Co-seismic deformation derived from GPS observations during April 20th, 2013 Lushan Earthquake, Sichuan, China

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Abstract We process the standard 30 s, static GPS data and the 1 s, high-rate GPS (HRGPS) data provided by the Crustal Movement Observation Network of China with GAMIT/GLOBK software package, and obtain the co-seismic displacements of near field and far field, and the epoch-by-epoch time series of HRGPS during Lushan earthquake. GPS data from about 20 sites in Sichuan province, which located between 40 and 450 km from the epicenter, are analyzed so as to study the characteristics of the static displacements and the dynamic crustal deformations, with periods ranging from several minutes to over a month. The result shows that: the static displacements caused by Lushan earthquake are limited to several centimeters; the nearest station SCTQ at 43 km from the epicenter has the largest static displacement of about 2 cm, while the other stations generally have insignificant displacements of less than 5 mm. the stations in the east of

Sichuan–Yunnan region shifts 5–10 mm toward the southwest, and the stations in the middle-west of Sichuan Basin moves indistinctively 1–2 mm toward the northwest; station SCTQ has the largest kinematic displacement of about 4 and 3 cm peak-to-peak on the north and east component, respectively, and is much greater than the static permanent displacement; for the stations located at a distance greater than 150 km from the epicenter, the kinematic motions are generally insignificant; exceptionally, station SCNC and station SCSN in central Sichuan Basin have significant kinematic motions although they are more than 200 km away from the epicenter.

Keywords Lushan earthquake · GPS seismology · Co-seismic displacement · Time series

1 Introduction

On April 20th, 2013, an earthquake struck Lushan country of Ya'an city in Sichuan province, causing great damages. According to the China Earthquake Networks Center (CENC), the epicenter of this Ms7.0 earthquake, with a depth of 13 km, is located at 30.3°N, 103.0°E. After the strike, some institutes provided the focal solution and rupture process of Lushan earthquake by different means. The focal mechanism determined by Liu et al. (2013), Zeng et al. (2013), and Wang et al. (2013) separately indicates that the earthquake occurred at the south part of the Longmenshan fault zone is a thrust event; Zhang et al. (2013) conducted a fast inversion of the rupturing process of the earthquake by using the Global Seismic Network (GSN) teleseismic waveform data, showing that the main shock lasted for 10.5–27 s and most of the energy released in 10.5 s; the focal solution provided by The

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Table 1 Epicentral distance of GPS stations

Site	Epicentral distance/km	Site	Epicentral distance/km	Site	Epicentral distance/km	Site	Epicentral distance/km
SCTQ	42.7	SCJL	210.0	SCLH	272.7	SCNN	352.4
SCXJ	116.8	SCDF	214.4	SCNC	272.8	SCGY	354.6
SCSM	134.8	SCXD	223.6	SCSP	273.1	SCXC	355.5
SCMB	155.6	SCMN	229.8	SCML	313.2	SCBZ	385.4
SCMX	174.2	SCSN	231.4	SCGZ	339.1	SCPZ	434.1
SCYX	184.5	SCJU	259.9	SCYY	348.1		

Global Centroid-Moment-Tensor (CMT) Project (Global CMT Web Page, <http://www.globalcmt.org/>) shows that the magnitude of the earthquake is Mw6.6 and the duration is about 10 s (Dziewonski et al. 1981; Ekström et al. 2012).

The focal mechanism, determined by observing the pattern of first motions of P waves, describes the patterns of fault movement and co-seismic deformation. However, this method can yet reproduce the real movement or deformation, and is limited in terms of the space–time characteristic of the earthquake, the distribution of the stations and the equipment (Yao and Zhang 2009; Wang et al. 2011).

Compared to focal mechanism solutions, GPS can be used to observe the deformations before and after the earthquake directly, compensating for those deficiencies described above. Years of conventional static GPS observations can be used to detect crustal movement, surface strain, and permanent displacement, providing information for analyzing the formation process, mechanisms and effects of an earthquake. High-rate GPS (1–50 Hz) can provide direct measurements of instantaneous deformation, which can be used to study the rupture process as well as post-seismic motion (Meng et al. 2007). In this paper, we process the standard 30 s, static GPS data, and the 1 s, high-rate GPS data to obtain the co-seismic displacements of near field and far field and the epoch-by-epoch time series during Lushan earthquake, and then analyze the surface deformation during Lushan earthquake in different time scales.

2 Data processing

Twenty-three continuous stations installed by Crustal Movement Observation Network of China (CMONOC) in the area of Sichuan province with the data recorded at both 30 s sampling rate and 1 s sampling rate are used in our analysis. The data include 40 days' conventional static GPS data (30 s) from April 1st, 2013 (day 091) to May 10th, 2013 (day 130) and 3 days' HRGPS data (1 s) around April 20th (day 110). Some of the data are excluded because the qualities are bad (SCNN, 30 and 1 s) or data sessions do not

cover the earthquake (SCGZ, 30 and 1 s; SCSP, SCML and SCBZ, 1 s). Figure 2 shows the locations of these stations and the epicenter which is displayed as the red beachball-like focal mechanism diagram. The epicentral distances of the stations are showed in Table 1.

2.1 Static processing

We use the GAMIT/GLOBK software package (version 10.4) (Herring et al. 2010a, b) to conduct the static baseline processing and network adjustment. We use four IGS stations in the area of China including BJFS, LHAZ, URUM, and WUHN combined with the network of CMONOC in Sichuan to obtain the daily position solutions expressed with respect to the International Terrestrial Reference Frame 2008 (ITRF 2008). The time series derived from GAMIT/GLOBK are used to estimate the pre-seismic and post-seismic velocities and the co-seismic displacements. The data of day 110 are not used in the static analysis as the displacements of the stations caused by the main shock and the frequent aftershocks (Liu et al. 2013) make the single static solution not reliable.

According to the method described in the paper of Zhang (2008), we estimate the co-seismic displacement. Here we consider merely the linear trend of tectonic deformation. The long-term periodic deformation is treated to be linear in a short period of time, and the insignificant inter-seismic and post-seismic deformation is ignored. We use a shorter span (10 days) of the time series after the earthquake and give them less weight in order to reduce the impact of rapid post-seismic motion. Meanwhile, solutions closer in time to the earthquake occurrence are given larger weights. The co-seismic displacements are determined with a precision better than 1.5 mm on the horizontal components and 3.5 mm on the vertical components.

2.2 Kinematic processing

The HRGPS data is processed in relative positioning mode. We use TRACK (version 1.27), the kinematic module of

the GAMIT/GLOBK software, to perform epoch-by-epoch solutions of the HRGPS data. TRACK uses floating point LC observations and the Melbourne–Wubben wide-lane combination to determine the double-difference carrier phase integer ambiguities. We use the IGS final orbits, and adopt an elevation cut-off angle of 10° . We also use the global ionosphere maps (<http://cddisa.gsfc.nasa.gov/pub/gps/products/ionex/>) to correct the higher order ionospheric effects, and global pressure and temperature model (GPT) (Boehm et al. 2007) model and global mapping function (GMF) (Boehm et al. 2006) to correct the tropospheric delay. The epoch-by-epoch solutions are estimated with the backward Kalman smoothing approach.

At least one reference station is required as TRACK performs relative kinematic positioning. A reference station should be with good data quality and stable position, be outside the epicentral area, but not be too far away from the kinematic stations (Xu et al. 2010; Xu et al. 2011; Yin et al. 2012). We use the TEQC software to evaluate the data quality (Estey and Meertens 1999). Based on the data analysis and the static positioning above, we choose SCXC and SCGY as the reference stations. We exclude the bad satellites (i.e., high multipaths) and keep the same selection of satellite during the full time window to improve stability of the solution.

We apply a modified sidereal filtering (Bock et al. 2000; Choi et al. 2004; Ragheb et al. 2007) to improve HRGPS positioning takes advantage of the ground track repeat period of the satellites. First, we process the data of day 109 and estimate the 1 Hz positions. The positions of day 109 are low-pass filtered to remove high-frequency noise, shifted by the mean satellite repeat period (23 h, 55 m, 54 s) and subtracted from the estimated positions on day 110. The method is described in detail in Ragheb et al. (2007). An example time series shown in Fig. 1 demonstrates its advantage.

Fig. 1 Time series for north component of SCM before and after sidereal filtering

3 Co-seismic static displacements

Horizontal co-seismic displacements of Lushan earthquake obtained from static GPS observations are shown in Fig. 2. As shown in the figure, the magnitude and direction of the co-seismic displacements, varying with different regions, indicate that the impacts of the earthquake on different regions are quite different. The station SCTQ, located at 1 km west of southern-range of Longmenshan front fault, is the nearest site from the epicenter (43 km) and suffers the largest displacement of about 2 cm. SCXJ, located about 100 km away from the epicenter, has only about 3 mm displacement. As for further stations, the displacements are generally less than 5 mm.

Western Sichuan is at the triple junction of the Bayan Har block, the Sichuan–Yunnan block, and the South China block (Sichuan Basin) (Zhang et al. 2003). Here it distributes many active fault zones, such as the Longmenshan fault zone, the Xianshuihe fault zone, the Anninghe–Zemuhe fault zone, and the Daliangshan fault zone. The co-seismic static displacements of the sites in different block regions have different magnitudes and directions, while the sites in the same block region basically have the same displacements characteristics. Almost all stations in eastern Sichuan–Yunnan block region shift 2–5 mm toward southwest. Stations in the middle-west of Sichuan Basin move 1–2 mm toward the northwest generally.

SCTQ and SCXJ, the two closest stations from the epicenter, have large displacements with different directions. SCXJ, in cross-strike (ca. NW–SE) direction of the causative faults, shifts toward the fault zone. The along-strike (ca. NE–SW) located station SCTQ moves along the fault zone.

For the vertical displacements, as shown in Fig. 3, we can see that the magnitudes are relatively small. The largest displacement is only 12 mm (SCJL). The sites with larger vertical displacements are basically distributed in the east of Sichuan–Yunnan block region and the southwest of Sichuan Basin. By contrast, the sites inside Sichuan Basin and at the northeast of the Bayan Har block region suffer slighter vertical displacements. Almost all stations uplift, which may result from the blocks squeezing each other. However, the vertical displacements are not obvious compared to the large scatter in the vertical daily positions.

Permanent displacements can be seen intuitively from the 3D components time series of daily positions. Figure 4 shows the day-by-day 3D time series of SCTQ and SCXJ. There are slips occurred on day 110 at both of the stations, without recovery. As a result of the large scatter in vertical components, it is difficult to distinguish the vertical displacements from the time series.

Fig. 2 Horizontal co-seismic static displacements of Lushan earthquake determined by GPS, with 70 % confidence ellipses

Fig. 3 Vertical co-seismic static displacements of Lushan earthquake determined by GPS, with 70 % confidence ellipses

Fig. 4 Position time series of stations SCTQ and SCXJ

4 Dynamic displacements carried out by kinematic solutions of HRGPS

We analyze the epoch-by-epoch solutions of the first 10 min in April 20th performed by high-rate GPS data and obtain 3D time series of surface dynamic displacements. Since the earthquake took place at 00:02:46 UTC, the first 10-min data would record the entire process of the earthquake.

The 3D time series of surface displacements are showed in Fig. 5. The subplots from left to right show the North, East and Up component separately. The time series of stations arranged from bottom to top are at increasing distance from the epicenter. In the time window (0–600 s), the mean of the displacement is subtracted from the origin value for each component of each station. We estimate the possible arrival time of surface waves according to the focal solution of The Global CMT Project, taking the speed of surface wave to be 3 km/s, and mark with magenta dotted lines in each subplot. Red dotted lines indicate the occurrence time of the earthquake.

The arrival of surface waves at SCTQ, SCXJ, and SCSM can be seen clearly, at least in the horizontal components. The station SCTQ shows a significant kinematic displacement of about 4 and 3 cm peak-to-peak on the north and east component, respectively. For SCXJ and SCSM, the peak-to-peak values of the deformations are 2–3 cm either on the north or the east components. The peak value of the kinematic motion is much larger than the static permanent displacement on each of these sites. The attenuation of surface wave causes reduction in the amplitude of the waveform with the distance from the epicenter. It is only in the east component that we can easily identify the seismic

signal of SCMB, while in north component the signal is close to the level of noise (ca. 3 mm). It is difficult to interpret the seismic signal directly from the time series for more distant sites. Because of the worse precision of vertical components of GPS positioning and week signals of vertical displacements, seismic signals are submerged in the noise and difficult to be detected.

It should be noted that, although SCNC and SCSN are far from the epicentral area, it is also easier, compared to other far field stations, to identify the seismic signal. It can be seen from the waveform that there is a discernible change in amplitude and frequency when the seismic wave arrives (marked with the red ellipses in Fig. 5). This may be due to the geographical structure of tectonic block in which they are located. As can be seen from Fig. 2, these two stations are located in central Sichuan Basin. Sichuan Basin is characterized by a simple and stable structure, with neither fracture distribution nor obvious internal velocity gradient zone in it (Zhang et al. 2003). Seismic waves propagating in this region will not be blocked so much, which means that the attenuation is low. For other regions, due to the blocking of fault zones and the impacts of structural changes, seismic wave attenuation is large. It means that for far field stations in these areas, it would be more difficult to detect seismic signals.

We also calculate the instantaneous velocity of each epoch by neighboring differential arithmetic, as shown in Fig. 6. We can find that the velocity of each site fluctuates slightly around zero as noises until the seismic wave arrives. Thus, the seismic signals can be easily detected in SCTQ, SCXJ, and SCSM, especially the 2.5 cm/s variation of SCTQ's velocity. The magnitude and the direction of

Fig. 5 Position time series derived from high-rate GPS

Fig. 6 Velocity time series of some SCTQ, SCXJ, SCSM, and SCMB

each site's velocity vary severely, meaning that the earthquake provides high frequency dynamic response of the stations.

5 Discussion and conclusions

Conventional static GPS observations and high-rate GPS observations collected from more than 20 stations in Sichuan are processed to compute the co-seismic displacements and short-term instantaneous surface movements during Lushan earthquake. The characteristics of surface movements and deformations during Lushan earthquake are then analyzed in different time scales. The result shows that:

- (1) The static displacements caused by Lushan earthquake are limited to several centimeters. The station SCTQ, which is located 43 km from the epicenter, has the largest static displacement of about 2 cm, while almost all the other stations have insignificant displacements of less than 5 mm.
- (2) The co-seismic displacement field shows that the GPS stations in the east of Sichuan–Yunnan region shift 5–10 mm to the southwest and rise 5–10 mm, and the stations in the middle-west of Sichuan Basin move 1–2 mm to the northwest and rise less than 2 mm, respectively.
- (3) Large kinematic motions are observed in the near field stations within about 150 km. The station SCTQ has the largest kinematic displacement of about 4 and 3 cm peak-to-peak on the north and east component, respectively. On each of these sites, the peak-to-peak value of the kinematic motion is much greater than the static permanent displacement. The short-term dynamic information also shows that the seismic waves attenuate fast. The waveform amplitudes reach the noise level (ca. 3 and 10 mm on the horizontal and vertical components, respectively) at stations located at a distance greater than 150 km from the epicenter, except SCNC and SCSN.

- (4) Two stations in central Sichuan Basin–SCNC and SCSN have significant kinematic motions during the earthquake although they are more than 200 km away from the epicenter.

The duration of an earthquake is very short (usually only tens of seconds). This kind of instantaneous motion can be captured by high-rate GPS. Although it is widely used in earthquake monitoring, dynamic solution of high-rate GPS has much lower precision than static solution does. For far-field or weak seismic signals, it turns to be inefficient due to strong noises. Conventional static solution with high accuracy up to mm level can be used for monitoring precisely crustal movements and permanent displacements caused by the earthquake. However, it is of low temporal resolution (usually daily solution). What's more, in order to get satisfactory result, long time of observations or multi-periods of measurements are needed. In this case, integrating the two methods in seismic studies deserves further discussions.

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