Regional-scale detection of unrecorded landslides in mountainous terrains by using interferometric stacking technique

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Abstract. Landslide hazard investigation by using a standard geological survey in a mountainous terrain can result in low accuracy and poor update rate. These deficiencies could lead to unrecorded landslides, which could be catastrophic. Synthetic aperture radar interferometry (InSAR), which can detect subtle ground surface movements in large areas, is considered as a promising solution for detecting unrecorded landslides in mountainous terrains. To evaluate its feasibility, this study conducted analysis work and associated field survey in Fengjie County. The county is characterized by a mountainous terrain and is located in a notoriously landslide-prone area in the Three Gorges reservoir in China. A total of 30 SAR images captured by the Sentinel-1A satellite in 2018 were processed to obtain the ground surface movements of the county. InSAR results identified 276 anomalous regions that were not recorded in the local inventory map. Of these regions, 18 were verified as unrecorded landslides on the basis of the field survey. The observable deformation of the landslides recorded in the local inventory map was also detected by InSAR. This work, which is not supposed to diminish the importance of standard geological surveys, could improve the accuracy and update rate of local inventory maps.

1. Introduction
The accelerating downslope movement of soil or rocks triggered by heavy precipitation can transform into a landslide, which may exert devastating financial and social impacts on individuals, families, local communities, businesses, and governments. Landslides can be mitigated using methods such as removing populations, installing active/passive retaining structures⁷, and applying regional-scale or local-scale early warning systems⁸[25]. However, these methods are only useful when landslides are recorded in the inventory map before their critical failure. Data from the China Geological Survey [27] in 2019 showed that more than 80% of landslides in China were not recorded in local landslide inventory maps before their failures. Therefore, unrecorded landslides should be identified to provide local authorities with situational awareness of potential risks and thereby reduce possible injuries, fatalities, and economic losses.

Current standard geological surveys, including the traditional walk-over survey, borehole drilling, and utilization of geophysical techniques or aerial/satellite imageries, are common techniques for
identifying landslide hazards. However, these methods could suffer from low accuracy and update rate due to high geological/geomorphologic complexity[4]. This dilemma has been verified in the Montescaglioso landslide in Italy[15], the Oso landslide in the U.S.[24], and the Xinmo landslide in China[8]; in all these events, the local landslide inventory did not indicate any hazardous phenomenon affecting the area actually hit by landslides.

Most landslides are known to deform or exhibit small magnitude failures prior to their ultimate failure [12]. Detecting these precursors, which may be ignored by standard geological surveys, is therefore attractive to decision makers and researchers so as to identify unrecorded landslides. In recent years, the in situ monitoring of landslide precursors has shifted from traditional methods to low-cost advanced sensors installed in the field[5] or airborne Lidar scanning techniques[14]. Meanwhile, developments in satellite technologies mean that detecting landslide precursors from a wide perspective is becoming increasingly possible. In particular, the interferometry synthetic aperture radar (InSAR) technique, which enables the measurement of ground surface motion of wide areas with millimeter to centimeter accuracy, has been demonstrated to be useful in landslide detection and mapping[11]. Although conventional InSAR techniques have been significantly improved over the last two decades, technical limitations remain when they are used in landslide detection in vegetated mountainous terrains[21]. These limitations include the following[3]: (1) the density of measurement points is strongly influenced by radar coherence especially in vegetated areas and thus limits the number of landslides that can be detected in vegetated areas; (2) geometric distortions are induced by the side-looking nature of synthetic aperture radar (SAR) in mountainous areas; (3) the one-dimensional displacement (line-of-sight [LOS] direction) obtained by InSAR cannot fully reveal the three-dimensional motion of a landslide; (4) landslides occurring in short time periods with high nonlinear deformation are difficult to investigate due to the revisit time of the satellite and wrapped nature of the phase information contained within interferograms. Consequently, landslide detection in vegetated and mountainous areas is a challenging target for InSAR techniques.

This work presents a case study to explore the feasibility of InSAR techniques for landslide detection in vegetated mountainous terrains. Regional-scale landslide detection in Fengjie county by using InSAR is proposed. The county is located in the upstream of the Three Gorges Reservoir, China. The reservoir is notoriously prone to geohazards, with more than 6,000 geohazards distributed in an area of 79,000 km². Seasonal precipitation events and associated water level fluctuations occurring especially during the monsoon season contribute to most of the landslides triggered in this region. Fengjie county is located in a mountainous terrain, and 45.7% of it is covered by forests. Hence, the county is especially suitable for estimating the possible lower-bound capability of InSAR techniques for landslide detection in similar areas. To achieve the aforementioned objective, we perform a multi-interferogram analysis of the C-band SAR images acquired by the Sentinel-1A satellite. The analysis reveals the mean annual ground surface velocities in the LOS direction. Geological analysis is then conducted to investigate the possible locations of unstable slopes that may trigger unrecorded landslides. Thereafter, field surveys are carried out to verify the accuracy of the detected unstable slopes. The results are conceived to be beneficial for local authorities as they update inventory maps efficiently before the monsoon season every year and promote their hazard mitigation strategies continuously.

2. Study area and data
The Three Gorges Dam in the Yangtze River has created a 660 km-long backwater reservoir area, leading to the relocation of 1.2 million people[23]. The reservoir region has a wet subtropical climate and abundant precipitation during the monsoon season[31]. In particular, approximately 67% of the precipitation takes place from May to September. In addition, a 30 m water level variation is formed by annual reservoir regulation during the monsoon season due to flood prevention. However, either rainfall or water level fluctuation results in pore water pressure variation in a slope and thus prompts the considerable decrease in slope stability[2][13]. Moreover, the literature shows that the long-term...
variation of water levels can lead to the deterioration of rock masses in the water level fluctuation zones of bank slopes[10]. Evidently, seasonal precipitation events and water level fluctuations are the root causes of landslide failures in this region[26].

The landscape in the reservoir region is shaped by major tectonic events. Yanshan orogeny in the Late Jurassic formed the terrain skeleton of the mountains. Following the Himalayan orogeny in the Neogene, long-term erosional processes gradually transformed the area into the present-day landscape with moderate- to low-altitude mountains and river valleys[22]. Furthermore, the lithology in these regions shows distinct features. The strata mainly include the Quaternary, Jurassic, and Triassic and comprise widely distributed sandstone and mudstone of the Jurassic[26]. The sandstone interbedded with mudstone layers of the Triassic Badong Formation and the Jurassic strata are known to be the most slide-prone strata in these regions, with the rock avalanches and landslides identified in these strata accounting for 87.3% and 91.1% of total events, respectively[17].

Fengjie county is dominated by a mountainous terrain and is located in the northeastern part of the reservoir region. According to local authorities, the land area of the county is 4,098 km², and more than 1,600 geohazards have been recorded in the local inventory map (Figures 1 and 2). In addition, 45.7% of the mountainous county is covered with forest vegetation. To evaluate the capability of InSAR techniques for landslide detection in the county, this work collects and analyzes the spaceborne SAR data acquired by Sentinel-1A. As no SAR data acquired by Sentinel-1A in descending tracks are available, only 30 SAR images with single ascending tracks (P84) in 2018 are processed.

3. Methodology

Although its capabilities have been demonstrated, InSAR has a number of intrinsic limitations in landslide detection and mapping over wide areas. As reported in the literature[3], the most important limitations are as follows: (1) spatial sampling of measures, (2) geometric effects, (3) one-dimensional nature of results, and (4) kinematics of landslides.

For the case of Fengjie county, several main limitations that may affect the application of InSAR techniques. First, the mountainous terrain and moderate forest coverage of the county affect the density of InSAR measurement points considerably and could limit the number of landslides to be investigated. Second, landslides triggered outside the range of the water level fluctuation zone are mainly induced by rainfall; thus, a high correlation exists between heavy precipitation events and nonlinear deformation accumulation, especially for the case of shallow landslides[16]. However, the revisit time of the Sentinel-1A satellite, which can only acquire a single SAR image every 12 days, may not be compatible with the deformation rate of landslides in the monsoon season. Finally, the deformation results obtained by InSAR can only reveal the movement status of the ground surface in the LOS direction induced by either natural landslides or human activities.

On the basis of these considerations, this study modifies the workflow of InSAR analysis to obtain the annual mean velocity results (detailed descriptions are found in[28]). Thereafter, the displacement results obtained by InSAR are interpreted with geological experience to identify the unrecorded landslides in the county. Although analysis thresholds for InSAR results have been proposed by several researchers[1][9][18][19][20][29][30], the direct utilization of these thresholds may surpass their verified ranges. Therefore, the analysis workflow proposed in this study is designed as follows:
Figure 3. Analysis workflow of landslide detection based on InSAR results

(1) On the basis of the local inventory map, the annual mean velocities obtained by InSAR are divided into two categories, namely, deformation occurring at recorded geohazards and others;
(2) Except for deformation occurring at recorded geohazards, clusters of measurement points with annual mean velocities greater than 20 mm/year are identified as “anomalous” regions, and the threshold is determined by local experience;
(3) Optical remote sensing images, digital elevation models, and geological maps are utilized to interpret whether the “anomalous” regions may indicate unrecorded landslides that could threaten the safety of local communities and/or high value infrastructure.
Following the mapping of the positions of the “anomalous” regions based on the InSAR results, a field survey is carried out to verify detection accuracy. A comprehensive evaluation of the detection accuracy for the unrecorded landslides is discussed in the next section.
4. Results

Figure 4. Sentinel-1A’s mean LOS velocity map of Fengjie county

The mean velocity map obtained from the ascending Sentinel-1A datasets is illustrated in Figure 4. Negative values represent the ground motion away from the satellite while positive values represent movements toward the satellite. InSAR measurement points are mostly located on the westward and eastward slopes due to the geometry of the side-looking radar. The absence of measurement points can be observed in deeply incised valleys and steep escarpments due to topographic distortions. Properly interpreting data requires focus not on a single measurement point but on clusters of measurement points that may indicate the integral deformation of unstable slopes. By utilizing the LOS velocity field, this study identifies 276 unrecorded slope instabilities and marks them as “anomalous” regions. These regions are then mapped on the basis of the proposed analysis workflow. A field survey is then conducted to evaluate the detection rate.
Figure 5. Field survey of suspected geohazards. (a) Photograph of traditional walk-over survey, (b) photograph of traditional walk-over survey based on interviews with local residents, (c) photograph of field survey with an unmanned aerial vehicle, (d) categorized results of field survey.

A field survey is conducted by means of traditional walk-over survey and the use of an unmanned aerial vehicle. Figure 5 illustrates the proportion of the field survey results, which are divided into four categories: (I) unrecorded landslide, (II) unrecorded landslide that would not threaten local residents or other high-value infrastructure, (III) deformation induced by human activities, and (IV) no obvious deformation recognized in the field. As shown in Figure 5(d), 68% of the “anomalous” regions can be identified with observable deformation in the field. By contrast, 87 “anomalous” regions cannot be recognized with obvious deformation.
Figure 6. Example from category III. (a) Mean LOS velocity map, (b) photograph acquired by unmanned aerial vehicle, (c) and (d) results of the field survey indicating cracks induced by slope instability.

A total of 104 “anomalous” regions are classified under category III. Figure 6 shows an example of category III. Integral clusters of measurement points with more than 30 mm/year in the LOS direction can be identified in the region. Dozens of houses can be recognized from optical remote sensing images, which indicate that local residents in this region may be vulnerable to slope instability that could trigger landslides under heavy rainfall. The field survey indicates several house cracks in the region. These house cracks show a high correlation with the blasting activity in a tunnel near the village. As human-induced slope instability can also trigger landslides, further investigation is needed to verify the potential risk for landslide triggering in this region.
Figure 7. Example from category III. (a) Mean LOS velocity map, (b) photograph acquired by unmanned aerial vehicle, (c) and (d) results of field survey indicating cracks induced by slope instability.

The field survey shows that 85 “anomalous” regions are identified as unrecorded landslides. In particular, 18 and 67 of these landslides are classified under categories I and II, respectively. Figure 7 depicts an example of category I. The LOS velocity map reveals that a cluster of measurement points on the slope can be observed with LOS movement exceeding 30 mm/y. This region is identified as an unrecorded landslide that has not been recorded in the local inventory map. According to field survey results, the landslide measures 330 m in length and 170 m in width. The thickness of the soil layer in this new landslide is approximately 12 m. Cracks on houses and roads, which are mainly perpendicular to the downslope direction, can be found in the field. The unrecorded landslide threatens the safety of 166 local residents.

To address the potential risk of unrecorded landslides for the local residents, we use spaceborne InSAR analysis in exploring the feasibility of updating the local inventory map with InSAR techniques. Figure 8 illustrates the updated inventory map based on the proposed analysis and field survey.

Figure 8. Updated local landslide inventory map
Figure 9. Aspect and slope of unrecorded landslides detected by InSAR

As shown in Figure 8, most of the unrecorded landslides are located in the north area of the county. To investigate the characteristics of the unrecorded landslides, we evaluate the slope and aspect of these targets. The results are shown in Figure 9. The analysis shows that the proposed landslide detection workflow is mainly suitable for slope instabilities occurring in the northeast and for slope angles between 10° and 20° because of the one-dimensional deformation obtained with ascending SAR images. We should note that unrecorded landslides can be detected by InSAR only if they accumulate enough deformation before their final failure. Given the threshold used in this work, landslides with accumulated deformation smaller than 20 mm/year may not be recognized as anomalous regions. Moreover, because the revisit time and spatial resolution of the Sentinel-1A satellite are fixed, landslide triggering in a short time or small volume cannot be detected as well.

The LOS velocity field data also reveal the surface motions of recorded landslides. The deformation of 461 recorded landslides are recognized by the clusters of measurement points with velocities exceeding 20 mm/year. The results suggest that in 2018, nearly 30% of the recorded landslides in Fengjie county accumulated observable deformation.

Figure 10. Detection of pre-existing landslide reactivations. (a) Boundaries of Outang landslide and Xinpu landslide, (b) mean LOS velocity map of the two landslides.

Figure 10(b) illustrates the mean LOS velocities in the Outang (OT) landslide and Xinpu (XP) landslide located along the reservoir. The OT landslide is a slow-moving dip-slope translational landslide with clayey sliding zone sandwiched between the landslide mass and the bedrock. The landslide mass can be divided into three parts with a total volume of 90 million m³. The XP landslide...
is a landslide group with three individual slide masses, namely, Daping slide mass, Shang’ertai slide mass, and Xia’ertai slide mass. The volumes of the slide masses are 0.68 million, 2.5 million, and 34 million. Xia’ertai, in particular, belongs to the type of landslide with slow-moving and transitional movement.

As shown in Figure 10(b), excessive deformation mainly occurs at the head of the OT landslide and the toe of the XP landslide. To determine the potential correlation between landslide movement and triggering factors, we extract the displacement time series of measurement point A located at the toe of the XP landslide. GPS data from a station located near measurement point A and water level fluctuation data are also acquired. The comparison between InSAR time series, GPS data, and water level fluctuation data is shown in Figure 11.

To validate the InSAR results using GPS data, we transform the InSAR time series toward a downslope direction. The InSAR and GPS time series data show excellent agreement. The InSAR time series extracted at measurement point A reveals a peculiar signal before the monsoon season (primarily April); the same is noted in the GPS data. To further investigate this anomalous movement, we obtain the water level fluctuation and compared it with the InSAR/GPS time series. As shown in Figure 11, a high correlation exists between the acceleration of InSAR time series and water level drawdown. The correlation implies the acceleration of the toe of the XP landslide being governed by external disturbance from water level drawdown.

5. Discussion and conclusions

This study presents regional-scale landslide detection by utilizing InSAR techniques. A total of 30 SAR images acquired by Sentinel-1A are processed to obtain the mean LOS velocity map of the study area. Analysis shows that 276 anomalous regions are not recorded in the local landslide inventory map. By conducting field survey, we classify 18 “anomalous” regions as unrecorded landslides. InSAR time series extracted from the toe of a known landslide is also validated with GPS data. The comparison between InSAR time series and water level fluctuations reveals a high correlation between the acceleration of landslide motion and water level drawdown in the early part of the monsoon season.

Fengjie county is located in the transition zone between the second and third steps of China’s topography. It features a complicated geological environment, which is vulnerable to landslide hazards especially in the monsoon season. On August 31, 2014, following a period of extremely intense rainfalls, more than 2,340 landslides were triggered in northeast Chongqing, including Fengjie county, Wushan county, Yuyang county, Wuxi county, and Kaizhou county. These counties all have...
mountainous terrains with moderate to high forest coverage. Hence, landslides in these regions would be difficult to characterize using standard geological methods. Although they are mainly used landslide hazard investigations, field surveys may suffer from low update rates, especially in developing regions with mountainous terrains. Moreover, human error can potentially affect the perception of landslide reactivation, especially in areas characterized by high geological and geomorphologic complexity. InSAR can detect subtle ground surface movements within a large area efficiently. However, InSAR suffers from a number of intrinsic limitations that must be considered in the analysis of landslides. According to the field survey results of this work, the use of the mean velocities of radar targets alone may not be enough to fully identify the anomalous ground surface movements and accelerations occurring in a certain region. Given the one-dimensional nature of the InSAR velocity results, landslides with various slopes and aspects may exhibit different detectable sensitivities in the InSAR mean velocity maps. Moreover, the kinematics of landslides mainly exhibits nonlinear deformation during the monsoon season in Fengjie county; InSAR processing based on linear deformation models would not be able to capture such motions. Human activities may also induce ground surface movements that would in turn cause the false detection of landslides. Correlation analysis of InSAR time series and precipitation or water level fluctuations may be applied to reduce the rate of false detection.

**Acknowledgements**

This study was financially supported by the Bureau of Planning and Natural Resources of Chongqing, China (Grant No. 19C2082). The Sentinel-1A images were provided by the European Space Agency.

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