EXPRESS LETTER

Geodetic model of the 2015 April 25 $M_w$ 7.8 Gorkha Nepal Earthquake and $M_w$ 7.3 aftershock estimated from InSAR and GPS data

Guangcai Feng, Zhiwei Li, Xinjian Shan, Lei Zhang, Guohong Zhang and Jianjun Zhu

1Laboratory of Radar Remote Sensing, School of Geosciences and Info-Physics, Central South University, Changsha 410083, China. E-mail: zwifi@csu.edu.cn
2State Key Laboratory of Earthquake Dynamics, Institute of Geology, China Earthquake Administration, Beijing 100029, China
3Department of Land Surveying and Geo-Informatics, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong

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SUMMARY

We map the complete surface deformation of 2015 $M_w$ 7.8 Gorkha Nepal earthquake and its $M_w$ 7.3 aftershock with two parallel ALOS2 descending ScanSAR paths’ and two ascending Stripmap paths’ images. The coseismic fault-slip model from a combined inversion of InSAR and GPS data reveals that this event is a reverse fault motion, with a slight right-lateral strike-slip component. The maximum thrust-slip and right-lateral strike-slip values are 5.7 and 1.2 m, respectively, located at a depth of 7–15 km, southeast to the epicentre. The total seismic moment $7.55 \times 10^{20}$ Nm, corresponding to a moment magnitude $M_w$ 7.89, is similar to the seismological estimates. Fault slips of both the main shock and the largest aftershock are absent from the upper thrust shallower than 7 km, indicating that there is a locking lower edge of Himalayan Main Frontal Thrust and future seismic disaster is not unexpected in this area. We also find that the energy released in this earthquake is much less than the accumulated moment deficit over the past seven centuries estimated in previous studies, so the region surrounding Kathmandu is still under the threaten of seismic hazards.

Key words: Satellite geodesy; Radar interferometry; Earthquake source observations; Seismicity and tectonics.

KEY POINTS

- Complete deformation field is mapped for 2015 $M_w$ 7.8 Gorkha Nepal earthquake.
- Source parameters of this event are estimated based on InSAR and GPS data.
- Seismic risk is reassessed around Kathmandu.

INTRODUCTION

On 2015 April 25, an $M_w$ 7.8 earthquake struck the village of Barpak, Gorkha district, central Nepal. This disaster claimed the lives of more than 8000 people and devastated the city of Kathmandu and its surrounding areas. The earthquake was followed by many powerful aftershocks, including two $>M_w$ 6.5 on 25 and 26 April, respectively. And the largest aftershock occurred on 12 May 2015 with a moment magnitude 7.3, at the border between the capital Kathmandu and Mt. Everest (see Fig. 1). The earthquake triggered hundreds of landslides and temporarily dammed rivers, seriously hindering the rescue efforts.

The $M_w$ 7.8 Gorkha Nepal earthquake occurred along the collision zone between the Indian and the Eurasian tectonic plates that converge at a rate of $\sim$20 mm yr$^{-1}$ (Bilham et al. 1997; Ad er et al. 2012). The stress accumulated by this convergence is periodically released in large earthquakes that occurred in the fault system of the Himalayan front. Actually, using the spatially sparse geodetic data (e.g. GPS, levelling) to measure the Himalayan convergence, geophysicists and geologists in the early 1990s have anticipated that great earthquake hazard would happen in Nepal (Bilham et al. 1997; Bilham & Ambraseys 2005). During the past century, the Himalayan arc has experienced several great thrust earthquakes, such as the Kashmir earthquake ($M_w$ 7.6 in 2005), the Kangra earthquake ($M$ 7.8 in 2005), the Assam earthquake ($M$ 8.6 in 1950) and the Bihar Nepal earthquake ($M_w$ 8.4 in 1934) (Sapkota et al. 2013; Feng et al. 2015a; see Fig. 1). However, none of their coseismic
surface deformations or fault-slip models have been extensively studied with geodetic data, except for the $M_w$ 7.6 Kashmir event mapped by the Aster images with the subpixel correlation method (Avouac et al. 2006). As for this Nepal earthquake, modern geodetic technologies (InSAR and GPS) permit a much more detailed study than was possible for any previous large earthquakes. So this event provides an excellent opportunity to study the source parameters of large earthquake and assess the potential seismic hazard in the Northern India and Nepal.

In this study, we first estimate source parameters for both the $M_w$ 7.8 Gorkha earthquake and its $M_w$ 7.3 aftershock using a combination of InSAR and GPS data. Then based on our model, we calculate the static stress change to identify whether the main shock has promoted failure of the largest aftershock. Finally, we discuss the implications and potential seismic hazards in this area.

## 2 DATA AND METHODS

Both InSAR and GPS measurements were used in this study to estimate source parameters of this event. The GPS displacement was kindly provided by the ARIA research team at JPL (http://aria-share.jpl.nasa.gov/events/20150425-Nepal_EQ/GPS/). It was derived from the difference between position solution 5–10 days before and 1–9 days after the earthquake, depending on the data availability. We included 13 GPS stations distributed along the Himalaya Mountain in our analysis. The largest observed horizontal and vertical displacements are 1.9 and 1.3 m at a station (KKN4) 10 km northwest of Kathmandu. Although the number and density of GPS stations are far from good enough for this earthquake study, the four key GPS stations around the peak displacement areas fortunately provided strong independent constraints for the fault-slip model.

The InSAR data consist of two parallel ascending ALOS2 Stripmap mode paths (P156 and P157) and two parallel descending ALOS2 ScanSAR mode paths (P47 and P48), which can detect the deformation of the main shock and the $M_w$ 7.3 aftershock independently (see Fig. 1). The detailed SAR data information is shown in Tables S1 and S2. For the main shock deformation, we processed the Stripmap mode data P156 from level 1.1 products with the traditional DInSAR method using the GAMMA software package (Wegmüller & Werner 1997; Feng et al. 2015b). We also utilized the ScanSAR results (P47 and P48) of UCSD SAR team processed by GMTSAR software package (Lindsey et al. 2015). However, these ScanSAR results were plagued with strong orbital errors, causing spatially long wavelength signals or ramps in the data. So we removed the phase ramp in every swath by a 2-D quadratic polynomial model after separating the ScanSAR results into five independent swaths (Feng et al. 2015b). This process can avoid the trade-off between the swaths in mosaic data when removing phase ramps. For the $M_w$ 7.3 aftershock deformation, we processed one ascending Stripmap mode data from P157 using GAMMA software package and utilized one descending ScanSAR interferogram (P48) from Lindsey et al. (2015) (see Table S2) after removing the phase ramps. So both the main shock and the $M_w$ 7.3 aftershock can be independently constrained by ascending and descending InSAR data in our study (see Fig. 2).

Coseismic InSAR data reveal that the maximum line-of-sight (LOS) displacement of the surface above the decollement is >150 cm about 10 km northwest of Kathmandu. The largest displacement along both the ascending and descending paths is located northwest of Kathmandu, near the GPS station KKN4. The LOS
displacements range from \(-72\) to \(151\) cm along the ascending orbits and from \(-78\) to \(112\) cm along the descending orbits. The InSAR measurements exhibit strong surface displacements, but show no clear phase discontinuities or surface fault in this event. The maximum LOS displacement of the \(M_w\) 7.3 aftershock, up to \(80\) cm, has also been detected by the descending P156. As InSAR interferograms can only detect relative motions, GPS vectors were employed to calibrate and verify the InSAR measurement. Our comparison indicates that the InSAR results enjoy a good agreement with GPS measurements.

3 Fault-Slip Modelling and Static Stress Changes

In the fault-slip modelling, we fixed the fault geometry to make sure it is consistent with the GCMT solution, the aftershock distribution, as well as the general orientation of the Himalayan Main Frontal Thrust (HMFT). The fault plane has a strike of \(290^\circ\) and with its length and width as \(225\) and \(185\) km, respectively. We inverted the dip for one single segment model based on a two-step nonlinear modelling method (Feng et al. 2015b) and found that a fault dip of \(7^\circ\) had an optimal data misfit for this study. This geometry is also consistent with the solution of Global CMT. To determine finer slip distribution, we discretized the fault plane into \(5\) km \(\times\) \(5\) km fault patches and solved for both the variable dip-slip and strike-slip for each patch because some strike-slip is required to fit the GPS measurement. Assuming a homogeneous elastic half-space and a Poisson’ ratio of 0.25, we constructed the Green’s functions of surface displacements.

We reduced the ALOS2 P157 result to 1503 points and the P47, P48 results to 887 and 3140 points, respectively, based on a method proposed by Feng & Jónsson (2012) considering both the fringe rate and the coherence. This method not only promises maximum deformation information but also ensures the robustness. To reduce the influence of shallow aftershocks, atmospheric delays and phase unwrapping errors, we manually masked areas with those errors before data reduction. We smoothed the solution with a Laplacian constraint for the fault slip and utilized the L-curve method to choose an optimal smoothing factor (Feng & Jónsson 2012; Feng et al. 2015b). The smoothing factors can balance the roughness of the fault slip and the data misfit. In this study, we made free for the strike-slip component, but made non-negative constraint for the dip-slip in the modelling based on the mechanism of GCMT and USGS. InSAR and GPS data were inverted for distributed slip using constrained least squares. The resulting slip distributions as well as the corresponding fits to the GPS are shown in Fig. 3. The corresponding fits to InSAR data are shown in Figs S1 and S2.
The residuals in InSAR LOS displacement are generally smaller than 4 cm, though the northern end of the rupture area has larger local misfits due to less constraint for the deep slip resolution. The best-fit slip model can predict the surface deformation, which is similar to the observed, with root mean square (RMS) errors for the GPS data: 2.7 cm for the north component, 1.8 cm for the east component and 0.9 cm for the up component. The average RMS misfits for the ascending and descending LOS displacements are 1.8 and 2.1 cm, respectively. The coseismic slip model from a combined inversion of GPS and InSAR data suggests that this event is a reverse fault motion, with a slight right-lateral strike-slip component. The maximum thrust-slip and right-lateral strike-slip are located at a depth of 7–15 km southeast to the epicentre, with the values of 5.7 and 1.2 m, respectively. This is consistent with the peak InSAR and GPS surface displacements over the region seen. Thrust-slip is generally concentrated in the upper crust shallower than 15 km. However, of the deep slip under 15 km, the ratio of strike-slip versus thrust-slip is 4.06 versus 3.73 × 10¹⁸ Nm and the strike-slip extends deeper due to less resolution on the strike-slip component, compared to the thrust-slip. The seismic rupture is thought to have propagated eastward because there is no large slip on the western side of the epicentre. This is also consistent with the distribution of aftershocks in the following month (see Fig. 1). Total estimated moment magnitude is \( M_w = 7.55 \times 10^{20} \) Nm, corresponding to \( M_w = 7.89 \), assuming 32 GPa shear modulus. In addition to the main shock, the finite fault model of the \( M_w = 7.3 \) aftershock was also estimated using ascending and descending InSAR data. The fault plane is approximately parallel with the main fault (see Fig. 3) and its preferred fault dip is 11°. The maximum thrust-slip and right-lateral strike-slip values are 3.5 and 0.5 m, respectively, located at a depth of 5–10 km, southeast to the epicentre of the \( M_w = 7.3 \) event. Compared with the main shock, the fault slip of this aftershock is much closer to the surface, though it has not reached the surface, either. Its total estimated moment magnitude is \( M_w = 6.85 \times 10^{19} \) Nm, corresponding to \( M_w = 7.20 \), close to that of GCMT, slightly smaller than that announced by USGS \( M_w = 7.3 \).

One of the three \( >M_w = 6.5 \) aftershocks occurred at the western end and two at the eastern end of the main rupture which has less fault slip in the main shock. In order to identify the promoting relationship between the main shock and aftershocks, we calculated the coseismic Coulomb stress at 12 km depth imparted by this earthquake with the source models we obtained above (Lin & Stein 2004). We assume a coefficient of friction 0.6 and use a shear modulus of 32 Gpa to match that used in the InSAR and GPS modelling. We found the three large aftershocks happened in the places with positive Coulomb failure stress and the aftershock locations correlate well with the areas having increased Coulomb failure stress, particularly the areas near the surface rupture and eastern end of the main rupture, where little energy was released in the main shock (see Fig. 4).

4 DISCUSSION AND CONCLUSIONS

Our geodetic inversion suggests that the slip is generally confined at a depth of 7–15 km and the largest slip occurred in the area 15–20 km northern of Kathmandu. This generally agrees with the results of teleseismic inversions of \( P \) and \( SH \) waves (NEIC 2015; Wei 2015), and a geodetic inversion using a few InSAR and GPS data (Barnhart 2015). Different from previous studies, we used the InSAR observation from both the ascending and descending orbits, covering the whole earthquake area. Our model presents that the peak slip is up to 5.7 m, larger than 4.5 m of the geodetic model from Barnhart (2015) and 5 m of the seismic model from Wei (2015). We also found that both the main shock and the largest aftershock have slight right-lateral strike-slip component in fault-slip models, which is consistent with the east moving trends of Tibet Plateau. We believe that the right-later strike-slip component would increase eastward along the HMFT, which is directly confirmed by the 1950 \( M_w = 8.6 \) right-lateral, strike-slip, Assam earthquake. Our result shows the total seismic moment of this Nepal earthquake is \( M_w = 7.89 \), close to the result (\( M_w = 7.9 \)) of GCMT and NEIC (2015). The moment magnitude inferred here is based on the static displacement including part of early afterslip and deformation of aftershocks, so the exact seismic moment should be slightly smaller. Our solution estimates based on InSAR data show that the maximum slip of \( M_w = 7.3 \) aftershock is up to 3.8 m, occurring at the place containing small coseismic slip (<0.5 m). Furthermore, two fault-slip models in Fig. 3 exhibit that a small area between the two rupture zones has not ruptured yet. Its potential moment magnitude is up to \( M_w = 6.8 \), so that area would be a potential seismic zone. This is also demonstrated by the Coulomb failure stress in Fig. 4.

The InSAR data have provided an extensive observation for the 2015 \( M_w = 7.8 \) Gorkha Nepal earthquake using both the ascending and descending orbits. It is the first time for the great Himalayan earthquake to be studied with a lot of details using geodetic technologies. The InSAR measurements show that the ruptured fault did not reach the surface in neither the \( M_w = 7.8 \) main shock nor the \( M_w = 7.3 \) aftershock, which is quite special for an on-land shallow earthquake larger than \( M_w = 7.5 \) around Himalayan front system. The 2008 Wenchuan earthquake (Feng et al. 2010), 2013 Balochistan earthquake (Feng et al. 2015a), 2005 Kashmir earthquake (Avouac et al. 2006), all have obvious surface ruptures and offsets. However, it seems common to great Himalayan earthquakes happened in the eastern Nepal. The 1833 (\( M_w = 7.7 \) Nepal) and 1934 (\( M_w = 8.4 \) Bihar–Nepal) events have long been categorized as blind events, though Bollinger et al. (2014) found that the 1225 and 1934 events did have surface rupture based on the new evidence from Patu and Bardibas strands of the HMFT. So what kinds and sizes of earthquakes occurred in this area will exhibit surface rupture are still far from clear.

One of the most noteworthy features of the fault slip in the main shock and the \( M_w = 7.3 \) aftershock is that their near surface fault slips (<7 km depth) are close to zero. So this earthquake is apparently...
absent of slip on the HMFT faults in the south of Kathmandu. Slip on the frontal thrust is essential for the Indian plate to move northward beneath the Himalaya and is known to be accompanied with most historical great Himalayan earthquakes. A pair of earthquakes in 1255 and 1344 resulted in an incremental slip of 3–5 m on this thrust fault, and the same fault was reactivated in the 1934 $M_w = 8.4$ Bihar–Nepal earthquake (Sapkota et al. 2013). As the current earthquake induced no surface fault slip, this earthquake is obvious smaller in magnitude than anticipated ($M > 8$; Feldl & Bilham 2006; Sapkota et al. 2013). It remains possible that the absent fault slip may drive creep processes on the southern decollement. However, the past 20 years’ geodetic measurements in the Nepal Himalaya indicate that no large slow slip event has been observed (Ader et al. 2012). So we believe the areas with no surface slip are the locking lower edge of HMFT and should be high seismic zone in future. The Coulomb failure stress in Fig. 4 also shows obvious positive in those areas.

Both InSAR surface displacement and aftershock distributions suggest that this event is located at a seismic gap between the 1934 and the 1505 events (see Fig. 1), the HMFT segment that has not ruptured since the historical event of 1344 (Bilham & Ambraseys 2005; Feldl & Bilham 2006). GPS results indicated that most of the convergence rate across the Himalaya of central Nepal has been absorbed by slip along a major basal thrust fault. The rates are 17.8 ± 0.5 mm yr$^{-1}$ in the central and eastern Nepal and 20.5 ± 1 mm yr$^{-1}$ in the western Nepal (Ader et al. 2012). However only about 15 per cent of the stress accumulated since 1344 was released in the past 700 yr, including 16 $M_w > 7$ earthquakes, moment magnitudes up to 8.5 (including the 2 $M_w > 7$ earthquakes of this study). So there still is a large deficit of seismic slip after this $M_w > 8$ event in this part of the Nepalese Himalaya and more earthquakes/tectonic movements $M_w > 8$ are needed to balance the long-term slip budget on the HMFT. Hence, the region surrounding Kathmandu might experience more earthquakes in the future. Earthquakes are more likely to occur in the west areas, rather than the east areas of the fault, as energy from the latter region had already been expended during the $M_w 8.4$ earthquake in 1934.

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REFERENCES


SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this paper:

Figure S1. InSAR predicted and residual coseismic interferograms from our fault model.

Figure S2. InSAR predicted and residual $M_w 7.3$ aftershock interferograms from our fault model.

Table S1. ALOS2 images used for generating interferograms of coseismic surface deformation.

Table S2. ALOS2 images used for generating interferograms of the $M_w 7.3$ aftershock surface deformation. (http://gji.oxfordjournals.org/lookup/suppl/doi:10.1093/gji/ggv335/-/DC1).

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