Monitoring the two-dimensional deformation of the old landslide in Woda Village with radar interferometry technology

Jiawei Dun, Wenkai Feng*, Xiaoyu Yi, Guoqiang Zhang

State Key Laboratory of Geohazard Prevention and Geoenvironment Protection, Chengdu University of Technology, Chengdu 610059, China

Corresponding author: fengwenkai@cdut.cn. https://orcid.org/0000-0001-7747-8836

Abstract Recently, large-scale sudden landslide disasters have occurred more frequently in the western parts of China. These disasters have characteristics of high position and concealment, and it is challenging to solve disaster prevention using the naked eye and traditional geographical means. Using GPS surface monitoring instruments to monitor landslide deformation is currently common, but it is limited because of high costs, harsh natural environment, and human interference. With the rise of interferometric synthetic aperture radar (InSAR), the quality of radar satellite data has improved, providing a new way for long-term monitoring and analysis of landslide historical deformation dynamics. This study used Sentinel-1A data provided by ESA (March 20, 2017–September 28, 2019) to conduct two-dimensional deformation monitoring of an old landslide in Woda Village, Yanbi Township, Jiangda County, Changdu, Tibet, and compared and analyzed two methods for rechecking with onsite engineering geological survey. The results show that detecting the overall and local deformation of the old landslide using InSAR technology is highly consistent with the field survey phenomenon. The deformation of the front and rear edges of the landslide is small, and the deformation of the middle part is large (>5 mm/a). Combined with rainfall data analysis, the landslide deformation and rainfall have a good response law, showing that rainfall affects the resurrection area in the front of the landslide. The overall performance is a partially resurrected traction sliding, and the main accumulation area in front of the old landslide is shown as a strong push from the middle to the front edge. InSAR technology demonstrates the potential of synthetic aperture interferometry in applying landslide monitoring to deformation monitoring results of the landslide and provides new ideas and references for similar old landslide inducement analysis and monitoring and early warning work.

1. Introduction
Large-scale sudden geological disasters are occurring more frequently in western parts of China. These disasters show strong concealment and high hazards, bringing huge challenges to geological disaster prevention and geological environmental protection.

At 6 AM on June 24, 2017, a mountain of about $450 \times 10^4$ m$^3$ in the back mountain of the Xincun Formation, Xinmo Village, Diexi Town, Maoxian County, Sichuan Province, suddenly slipped along the bed. It caused more than 80 people to be missing or killed, causing widespread concern at home and abroad [1]. After the disaster, Italy Tre Altamira et al. [2] analyzed 45 Sentinel-1 radar satellite images from December 2014 to June 2017 using interferometric (In) synthetic aperture radar (SAR) (InSAR) technology and confirmed that the significant deformation of the Xinmocun landslide...
occurred a few months before the landslide. At 4 AM on October 11, 2018, a large reservoir bank rock landslide occurred in Baige Village, Boluo Township, Jiangda County, Changdu, Tibet, in the Jinsha River Basin. Xu Qiang et al. [3] analyzed the radar satellite data before the Baige landslide and highlighted that one year before the landslide disaster, the maximum displacement of the slope in the source area was ~25 m. These cases illustrate that InSAR technology has significant advantages in identifying and monitoring hidden geological disasters in areas that are in high positions, difficult to traffic, and inaccessible.

InSAR technology is a new type of earth observation technology that has emerged in the past 20 years. It has the advantages of all-weather work, wide coverage, high detection accuracy, noncontact, and low overall cost. It has broad application prospects in geological disaster early warning and monitoring in complex mountainous areas. For early identification and deformation monitoring of landslides using the small baseline subsetSBAS technology, many scholars have achieved corresponding substantive results. Yu Rui et al. [4] used SBAS-InSAR technology to conduct global and local monitoring of slow landslides in Xihe County, Gansu Province, revealing the dominant factors affecting landslide body movement. Liu Xiaoyi et al. [5] investigated the creep landslide in the Xianhe fault zone and obtained its time-series deformation characteristics using SBAS-InSAR technology and analyzed its development and change law. Nie Bingqi et al. [6] conducted landslide deformation detection and hidden danger identification in Danba County using SBAS-InSAR technology, verifying the consistency of InSAR monitoring results and field investigation. Therefore, SBAS-InSAR technology provides critical support for investigating and analyzing geological hazards. To make full use of spaceborne radar earth observation technology, conducting targeted engineering geological surveys and review work is conducive to the correct understanding of the regularity of InSAR interpretation data. Furthermore, it is also conducive to the accuracy of disaster early warning research and judgment to significantly enhance the technical strength of China’s scientific disaster prevention and mitigation.

The huge old landslide in Woda Village is a hidden danger point of the regional geological hazard investigation database. It is in Woda Village, Yanbi Township, Jiangda County, on the right bank of the Jinsha River, 42 km away from the Baige landslide. Based on 39 SAR datasets of Sentinel-1A from March 30, 2017, to September 28, 2019, in the old landslide area of Woda Village, this study analyzes the deformation characteristics of the old landslide’s accumulation using SBAS-InSAR technology and conducts field engineering geological investigation and review work. The applicability of SBAS-InSAR technology to geological disaster early warning and monitoring in complex mountainous areas is analyzed, providing a new idea and reference for monitoring and early warning of similar old landslides.

2. Study area
The old landslide of Woda Village is in Woda Village, Yanbi Township, Jiangda County, Changdu, Tibet Autonomous Region (E93°26′06″ longitude and N31°26′06″ latitude) (Figure 1). Early regional geological disaster surveys show that the landslide disaster occurred in the geological history period of this section. The landslide accumulation mass is easy to revive under precipitation, earthquakes, and water-level fluctuation; therefore, it is necessary to focus on monitoring and research.

From analyzing the comprehensive optical remote sensing interpretation map (Figure 2), the length of the old landslide is ~1.9 km, the width is ~1.7 km, and the main sliding direction is NE30°. The old landslide accumulation is partially revived and ~0.88 km long, the width is ~1.08 km, and the area is ~0.925 km². The landslide body is semicircular, and the front edge is in the form of a cliff that gradually changes to steep. The maximum height difference between the gentle part and the river surface is ~240 m. The front end is steeply inclined, and the foot of the slope is the Jinsha River valley, with an elevation of ~2950 m. The back is relatively flat. From previous investigations, the upper covering layer of the old landslide is Quaternary landslide deposits, containing gravel and gravel clay, 20–30 m thick, the underlying bedrock is metamorphic shale, and the rock formation is about 240° ≤ 80°.
3. SAR data and processing methods

3.1. SAR data
The single-look complex SAR image data used in this article comes from the earth observation satellite Sentinel 1A launched by the European Space Agency on April 3, 2014. The data coverage area is shown in Figure 3(a). The C-band is used, the image is SAR 99 orbit data, from March 30, 2017, to September 28, 2019 (24 days, 39 scenes), the orbit direction is ascending, and the imaging center is incident. The angle is 36.2°, the IW wide-imaging mode is used, the ground resolution is 5 m × 20 m, the width is 250 km × 250 km, the polarization mode is VV, and the azimuth and range sampling intervals are 2.329 m and 13.956 m, respectively. In this study, 30 m resolution ALOS World 3D (AW3D30) DEM provided by JAXA in Japan was used as external data to eliminate the influence of the terrain phase.

3.2. Technical principle and acquisition of deformation rate
3.2.1. SBAS-InSAR technology principle
To reduce time and space decoherence, Berardino et al. [7] proposed a short-baseline differential interferometry method based on the research of Usai et al. [8]. The basic principle of N + 1 scene single-view complex images, the imaging time is \( (t_0, t_1, \ldots, t_n) \), a certain difference decomposition wrap image is set to \( j \), and a certain pixel \((x, r)\) corresponds to the unwrapping phase. It can be expressed as Equation (1) [9]

\[
\delta \phi_j(x, r) = \varphi(t_0, x, r) - \varphi(t_n, x, r) \\
\approx \delta \phi_j^{\text{DEM}}(x, r) + \delta \phi_j^{\text{slo}}(x, r) + \delta \phi_j^{\text{atm}}(x, r) + \delta \phi_j^{\text{noise}}(x, r).
\]

\( \delta \phi_j^{\text{DEM}}(x, r) \) is the phase formed by the DEM error, \( \delta \phi_j^{\text{slo}}(x, r) \) is the phase generated by slope deformation, \( \delta \phi_j^{\text{atm}}(x, r) \) is the phase generated by the atmospheric influence between \( t_B \) and \( t_A \), and \( \delta \phi_j^{\text{noise}}(x, r) \) is the phase caused by noise. The first three terms at the right end of Equation (1) can be expressed as Equation (2)
\[
\begin{align*}
\delta \phi^{(j)}_{\text{RM}}(x, r) &= \frac{4\pi B_j A \Delta Z}{\lambda} R \sin \theta \\
\delta \phi^{(j)}_{\text{RM}}(x, r) &= \frac{4\pi}{\lambda} \left[ d(t_{g}, x, r) - d(t_{s}, x, r) \right] \quad \forall j = 1, \ldots, M \\
\delta \phi^{(j)}_{\text{RM}}(x, r) &= \phi_{\text{RM}}(t_{g}, x, r) - \phi_{\text{RM}}(t_{s}, x, r)
\end{align*}
\]  \tag{2}

\(B_j\) represents the vertical component of the spatial baseline along the radar’s line of sight (LOS), \(\lambda\) is the wavelength, \(\theta\) is the radar-viewing angle, \(\Delta z\) is the DEM error, \(R\) is the slant distance from the radar to the observation object, 
\(d(t_{g}, x, r)\) and \(d(t_{s}, x, r)\) respectively represent the cumulative deformation of the viewing direction relative to the reference time \(t_0\). \(M\) is the number of interferograms. If \(N\) represents the total number of SAR images, there is \(\frac{M}{2} \leq M \leq \frac{N(N-1)}{2}\), and the least squares or singular value decomposition (SVD) is performed on the \(M\) unwrapping phases.

Because \(M\) interferograms are generated during processing, \(M\) equations can be obtained using Equation (2) expressed as Equation (3) in matrix form

\[
\delta \phi(x, r) = A \phi(x, r)
\]  \tag{3}

\(A\) is an \(M \times N\) coefficient matrix, \(\phi(x, r)\) is a matrix of unknown deformation phases corresponding to \((x, r)\) points at \(N\) times. When \(M \geq N\), Equation (4) is obtained using the least squares method

\[
\phi(x, r) = \left(A^T A\right)^{-1} A^T \delta \phi(x, r)
\]  \tag{4}

When \(M < N\), the equation has countless solutions, and the SVD method is used to jointly solve multiple small baselines. Finally, the cumulative deformation corresponding to different moments can be obtained.

Figure 3. Data coverage and time-space baseline map. (a) SAR data coverage (b) Image time baseline map (c) Image space baseline map
3.2.2. LOS directional deformation rate

This article uses the SARscape module in ENVI to perform interference processing on Sentinel-1A data using the SBAS algorithm, generating 109 interference pairs. The time baseline is 75 days, and the critical baseline is 2%. Figures 3(b) and 3(c) show the connection method of the time and space baselines of each image pair. The green dots in the figure represent the imaging time of 39 scene images, and the yellow dots represent the imaging time of the reference main image. Perform the first inversion, the second inversion, geocoding, and raster vector conversion on the synthesized interferogram to generate the average surface deformation rate (mm/a) along the radar LOS. Finally, obtain the deformation results in the time-series.

3.2.3. Two-dimensional deformation rate

Because landslides mostly slide along the slope surface, the deformation information toward the radar LOS cannot accurately reflect the slope surface’s true deformation [10]. Consider the geometric relationship between the radar LOS, slope, and vertical settlement directions (Figure 4). If the motion occurs along the direction specified by the unit vector \( \hat{u} \), Equations (5), (6) [11], and (8) [12] are used to convert the LOS deformation rate into the slope and vertical deformation rates.

![Figure 4 Schematic diagram of radar imaging geometry][11]

\[
\hat{u} = \begin{bmatrix}
-\sin \alpha \cos \phi \\
-\cos \alpha \cos \phi \\
\sin \phi
\end{bmatrix}
\]

\[V_{\text{Slope}} = V_{\text{Los}} / \cos \beta \]  

In Equation (6), \( \cos \beta \) can be calculated using Equation (7) [11]

\[
\cos \beta = \frac{(-\sin \alpha \cos \phi)(-\sin \theta \cos \alpha_s) +}{\sin \phi \cos \theta}
\]

\[= \frac{(-\cos \alpha \cos \phi)(\sin \theta \sin \alpha_s) +}{\sin \phi \cos \theta}
\]
6}

\[ V_u = \frac{V_{Los} + V_{Slope} \sin \theta \cos \left[ \delta - \left( \frac{\alpha_s}{2} \right) \right]}{\cos \theta} \]

\( \hat{u} \) represents the unit vector of the motion direction, \( V_{Slope} \) represents the deformation rate along the slope direction, \( V_{Los} \) represents the deformation rate along the radar’s LOS, \( V_u \) represents the vertical deformation rate, \( \alpha_s \) is the angle between the azimuth and the true north directions, \( \alpha_s = \frac{\beta}{2} \pi \) is the azimuth LOS direction, and \( \delta \) is the landslide’s azimuth. \( \alpha \) is the slope direction, \( \beta \) is the apparent slope angle, \( \theta \) is the incident angle, and \( \phi \) is the slope angle.

To avoid the extremely abnormal phenomenon of absolute value in the process of \( V_{Los} \) to \( V_{Slope} \) conversion, Herrera [13] proposed \( \cos \beta = \pm 0.3 \) as the fixed threshold, that is \( V_{Slope} \). It cannot be greater than 3.33 times of \( V_{Los} \). When \(-0.3 < \cos \beta < 0\), \( \cos \beta = -0.3; 0 < \cos \beta < 0.3, \cos \beta = 0.3 \).

4. Deformation result analysis

Combined with remote sensing image analysis, the surface vegetation coverage density of the landslide’s central and trailing edges are small, many coherent points exist, the interference effect is better, and an obvious rate accumulation occurs. The vegetation cover in parts of the landslide is dense, causing the image to lose coherence and rate. The dots are relatively rare.

Figure 5. Deformation rate map from March 2017 to September 2019 (LOS direction)

Figure 6. Deformation rate map from March 2017 to September 2019 (slope direction)
A negative value of the deformation rate indicates that the deformation point moves away from the satellite sensor, and a positive value indicates that the deformation point moves closer to the satellite sensor. From the InSAR view-direction deformation analysis, the deformation values in Figure 5 are negative, indicating that the entire landslide slides down toward the Jinsha River, conforming to the law of movement of the landslide body. From Figure 5, the strong landslide deformation occurs in the middle and front edge of the landslide (the purple-dashed circle in Figure 5), and the red area within the purple-dashed circle has the largest deformation at a deformation rate of \( \geq 80 \, \text{mm/a} \).

Figures 6 and 7 show the annual average velocity of the Woda Village landslide along the slope \( V_{\text{slope}} \) and vertical \( V_{u} \) directions, respectively. The interpreted strong deformation zone is roughly consistent with the LOS direction. Because multidirectional deformation affects the landslide’s deformation, the results of the two-dimensional deformation transformation of the LOS direction deformation rate are different. The deformation rate along the slope direction is the largest, indicating that the slope and vertical deformations affect deformation in the strong deformation area. However, deformation along the slope direction has a greater impact on deformation in the strong deformation area than the vertical deformation.

5 Engineering geological survey and review
To review and interpret the data, onsite engineering geological surveys and reviews were conducted. The field survey shows that the landslide body’s front edge is steep. The middle and front parts have a large slope and trees grow luxuriantly. The middle part is a gentle slope platform comprising mostly cultivated land with sporadic growth of trees. The back part is the ancient landslide source area (Figure 8(a)). Affected by the combined effect of the undercut erosion of the gully and the steeply dipping void surface of the front edge, the front edge of the landslide has developed many collapse deformation bodies (B01–B04) toward the gully and void surface, and surface cracks of the collapse deformation bodies are transversely tensioned. The staggered ridge is developed, the cracks open 2 cm–10 cm, the maximum staggered distance is 1 m–2 m, and the obvious base-cover interface can be observed on the front cliff (Figure 8(b)). Many small sliding deformation bodies (H01–H03) developed in the middle part of the landslide revitalization area. The slope body develops cross-cutting stepped ridges, ranging in height from tens of centimeters to several meters, extending from tens to hundreds of meters, and many upper parts of the ridges exist plowing and bushes, indicating that the
formation of steep ridges takes a long time (Figure 8(c)). Saber trees are visible, and the stable time is estimated to be at least 10 years with the age of the trees (Figure 8(d)).

Figure 8. Photographs of the Old Landslide in Woda Village

5.1. Analysis of overall deformation and deformation rate of the landslide

The resurrection zone is mostly located in the middle and lower parts of the old landslide body. The rear edge of the strong deformation zone \(I_{scene}\) is at the steep and gentle junction of the old landslide. The borders on both sides extend to the boundary of the old landslide according to the topography (Figure 5), with internal cracks and lower faults. The sills and local collapse are obvious. The deformation signs have high consistency with the characteristics of the deformation rate map (Figure 5) obtained using the SBAS-InSAR method. Take a point A in the red area where the deformation rate of the apparent landslide deformation rate map (Figure 5) is large, and draw the historical cumulative displacement deformation curve at that point. Compare and analyze the cumulative rainfall curve collected from January 2017 to August 2019 (Figure 9). With the sharp increase in rainfall in three periods (May 2017–June 2017, May 2018–August 2018, and June 2019–July 2019), the A-point shape variable significantly accelerates. During less rainfall, the A-point variable increases slowly, and the deformation trend and rainfall have a good response law. From the field investigation, the highest elevation of water-level fluctuation of the Jinsha River is 2930 m–2950 m, whereas the local resurrection area of the landslide is 3220 m–3580 m away from the influence area of the water-level fluctuation of the Jinsha River. The middle and front resurrection areas of the landslide are mostly affected by rainfall, which is a type of old landslide.
Figure 9. InSAR time-series deformation and rainfall response

From the analysis of the apparent deformation rate of the landslide (Figure 5), gray (−40 mm/a to −20 mm/a), yellow (−60 mm/a to −40 mm/a), orange (−80 mm/a to −60 mm/a), and red (−102 mm/a to −80 mm/a) areas in the middle part of the slope (within the trap range of the purple-dotted line) are interlaced, disorderly distributed, and different. This indicates that the strong deformation in this area reflects the landslide’s fracture sill development. Blue shows the radar deformation rate at the front and rear edges of the landslide area (−20 mm/a to 0 mm/a); therefore, the deformation in this area is small, and the difference in deformation is not obvious during radar monitoring. Based on the above radar deformation rate and zoning analysis, the overall distribution trend of the deformation rate (Figure 5) is divided into strong (I_{radar}) and uniform (II_{radar}) deformation areas. The apparent deformation rate along the landslide’s main sliding direction during different periods from March 2017 to September 2019 (Figure 10(a)–Figure 12(a)) is analyzed. The deformation variable of the front and rear edges of the old landslide is relatively small each year. In the middle part, the maximum deformation is about −125 mm/a, −100 mm/a, and −55 mm/a from 17 to 19 years. Because the slope’s front edge is steep, the slope of the front edge is too different from that of the entire slope. Considering the distortion of the front edge SAR image caused by overlay and shadow caused by topographic factors [14], the deformation rate of the front edge of the old landslide is uncertain. Based on the field investigation and deformation rate analysis results, the landslide’s current sliding deformation is mostly toward the gully and steep free face, and the failure form is mostly in the front edge scattering and local collapse, showing traction sliding of the local revival of the entire old landslide.
5.2. Analysis of local deformation and deformation rate of landslide

In the field review stage, four collapse deformation bodies (B01–B04) and three sliding deformation bodies (H01–H03) in the middle and lower parts of the landslide were carefully investigated. The four collapse deformation bodies are surface landslides with a small scale, and the skew range of trees is at the gully mouth, indicating that concentrated rainfall causes deformation. Among the three sliding deformation bodies, H02 and H03 were caused by deformation of the front free surface, and H01 was caused by rainfall and human engineering activities. The following analyzes sliding deformation body H01.

The H01 sliding deformation body is in the middle and rear parts of the slope, on the upper side of the road in Woda Village, and the sliding direction is consistent with the slope aspect (Figure 13 (a)). From the review, the front edge of H01 is the village road of Woda Village, and the retaining wall of the village road was uplifted around 2013 (Figure 13(b)). During mid-2018, the H01 sliding deformation body experienced relatively strong deformation, resulting in multiple cracks and a staggered platform sill in the field above the retaining wall (Figure 13 (c)). The houses near the bottom
are intact and undamaged, indicating that it is only the local traction sliding deformation of the surface rock and soil under the effect of rainfall recently.

To analyze the correlation between the sliding properties of the H01 sliding deformation mass and the radar deformation rate signals in detail, profile lines are arranged along the main sliding direction of H01, and 1# to 4# monitoring points are selected in turn. The historical cumulative displacement and deformation curves of the landslide over three years are drawn using Figure 6 (Figure 13(d)). From the figure, the historical cumulative variable of the 4# monitoring point is larger, and the increasing range is larger. The increasing range of historical cumulative variables of 1# to 3# monitoring points is the same. The deformation rate of the leading edge is much higher than that of the middle and rear edges, indicating that the H01 sliding deformation body belongs to the tractive sliding deformation.

![Figure 13. Comparison of SBAS-InSAR monitoring data of H01 landslide with field view](image)

From the analysis of the deformation rate points along the slope and vertical directions at the development of the lower staggered sill at the rear edge of the landslide, the deformation rate along the slope direction (Figure 6 and Figure 13 (a)) is different in color, and the deformation rate is considerably different. The deformation rates of 140 mm/a, 160 mm/a, and 180 mm/a are distributed, consistent with fracture-forming characteristics. From the analysis of the vertical deformation rate (Figure 7), a multistage orange deformation rate (−100 mm/a to −80 mm/a) appears near the yellow deformation rate (−80 mm/a to −60 mm/a) at the trailing edge, indicating that multistage downward dislocation settlement occurs in this area. The two phenomena confirm the existence of a multilevel
down-staggered sill in the strong deformation area of the landslide, showing creep deformation, consistent with the phenomenon of the geological survey.

6 Conclusions

(1) By analyzing the deformation rate zoning and the difference between deformation points in the visual, slope, and vertical directions, the Woda Village landslide was preliminarily divided into strong (I_{radar}) and uniform (II_{radar}) deformation areas, consistent with the strong (I_{scene}) and weak (II_{scene}) deformation areas determined on the scene.

(2) From analyzing the profile deformation rate along the landslide’s main sliding direction during different periods from March 2017 to September 2019, the deformation of the trailing and leading edges is smaller, and the deformation of the middle part is larger, with a maximum of −125 mm/a, −100 mm/a, and −55 mm/a (LOS) respectively. Considering the influence of terrain factors on the deformation rate of InSAR front, combined with field investigation and analysis, the deformation of the landslide is currently mostly toward the gully and steep free face, and the failure form is mostly front edge scattering and local collapse. The overall performance is traction sliding of the local revival of the old landslide.

(3) From the distribution of deformation rate values in the slope aspect and vertical deformation rate maps, and the different value characteristics, the local collapse and location of multistage sill development were preliminarily determined, correlating well with field geological surveys.

(4) SBAS-InSAR technology analysis and the field investigation review show that the old landslide resurrection deformation signs correlate well with SBAS-InSAR technology interpretation results. It has broad application prospects for geological disaster early warning and monitoring in complex mountainous areas and provides new ideas and reference for similar old landslide monitoring and early warning.

References

[1] Xu Q, Li W L, Dong X J, et al. 2017. Preliminary study on characteristics and genetic mechanism of Xinmo Village landslide in Diexi Town, Mao County, Sichuan Province[J]. Journal of Rock Mechanics and Engineering, 36(11): 2612-2628.

[2] TRE ALTAMIRA. 2017. Data in focus: precursor of Moxian landslide measured from space [EB/OL].http://tre-altamira.com/news/data-focus-precursor-moxian-landslide-measured-space/. 2017-06-29.

[3] Xu Q, Zheng G, Li W L, et al. 2018. Analysis of two landslides in the Jinshajiang Baige in October and November 2018 - the event of blocking the river. Journal of Engineering Geology. 26(06): 1534-1551.

[4] Yu R. 2014. Xi'an County Landslide Monitoring Research Based on Short Baseline (SBAS) Technology[D]. Nanjing Normal University.

[5] Liu X Y, Yang Z H, Guo C B, et al. 2017. Characteristics of creeping landslide in Xianshuihe fault zone based on SBAS-InSAR[J]. Modern geology, 2017(05):92-104.

[6] Nie B Q. 2018. Landslide Deformation Detection and Identification Based on InSAR Technology-a Case of Danba County[D]. Chengdu University of Technology

[7] Berardino P, Fornaro G, Lanari R. 2002. A new algorithm for surface deformation monitoring based on small baseline differential SAR interferograms[J]. IEEE Transactions on Geoscience & Remote Sensing, 40(11):2375-2383.

[8] Usai G, Manzo M, Lanari R. 2000. A quantitative assessment of the SBAS algorithm performance for surface deformation retrieval from D-InSAR data[J]. Remote Sensing of Environment, 102(3):195-210.

[9] He X F, He M. 2012. InSAR Earth Observation Data Processing Method and Comprehensive Measurement [M]. Beijing, Science Press.

[10] Dai K R, Zhuo G C, Xu Q, et al. 2019. Radar Interferometry for Two-Dimensional Deformation of Landslides in Nantun Township, Gansu Province [J/OL]. Journal of Wuhan
University (Information Science Edition): 1-9. https://doi.org/10.13203/j.whugis20190092.

[11] Cascini L, Fornaro G, Peduto D. 2010. Advanced low- and full-resolution D-InSAR map generation for slow-moving landslide analysis at different scales [J]. Engineering Geology, 112(1):29-42.

[12] Colesanti C, Wasowski J. 2006. Investigating landslides with space-borne Synthetic Aperture Radar (SAR) interferometry [J]. Engineering Geology, 88(3): 173-199.

[13] Herrera G, F. Gutierrez, J.C. Garcia-Davalillo, et al. 2013. Multi-sensor advanced DInSAR monitoring of very slow landslides: The Tena Valley case study (Central Spanish Pyrenees) [J]. Remote Sensing of Environment, 128 (none): 31-43.

[14] Zhang Y. 2018. Surface deformation monitoring based on InSAR technology and early identification of landslide [D]. Lanzhou University.

Acknowledgments

This study was funded by the National Natural Science Foundation of China (Grant Nos: 41977252, U2005205) and the State Key Laboratory of Geohazard Prevention and Geoenvironment Protection Independent Research Project (Grant No. SKLGP2020Z001), and the Zhejiang Huadong Construction Engineering Co., Ltd Research Project (KY2020-HDJS-19).