Co- and post-seismic surface horizontal displacement caused by Lushan  $M_S7.0$  earthquake. **a** Co-seismic simulation result (The *black arrows* represent co-seismic result and the *gray arrows* represent the simulation result 30 years after the earthquake). **b** The difference between co-seismic displacement and post-seismic displacement in 30 years



**Fig. 5** Co- and post-seismic surface vertical displacement and gravity changes caused by Lushan  $M_S7.0$  earthquake. **a, b** show the vertical displacement changes; **c, d** show the gravity changes. **a, c** represent co-seismic simulation result; **b, d** represent the simulation result 30 years after this earthquake. The *rectangles* indicate the fault plane and the *beach balls* show the focal mechanism of this earthquake

effect, vertical displacement field changes significantly: a. the area with vertical uplifting caused by the Lushan Earthquake becomes larger; b. the directions of the movement on both sides of the fault have changed, c. the influence of co-seismic effect near the epicenter becomes weaker with an exemption of vertical displacement. Overall, compared with the horizontal deformation, the vertical displacement is larger, which is also consistent with the characteristics of this earthquake.

### 3.3 Simulation of co- and post-seismic gravity change on the surface

The fault dislocation leads to the correspondent gravity changes, inevitably. According to the simulated results, surface gravity changes are mainly influenced by vertical displacement in the near field (Fig. 5c, d). The image of gravity changes is in good consistent with the image of vertical field deformation. Four quadrants can be clearly observed in the distribution pattern of co-seismic gravity changes compared with the vertical displacement, and the maximal positive and negative variations are 45 and  $-0.47 \mu\text{Gal}$ , respectively, and the gravity changes with larger amplitude mainly focus on the hanging wall of the fault. The gravity field varies dramatically in a small area near the source region, and the gradient of gravity change is quite steep; on the contrary, in the far field, the change of gravity is relatively smaller, and its attenuation is slower, which make the variation area is larger in size.

In order to further clarify the characteristic of post-seismic surface deformation and gravity changes caused by Lushan earthquake, we calculate postseismic gravity changes in 30 years after the earthquake (Fig. 5d). Compared with co-seismic results, the distribution of post-seismic gravity changes obviously, and appears three distinct asperities, the maximal positive and negative variation are 44.55 and  $-0.985 \mu\text{Gal}$ , respectively, and the influence caused by the viscoelastic relaxation effect is weak. However, the area with obvious gravity changes in the near field become larger. Similar to the vertical displacement after 30 years, the directions of the gravity changes on both sides of the fault have changed. Another obvious phenomenon is that the range of the gravity changes becomes larger in the far field.

## 4 Discussion and conclusions

Based on the finite fault rupture model, we calculate co- and post-seismic surface deformation and gravity changes of Lushan earthquake, and analyze the influence of co- and post-seismic surface deformation, gravity changes. According to the simulation results, the deformation and

gravity changes caused by Lushan earthquake have the following main characteristics:

- (1) The relaxation adjustment of post-seismic deformation varies dramatically in the first 10 years after the main shock and then tends to get stable gradually. The influence of co- and post-seismic of Lushan earthquake will last at least 10 years.
- (2) The deformation caused by Lushan earthquake is mainly influenced by co-seismic effect near the rupture plane, on the contrary, post-seismic deformation caused by viscoelastic relaxation far from the rupture fault. Horizontal displacement caused by viscoelastic relaxation effect is about 5 cm near the source region, which will lead to an average change of  $\sim 2 \text{ mm/a}$  for GPS observations in 10 years after earthquake. This shows that the post-seismic relaxation influence is equal to or larger than the accuracy of GPS observation. Therefore, using the geodetic data to research tectonic movement, we should not only consider the coseismic effects caused by earthquake, but also take the viscoelastic relaxation effect into account.

One thing needs to pay attention is that the complexities of rupture have a significant impact on the model computation, which will cause some uncertainties of the result. If enough field observations, more geodetic data and higher precise rupture model are available in the future, a better result should be expected.

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