Using advanced InSAR time series techniques to monitor landslide movements in Badong of the Three Gorges region, China

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ARTICLE INFO

Article history:
Received 23 March 2011
Accepted 21 October 2011

Keywords:
Landslide
Three Gorges
InSAR
Small baseline InSAR
Time series

ABSTRACT

The Three Gorges occupy 193 km of the middle reaches of the Yangtze River between Fengjie in Chongqing and Yichang in Hubei Province, China. Due to steep valley–side slopes and long-term river incision, landslides are a major hazard in the Three Gorges region. In this study, we employ the SBAS InSAR technique to process Envisat SAR images collected between 2003 and 2010. Our time series results enable identification of two distinct landslides with deformation rates of up to 10–15 mm/yr in Badong County, and field evidence is used to verify the positions of these failures. With both descending and ascending observations, two-dimensional velocity fields in north and up directions are recovered to better understand the landslide movements. Obvious correlation between seasonal landslide movements and water level changes is observed, which not only provides strong support of our InSAR time series results, but also indicates the impacts of water level changes to landslide activities.

1. Introduction

The Yangtze River, the third longest in the world and the longest in China, is a major waterway that has been the location of human settlement for millennia (Beardsley et al., 1985; Wright and Nittouer, 1995). The Three Gorges region, in the middle reaches of the Yangtze River where it is deeply incised into bedrock, is an area of known geological hazards including landslides and rock falls. Construction of the Three Gorges dam (Shen and Xie, 2004; Wang, 2002) began in 1994, and since June 2003 the dam has provided hydro-electrical power and has assisted downstream flood control. The Three Gorges reservoir is approximately 663 km long and up to 1576 m wide at the designed highest water level of 175 m above sea level (SCGPGCEO, 2008). The average water level rise after the dam’s construction is about 110 m and the water level varies between 145 m and 175 m bi-annually. The frequency of water level change is greater than under pre-existing natural conditions (Yin and Li, 2001). Consequently, the changeable hydro-geological conditions of the landslide zones will affect slope stability in the region, in addition to the threat from heavy summer precipitation (He et al., 2008). These slope instabilities include the reactivation of old landslides and the triggering of new failures in the new settlements which house 1.27 million immigrants (Liu et al., 2004; SCGPGCEO, 2009). In the third period of the hazard prevention and control project of the Three Gorges region from 2005 to 2011, 2977 potentially unstable sites were identified of which 2686 were classified as slump–masses but only 255 of these sites have been treated with engineering methods (Caijing Magazine, 2009).

Significant landslides occurred in the Three Gorges region prior to the dam construction. Two landslides occurred in the Huangtupo zone, Badong County on June 10th 1995 and November 20th 1995 causing a total of 5 deaths and 9 injuries (Wu et al., 2006). On June 12th 1985, 1371 local residents were evacuated when surveyors observed the beginning of a landslide (Wang and Tan, 1991). After evacuation, about $3 \times 10^6$ m$^3$ of landslide debris destroyed the whole of Xiantan Town, blocked one-third of the width of the Yangtze River and triggered a wave in the river up to 54 m above the normal flow level along a 42 km river reach (Wang and Tan, 1991). This example shows the scale of the pre-dam hazard and illustrates how landslide monitoring successfully saved lives following long-term landslide monitoring in the region. Unfortunately, frequent monitoring of large areas is difficult due to the nature of the terrain affecting both conventional surveys and inhibiting GPS signals.

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Interferometric Synthetic Aperture Radar (InSAR) employing radar waves transmitted from spaceborne antennae and backscattered from the Earth’s surface can be used to detect range changes between different radar acquisitions (Massonnet and Feigl, 1998). With its wide coverage and sub-centimeter accuracy, InSAR has been used to study dynamic surface processes including earthquakes and faults (Massonnet et al., 1993; Gourmelen et al., 2010), volcano dynamics (e.g. Massonnet et al., 1995; Lu et al., 2010; Lu and Dzurisin, 2010), glacier movement (Goldstein and Engelhardt, 1993), subsidence and landslides (e.g. Fruneau et al., 1996; Colesanti and Wasowski, 2006; Strozzi et al., 2010; Tomas et al., 2010). However, the application of conventional InSAR is limited by three major factors: error in the digital elevation model (DEM) used in interferometric processing; temporal and spatial decorrelation; and atmospheric effects.

Firstly, each interferogram contains topographic information in the form of fringes, known as topography fringes. To measure surface deformation, the topography fringes should be removed. This is usually implemented using a DEM (e.g. SRTM DEM, ASTER GDEM) and satellite geometry information. Both the uncertainty in DEM itself and the inaccurate satellite geometry information generate DEM errors in the topography removal step. As the impact of DEM errors on interferograms is a function of perpendicular baselines, DEM errors can be estimated with multiple interferograms.

Secondly, changes in the scattering properties of the Earth surface, often caused by changes in vegetation or dielectric properties of soil, are referred to as temporal decorrelation effects (Zebker and Villasenor, 1992). The Three Gorges region has high and spatially variable vegetation densities (e.g. in the Yichang City area, near the Three Gorges, Zhang et al. (2009a) report land cover as: 41.4% forest, 28.8% cultivated crops, 1.8% dense grass, 6.7% medium and sparse grass, 10.9% shrubs, 7.2% water, 3.0% urban residential and 0.2% bare land), which causes significant decorrelation. The longer the time interval between radar images, the greater the temporal decorrelation can be. Spatial decorrelation occurs due to different incidence angles of radar beams during radar scanning (Zebker and Villasenor, 1992). The longer the perpendicular baseline (i.e. satellite separation) between the radar images, the higher the likelihood of spatial decorrelation.

Thirdly, the phase delay in radio signal propagation through the atmosphere (especially the part due to tropospheric water vapour) represents one of the major limitations of repeat-pass InSAR (Hansen, 2001; Li et al., 2005, 2006, 2009a,b). Zebker et al. (1997) suggested that a 20% spatial or temporal change in relative humidity could result in a 10–14 cm error in deformation measurement retrieval, independent of baseline parameters.

All the three abovementioned issues can be addressed with the Small Baseline Subset (SBAS) InSAR technique, which uses interferograms with small baselines to minimize the effects of baseline decorrelation and inaccuracies in topographic data used (e.g. Berardino et al., 2002; Mora et al., 2003; Lanari et al., 2007; Hooper, 2008). The Badong area of the Three Gorges has previously been studied by Perissin and Ferretti (2007) and Wang et al. (2008) using both Quasi Persistent Scatterers technique (QPS) and StaMPS/PS technique (Hooper et al., 2007). They detected two subsidence areas on the south bank of Yangtze River using four-year Envisat ASAR descending track data from Tracks 075 and 347 collected between August 2003 and June 2007 (Wang et al., 2008).

Corner reflectors can be used as stable targets during radar acquisitions, and have been utilised in the Three Gorges region (Xia et al., 2004). Corner reflectors can maximize the radar cross section and backscattering power, so a pixel containing a corner reflector should appear as a bright point on a radar amplitude image. Ten Artificial Triangular Trihedral Corner Reflectors were installed in the Three Gorges to study mass movements. An experiment with manual adjustments of the corner reflector heights showed a high ratio of failure detection mainly due to atmospheric effects (Xia et al., 2004). This highlights the difficulties of using InSAR in this region, which also suggests the importance of the mitigation of atmospheric effects to obtain a reliable solution. In this paper, we focus on the Badong region (Fig. 1) and identify land movements using the StaMPS/PS technique (Hooper, 2008) with Envisat ASAR datasets spanning seven years. Firstly, the small baseline method is used to detect coherent pixels throughout the seven years by forming a robust small baseline interferometric network with reliable interferometric pairs (Fig. 2). Secondly, unlike QPS, StaMPS/BSAS does not require any assumed deformation model, so no prior knowledge of the temporal pattern of deformation is required. Thirdly, previous studies (e.g. Wang et al., 2008) only show surface displacement signals in the radar line of sight (LOS). In this paper, two descending (i.e. Tracks 075 and 347) and one ascending (i.e. Track 068) tracks are employed to derive 2D landslide surface movements. Fourthly, correlations between water level changes, rainfall and landslide movements are investigated.

2. Advanced InSAR time series techniques

The small baseline approach proposed by Berardino et al. (2002) combines interferograms with a small perpendicular baseline, small time interval and small Doppler centre frequency difference to create a dataset which minimizes the spatial decorrelation and topographic error for the group of small baseline interferograms. Minimum coherence of 0.5, decorrelation time of 1500 days and critical baseline of 1070 m are set to find the initial small baseline network. Visual inspection is then applied to exclude the interferograms with low coherence in the small baseline network.

The slowly decorrelating filtered phase (SDFP) pixels are selected in further time series analysis because radar echoes from SDFP pixels have Gaussian circular statistics and are independent from noise, remaining detectable over a long time period (Hooper, 2008). For SDFP pixels dominated by Gaussian scattering mechanisms, amplitude dispersion $D_A$ is used as a good indication of phase stability to reduce the number of SDFP candidates (Hooper, 2008). The selection of amplitude dispersion follows the method introduced in Peyret et al. (2011). A wide range of amplitude dispersion index thresholds are set to process the small baseline interferogram datasets. A higher threshold results in a denser SDFP map, but the chance of including unreliable deformation may also increase. Above a certain threshold, the mean velocity pattern ceases to conform to the ones with lower thresholds. Therefore, the highest threshold which keeps the mean velocity similarity with lower thresholds is chosen. In this study, an amplitude dispersion threshold of 0.6 was adopted to increase computational efficiency during the search for SDFP pixels. After amplitude analysis, the SDFP pixels are refined using the spatial correlation of phase measurements (Hooper, 2008).

Integer cycle ambiguities of the wrapped phase of SDFP pixels are estimated using the three-dimensional SNAPPHU phase unwrapping approach (Chen and Zebker, 2001; Hooper and Zebker, 2007). The unwrapped interferograms are then inverted to obtain the time series of phase change of SDFP pixels using a least-squares method (Schmidt and Bürgmann, 2003). In this study a 2π phase change corresponds to a range change of 28.1 mm (i.e. half-wavelength) for conversion from phase to range.

Spatially correlated DEM error due to inaccurate DEM mapping is estimated by bandpass filtering of surrounding pixels, and spatially uncorrelated DEM error due to phase centre deviation can be estimated through its correlation with the perpendicular baseline (Hooper, 2008). The estimated DEM errors are then removed in our results. The effects of atmospheric delay in the reference
SAR image can be estimated as the signals present in every relevant interferogram, and atmospheric effects in slave images can be derived using spatial and time filtering. However, the performance of atmospheric filtering varies from case to case, as it can easily lead to misestimation of deformation signals if both deformation and atmospheric noise represent similar patterns and temporal behaviors (Peltier et al., 2010). In this study, we therefore estimated a best-fit plane of each unwrapped interferogram to account for orbit errors and long wavelength atmospheric effects (Ofeigsson et al., 2011), because the area of interest is small (∼2.5 km × 8.0 km). A comparison between InSAR time series with atmospheric filtering and those with a best-fit plane suggested that higher deformation consistency between adjacent descending tracks was achieved when a best-fit plane was used to account for atmospheric effects.

3. Study area

3.1. Data

Three groups of Envisat ASAR images were used to investigate the Badong landslides: 41 images from Track 075 collected between August 2003 and July 2010 (Fig. 2a), 31 images from Track 347 collected between January 2004 and April 2010 (Fig. 2b), and 13 images from Track 068 collected between December 2008 and March 2010 (Fig. 2c). The former two are descending tracks where Badong is observed by the Envisat ASAR antenna from the east, while the last one is an ascending track where Badong is observed from the west. The radar line of sight (LOS) deformations are thus different as are the real surface displacements projected onto different LOS directions.

3.2. Geological setting

3.2.1. Geological setting of the Badong area

The Three Gorges is formed by severe incision of Palaeozoic and Mesozoic limestone dominated mountains although there is a debate on the timing (Li et al., 2001; Richardson et al., 2010). According to Liu et al. (2004), landslides in Badong mainly occur in soft lithology blocks that are composed of sandstone, thin limestone and shale formations. General geological conditions of Badong are given in Fig. 3(a).

3.2.2. Geological setting of the Huangtupo landslide

The Huangtupo area was constructed after May 1984 as much of the old Badong County is now beneath the Three Gorges reservoir water level. There are ∼20k residents in the area potentially affected by the Huangtupo landslide, at least until the completion of a new district, Shennongxi, to which Huangtupo residents will be further relocated. Two landslide events occurred in the Huangtupo zone of Badong County (Fig. 1) on June 10th 1995 and November 20th 1995, respectively, which highlights the continuing risk and the necessity of continued landside monitoring.

The Huangtupo landslide is located between two narrow, steep gullies draining into the Yangtze River (Fig. 3(b)). The surface of the Huangtupo landslide has gradients of approximately 40°, 15–20° and 30–35° in the upper, middle and lower parts, respectively. Wu et al. (2006) reported that the Huangtupo landslide has two Triassic geological units: T2b2 and T2b3 (Fig. 3(b)). The upper Unit T2b2 is approximately a 10 m thick pelite alternating with pelitic siltstone layers containing 40–65% clay minerals, predominantly illite. Unit T2b3 is a 364 m thick pelitic limestone. Failure of Unit
T₂b² from the upper part of the Huantupo landslide covered some lower areas so some of this older T₂b² is found on the top of the younger T₂b² in the middle part of the landslide (Wu et al., 2006). Limited borehole data from the Yangtze River Water Resources Commission show that Huantupo is a deep-seated landslide, with

Fig. 3. (a) Geological structure of Badong (adapted from Deng et al., 2000). Legends: 1: banks of Yangtze River; 2: dipping faults to the north; 3: strike-slip faults; arrow in direction of slip; 4: syncline; 5: anticline; 6: rough location of Huantupo. (b) Geological map of the Huantupo landslide (adapted from Deng et al., 2000; Tang and Hu, 2009). 1: Huantupo landslide; 2: pelitic limestone, Badong formation; 3: pelite alternating with pelitic siltstone, Badong formation; 4: loose rock fall deposits; 5: location of ongoing rock creep and toppling; 6: landslide boundary between purplish-red debris originating from 3 and khaki materials from 4; 7: boundary of area of toppling failure; 8: surface slope direction; 9: cleavage attitude; 10: perpendicular cleavage. Points marked 1 and 2 are the 1995 landslide locations.

a failure surface depth of about 50–100 m and has a volume of 40 × 10⁶ m³ (Wu et al., 2006).

4. Time series results

4.1. Mean velocities

As no independent ground truth data are available in this area, Badong city council building was chosen as a reference. This is because no landslide risk has been reported here. The mean value of all the pixels in the reference area (which varied from 4 to 6 on different images) is set to zero for each Track. The two landslides identified in Fig. 4 are referred to here as the West and East landslides. Liu et al. (2004) reported there are seven known landslides in Badong. However, the locations and dimensions of the landslides given by Liu et al. (2004) are not completely consistent with the landslide trace pattern described by Wu et al. (2009). The East landslide is the Huantupo landslide described in Deng et al. (2000), Tang and Hu (2009) and Wu et al. (2009). The west landslide lies close to the west of Zhaoshuling landslide described in Liu et al. (2004) (Fig. 4). Because of the lack of obvious deformation signals in Zhaoshuling landslide, only Huantupo landslide in Liu et al. (2004) is discussed in this study.
The standard deviation of the mean velocity at each coherent pixel provides an estimate of the precision of the mean velocity estimates (Fig. 5). There are two possible implications of the standard deviations: (1) the higher the standard deviation, the lower (worse) the precision of the corresponding mean velocity; and (2) as the mean velocity assumes linear deformation, a high standard deviation may suggest that this assumption is not sound, i.e. the deformation may not be temporally linear. It is likely that the instant deformation rate is greater than the mean velocity and deformation increments between adjacent images may provide better information on the hazard. The two adjacent Tracks 075 and 347 are used to assess the accuracy of the mean velocity estimates in the study (Section 4.2) to improve confidence in the estimates of mean velocity. The coefficient of variation (CV) is defined as the ratio of the standard deviations (Fig. 5) to the mean velocities (Fig. 4). The CV values range from 0 to 0.3 for most SDPP pixels in landslide areas of Tracks 075, 347 and 068, so the mean velocities derived from Tracks 075 (Fig. 4a), 347 (Fig. 4b) and 068 (Fig. 4c) are robust estimates of deformation at SDPP pixels in the landslide area. Although the standard deviations for Track 068 (Fig. 5c) on most pixels in the East and West landslides are relatively low as 1–3 mm/yr, the standard deviations (Fig. 5c) for pixels adjacent to the Yangtze River in the East landslide areas are still as high as 5–7 mm/yr. The short data period of 15 months for the 13 SAR images from Track 068 may account for this variability, especially as deformation adjacent to the river may be influenced by water level fluctuations in the dam.

4.2. Validation of InSAR time series

Data from both landslides show progressive lowering of the ground surface, and data from different tracks are generally consistent (Fig. 6). Overall deformation is of the order of 20–40 mm over a seven-year period, but phases of both relative upward ground movement and more rapid downward movement are identified. The two adjacent descending tracks (i.e. Tracks 075 and 347) have similar incidence and azimuth angles, and both span the full time interval between 2004 and 2010. Comparisons between these...
tracks are used to assess the accuracy of InSAR derived time series results. As both Tracks 075 and 347 were acquired within the same incidence angle of 23° in Swath I2 mode, the deformations compared are still in the radar line of sight.

RMS is estimated by the displacement differences between the estimated displacement values from Track 347 and the interpolated displacement values from Track 075 at the SAR acquisition times of Track 347. The systematic offset due to different reference images is also considered. The RMS values for Points P1, P2, P3 and P4 in Fig. 4 are 1.68, 5.91, 3.11 and 2.57 mm, respectively. For these four points, the RMS values between Tracks 075 and 347 are much smaller than the magnitude of deformation, which suggests that the deformation time series is consistent between the two tracks.

The mean velocities derived from the deformation time series are also compared for each common pixel of Tracks 075 and 347 (Fig. 7). Although these velocity differences are up to 5 mm/yr, 57% of pixels have differences less than 1 mm/yr. This consistency in velocities suggests that the deformation time series and velocities from our study are reliable.

4.3. Two-dimensional velocity fields

Descending and ascending tracks have different incidence and azimuth angles and provide different perspectives on ground movement. Previous studies have used multiple interferograms with different geometries to recover 2D and/or 3D surface displacement fields (Fialko and Simons, 2001; Wright et al., 2004; Gourmelen et al., 2007; Bechor and Zebker, 2006). A similar approach is used to investigate 2D velocity fields in Badong with three LOS mean velocity maps from Tracks 068, 075 and 347. The similar satellite geometries for 075 and 347 does not allow full recovery of 3D north, east and vertical velocities, but 2D north and vertical velocities can be recovered assuming that there is no movement in the west–east direction. During field inspection of the Huangtupo area, parallel surface cracks were observed in hill slope materials, roads and buildings at different elevations with a W–E orientation, suggesting that landslide movement is likely to be dominated by north and vertical components. Their observation equations can be written as:

\[
\begin{pmatrix}
\sin \phi_075 \sin \theta_{075} \\
\sin \phi_{068} \sin \theta_{068} \\
\sin \phi_{347} \sin \theta_{347}
\end{pmatrix}
\begin{pmatrix}
V_n \\
V_e \\
V_d
\end{pmatrix}
=
\begin{pmatrix}
V_{LOS075} \\
V_{LOS068} \\
V_{LOS347}
\end{pmatrix}
\]

where \(\phi\) is the azimuth of the satellite heading vector (positive from North) and \(\theta\) is the radar incidence angle. Subscripts 075, 068 and 347 are the track numbers, and \(n\) and \(e\) refer to north and vertical (upwards positive) movements, respectively.

Eq. (1) can be rewritten as:

\[
A \cdot V = LOS
\]

where \(A\) is the \(3 \times 2\) coefficient matrix by satellite geometry, \(V\) is the \(2 \times 1\) velocity matrix and \(LOS\) is the \(3 \times 1\) line of sight matrix for Tracks 075, 068 and 347. Applying orthogonal projections to the inconsistent system of Eq. (2), a least squares solution of the 2D velocity field \(V\) will also be a solution to the associated normal system:

\[
A^T \cdot A \cdot V = A^T \cdot LOS
\]

The least square solution of the 2D velocity field \(V\) (Fig. 8) is thus given by:

\[
V = (A^T \cdot A)^{-1} \cdot A^T \cdot LOS
\]
Using Eq. (5),
\[ B = (A^T \cdot A)^{-1} \cdot A^T \]  

Eq. (4) can be simply written as:
\[ V = B \cdot \text{LOS} \]  

Based on Eq. (6), the standard deviations of the north and vertical velocity can be calculated from the standard deviations of LOS velocities (Fig. 5) following uncertainty propagation theory (Dijkstra, 2010):
\[ \text{cov}(V) = B \cdot \text{cov}(\text{LOS}) \cdot B^T \]  

The full form of Eq. (7) can be written as:
\[ \begin{pmatrix} \sigma_n^2 & \text{cov}_{nv} \\ \text{cov}_{nv} & \sigma_v^2 \end{pmatrix} = B \begin{pmatrix} \sigma_n^2 & \text{COV}_{075,068} \\ \text{COV}_{075,068} & \sigma_v^2 \end{pmatrix} B^T \]  

In the equations above, \( T \) and \( (\cdot)^{-1} \) represent matrix transpose and inversion, respectively. \( \sigma_n^2, \sigma_v^2 \text{ and } \sigma_{uv}^2 \) are the variances of the velocities of Tracks 075, 068 and 347, respectively, which were calculated in Section 4.1 from the radar line of sight deformation time series. COV_{075,068} is the covariance between the velocities of Tracks 075 and 068. The off-diagonal covariance terms in Eq. (8) are all zero as the different Tracks provide independent, uncorrelated observations. \( \sigma_n^2 \text{ and } \sigma_v^2 \) are the variances for north and vertical velocities, respectively, expressed as standard deviations \( \sigma_n \text{ and } \sigma_v \) and mapped in Fig. 9.

For the East landslide, movements in both the downward and northward directions can be seen from the two dimensional velocity fields (Fig. 8). Uncertainty in the north velocity field is high as the mean standard deviation of all the pixels is 8.29 mm/yr (Fig. 9a). Two explanations may account for this large standard deviation: the first is the large standard deviation in Track 068 along the Yangtze River due to short data interval (Fig. 5c); the other is low
sensitivity of InSAR observation to the north component due to near vertical radar looking angles and the near polar orbits. The vertical velocity standard deviations are small with the mean value of 3.84 mm/yr. Most pixels from the upper slopes show vertical velocity standard deviations from 2–3 mm/yr, while most pixels adjacent to the Yangtze River have values of 5–7 mm/yr (Fig. 9b). The downward movements of the upper part of the East landslide are reliable as its 2–3 mm/yr standard deviations are much smaller than the 7–12 mm/yr vertical rate (Fig. 8b). For the West landslide, although common pixels for Tracks 075, 068 and 347 are sparse, downward movements could still be identified (Fig. 8b) with low standard deviations (Fig. 9b).

5. Landslide analysis

5.1. Surface movements of the west and east landslides

Points P1 and P2 are located on the west and east landslides, respectively (Fig. 4d). The RMS values between T075D and T347D for P1 and P2 are 1.7 mm and 5.9 mm, respectively. These RMS values are much smaller than the total deformation that P1 and P2 exhibit. The high consistency between these two adjacent tracks provides confidence that our time series results from P1 and P2 are reliable. Both descending tracks 075 and 347 show that the cumulative LOS deformation magnitudes of P1 and P2 are 20 mm and 30 mm, respectively. Not only are the LOS deformation magnitudes different between P1 and P2, but also the pattern of deformation between successive SAR acquisitions are different. For example, point P2 (Fig. 6) on the East (Huangtupo) landslide has a consistent 20 mm drop from January 2004 to October 2004 at both Tracks 075 and 347. This is not observed at P1 on the West landslide. Similarly, P1 (Fig. 6) shows a constant rise of 6 mm from March 2007 to July 2007 from Track 075. This is not observed from P2 either. No radar image from Track 347 covers that time period. These differences suggest that movements of P1 (West landslide) and P2 (East landslide) are not correlated, and both the pattern and magnitude of their movements are different. There is correspondence between the two points on the West (P1 and P3) and the two points on the

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East (P2 and P4) landslide, suggesting that movement on each slide is affecting the whole of the feature.

5.2. Correlation analysis with water level and rainfall

Discrepancies in the time series deformation signals (Fig. 6) between different tracks could be due to different look angles and different temporal sampling of temporally variable events. All the tracks exhibit similar patterns of seasonal fluctuations (Fig. 6). On the other hand, both rainfall and water level exhibit strong seasonality in this region. Generally, rainfall between May and September accounts for 61–70% of the 1100–1522 mm annual precipitation in west Hubei province (Bao et al., 2009). Water level records show that the Three Gorges Dam began its first water impoundment on 1st June 2003. On 15th June 2003, the water level reached 135 m; on 21st September 2006, Three Gorges Dam began water impoundment to 156 m, which was reached on 27th October 2006; experimental water impoundment to 175 m started on 28th September 2008, with peak level of 172.8 m on 10th November 2008; after a water level drop, another round of water impoundment began on 15th September 2009 with peak level of 171.43 m on 24th November 2009 (Dai et al., 2010; Zhang et al., 2009b). The water level of Three Gorges Reservoir can be divided into three different stages: 135 m, 156 m and 175 m impoundments with individual local peaks of I, II, III, IV, V, VI, VII and VIII (Fig. 10).

Correlation between water level fluctuations and landslide seasonal signals can be identified in P2 from the East landslide (Fig. 10). For instance: (a) water level between VII and VIII of 30 m pre-dam water level change in impoundment 175 m matches the simultaneous deformations of P2 in Track 347 when no Track 075 image is available; (b) water level between V and VI, and then between VI and VII of around 15 m water level change in impoundment 156 m match the deformation from Track 075 in P2 when Track 347 images are rarely distributed and none Track 068 image is available; (c) water level between III and IV of the order of 5 m in impoundment 135 m matches the deformation from Track 347 in

![Graph](Image)

**Fig. 10.** Surface displacement time series of P1 and P2 in radar line of sight direction, pre-dam water level and monthly rainfall in Three Gorges Reservoir. Rainfall data comes from Li et al. (2010). Water level data comes from Dai et al. (2010).
Fig. 11. Deformation profile SN of the Huangtupo landslide from Track 075. Line SN is marked in Fig. 4d. All the deformation is relative to the first scene on 17 August 2003. Dashed line in each scene stands for zero deformation. Each dot black represents a SAR pixel in Profile SN. The approximated deformation tendencies of the dots are given in solid lines in each scene. Available pre-dam water level in SAR acquisition date is also given.

P2 when Track 075 images poorly cover this period; (d) water level in impoundment 135 among I, II and III in the order of 5 m impact the deformation of P2 in both Tracks 075 and 347. Seasonal deformation can be estimated simply by removing a long term linear rate from the observed InSAR deformation. In the three different impoundments, the seasonal deformation responds with different sensitivity to the water level change. The change of water level in impoundment 135 is only 5 m compared with the next two impoundments of 15 m and 30 m (Fig. 10), but the seasonal deformation of P2 is −10–5 mm in impoundment 135 compared with the next two impoundments of −5–3 mm and −6–5 mm. For P1 from the West landslide, a lag in correlation between water level and landslide seasonal signals can be identified sometimes (Fig. 10). For instance: (a) water level peak VII matches the deformation from Track 068 by a lag in P1; (b) water level rise during peak V matches the deformation from Track 075 by a lag in P1.

The drop of pre-dam water level in the Three Gorges Reservoir during the first five months of each year is to make enough reservoir capacity for big flood between May and September as a result of intense precipitation. Correlation between landslide activities and monthly rainfall is also investigated. For P2, it seems the local deformation valleys meet precipitation peaks (Fig. 10). This may be due to the fact that the water level has began to drop before the rainy season and therefore the local deformation valley correlated with this water level drop may meet the rainy season. For P1, correlation between deformation and rainfall is not clear.

The long-term deformation tendency is shown by the InSAR time series results (Figs. 6 and 11). Evidence of ongoing deformation was confirmed by field observations, with cracks in buildings and roads within the landslide areas. The cracks on concrete surfaces may be caused by landslides but as concrete weathers its tensile strength may change leading to cracking on the surface (Roy et al., 1999). Cracks were also observed in rocks – again this may be affected by weathering that may exert sufficient pressure to separate rock fragments (Chen et al., 2000). However, cracking was found in rocks that have only been at the surface since the construction of the new city which may indicate that these cracks pre-date relocation and indicate longer-term landsliding. Also, the eastern, Huangtupo, landslide detected here has previously been identified and located in the same position (Wu et al., 2006).

6. Discussion and conclusion

In this paper, InSAR time series techniques have been successfully applied to identify surface deformation in Badong County, Three Gorges region, China from 2003 to 2010. Our time series results in Badong show consistent linear movement trends between two descending tracks with an overall RMS value of <2 mm, which enables the identification of the East landslide and the West landslide. They are two distinct landslides with different moving patterns and magnitudes. The locations of the East landslide identified in this study is consistent to the one suggested in previous studies (Deng et al., 2000; Tang and Hu, 2009; Wu et al., 2009). With both ascending and descending tracks, two-dimensional velocity fields in north and vertical directions have been recovered. The eastern landslide is moving northward (downslope) at the rate of 4–5 mm/yr while exhibiting a downward rate of 7–12 mm/yr. The western landslide is moving at the rate of 2–3 mm/yr with movement mainly vertically downward. Correlations between landslide seasonal deformations and water level changes are observed for both the eastern and western landslides, although these kinds of responds exhibit different time lag and different sensitivity in each impoundment.

A possible mechanism for such river bank landslides is that when the water level adjacent to the slope falls rapidly the ground-water level cannot dissipate quickly enough, leaving an artificially
high water table. This subjects the slope to a hydraulic pressure drive, leading to potential instability. We do not know if the water level changes affect the long term rate of landslide in Badong. The long term rate in our study period is relatively stable in seven years. Although correlations between water level fluctuation and seasonal landslide signals are observed, we cannot exclude the impacts of other factors such as cumulative precipitation and natural geological condition. It is beyond the scope of this paper to conclude if water filling by the dam affected the landslide rate because ASAR data are not available before 2003, the year that the dam started to function (Fig. 10).

In situ direct shear tests were carried out in a limited number of landslides investigation projects in this region by Wen et al. (2007). The slip zones of the large landslides in the Three Gorges region reach their in situ residual strength at shear displacement longer than 20 mm (namely 40–50 mm) (Wen et al., 2007). Greater magnitude of deformation is observed in the lower part of the Huangtupo landslide from the profile plot in Fig. 11. The two-dimensional velocity fields give vertical rates of 7–12 mm/yr in Huangtupo. The deformation rate of sliding zone can be greater than this vertical rate. As a result, the shear displacement in our study period is greater than 50 mm. The shear stress may have reached the steady state under which it remains constant while the shear strain increases.

The mean surface slope map (Fig. 1c) shows no clear correlation between landslide activity as represented by the mean velocity map (Fig. 4) and topographic slope. This may indicate that these landslides are not shallow landslides; the movement of which is generally correlated with topographic slope (Montgomery and Dietrich, 1994). This finding is consistent with the landslide depth previously suggested for the Huangtupo landslide (Wu et al., 2006).

This paper has demonstrated the capability of the small baseline InSAR technique for monitoring landslide hazards, even in regions with steep slopes and dense vegetation. It is suggested that this technique could be used on a continuous basis to monitor landslide activity and hazard in Badong and for other landslide sites in the Three Gorges area.

Acknowledgements

This work is supported by a China Scholarship Council (CSC) scholarship to PL. Part of this work is supported by the Natural Environmental Research Council (NERC) through the GAS project (Ref.: NE/H001085/1) as well as by a China NSFC Project (ID: 41074005). The ENVISAT images were supplied through the ESA-MOST Dragon 2 Cooperation Program (ID: 5343). We thank JPL/Caltech for the use of ROI,PAC, TU-Delft for DORIS and Andy Hooper for StaMPS in our data processing and analysis. Figs. 1b, 4, 5, 7, 8 and 9 were prepared using the public domain Generic Mapping Tools (Wessel and Smith, 1998). We are grateful to A. Singleton for useful discussions. Constructive comments from B.-F. Wu (Associate Editor), R. Tomas, Z. Lu, N. Gourmelen and an anonymous reviewer significantly helped to improve the manuscript.

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