Landslide monitoring by combining of CR-InSAR and GPS techniques

Wu Zhu a,c,*, Qin Zhang a,b, XiaoLi Ding c, Chaoying Zhao a,b, Chengsheng Yang a,b, Feifei Qu a, Wei Qu a,b

a College of Geology Engineering and Geomatics, Chang’an University, No. 126 Yanta Road, Xi’an 710054, China
b Key Laboratory of Western China’s Mineral Resources and Geological Engineering, Ministry of Education, No. 126 Yanta Road, Xi’an 710054, China
c Department of Land Surveying and Geo-Informatics, Hong Kong Polytechnic University, Hong Kong, China

Received 19 November 2012; received in revised form 21 November 2013; accepted 3 December 2013
Available online 10 December 2013

Abstract

Considering the limitations related to the landslide monitoring by Interferometric Synthetic Aperture Radar (InSAR) technique, the method of integration of Globe Positioning System (GPS) with Corner Reflector Interferometric SAR (CR-InSAR) techniques is proposed in this paper. Firstly, deformation in radar line-of-sight (LOS) direction is optimized by introducing the GPS-measured height and atmospheric delay products into the CR-InSAR model. Then, GPS-measured horizontal deformation and CR-InSAR measured LOS deformation are combined to produce the more accurate vertical deformation. Finally, high precision three-dimensional deformation (N, E, U) is projected to the along-slope direction to monitor the actual movement of landslide. In order to test this method, four X-band stripmap-mode TerraSAR images, eight Trihedral Corner Reflectors (TCR) data and eight GPS observed data are collected to monitor the deformation of three potential landslide fields located at the north of Shaanxi province, China. The detailed analysis demonstrates that the estimated precision of along-slope direction is about two times better for proposed method (±1.1 mm) versus GPS (±2.1 mm) in this case. Meanwhile, our result indicates that almost all of the monitoring points present the trends of sliding down along the slope at the different levels from April 9 2011 to August 30 2011, showing the certain instability. Further investigation of the relationship between the magnitudes of displacement at CR points and the implementation of early control reflects the rationality of our result. Our proposed method could provide of the strong support in the high precision landslide deformation monitoring.

© 2013 COSPAR. Published by Elsevier Ltd. All rights reserved.

Keywords: Landslide monitoring; Corner Reflector; Globe Positioning System; Interferometric Synthetic Aperture Radar

1. Introduction

Landslides represent one of the most diffuse natural hazards in many parts of the world, threatening and influencing the socio-economic conditions of many countries (Turner and Schuster, 1996). Due to the difficulties of putting countermeasures into effect in terms of mitigation works, a deep knowledge of potential landslide deformation monitoring and prediction is required (Chacon et al., 2006). As an advanced space observation technique, Interferometric Synthetic Aperture Radar (InSAR) has demonstrated its potential for landslide deformation monitoring under certain conditions (Fruneau et al., 1996; Singhroy et al., 1998; Rott et al., 1999; Vietmeier et al., 1999; Crosetto et al., 2005; Yin et al., 2010; Strozzi et al., 2010; Motagh et al., 2013; Jin et al., 2013). However, the application of the InSAR technique to the landslide monitoring is still a challenging topic. It is limited by the temporal decorrelation, the residual topographic phase error and atmospheric delay phase error, as well as the one-dimensional (1D) line of sight (LOS) direction. Temporal decorrelation is caused by the variations of the
ground target scattering characteristics and would become more serious in the areas surrounded by the thick vegetation and soft soil, like the landslide region (Ferretti et al., 2007; Hanssen, 2001; Zebker and Villasenor, 1992). The residual topographic phase error is mainly caused by the inaccurate elevation data and is usually difficult to be completely separated from the deformation phase, particularly in the landslide area with complex terrain (Massonnet and Feigl, 1998; Samsonov et al., 2011). The residual atmospheric delay phase error is caused by the spatial and temporal variations of atmosphere between master image and slave image, which is also difficult to be separated from the deformation phase, particular for the tropospheric delay correlated with terrain elevation (Li et al., 2006). The InSAR-observed deformation only represents the LOS direction which can not directly reflect the actual movement of landslide and should be projected to the slope direction (Yun et al., 2007; Singh et al., 2005).

To address the above limitations, we propose a method of combining of the Corner Reflector Interferometric SAR (CR-InSAR) and the Globe Positioning System (GPS) techniques to monitor the landslide. The pioneering researches have showed the potential ability on landslide monitoring by using CR-InSAR technique due to its sub-millimeter deformation precision in LOS direction and high coherence during a long time (Xia et al., 2004, 2008; Ferretti et al., 2007; Fu et al., 2010; Froese et al., 2008). Nevertheless, it is still limited by the residual topographic phase error, atmospheric delay phase error and 1D LOS deformation in the application of landslide monitoring. As a mature technique, GPS can provide of accurate surface height data and corresponding atmospheric delay products (Zhang and Li, 2005; Jin et al., 2007). Therefore, CR-InSAR model can be refined through removing the residual topographic phase error and atmospheric delay error with the help of GPS-measured height and atmospheric delay products. Additionally, the fact that GPS is more sensitive to the horizontal deformation while CR-InSAR is more sensitive to the vertical deformation makes it possible to combine of the GPS-measured horizontal deformation and CR-InSAR measured LOS deformation to create high precision along-slope direction deformation. In other words, our proposed method combines the merits of GPS and CR-InSAR to overcome the limitations of landslide monitoring by single GPS and InSAR techniques.

In this paper, combining of the CR-InSAR and GPS techniques to monitor the landslide deformation will be shown. Firstly, the theory of generating high precision along-slope direction deformation by integration of CR-InSAR and GPS is deduced in Section 2. Then, the background of experimental area and corresponding data are introduced in Section 3. After that, the experimental result is analyzed in Section 4. Finally, the result is discussed in Section 5 and conclusion is drawn in Section 6.

2. Methodology

2.1. Refined LOS deformation based on the integration of CR-InSAR and GPS

Considering $N+1$ SAR images acquired in an ordered time sequence $[t_1,t_2, \ldots, t_{N+1}]$ and generating $Y$ interferograms, the flattened interferometric phase at CR point $(i, j)$ in $m$th interferogram can be expressed as (Kampes, 2006; Hanssen, 2001):

$$
\phi_{i,j}^{m} = -2k_{i,j}^{m} \pi + \phi_{def,i,j}^{m} + \phi_{topo,i,j}^{m} + \phi_{orb,i,j}^{m} + \phi_{atm,i,j}^{m} + \phi_{noi,i,j}^{m}
$$

(1)

where $k_{i,j}^{m}$ is integer ambiguity, $\phi_{topo,i,j}^{m}$ is the topographic phase, $\phi_{def,i,j}^{m}$ is the component due to the ground deformation in LOS direction between both SAR acquired time interval, $\phi_{atm,i,j}^{m}$ is the atmospheric delay phase, $\phi_{noi,i,j}^{m}$ is the phase due to the orbit errors, and $\phi_{noi,i,j}^{m}$ is the noise term that includes potentially thermal noise, decorrelation errors et al. Basically, topographic phase $\phi_{topo,i,j}^{m}$ is defined as:

$$
\phi_{topo,i,j}^{m} = -\frac{4\pi}{\lambda} B_{i,j}^{m} \frac{h_{i,j}}{R_{i,j}^{m} \sin \theta_{i,j}^{m}}
$$

(2)

where $B_{i,j}^{m}$ is the perpendicular baseline at CR $(i, j)$, $h_{i,j}$ corresponds to the height of $(i, j)$, $\lambda$ represents the radar wavelength, $R_{i,j}^{m}$ is the slant range distance from master sensor to target $(i, j)$, and $\theta_{i,j}^{m}$ is the incidence angle at CR $(i, j)$.

Phase $\phi_{def,i,j}^{m}$ is described by the LOS ground deformation $d_{i,j}^{m}$:

$$
\phi_{def,i,j}^{m} = -\frac{4\pi}{\lambda} d_{i,j}^{m}
$$

(3)

In order to simplify the Eq. (1), height and atmospheric delay (tropospheric delay and ionospheric delay) products derived from GPS are introduced to calculate topographic phase $\phi_{topo,i,j}^{m}$ and atmospheric delay phase $\phi_{atm,i,j}^{m}$. It should be noted that GPS-observed height needs to be converted to the SAR height system due to the different height datum between GPS and SAR system. Similarly, GPS-observed zenithal atmospheric delay should be converted to radar LOS direction. Generally, $\phi_{atm,i,j}^{m}$ and $\phi_{def,i,j}^{m}$ can also be weaken or even eliminated by constructing network in space since they are strongly correlated in space (Williams et al., 1998; Li et al., 2004, 2006). The noise phase $\phi_{noi,i,j}^{m}$ can be ignored for CR points because they can keep high coherence during a long time interval. Then, observation Eq. (1) is simplified as:

$$
\phi_{i,j}^{m} = -2k_{i,j}^{m} \pi - \frac{4\pi}{\lambda} d_{i,j}^{m} + \phi_{res,i,j}^{m}
$$

(4)

where $\phi_{res,i,j}^{m}$ represents the residual phase composed of the residual topographic phase, residual orbit phase, residual atmospheric phase and residual noise phase and can be taken as a random variable with an expectation $E(\phi_{res,i,j}^{m}) = 0$. After constructing the network, the double
phase difference between adjacent CR \((i, j)\) and \((k, l)\) can be expressed as:

\[
\Delta \phi_n^{m}(i,j)(k,l) = -2\Delta k_m^{m}(i,j)(k,l) \pi - \frac{4\pi}{\lambda} \Delta d_{\text{los}}^{m}(i,j)(k,l) + \Delta \phi_{\text{rest}}^{m}(i,j)(k,l) \tag{5}
\]

where:

\[
\begin{align*}
\Delta \phi_n^{m}(i,j)(k,l) &= \varphi_n^{m,i,j} - \varphi_n^{m,k,l} \\
\Delta k_m^{m}(i,j)(k,l) &= k_m^{m,i,j} - k_m^{m,k,l} \\
\Delta d_{\text{los}}^{m}(i,j)(k,l) &= d_{\text{los}}^{m,i,j} - d_{\text{los}}^{m,k,l} \\
\Delta \phi_{\text{rest}}^{m}(i,j)(k,l) &= \varphi_{\text{rest},i,j}^{m} - \varphi_{\text{rest},k,l}^{m}
\end{align*} \tag{6}
\]

The double integer ambiguity difference \(\Delta k\) can be determined through unwrapping the CR network, e.g., minimal cost flow (MCF) method, path-following method, and then the observation equation is written as:

\[
\Delta \phi_n^{m}(i,j)(k,l) = -\frac{4\pi}{\lambda} \Delta d_{\text{los}}^{m}(i,j)(k,l) + \Delta \phi_{\text{rest}}^{m}(i,j)(k,l) \tag{7}
\]

Time intervals for \(N+1\) SAR images are expressed as:

\[
t = [t_2 - t_1 \ t_3 - t_2 \ \cdots \ t_i - t_{i-1} \ t_{i+1} - t_i \ \cdots \ t_{N+1} - t_N]^T \tag{8}
\]

The corresponding time series deformation differences between adjacent CR \((i, j)\) and \((k, l)\) are written as:

\[
\Delta d_{\text{los}}^{m}(i,j)(k,l) = \sum_{p=m}^{t-1} \Delta d_{\text{los}}^{p}(i,j)(k,l) \tag{9}
\]

Expanding to \(Y\) interferograms:

\[
\Delta \phi_{\text{los}}^{m}(i,j)(k,l) = -\frac{4\pi}{\lambda} \times R \times \Delta d_{\text{los}}^{m}(i,j)(k,l) + \Delta \phi_{\text{rest}}^{m}(i,j)(k,l) \tag{10}
\]

where:

\[
\begin{align*}
\Delta \phi_{\text{los}}^{m}(i,j)(k,l) &= \Delta \phi_{\text{los}}^{1}(i,j)(k,l) \quad \Delta \phi_{\text{los}}^{2}(i,j)(k,l) \quad \cdots \quad \Delta \phi_{\text{los}}^{Y}(i,j)(k,l) \\
\Delta \phi_{\text{rest}}^{m}(i,j)(k,l) &= \Delta \phi_{\text{rest}}^{1}(i,j)(k,l) \quad \Delta \phi_{\text{rest}}^{2}(i,j)(k,l) \quad \cdots \quad \Delta \phi_{\text{rest}}^{Y}(i,j)(k,l)
\end{align*} \tag{11}
\]

The deformation difference in \(m\)th interferogram (assuming master image acquired time \(t_m <\) slave image acquired time \(t_i\)) can be expressed as a linear combination of Eq. (9):

\[
\Delta d_{\text{los}}^{m}(i,j)(k,l) = \sum_{p=m}^{t-1} \Delta d_{\text{los}}^{p}(i,j)(k,l) \tag{12}
\]

Expanding to \(Y\) interferograms:

\[
\Delta \phi_{\text{los}}^{m}(i,j)(k,l) = -\frac{4\pi}{\lambda} \times R \times \Delta d_{\text{los}}^{m}(i,j)(k,l) + \Delta \phi_{\text{rest}}^{m}(i,j)(k,l) \tag{13}
\]

where design matrix \(R\) describes the linear combination of phase difference for each interferogram. A simple least squares method (LS) is conducted to determine the time series deformation differences \(\Delta d_{\text{los}}^{m}(i,j)(k,l)\). Finally, time series deformations \(d_{\text{los}}\) for every CR in LOS direction are obtained by spatial integration along a stable reference CR point.

2.2. Along-slope deformation by combining CR-InSAR LOS deformation and GPS horizontal deformation

CR-InSAR can only measure the deformation along the LOS direction, which can not directly reflect the actual movement of the landslide, and should be projected to the down-slope direction. In this study, we try to combine the CR-InSAR measured LOS deformation and GPS measured horizontal deformation to monitor the down-slope direction movement of landslide. Down-slope deformation at CR \((i, j)\) can be expressed as (Cascini et al., 2010):

\[
d_{\text{slope},i,j} = d_{i,j} \times u_{i,j} \tag{14}
\]

\[
d_{i,j} = \begin{bmatrix} d_{\text{east},i,j} \\ d_{\text{north},i,j} \\ d_{\text{zenith},i,j} \end{bmatrix} \tag{15}
\]

\[
u_{i,j} = \begin{bmatrix} u_{\text{east},i,j} \\ u_{\text{north},i,j} \\ u_{\text{zenith},i,j} \end{bmatrix} = \begin{bmatrix} -\sin \varphi \cos \theta \\ -\cos \varphi \cos \theta \\ \sin \varphi \end{bmatrix} \tag{16}
\]

where \(d_{\text{slope},i,j}\) is the along-slope deformation, \(d_{i,j}\) is 3D deformation vector, \(u_{i,j}\) is the unit vector of slope, \(\varphi\) is defined as the local direction of steepest descent and \(\theta\) is defined as the angle between the north direction and the projection of the LOS on the horizontal surface (Cascini et al., 2010; Colesanti and Wasowski, 2006). 3D deformation is needed if we want to obtain the along-slope deformation based on Eqs. (15)-(17). The relationship between the LOS deformation \(d_{\text{los},i,j}\) and the 3D deformation \(d_{i,j}\) is defined as:

\[
d_{\text{los},i,j} = (d_{i,j})^T \times r_{i,j} \tag{17}
\]

where \(r_{i,j}\) is the unit vector of LOS, \(\theta\) is local incidence angle and \(\varphi\) is the satellite flight azimuth. The fact that GPS is more sensitive to the horizontal deformation comparing with the vertical deformation while CR-InSAR is more sensitive to the vertical deformation makes it possible to combine the GPS horizontal deformation and CR-InSAR LOS deformation to calculate high precision along-slope direction deformation. Considering Eq. (18), high precision vertical deformation at CR \((i, j)\) can be derived from CR-InSAR LOS deformation and GPS horizontal deformation:

\[
d_{\text{zenith},i,j} = \frac{d_{\text{los},i,j} - d_{\text{east},i,j}r_{\text{east},i,j} - d_{\text{north},i,j}r_{\text{north},i,j}}{r_{\text{zenith},i,j}} \tag{18}
\]

Finally, along-slope deformation is determined by combining Eqs. (15) and (19).
3. Data and experimental area

3.1. Background of experimental area

We take a potential landslide field located at the north of Shaanxi province, China, as the experimental area to verify the rationality of our method (Fig. 1(a)). The prior geological investigation showed that three landslides, marked as H1, H2 and H3, were zoned over the research region (Fig. 1(b)). H1 landslide, located at the rear of an oil storage factory, was a gully before 2008 and was landfilled to meet the needs of the construction of the factory in 2008, so it was a filling landslide. H1 landslide with main sliding direction of $210^\circ/C176$°, width of 118 m, length of 60 m, average of 6 m thickness, and volume of $4.25 \times 10^4$ m$^3$, belonged to a little-model landslide. Comparing with H1 landslide, H2 landslide belonged to a medium-model pull-type landslide, where main sliding direction is about $250^\circ/C176$°, slope angle is about $22^\circ/C176$°, the width is 250 m, length is 255 m, average of thickness is 15 m, volume is about $95.63 \times 10^4$ m$^3$. H3 landslide was a large-model ancient landslide, where main sliding direction is about $220^\circ/C176$°, slope angle is about $12^\circ/C176$°, the width is 255 m, length is 375 m, average of thickness is 15 m, volume is about $146.25 \times 10^4$ m$^3$. It was reported that some ground fissures were detected at these landslide regions since May 12th 2008 Wenchuan earthquake and therefore slope control technique was carried out to those unstable landslides in April 2009. Recently, the new ground fissures were observed by local residents, threatening the security of their lives and properties (Fig. 1(d)). With the purpose of giving the early warning and reducing the landslide damage, this study tries to use mentioned method to monitor the deformation of these active landslides.

3.2. Data introduction

3.2.1. InSAR data

In this study, four X-band stripmap-mode TerraSAR images with three meters spatial resolution and eleven days temporal resolution were acquired over the experimental region (Fig. 1(a)). Six interferograms were formed and the corresponding parameters are shown in Table 1. All the six interferograms were involved in the process due to the CR can preserve the high coherence under the large temporal baseline and perpendicular baseline (Zhu et al., 2010; Xu, 2010). Trihedral Corner Reflector (TCR) was installed at the potential landslide areas based on the radar incidence angle and flight angle (Fig. 2(a)) (Xia et al., 2004). The pixel-level location of TCR was easily identified by transferring the geodetic coordinate derived from the GPS to SAR coordinate (Fig. 2(b)). However, pixel-level location was not precise enough to position the phase centre of TCR and should be resampled to the sub-pixel-level location. This process can be carried out by interpolating the intensity map to search the maximal amplitude value for each TCR (Xia et al., 2004). Then, the location of the maximal amplitude value was considered as the phase

![Fig. 1. Background of the experimental area. (a) the shaded relief map of the experimental area, where the corresponding area are superimposed to the DEM, the black rectangle is the coverage of the SAR image, red rectangle is the coverage of the research area and the top-right corner is the geographic location of the experimental area; (b) three potential landslide regions zoned by red curve and marked as H1, H2 and H3 over the experimental area; (c) plan sketch of three potential landslide; (d) photographs of the three potential landslide. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)](image-url)
centre of TCR. In this study, we used 100 times factors to interpolate the intensity map in order to obtain the TCR location with the accuracy of 0.01 pixels (Fig. 2 (c)). It was worth noting that eight of ten TCRs were used to monitor the landslide movement in this study as two TCRs were destroyed in the image acquired in April 2011.

3.2.2. GPS data

GPS observation periods kept consistent with the time of SAR image with the purpose of obtaining the synchronous products. In this experiment, chock ring antenna (Mode: LeiAT504) and dual-frequency GPS receiver (Mode: LeicaGRX1230) were installed on the observation platforms, as shown in the Fig. 3(a). Some measures were established to ensure the high quality observations, e.g., observation time was more than 6 h, number of effective satellites was more than 4, and time sampling interval was 15 s. Two stations were selected as the reference points in the GPS processing and the network was shown in Fig. 3(b). Table 2 showed the final GPS-measured 3D deformation and corresponding root mean square error (RMSE) from April 9 2011 to August 30 2011. This result has subtracted the deformation in DJ01 in order to keep consistent with the CR-InSAR, which took DJ01 as the reference point.

4. Results and analysis

4.1. LOS deformation

LOS deformation was obtained from the method introduced in the Section 2.1, where conventional InSAR processing was conducted by GAMMA SAR software (Werner et al., 2000). Main processing strategies were listed as follow: (1) intensity cross-correlation method was applied to coregistrare the master and slave images with Table 1

<table>
<thead>
<tr>
<th>Number</th>
<th>Master</th>
<th>Slave</th>
<th>Temporal baseline (days)</th>
<th>Perpendicular baseline (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20110409</td>
<td>20110420</td>
<td>11</td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>20110409</td>
<td>20110808</td>
<td>121</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>20110409</td>
<td>20110830</td>
<td>143</td>
<td>-336</td>
</tr>
<tr>
<td>4</td>
<td>20110420</td>
<td>20110808</td>
<td>110</td>
<td>15</td>
</tr>
<tr>
<td>5</td>
<td>20110420</td>
<td>20110830</td>
<td>132</td>
<td>-351</td>
</tr>
<tr>
<td>6</td>
<td>20110808</td>
<td>20110830</td>
<td>22</td>
<td>-366</td>
</tr>
</tbody>
</table>

Fig. 2. (a) Field photo of the Corner Reflectors installed over the experimental area; (b) CRs are identified in the intensity map; (c) CR is resampled to determine the sub-pixel-level location.

Fig. 3. (a) Field photo of the GPS in this study; (b) GPS network, where blue circles stand for the reference points and red circles stand for the monitoring points. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
the aim at making sure coregistration precision be better than eighth pixel; (2) generating flattened interferograms; (3) extracting CR phase from the flattened interferograms at the sub-pixel-level location; (4) removing the topographic phase and atmospheric delay phase using GPS-measured height and atmospheric delay. (5) creating CR Delaunay triangulation network; (6) unwrapping the CR network with the MCF method (Costantini and Rosen, 1999); (7) spatial integration along reference CR to obtain LOS displacements. In this experiment, DJ01 was taken as the reference CR to produce the time series deformation of DJ02–DJ08 in LOS direction.

The atmospheric effect on CR-InSAR model was mainly from the ionosphere and troposphere. Generally, ionospheric effect was more significant at the low frequency SAR system (e.g., L-band) while was very weak at the high frequency SAR system (e.g., C-band and X-band) (Hansen, 2001; Xu et al., 2008). Therefore, we only estimated the tropospheric delay in this study using the GAMIT software. After transferring the zenith direction to the LOS direction, the tropospheric phase delay difference between April 9 2011 and August 30 2011 was shown in Fig. 4(a). It was observed from the Fig. 4(a) that the tropospheric phase delay among the eight CR points changed slightly: the standard deviation was 0.13 mm and the maximum difference was 0.3 mm. We think this slight change is due to the short distance among the CR points, where the maximum distance is 351 m (Fig. 4(b)). In view of this point, the atmospheric delay phase in this case was almost cancelled when performing the double phase difference.

Topographic phase was estimated and then removed from the CR-InSAR model based on the Eq. (2), where GPS-measured elevation was involved in the calculation. In order to show the differences with and without the GPS-measured elevation, the LOS deformation spanning from the April 9 2011 to August 30 2011 derived from the DInSAR and CR-InSAR was shown in Fig. 5. In this case, the DInSAR selected the ASTER GDEM with 1 arc-second (approximately 30 m) spatial resolution as the external DEM to remove the topographic phase (Fujisada et al., 2005). Prior comparison of the elevation difference between the ASTER GDEM and the GPS-measured elevation at CR points shows that the maximum difference between them is 43 m, the minimum is 23 m and the average is 30 m (Table 3). It’s no doubt that this difference can inevitably cause the difference of LOS deformation between DInSAR and CR-InSAR in Fig. 5. In the same situation, we calculated the difference of LOS deformation between

---

Table 2
3D deformation and corresponding precision observed by the GPS technique (20110409–20110830).

<table>
<thead>
<tr>
<th>Station ID</th>
<th>DN (mm)</th>
<th>RMSE of DN (mm)</th>
<th>DE (mm)</th>
<th>RMSE of DE (mm)</th>
<th>DV (mm)</th>
<th>RMSE of DV (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DJ02</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>-6</td>
<td>4</td>
</tr>
<tr>
<td>DJ03</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>DJ04</td>
<td>-3</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>-7</td>
<td>4</td>
</tr>
<tr>
<td>DJ05</td>
<td>0</td>
<td>1</td>
<td>-1</td>
<td>1</td>
<td>-2</td>
<td>4</td>
</tr>
<tr>
<td>DJ06</td>
<td>-4</td>
<td>1</td>
<td>-2</td>
<td>1</td>
<td>-10</td>
<td>4</td>
</tr>
<tr>
<td>DJ07</td>
<td>-3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>-15</td>
<td>4</td>
</tr>
<tr>
<td>DJ08</td>
<td>4</td>
<td>1</td>
<td>-6</td>
<td>1</td>
<td>-34</td>
<td>4</td>
</tr>
</tbody>
</table>

DN: Deformation in north direction.
DE: Deformation in east direction.
DV: Deformation in vertical direction.
RMSE: Root Mean Square Error.

Fig. 4. (a) GPS measured tropospheric delay in LOS direction between the April 9th 2011 and August 30 2011 at SAR time; (b) the CR Delaunay triangulation network, where DJ01 is taken as the reference point.
DInSAR and CR-InSAR and found that the maximum difference is $17.4 \text{ mm}$, the minimum is $6.4 \text{ mm}$ and the average is $12.6 \text{ mm}$ (Table 3). The correlation between the elevation difference and the LOS deformation difference is about $0.78$, indicating the main error contribution of the DInSAR result is from the inaccurate DEM.

The final LOS deformation during April 20th 2011 to August 30 2011 is shown in Fig. 5 (b). As for the precision of this result, we estimated it from the component of interferometric phase described in Eq. (1). Firstly, topographic phase error can be neglected due to the accurate elevation product derived from GPS. Then, the process of phase unwrapping is regarded as valid when considering the small deformation in this case (Table 3) and the comparable result with GPS (Table 2). Thirdly, owning to the deployed reflectors very close to each other, atmospheric phase delay error and orbit error can be reasonably cancelled by the double phase difference. Subsequently, inherent phase noise error is estimated from the signal-to-clutter ratio (SCR) described in (Ferretti et al., 2007). In this case, the LOS deformation error caused by the phase noise is about $0.2 \text{ mm}$ for each CR points (Table 4). The last error source is the artificial error when installing the CR on the observation platform. The CR is firstly assembled to keep the steady of the structure and then is fixed to the centre of the platform through fastening nut with $0.3 \text{ mm}$ screw pitch. During the process of fixing, it is estimated that the artificial error is about 2 screw pitch ($0.6 \text{ mm}$). Therefore, the conservative precision of LOS deformation in this case is about $1 \text{ mm}$.

### 4.2. Along-slope direction deformation

The main processing procedure to produce the along-slope direction deformation was described as: (1) reading the local incidence angle and satellite flight azimuth to calculate the unit vector of LOS direction using Eq. (19). In our experiment, average local incidence angle was about $35^\circ$ and satellite flight azimuth for ascending orbit was about $-7.44^\circ$. The scaling factors in east, north and vertical were about $-0.586$, $-0.074$ and $0.819$, respectively.

### Table 3

<table>
<thead>
<tr>
<th>Station ID</th>
<th>DInSAR LOS Deformation (mm)</th>
<th>CR-InSAR LOS Deformation (mm)</th>
<th>The differences (mm)</th>
<th>DEM error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DJ02</td>
<td>$13.5$</td>
<td>$0.8$</td>
<td>$12.7$</td>
<td>$26$</td>
</tr>
<tr>
<td>DJ03</td>
<td>$14.6$</td>
<td>$1.1$</td>
<td>$13.5$</td>
<td>$25$</td>
</tr>
<tr>
<td>DJ04</td>
<td>$9.9$</td>
<td>$3.5$</td>
<td>$6.4$</td>
<td>$23$</td>
</tr>
<tr>
<td>DJ05</td>
<td>$15.1$</td>
<td>$2.9$</td>
<td>$12.2$</td>
<td>$28$</td>
</tr>
<tr>
<td>DJ06</td>
<td>$25.3$</td>
<td>$11.7$</td>
<td>$13.6$</td>
<td>$34$</td>
</tr>
<tr>
<td>DJ07</td>
<td>$22.9$</td>
<td>$9.1$</td>
<td>$12.8$</td>
<td>$34$</td>
</tr>
<tr>
<td>DJ08</td>
<td>$35.5$</td>
<td>$18.1$</td>
<td>$17.4$</td>
<td>$43$</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td></td>
<td>$12.6$</td>
<td>$30$</td>
</tr>
</tbody>
</table>

### Table 4

<table>
<thead>
<tr>
<th>Station ID</th>
<th>SCR (dB)</th>
<th>LOS deformation error (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DJ02</td>
<td>$69.5$</td>
<td>$0.2$</td>
</tr>
<tr>
<td>DJ03</td>
<td>$71.3$</td>
<td>$0.2$</td>
</tr>
<tr>
<td>DJ04</td>
<td>$71.3$</td>
<td>$0.2$</td>
</tr>
<tr>
<td>DJ05</td>
<td>$71.4$</td>
<td>$0.2$</td>
</tr>
<tr>
<td>DJ06</td>
<td>$69.7$</td>
<td>$0.2$</td>
</tr>
<tr>
<td>DJ07</td>
<td>$69.5$</td>
<td>$0.2$</td>
</tr>
<tr>
<td>DJ08</td>
<td>$68.2$</td>
<td>$0.2$</td>
</tr>
</tbody>
</table>

SCR: signal-to-clutter ratio.
indicating the LOS deformation mainly came from the contribution of east direction and vertical direction; (2) computing the high precision vertical deformation by integrating of the CR-InSAR measured LOS deformation with the GPS measured horizontal deformation (Table 5). According to the error propagating theory, the estimated precision of vertical deformation was about 1.4 mm, which was about the one-third of the GPS measured precision; (3) generating unit vector of slope direction by introducing the slope angle and slope azimuth using Eq. (17) (Table 5); (4) producing the along-slope direction deformation through Eq. (15). The final result spanning from April 9 2011 to August 30 2011 was delineated by Fig. 6, where the left picture showed the result derived from this paper’s method and the right picture showed the result from the GPS observation.

5. Discussion

As shown in Fig. 6, the along-slope direction deformation presents the similar trend at seven CR points during April 9 2011 to August 30 2011 between our method and GPS, indicating the validation of our method. However, the magnitudes between both methods are different, where the RMSE of difference is about 1.89 mm, the maximum difference is −3.06 mm and the minimum difference is 0.65 mm. It is no doubt that different vertical displacement between both techniques leads to the differences in along-slope direction deformation. As already mentioned, the precision of vertical deformation derived from our proposed method is about three times better than GPS technique. Therefore, the precision of along-slope direction deformation should also be better than GPS. In this case, it is about two times better for our method (±1.1 mm) versus GPS (±2.1 mm) based on the error propagating theory (Fig. 6).

It is observed from the Fig. 6 that almost all of the CRs’ displacements in along-slope direction present the negative values at the different levels, suggesting these points are the trends of sliding down along the slope at different levels from April 9 2011 to August 30 2011, especially for DJ02, DJ06, DJ07 and DJ08. Further investigation shows that the points where landslide control techniques have been implemented in April 2009 present the relatively small movements e.g., DJ03, DJ04 and DJ05, while the points where landslide control techniques have not been implemented present the relatively large movements, e.g., DJ02, DJ06, DJ07 and DJ08. This phenomenon reflects the rationality of the result from another point.

Table 5

<table>
<thead>
<tr>
<th>Station ID</th>
<th>( \mu_{\text{north}} )</th>
<th>( \mu_{\text{east}} )</th>
<th>( \mu_{\text{zenith}} )</th>
<th>( \text{D}V_{\text{CR-InSAR+GPS}} ) (mm)</th>
<th>RMSE (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DJ02</td>
<td>0.28</td>
<td>0.82</td>
<td>0.49</td>
<td>−3.2</td>
<td>1.4</td>
</tr>
<tr>
<td>DJ03</td>
<td>0.11</td>
<td>0.86</td>
<td>0.49</td>
<td>−1.3</td>
<td>1.4</td>
</tr>
<tr>
<td>DJ04</td>
<td>0.36</td>
<td>0.79</td>
<td>0.49</td>
<td>−4.5</td>
<td>1.4</td>
</tr>
<tr>
<td>DJ05</td>
<td>0.28</td>
<td>0.82</td>
<td>0.49</td>
<td>−4.2</td>
<td>1.4</td>
</tr>
<tr>
<td>DJ06</td>
<td>0.64</td>
<td>0.58</td>
<td>0.37</td>
<td>−16.0</td>
<td>1.4</td>
</tr>
<tr>
<td>DJ07</td>
<td>0.78</td>
<td>0.37</td>
<td>0.37</td>
<td>−9.3</td>
<td>1.4</td>
</tr>
<tr>
<td>DJ08</td>
<td>0.78</td>
<td>0.37</td>
<td>0.37</td>
<td>−25.8</td>
<td>1.4</td>
</tr>
</tbody>
</table>

\( \mu_{\text{north}} \): North unit vector of slope direction.

\( \mu_{\text{east}} \): East unit vector of slope direction.

\( \mu_{\text{zenith}} \): Vertical unit vector of slope direction.

\( \text{DV}_{\text{CR-InSAR+GPS}} \): Vertical deformation derived from combining of CR-InSAR and GPS.
6. Conclusion

Monitoring the landslide deformation and giving the early warning are an important element in reducing and preventing the landslide damage. InSAR technique has demonstrated its potential for the landslide monitoring under the certain conditions. However, the limitations are found in the application of the InSAR technique to the landslide monitoring. In such situation, combining of the CR-InSAR and GPS techniques is proposed to overcome these limitations in this study. The main advantages of this method is embodied in: (1) overcoming the limitation of temporal decorrelation in InSAR; (2) removing the residual topographic phase error in CR-InSAR model; (3) eliminating the atmospheric delay error; (4) obtaining high precision along-slope direction deformation. In this paper, we firstly introduced the theory of creating along-slope direction deformation by integrating of the CR-InSAR and GPS techniques. Then, for testing the proposed method, four X-band stripmap-mode TerraSAR images, eight Trihedral Corner Reflectors (TCR) data and eight GPS observed data were collected to monitor the deformation of the three potential landslide field located at the north of Shaanxi province, China. Owning to the deployed reflectors very close to each other, atmospheric phase delay error and orbit error can be reasonably cancelled by the double phase difference in this case. The topographic phase is clearly removed with the help of the accurate elevation product derived from GPS. Therefore, the conservative precision of LOS deformation in this case can reach to 1 mm. In order to retrieve the along-slope deformation, high precision vertical deformation is computed by combining the CR-InSAR measured LOS deformation and GPS measured horizontal deformation. The result shows that the estimated precision of the vertical deformation is about 1.4 mm, which is almost three times better than the GPS. The same situation, the precision of estimated along-slope deformation is about two times better for proposed method (±1.1 mm) versus GPS (±2.1 mm). Our result indicates that almost all of the monitoring points present the trends of sliding down along the slope at the different levels from April 9 2011 to August 30 2011, showing the certain instability. The relationship between the magnitude of displacement and implementation of early control reflects the rationality of the result. Our result could provide of the strong support in the high precision landslide deformation monitoring.

Acknowledgements

This research was funded by Chang’an university (Xi’an, China) through Natural Science Foundation of China projects (NSFC) (Nos.: 40802075,41072266,41274005,41202189 and 41372375), the Ministry of Land & Resources (China) projects (No: 1212011220142, 1212010914015) and by Hong Kong Polytechnic University (Hong Kong, China) through Research Grants Council of the Hong Kong projects (PolyU5154/10E, PolyU5146/11E). TerraSAR-X data are provided under DLR research proposal (paver_- GEO1366). We are also grateful to the anonymous reviewer and the Editor, Prof. Shuanggen Jin, for their constructive comments to improve this paper.

References


