Deformation Monitoring and Evaluation of Mountain Slope Stability Combined With Ground-based Radar and Spaceborne InSAR Methods

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Research Article

Keywords: ground-based radar, spaceborne InSAR, deformation monitoring, slope stability, time series InSAR

Posted Date: June 1st, 2021

DOI: https://doi.org/10.21203/rs.3.rs-555768/v1

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Abstract
In this paper, ground-based radar and spaceborne Interferometric Synthetic Aperture Radar (InSAR) images were combined to monitor slope stability and analyze the main deformation factors of an ancient landslide on the right bank of the Dajinchuan River in Danba County, Sichuan Province, China. We applied the short baseline set (SBAS) time series strategy with 656 scenes of ground-based radar between September 13-17, 2019, and 62 scenes of Sentinel-1 data from July 2018 to October 2020. Combined with high-resolution satellite images and digital elevation model (DEM) data, we acquired trace and quantitative deformation features and discussed the factors that contributed to slope instability, such as geological structure, topography, external environment and human activities. The largest deformation area detected by ground-based radar is located in the bedrock above the target area with a maximum cumulative deformation of more than 30 mm during the detection time. The maximum average annual deformation rate detected over the region by spaceborne InSAR is over 40 mm/a. We analyzed the differences between the ground-based radar and spaceborne InSAR and the reasons for the differences. This study provides references and suggestions for investigating potential landslide risks by combining ground-based radar and spaceborne InSAR technology.

Keywords
ground-based radar; spaceborne InSAR; deformation monitoring; slope stability; time series InSAR
Declarations

Funding

This work was financially supported by Research Grants from the National Institute of Natural Hazards, MEMC, (grant numbers ZDJ2019-17 and ZDJ2020-04), and the National Natural Science Foundation of China (41772219).

Conflicts of interest/Competing interests

The authors have no financial or proprietary interests in any material discussed in this article.

Availability of data and material

The sentinel-1 data and regional geological data can be downloaded from Internet, the ground-based radar cannot be deposited.

Code availability (Not applicable)

Authors' contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Yanchao Wang, Wenliang Jiang, Yongsheng Li. The ground-based radar data was collected by Bingquan Li and Yi Luo. The first draft of the manuscript was written by Yanchao Wang and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Ethics approval

No conflict of interest exits in the submission of this manuscript, and manuscript is approved by all authors for publication. I would like to declare on behalf of my co-authors that the work described was original research that has not been published previously, and not under consideration for publication elsewhere, in whole or in part. All the authors listed have approved the manuscript that is enclosed.

Consent to participate

It has been approved by all co-authors.

Consent for publication

This manuscript’s publication has been approved by all co-authors.
1. Introduction

China is among the countries with the most serious geological disasters in the world. Unfortunately, accurately predicting and warning about geological hazards are challenging tasks (Hongqi Chen et al. 2011). At present, more than 300,000 hidden geological hazards have been found in China, but nearly 70% of the major geological disasters that have occurred in recent years were not found within the scope of these hidden hazards, and a large number of hidden hazards have not been found (Xu 2020). Landslides are one of the most important geological disasters, and they not only threaten human lives but also seriously damage the environment, resources and property. With the sustained and rapid development of the national economy, large-scale projects, such as urbanization, railways and hydropower projects, have been developing in depth. For example, the construction of the Sichuan-Tibet Railway and the Baihetan Dam will greatly transform the engineering geological conditions. Therefore, an increasing number of construction projects and engineering projects will be exposed to increased geological hazards, which will increase the disaster risk level. On the other hand, the aggravation of global warming and climate change in recent years has led to an increase in “warming and wetting” of the Tibetan Plateau (Duan et al. 2016), and the influence of major natural disasters and disaster chains will become more significant. In addition, because transformation and destruction of the natural environment caused by human disturbance are better, the balance of the natural environment has changed, and the deterioration of the natural environment will eventually feedback to human society. Therefore, it is of great significance to strengthen the identification and dynamic monitoring of geological hazards to achieve advanced risk perception, early warning and accurate emergency response of geological hazards. Thus, procedures are necessary and important guarantees to reduce the casualties and economic losses caused by geological hazards.

Recently, the rapid development of sky-ground multiplatform measurement technology has provided important technical means for risk assessment, early warning and emergency monitoring of geological hazards. Many scholars have carried out a
large number of studies on the early identification and dynamic monitoring of geological hazards (Casagli et al. 2017; Lu Zhang et al. 2018; Lu et al. 2019). Among these platforms, optical satellites and InSAR satellites are the most widely used at present. However, the role of spaceborne technology is more focused on the early identification of geological hazards. In the field of unmanned aerial vehicles, aerial photogrammetry plays an important role in high-precision geological hazard surveys and emergency observations due to its flexibility and relatively low cost. In addition, ground-based radar technology has also been an important supplement to ground-based observation technology, which can carry out long-distance and high-precision observations of major geological hazards; therefore, it is very important to avoid in situ instrument deployment for monitoring and early warnings of major geological hazards and emergency observations (Luo et al. 2020). At present, the application of ground-based radar observation technology in geological hazard monitoring is still in the experimental and exploration stage.

In this study, the mountain slope stability of an ancient landslide on the right bank of the Dajinchuan River in Danba County, Sichuan Province, China, is monitored by ground-based radar and spaceborne InSAR methods. Combined with high-resolution image and DEM data, we study the trace features and quantitative deformation features of the ancient landslide. The influence of landform, slope direction, geological structure, river erosion, stratum rock group and human activity on the hidden hazards are also analyzed. At the same time, the difference and relationship between the ground-based radar and spaceborne InSAR are analyzed and compared, and the main factors that cause the differences are discussed. This study will provide references and suggestions for monitoring the hidden danger of geological hazards by combining ground-based radar and spaceborne InSAR technology.

2. Study area description

The study area is located in Jiaju village, Danba County, Sichuan Province. Danba County is located from the first to second step of the topographic transition zone in
China, where the terrain is extremely complex and significantly characterized by an alpine canyon landform. The Dadu River cuts across Danba County from north to south (Fig 1), with river channels of 1000 to 3000 m in depth. In contrast, influenced by the high mountain and canyon topography, Danba County is characterized by the Tibetan Plateau monsoon. Moreover, the area is also characterized by obvious vertical zonality due to topographic factors. With increasing altitude, both the temperature and evaporation decrease gradually; however, the precipitation increases. The precipitation is mainly concentrated between May and September, the rainy season and dry season are obviously different, and the temperature varies greatly from day to night.

Danba County is situated in the contact zone of several tectonic blocks, including the Bayankara block and Sichuan-Yunnan rhombic block. Under the action of several phases of mountain building and metamorphism, the geological structures are extremely complicated, with diversified folding structures and interlaced fault structures trending NW. The complex lithologies are mainly metamorphic rocks, and the strata are relatively complete with only a few missing strata (Nie 2018). Geological disasters occur frequently in Danba County and are characterized by sudden occurrence, strong concealment, and significant damage (Minghui Li et al. 2008). With the increase in construction projects, especially the multistage water-power engineering projects in the Dadu River, geological disasters in this region are becoming increasingly serious, and many old landslides have been reactivated.

The study area of this paper is located on the right bank of the Dajinchuan River (Fig 2), a tributary of the Dadu River. The study area is also situated at the foot of the right front slope of the old, large Jiaju landslide group, which consists of many secondary landslides that led to multiple bank deformation events along the Dajinchuan River. The observation area of the ground-based radar in this study is the slope bedrock of a secondary ancient landslide. The front edge of the ancient landslide is approximately 1.4 km in length, and the height difference between the front and back edges of the landslide is more than 700 meters. The general terrain slope exceeds 25 degrees according to the DEM data. Two rock fractures extending in the northeast
direction can be clearly interpreted from the Google Earth images in the observation area of the ground-based radar (Fig 2(c)). The upper fracture is approximately 820 m in length, and the lower fracture is approximately 600 m in length. To study the deformation feature of this bedrock slope of the ancient landslide, we utilized ground-based radar and the satellite InSAR method. The deformation results measured by the two methods are analyzed, and these results may help to better understand the landslide in similar studies.

Fig 1(a) Regional hillshade map of the study area. A Shuttle Radar Topography Mission (SRTM) hillshade map is used as the base map. (b) Regional geological setting surrounding the study area
Fig 2 Geographic location map. (a) The whole picture of the Jiaju landslide group. (b) The location and range of ground-based radar. (c) The surface fissure on the slope.

3. Data and methods

3.1 Measurement principle of ground-based radar

The ground-based radar data used in this study are acquired by the portable radar interferometer GPRI-II (Gamma Portable Radar Interferometer) produced by GAMMA company. This interferometer uses real aperture radar with a radar frequency of 17.2 GHz (Ku band), bandwidth of 200 MHz, wavelength of 0.0176 m and effective...
measurement range from 0.05 to 10 km. The deformation monitoring accuracy can reach the submillimeter level with an azimuth resolution of 6.28 m (when the distance is 1 km) and a range resolution of 0.75 m. The GPRI-II is mounted on a tripod and measured at 360° by a rotating scanner with three antennas, one transmitting signal and two receiving the echo signal.

GPRI-II uses a frequency-modulated continuous wave (FMCW) to measure the velocity and distance of the target by the frequency differences between the transmitted signal and received signal. This technique is suitable for data acquisition and digital signal processing with low difference frequency signals and simple hardware processing. Compared with SFCW (step frequency continuous wave), GPRI-II can improve the scanning speed and reduce the influence of the atmospheric delay phase on the monitoring precision, reducing the phase distortion caused by system noise in the long-term scanning process. At the same time, GPRI-II can generate a DEM by means of two antennas. The system generally uses the continuous observation mode to continuously observe the target area.

The range resolution of GPRI-II is

$$\Delta d_r = \frac{c}{2B}$$

where C is the speed of light and B is the bandwidth. As seen from the above equation, the range resolution is independent of the distance between the instrument and the observed target.

The azimuth resolution is

$$\Delta d_{az} = \sin(\theta_{-3dB}) \cdot R$$

$$\theta_{-3dB}$$ is the width of the half-power wave velocity, and R is the azimuth distance.

Since the spatial baseline of GPRI-II is 0 and the observation mode is continuous, the interferometric phase of GPRI-II does not include the terrain phase and the geometric phase component between the two positions; thus, the interferometric phase is

$$\Delta \phi = \phi_{defo} + \phi_{atmo} + \phi_{noise} + 2k\pi$$

In the formula, $$\phi_{defo}$$ is the deformation phase, $$\phi_{atmo}$$ is the atmospheric delay
phase, and $\phi_{\text{noise}}$ is the noise phase.

Compared with the spaceborne InSAR system, the ground-based radar system has several unique advantages (Wu et al. 2019; Tiandong Chen 2020). First, the precision of the ground-based radar is higher up to the submillimeter level as its wavelength is shorter. Second, the observation period of ground-based radar is shorter, and the time sampling rate is higher to simplify the phase unwrapping process and achieve rapid real-time monitoring. Third, the ground-based radar system is more portable and flexible because it can be monitored at any time according to the conditions of the disaster, and the observation angle and observation time interval can be adjusted, making it more suitable for slope deformation monitoring. Finally, the ground-based radar installed on the observation station has no influence on the space baseline or orbit error.

### 3.2 Ground-based radar data acquisition

To obtain the echo signal as much as possible and ensure the stability of the platform, the set-up position of GPRI-II should consider the following four conditions (Bingquan Li et al. 2019). The first is good visibility, and the equipment should be set up in a position with high visibility and no obstacles between the equipment and target area. Second, a reasonable observation distance, that is, the appropriate monitoring distance, should be selected according to the actual situation of the site, such as the topography, engineering, hydrology and other conditions. The larger the distance is, the weaker the radar receiving echo signal, and the worse the monitoring effect. The third condition is that the equipment should be placed on a stable observation platform to reduce the influence of any small equipment movement on the observation accuracy. The last condition is a suitable viewing angle. The smaller the angle is, the more sensitive the radar is to the intensity of the deformation signal, but it is disadvantageous to receive the echo signal. In ground-based radar deformation monitoring, the observation parameters should be adjusted at the beginning according to the environmental factors and the quality of the observation data because the subsequent data processing accuracy has a great impact.
In this study, the instrument was set up in the Jiajuzangzhai tourist center in a continuous observation mode. The monitoring time was from 8:27 to 21:37 on September 13, 2019, and from 16:46 on September 15 to 13:26 on September 17, 2019. The time interval between the two receiving antennas was approximately 10 minutes and one scene, and the total number of images was 656 scenes. The observed parameters are shown in Table 1.

### Table 1 Measured parameters of the ground-based radar

| Index           | Parameter                      |
|-----------------|--------------------------------|
| Platform location | 101.878°E, 30.905°N            |
| Platform elevation  | 1927.3 m                     |
| Measurement range  | 0.45-1.3 km                  |
| Coherence threshold  | 0.35                         |
| Antenna-pitch    | 20°                           |
| Azimuth         | 229.3°                        |

3.3 Data processing flow

GPRI-II ground-based radar and spaceborne InSAR have basically the same time series analysis process; the largest difference is that the ground-based radar spatial baseline is 0, without image registration and terrain phase compensation. The processing flow of ground-based radar data mainly includes data preprocessing, interference processing, coherent point extraction, phase filtering, phase unwrapping, atmospheric correction, time series analysis and geocoding (Wang et al. 2019a; Wang et al. 2019b).

During the process of coherent point extraction, an adequate number of high quality coherent points are very important to the precision of deformation monitoring results. The methods of coherence point extraction mainly include the amplitude departure threshold method, local coherence method (coherence coefficient threshold
method) and nonlocal method. In this paper, a nonlocal method is used to extract coherent points by selecting homogeneous or similar pixel estimates from the surroundings of each resolution unit.

In the process of phase unwrapping, there is a $2k\pi$ relation between the initial phase and the true phase in the interferogram. The initial phase is the winding phase between $-\pi$ and $\pi$, which is the main value of the true phase. The interference phase needs to be decoded to obtain the true phase. Considering the stability and time effect of phase unwrapping, the three-dimensional phase unwrapping method is adopted in this paper.

Atmospheric correction is also necessary for ground-based radar data (Xining Zhang et al. 2017). Ground-based radar relies on the phase information of radar signals for ranging, but the accuracy of ranging is affected by the changes in the refractive index of the radar signals because of the atmosphere. Even for short-term monitoring, shortwave band ground-based radar is also very sensitive to weather changes, so improving the measurement error caused by atmospheric phases has become the key technology to improve the observation accuracy of ground-based radar. In this paper, an iterative decomposition model is used to correct the effect of atmospheric variations on the deformation results.

We use the singular value decomposition method (Li et al. 2013) to generate the deformation time series diagram. The deformation characteristics, including the spatial distribution, deformation intensity and future development trend, can be estimated by the time series map of deformation, which provides a basis for emergency response.

### 3.4 Other auxiliary data

To investigate the features of the slope, as well as for comparison with the deformation results obtained by ground-based radar GPRI-II, remote sensing data from different platforms were also employed, including spaceborne InSAR and high-resolution Google Earth images. A total of 62 scenes of Sentinel-1 data from July 2018 to October 2020 were selected for deformation analysis.

Other auxiliary data, including geological maps and meteorological and
hydrological data, were also employed in the study.

4. Results and analyses

4.1 Deformation results of ground-based radar

The effective monitoring time of ground-based radar is from 8:27 on 13 September to 21:37 on 13 September and from 16:46 on 15 September to 13:26 on 17 September. The maximum monitoring distance is approximately 1300 m, and the minimum monitoring distance is approximately 450 m. According to the processing flow in section 3.3, we set the parameters, which include the unit window size and time baseline. Since the data format of the data acquisition system synchronized to the ground-based radar data processing system is binary, it needs to be converted to MAT format. The average coherence criterion is used to extract the coherent points, and the nonlocal coherence algorithm is used to set the coherence threshold value to 0.35, the nonlocal window to 15, the similarity threshold value to 0.9, the minimum similarity point to 10, and the maximum similarity point to 45. Some of the differential interferograms produced during ground-based radar data processing are shown in Fig 3. The numbers at the top of each figure represent the observation dates of the two data points used to generate the differential interferograms. As shown in Fig 4, there is obvious deformation in the monitoring area. The main deformation area is above the continuous curve. The maximum cumulative deformation is more than 30 mm.
Fig 2 Examples of differential interferograms generated during the processing of ground-based radar data. The two numbers in the upper part of each figure denote the observation dates of two data points used to generate the differential interferogram. 20190913084754-20190913085754 denotes the differential interferogram generated between two data points observed at 8 h 47 m 54 s on September 13, 2019, and at 8 h 57 m 54 s on September 13, 2019. The origin point of the coordinate system is the position of the ground-based radar.
Fig 4 (a) Cumulative slips of the slope deformation along the LOS direction measured by the ground-based radar device. The number at the top of the figure represents the time when ground-based radar began and ended observations, that is, the observation time range of the cumulative deformation map generated; and 20190913082754-20190917132654 represents ground-based radar observation time from 8:27:54 on September 13, 2019 to 13:26:54 on September 17, 2019. The origin of the coordinates represents the position of the ground-based radar. (b) and (c) are the results of the accumulated deformation of the selected points in the time series of 0~13.5 h and 56~101 h, respectively.

4.2 Deformation results from spaceborne InSAR

Sixty-two scenes of Sentinel-I downorbiting data covering the study area from
July 2018 to October 2020 were processed using GAMMA software, and the average annual deformation rate of the study area over this period was obtained using the short baseline set (SBAS) processing method (Fig 5(a))(Yongsheng Li et al. 2013). The maximum average annual deformation rate in the region is over 40 mm/a. The main deformation areas monitored are located along the banks of the Dadu River and its tributary, the Dajinchuan River. These deformation areas all have different degrees of human activities, such as road construction.

In the observation area of ground-based radar, the gray line in Fig 5(a), three points are selected for time series analysis. The result of the line-of-sight cumulative deformation is shown in Fig 5(b). The maximum cumulative deformation is approximately 80 mm, which is located in the lower part of the continuous bedrock curve of the landslide’s back wall.
Fig 5(a) Regional annual deformation rate map measured by Sentinel-1 data, and P1, P2 and P3 are the three points selected in the observation area of ground-based radar. The gray line is the scanning angular scope of ground-based radar. (b) The line-of-sight cumulative deformation map of three selected points P1, P2 and P3 in the study area.

5. Discussion
5.1 Deformation analysis of the mountain slope

We match the ground-based radar and spaceborne InSAR data accurately and superpose to the Google Earth 3D image (Fig 6) to compare the image features of different deformation regions. According to the interpretation of satellite remote sensing images, the main target area of this observation is located on the right wall of a pre-existing ancient landslide. The accumulation body of the early ancient landslide is mainly located at the left foot of the ancient landslide, which is the upper part of the scenic area. Some accumulation bodies remain on the right side of the ancient landslide. The target area observed by ground-based radar is mainly on the right side of the ancient landslide, and the back wall is the blind area, which is not effectively covered.

By monitoring the right wall of the ancient landslide with ground-based radar, some deformation is observed in the area. The largest deformation area detected by ground-based radar is located in the bedrock above the target area. The maximum deformation area is approximately 150 m across the slope and 300 m up and down the slope. This deformation belongs to the back wall bedrock zone of the pre-existing ancient landslide body and is a push-type landslide.

At the same time, in the deformation map obtained by spaceborne InSAR monitoring, there is a large range of deformation in the target area, especially in the bottom and upper parts. The bottom deformation region is the left front accumulation of the pre-existing landslide body, which is the area of continuous curving road in the upper part of the scenic spot. The upper deformation region is located in the lower part of the maximum deformation region observed by ground-based radar and corresponds to the continuous curve region on the right wall of the landslide. The deformation of two continuous curved road areas is the result of road construction and can be found in the InSAR long time series result. In contrast, the maximum deformation region observed by ground-based radar reflects the effect of rainfall on slope stability due to the September flood season. The deformation in this area is at a large scale, and local periodic deformation occurs in relation to the flood season.
5.2 Main factors influencing slope deformation

In general, the factors that affect the stability and deformation of geological slopes include geological structure, topography, external environment and human activities. Based on the observational results analysis, deformation is the result of these abovementioned factors.

In terms of geological structure, Danba County lies at the intersection of three important active tectonic belts, namely, the northwest Xianshui River Fault Zone, the northeast Longmen Mountain thrust zone and the nearly south-north Anninghe Fault Zone. These three fault zones are all active Holocene fault zones with important seismogenic tectonic settings. Geological hazards in this area are prone to occur because of strong tectonic activity and broken internal blocks under the influence of three active tectonic belts. In addition, the block is located at the front of the Bayankara Block and is in a strong uplift region along the Longmen Mountains tectonic belt. Therefore, this region is characterized by high mountains and deep valleys, and rapid and serious valley undercutting is taking place. The slope angle on the left bank of the river is 36°, and the slope gradient on the right bank is more than 30°. Under the influence of both the uplift of the mountain body and the deep cut of the valley, the increase in the effective open plane formed at the front of the deformation body increases the gravitational potential energy of the slope, leading to the decrease in the
stability of the slope, and creep deformation of the slope easily occurs under the action of gravity. There are cracks in the broken rock of the bedrock slopes, and rainfall can easily permeate the bedrock, which promotes slope sliding along the bedding surface and affects the stability of slopes. Therefore, strong tectonic activity is the most important factor for the development of geological hazards in Danba County.

In terms of topography and geomorphology, the slope angle of a geological body is an important factor that affects its stability. Generally, geological bodies with slope angles greater than 10° are subject to unstable deformation under the action of gravity (Donnarumma et al. 2013; Luo et al. 2020). According to the regional DEM, the slope angle of the whole terrain is more than 30° and the gradient is more than 0.58, while the slope angle of the local slope of ground-based radar is more than 20° and the gradient is more than 0.41 (Fig 7). Whether considering the whole terrain or the local terrain, the slope of the terrain is very large, and it easily loses stability and deforms under disturbances by internal structural factors and external artificial factors.

In addition, there is a gentle platform in the upper part of the observation slope, which presents as a low-slope above and steep characteristics below over the whole terrain. This topographic feature is not conducive to rapid drainage of heavy rainfall during the flood season (Luo et al. 2020). Under the condition of poor drainage at the top, the accumulated water will gradually permeate into the interior of the formation, thus acting as a lubricant in the interior of the rock formation, causing the slope to be more prone to instability and deformation under the action of gravity. This finding also shows that the deformation observed by ground-based radar in this study is mainly concentrated in the flat-top area of the platform.
The external environmental factors are mainly hydrometeorological conditions, erosion and weathering. Danba County is in the Tibetan Plateau monsoon climate in the Northern Hemisphere subtropical climate zone, located in the Dadu River Valley Watershed. Rainfall is concentrated in June-August, and the annual total precipitation is generally 500-1000 mm. Mountain torrents and mud-rock flows frequently occur in Danba County under the influence of heavy rainfall; for example, the Danba County region suffered 60-year floods in June 2020 under the influence of heavy rainfall, and several places, including Banshanmen, Donggu, and Mozigou, suffered flood debris flows. River erosion is also very strong due to the breaking and cutting of the valley because of the influence of heavy rainfall and strong tectonic activity. The water level rises and falls steeply during the flood season, and the dynamic water pressure and uplift force change rapidly in the slope. When the water level falls rapidly, the abnormal increase in hydrodynamic pressure and the rapid decrease in uplift force play a large role in triggering the failure of the slope, and the foot of the slope is easily cut so that the upper rock mass loses its support, and then, the slope loses its stability.

In addition to the above natural factors, human activities, especially engineering construction disturbance factors, which increase with the development of the social economy, are also important factors affecting the stability of slopes. These effects include engineering cut slopes and slope angles and persistent engineering disturbances. The remote sensing images show that there is a continuous curved road in the middle of the slope. Although the road scale is not large, this curved road has the phenomenon of
horizontal repeated slope cutting, and there is a large range of construction in the top
platform of the observation area, which changes the slope gradient and forms the terrain
characteristics mentioned above. The strong deformation area observed by ground
radar is located in the upper part of the road construction area. Under the influence of
the slope-cutting disturbance, two clear and continuous surface fissures were formed in
the upper part of the platform, one of which was more than 900 m in length and the
other was more than 600 m in length. According to remote sensing image records,
roads were built from 2011 to 2012; although the scale was small, roads became one of
the important factors that induced slope instability and deformation under the
disturbance of long-term human activities.

5.3 Difference analysis of spaceborne and ground-based observation results

The main reasons for the inconsistent characterization results of the deformation
area between spaceborne InSAR and ground-based radar include the inconsistent time
period length of satellite and ground observations, the observation mode and angle of
satellite and ground surface, the difference in deformation reference points, the
mismatch of image resolution and observation accuracy, and the phase difference.

In terms of the observation time cycle, spaceborne InSAR data were collected
from July 2018 to October 2020, with a 12-day interval of 62 scenes. The ground-based
radar monitoring time was from September 13 to September 17, 2020. There is a large
difference in the observation time and the collection time interval between them.
Spaceborne InSAR has a larger time span, longer acquisition interval, and
ground-based radar has a smaller time span, shorter acquisition interval, higher time
resolution and better data accuracy.

In terms of the difference between the observation mode and the incident angle,
the ground-based radar and spaceborne InSAR monitoring schematic diagram is shown
in Fig 8. Ground-based radar is installed in a flat field opposite the study area and
scanned by a rotating scanner at a set angle. The elevation angle of this experiment is
20°, and the range of radar scanning angles is -20°~20°. Sentinel-1 data have a variety
of imaging modes. The interference width mode is the default mode for land cover.
Progressive terrain scanning technology TOPSAR is used to obtain three subbands, and the incident angle is in the range of 29°–46°. The imaging mode and the observation angle are different, and the angle of the line-of-sight deformation is also different, which affects the observation result.

![Diagram](image)

**Fig 8(a)** Ground-based radar monitoring plan sketch (b) Ground-based radar monitoring profile sketch (c) A schematic of the Sentinel-1 imaging mode

The reference datum points of deformation are different. The base point of ground-based radar is located at the foot of the slope, so the observed deformation is closer to the real deformation characteristics of the landslide. The spaceborne InSAR data reference point is relatively stable in the whole image, which is located a large distance from the slope, so the deformation shown is also relative to other reference points. There may be overall deformation in a region that either increases or counteracts the true deformation of the slope.

In terms of imaging resolution and deformation monitoring accuracy, the medium resolution of the spaceborne InSAR Sentinel-1 is 5 m × 20 m, and the time series processing accuracy is at the mm level. The range resolution of the ground-based radar is 0.75 m, and the azimuth resolution at 1 km is 6.8 mrad with submillimeter accuracy. The data precision of the ground-based radar is obviously higher than that of spaceborne data, but it is not suitable for long-term and large-scale observations, and spaceborne data are not suitable for small-scale deformation objects.

In data processing, the space baseline of ground-based radar is 0, there is no need for terrain phase compensation, and there is no influence from an orbit error. The influence of the atmosphere is weak due to the limited observation distance. In contrast,
there is not only the influence of the spatial baseline but also a large interference of atmospheric error in spaceborne InSAR data processing, so it is necessary to repeatedly remove the influence of internal and external noise from various systems, which will greatly reduce the accuracy of the observation data.

5.4 Applicability of multiple remote sensing platforms for potential geological hazards

The above studies show that there are usually some differences between the ground-based radar and spaceborne InSAR results of deformation monitoring. These differences are caused by the observation time period, the observation geometric model and incidence angle, the deformation reference point, the image ground resolution and the deformation monitoring accuracy. However, this difference is not due to the large contradiction between the two technical methods but a reasonable physical phenomenon, which is a multiangle solution to a problem and is formed by a variety of physical factors. This finding also reflects the advantages and disadvantages of spaceborne InSAR and ground-based radar in deformation monitoring of geological disasters. Therefore, in actual research, the two methods can be combined to form an effective technical complementary scheme.

By combining satellite data and ground-based monitoring technology, the deformation mechanism and factors influencing geological slopes can be studied from more perspectives and aspects (Yongsheng Li et al. 2020). Topographic transformations produced by human disturbances can be recorded by satellite data with high spatial and temporal resolutions. Due to the limitation of spatial and temporal resolution, the spaceborne InSAR method is suitable for the early identification and investigation of the risk of geological hazards. By comparison, ground-based radar is suitable for geological hazard monitoring, early warning and emergency observation due to its advantages of higher deformation observation precision, flexible observation angle and easy deployment (Caduff et al. 2015; Casagli et al. 2010; Nico et al. 2004; Qin et al. 2020). In addition, ground-based radar is the most suitable technique for deformation observations with high precision in real time to determine the potential of secondary
landsides for safety during emergency responses (Antonello et al. 2004; Atzeni et al. 2015) in the postdisaster phase (Luo et al. 2020). In the case of geological hazards, UAVs can be rapidly deployed to capture orthophoto image data to evaluate the influence and damage intensities during a disaster for emergency response purposes for the first time (Casagli et al. 2017; Nikolakopoulos and Koukouvelas 2017).

In recent years, advances in earth observation (EO) from the ground surface, aircraft and space have dramatically improved our ability to detect and monitor active landslides (Bardi et al. 2014; Dai et al. 2020; Bardi et al. 2016). Various RS platforms, including satellites, UAVs, ground-based radar instruments, etc., have been widely used in the investigation of geological hazards and in the assessment of disaster emergencies. Because the characteristics of each platform differ from those of other platforms, different RS platforms may play various roles in different phases of landslide hazard evaluations, including the before and after landslide phases. Therefore, different platforms and measurement models may have different applications in various scenarios and stages of disaster evolution due to their different advantages and disadvantages, which can be combined to solve the qualitative investigation and quantitative measurement of hidden geological hazards and their deformation characteristics. With the support of all these platforms, we can study all elements and entire chains of geological disasters. Therefore, satellite-based and ground-based observation technologies can effectively complement each other in the time axis and deepen the understanding of the development trend of geological hazard deformation by constructing the working mechanism of their coordination to provide important technical support to prevent risks of major geological disasters. By summarizing nearly all RS methods suitable for geological hazard investigation, different features and parameters are listed briefly for reference in Table 2 for different scenarios and stages.

Table 2 Application characteristics of sky-ground observation technology in geological disaster detection

| Platform                      | Advantages               | Hazard scene and stage                  | Application objective                              | Resolution/Pr precision | Disadvantages                      |
|-------------------------------|--------------------------|-----------------------------------------|---------------------------------------------------|-------------------------|-----------------------------------|
| Optical satellite data        | Wide amplitude, multiband | Early identification of hidden dangers  | Trace characteristics survey, disaster risk assessment, large-scale risk census | Submetre                | Affected by vegetation cover, affected seriously by weather |

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| Method               | Characteristics                                                                 |
|---------------------|---------------------------------------------------------------------------------|
| Spaceborne InSAR    | Wide amplitude, all-weather, all-time, Early identification of hidden dangers    |
|                     | Survey of deformation characteristics, disaster risk assessment, large-scale risk |
|                     | census, Time series: mm/s, Long revisit cycle, current dependence on foreign      |
|                     | satellites, high-resolution data is expensive                                  |
| UAV-based tilt      | High resolution, 3D modeling, flexible deployment, Disaster investigation,        |
| photogrammetry      | emergency assessment, Trace feature survey, disaster risk verification, disaster  |
|                     | assessment, Small imaging width                                                |
| UAV-SAR             | High resolution, all-weather, all-day, flexible deployment, Disaster investigation,|
|                     | emergency assessment, Trace feature survey, disaster risk verification, disaster  |
|                     | assessment, UAV-SAR does not support interference processing and has small       |
|                     | imaging width                                                                  |
| GNSS                | High-precision real-time continuous monitoring, Monitoring, forecasting and early |
|                     | warning, Deformation characteristics investigation and dynamic monitoring of     |
|                     | landslide disaster risk, Sparse points, high observation cost and insufficient   |
|                     | remote landslide monitoring                                                     |
| Ground-based        | All-day, high precision real-time continuous monitoring, Monitoring, forecasting and|
| SAR                 | early warning, Deformation characteristics investigation and dynamic monitoring  |
|                     | of landslide disaster risk, Affected by vegetation and atmosphere, suitable for |
|                     | single landslide monitoring                                                     |

### 6. Conclusion

Based on 656 ground-based radar images collected from September 13-17, 2019, and 62 spaceborne SAR observations from July 2018 to October 2020, this paper analyzed the deformation information extraction of an ancient landslide on the right bank of the Dajinchuan River in Danba County. The maximum deformation area monitored by ground-based radar is located at the upper part of the continuous curve of bedrock on the back wall of the ancient landslide, and the maximum deformation is more than 30 mm. Spaceborne data also measure deformation here, but the measured maximum deformation area is located in the continuous curved area in the lower part of the maximum deformation area observed by ground-based radar, and the annual average deformation rate is more than 40 mm/a.

Combined with the local geological topography, meteorological precipitation and other data, this paper analyzed the main factors affecting the deformation of bedrock in...
the region, including geological structure factors, topography and geomorphology factors, hydrological and meteorological conditions, erosion, weathering and human activities. Additionally, we discussed the reasons for the difference in the deformation results between the two observation methods and provided suggestions for the scheme of satellite-ground coobservation. By complementing each other in the time axis, the effectiveness of spaceborne InSAR in the early identification of geological hazard risks and the advantages of ground-based radar for the high-precision observation of key deformation targets were brought into play. The cooperative working mechanism of the two was more conducive to identifying hidden geological hazards and monitoring risk sources.

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Figure 1

(a) Regional hillshade map of the study area. A Shuttle Radar Topography Mission (SRTM) hillshade map is used as the base map. (b) Regional geological setting surrounding the study area (China Geological Survey, 2014). The red line denotes the main faults in this region. YKFZ: Yuke fault zone; JTFZ: Jintang
Figure 2

Geographic location map. (a) The whole picture of the Jiaju landslide group. (b) The location and range of ground-based radar. (c) The surface fissure on the slope. Note: The designations employed and the
presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

**Figure 3**

Examples of differential interferograms generated during the processing of ground-based radar data. The two numbers in the upper part of each figure denote the observation dates of two data points used to generate the differential interferogram. 20190913084754-20190913085754 denotes the differential interferogram generated between two data points observed at 8 h 47 m 54 s on September 13, 2019, and at 8 h 57 m 54 s on September 13, 2019. The origin point of the coordinate system is the position of the ground-based radar.
Figure 4

(a) Cumulative slips of the slope deformation along the LOS direction measured by the ground-based radar device. The number at the top of the figure represents the time when ground-based radar began and ended observations, that is, the observation time range of the cumulative deformation map generated; and 20190913082754-20190917132654 represents ground-based radar observation time from 8:27:54 on September 13, 2019 to 13:26:54 on September 17, 2019. The origin of the coordinates represents the
position of the ground-based radar. (b) and (c) are the results of the accumulated deformation of the selected points in the time series of 0~13.5 h and 56~101 h, respectively.

Figure 5

(a) Regional annual deformation rate map measured by Sentinel-1 data, and P1, P2 and P3 are the three points selected in the observation area of ground-based radar. The gray line is the scanning angular scope of ground-based radar. (b) The line-of-sight cumulative deformation map of three selected points.
P1, P2 and P3 in the study area. Note: The designations employed and the presentation of the material on
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Figure 6

(a) Map of ground-based radar monitoring results superimposed on Google Earth; (b) Map of Sentinel 1
monitoring results superimposed on Google Earth. Note: The designations employed and the presentation
of the material on this map do not imply the expression of any opinion whatsoever on the part of
Research Square concerning the legal status of any country, territory, city or area or of its authorities, or
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Figure 7

Sketch map of the slope and angle of the study area Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 8
(a) Ground-based radar monitoring plan sketch (b) Ground-based radar monitoring profile sketch (c) A schematic of the Sentinel-1 imaging mode