Soils and Rocks

An International Journal of Geotechnical and Geoenvironmental Engineering

www.soilsandrocks.com

ISSN 1980-9743
ISSN-e 2675-5475

Applicability of the InSAR technique for slope monitoring

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Review Article

Keywords
Remote sensing
Synthetic Aperture Radar
Interferometry
Geotechnical monitoring

Abstract

Interferometry is a technique that can be applied to SAR (Synthetic Aperture Radar) images that allow obtaining Digital Elevation Models, displacement measurements and assistance for monitoring large areas and/or engineering constructions. The objective of this paper is to present aspects related to the technique of Interferometry SAR (InSAR) applied to the monitoring of slopes. To do so, a systematic bibliographical review was used, through research platforms in scientific collections, in order to highlight the functioning and method of operation of InSAR. Besides that, the practical experience of the authors contributed to a critical analysis of the remote sensing technique addressed. The results show theoretical aspects related to the operation of SARs on board satellites, highlighting their characteristics, orbital systems, types of imaging geometry, as well as the principles of interferometric processing of SAR images. Practical applications demonstrate the potential of InSAR with an emphasis on slope monitoring, highlighting its ability to acquire topographic information on a millimeter scale, monitoring the long-term temporal evolution of displacements, the possibility of composing a monitoring system allowing directing the implementation of other instruments for evaluating the in situ conditions and some limitations regarding the time interval (satellite revisit time) for the acquisition of the displacement data.

1. Introduction

Extreme events and disasters that occur due to dynamics on the Earth's surface mostly affect the population, especially those who are in a vulnerable situation. Investigating, preventing and mitigating these events/disasters become actions of extreme necessity. Accordingly, there has been a rapid improvement in the techniques and equipment that are used to make land measurements remotely, providing subsidy to ensure effective follow up and monitoring (Zhang et al., 2021).

Remote sensing has been used due to its ability to observe without the need for direct contact with the target to be studied (Novo, 2010). InSAR (Synthetic Aperture Radar Interferometry) was developed more than 25 years ago (Gabriel et al., 1989), being an active remote instrumentation technique that measures displacements of the Earth's surface with great spatial coverage and with good precision (Pu et al., 2023). The technique consists of comparing the backscatter of the radar phase at different times to recover phase variations over time and obtain displacement information. It is usually composed of a transmitting antenna and a receiving antenna (Castellazzi et al., 2017).

According to Henderson et al. (1998) interferometry is an alternative to conventional photogrammetric techniques for generating topographic maps with high resolution, having the advantage of using data obtained by SAR (Synthetic Aperture Radar), which have the ability to operate during day and night, and also under any weather condition (Wasowski & Bovenga, 2014). The increasing use of InSAR to analyze geological risks has been evidenced due to the increase of studies that are currently found in the scientific literature (Novellino et al., 2017).

Thus, this article sought to contribute to the technical literature by presenting and discussing case studies that used InSAR as a tool for monitoring displacements in geotechnical applications. The study also aimed to contribute to the understanding of the advantages and limitations of this instrumentation for collecting information that can be used in landslide risk management.

2. Materials and methods

In this paper, a systematic bibliographical review was used in order to verify scientific productions on the aspects of InSAR technology applied to slope monitoring. To define

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Submitted on June 13, 2023; Final Acceptance on October 25, 2023; Discussion open until February 28, 2024.
https://doi.org/10.28927/SR.2023.008023

the technical publications to be analyzed in the results of this research, a search was performed on research platforms considering the methodology proposed by Moher et al. (2010) known as Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA), which consists of four steps: Identification, Selection, Eligibility, and Inclusion.

The identification stage constitutes the initial search for possible papers on the topic of geotechnical monitoring based on InSAR technology. The keywords in English "InSAR" and "Landslide" were applied simultaneously in the Scopus database, present in the titles, abstracts or keywords of the articles. Then, in the selection stage, the most recent publications (2018-2022) and in the final version of publication were filtered. In the third step, eligibility, those articles that were directly related to the subject of study were checked. The last step, inclusion, consisted of reading them to choose the most representative articles in relation to the objective of this paper, considering the fundamental characteristics, advantages and limitations of InSAR, in addition to the presentation of applications of the technique in monitoring slopes.

During the bibliographical research, a theoretical basis was made in order to understand the equipment, procedures and characteristics of the InSAR technology well. The supporting references allowed the conception of theoretical aspects about the study approach, highlighting the basic knowledge to understand the theme. Applications were approached in different contexts, exploring InSAR's potential for slope monitoring. It is also noteworthy that the practical experience of the authors, obtained through the development of technical projects, allowed a critical analysis of the instrumentation method presented, as well as contributions to the proposed discussion.

3. Theoretical aspects

3.1 Remote sensing with SAR

Satellites orbit Earth following solar-synchronized, near-polar paths, with an altitude ranging between 500 and 800 km above the surface. According to Intrieri et al. (2019), the combination of the Earth's rotational movement and their orbits makes satellites capable of collecting information about the same target with two acquisition geometries in opposite directions: ascending (from the South Pole towards the North Pole) and descending (from the North Pole towards the South).

A SAR technology radar operates in the microwave electromagnetic spectrum range ($\lambda = 1\text{-}100$ cm) under virtually any meteorological and lighting condition (Hartwig, 2014). SAR has its own light source, regardless of daylight and weather conditions, and can pass through clouds, smoke and haze.

SAR imaging consists of a radar installed on a platform, which can used on land mobile platforms (Bozzano et al., 2011; Nader, 2013; Woods et al., 2020), in aircraft such as airplanes, helicopters and drones (Moreira et al., 2019) and from polar orbit satellites, which is discussed in this study. In the orbital configuration there is a wide variety of options for resolution, coverage and acquisition angles. The temporal density of any InSAR-based monitoring is limited by the satellite's repeated trajectory, which normally varies between 45 and 6 days, depending on its altitude and orbital configuration (Castellazzi et al., 2017).

Orbital systems (satellites) follow synchronous orbits and use electromagnetic waves in different bands, the most common being X ($\lambda \sim 3$ cm), C ($\lambda \sim 6$ cm), and L ($\lambda \sim 23$ cm) (Paradella et al., 2021). In addition to spatial resolution (band type), there are several orbital systems that allow different temporal acquisitions, known as revisit times, which is an important characteristic, as it indicates the time required for the satellite to pass over the same area performing the imaging.

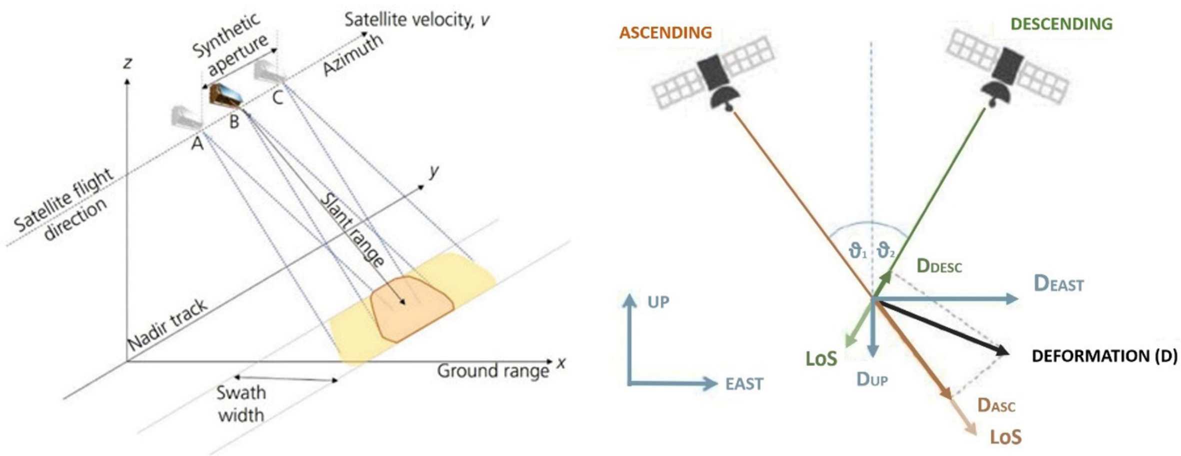
According to Nader (2013) the operation sequence of an imaging radar consists of (1) the antenna transmits a pulse of radiation towards the ground; (2) when the pulse hits the ground it spreads out in all directions; (3) part of the scattering returns towards the radar (backscattering); (4) the antenna captures the backscattered signal and records its amplitude, phase, polarization and return time; (5) the captured signals are subsequently processed, jointly, to form an image of the imaged surface.

Figure 1a shows the fundamental aspects of the imaging system, the azimuth of sight (angle formed between the direction of the flight and the aim of the antenna, in the horizontal plane), the direction in range, the direction in azimuth**,** the range in the terrain that is the sensor-target distance measured on the ground, the inclined range which is the actual sensor-target distance, the height of the platform (H); and the imaging range – swath (total width of the imaged terrain).

The geometry of a SAR is a LOS (Line of Sight) lateral view, with the lightning beam being irradiated at an angle orthogonal to the direction of trajectory of the imaging object (Figure 1a). A two-dimensional image (range x azimuth) of the imaged terrain is obtained by detecting the backscattered signal, by combining the movement of the sensor and the periodic transmission of pulses orthogonally to the satellite trajectory direction (Gama et al., 2015).

Another important aspect related to the acquisition of radar images is connected to the determination of the displacement obtained by interferometry. As the radar is sensitive only to displacements along its line of sight, the components of displacement perpendicular to this direction are not detected (N-S). In addition, the determination of vertical and horizontal displacements (L-W) can be obtained by combining measurements from both orbits (ascending and descending) (Carlà et al., 2016; Paradella et al., 2015). Figure 1b schematically shows the combination of ascending and descending LOS targets (Szucs et al., 2021).

According to Fuhrmann & Garthwaite (2019) it is possible to combine several independent InSAR analyzes if



(a) (b)

Figure 1. a) image geometry of the side view radar system (Selvakumaran et al., 2022); b) schematization of the deformations in the ascending LOS and descending LOS views, representing the decomposition of the deformations in the vertical and east-west directions (Szucs et al., 2021).

we have LOS measurements available considering two factors: (i) images from the same location and (ii) in the same period of time. To meet requirement (i), it is necessary to perform spatial interpolation, since the location of selected InSAR pixels usually differs in each set of analyzed images. And to achieve requirement (ii) it is necessary to interpolate in time, considering that the acquisition dates are usually different from each type of image acquisition geometry.

3.2 InSAR

The term interferometry comes from the word interference, which makes use of the principle of superposition of waves of any kind to express some phenomenon and/or property studied. The phase difference (Δφ) is the fundamental information for interferometry.

The fase (φ) is a physical quantity that represents the stage of the cycle that the wave is in at a given moment relating to the distance from the emitting source. In the SAR system, each transmitted signal resembles a sinusoidal function of the type $\sin(\varphi)$. In the case of a target located at a distance r in relation to the SAR, the phase of the return signal is given by (Equation 1), the 4π term being related to the inclined distance (R) of the signal's departure and return (Ferretti et al., 2007):

$$\varphi = \frac{4\pi}{\lambda} R \tag{1}$$

A InSAR is applied to understand changes in the natural relief of the earth's crust and its elements over time (Mura, 2000; Gaboardi, 2002). To obtain an interferogram, at least one pair of SAR images of complex format (Single-Look Complex – SLC) is required to generate a third complex image, called an interferometric image, where the phase of each pixel is formed by the phase difference between the correspondent pixels in the two original images (Paradella et al., 2021).

3.2.1 Interferometric fase

SAR emits radiation that hits the scatterers on the target and returns to the sensor to generate the image. The transmission and reception of radiation on targets with different distances from the radar results in a delay that causes a phase shift between the signals. Using processing techniques, it is possible to calculate the intensity and phase of the backscattering signal for each soil resolution cell (Ulaby, 1982; ESA, 2007; Gama et al., 2013).

The phase difference between pixels at corresponding positions in two images, called an interferogram, is related to the difference in distance between the two trajectories during acquisitions; knowledge about the position of the sensor at the time of acquisitions; the length of the baseline; to the height of the target on the surface and to the wavelength of the sensor system, making it possible to reconstruct the geometry of the SAR system at the time of acquisitions (Taylor et al., 1999).

3.2.2 Interferometric coherence

Interferometric coherence measures the phase correlation between the pixels of a reference image (master) with a repetition image (slave) (Sabater et al., 2011). In an ideal situation of SAR interferometric processing, the obtained phase difference is related to the signal path difference. However, the existing noises in the process of emission and reception of waves affect the phase, interfering with the quality of the interferogram.

According to Hanssen (2001) the viability of the InSAR technique depends on the high interferometric coherence, being calculated by the module of the complex correlation coefficient (Just & Bamler, 1994; Zhou et al., 2009). The coherence image is related to the standard deviation of the interferometric phase, allowing to evaluate whether the two SAR images are suitable for interferometric processing. Thus, high coherence values demonstrate phase stability, representing a similarity in the characteristics of the backscattered energy on the surface target in the two antenna passages through the same location (Victorino, 2016).

3.2.3 Error causes

The interferogram provides information relative to phase 2π, not representing the total number of complete cycles ($2\pi n$) of the wavelength, since the interferogram may contain several 2π cycles (Hanssen, 2001). To remove this ambiguity, the phase unwrapping process is used, which consists of reconstructing the original interferometric phase, determining the absolute phase (unwrapped) of the interferogram.

Speckle is considered a multiplicative noise, inherent to the coherent nature of a SAR image, which reduces the accuracy of the phase shift and can appear as errors in the interferogram (Goldstein et al., 1988).

The loss of coherence between SAR images of a common area acquired at different times can be attributed to three main factors (Nievinski, 2004; Victorino, 2016):

- Temporal Decorrelation: causes the most severe loss of coherence, can be caused by any environmental change (vegetation movement/removal, soil erosion) between the two SAR records that form the interferogram;
- Geometric Decorrelation: indicates a significant change in the spatial baseline length between two SAR images. It causes changes in the angle of incidence and causes geometric differences, leading to decorrelation of the electromagnetic signal; and
- Atmospheric Effects: changes in the behavior of the atmosphere (humidity, pressure, temperature) due to the refractive conditions of the environment, contribute to delaying the propagation of the Radar signal.

3.3 Image processing

3.3.1 Differential Interferometry SAR (DInSAR)

Is a classic and pioneering remote sensing technique for detecting surface changes (deformation) in relation to the satellite's line-of-sight direction (Sansosti et al., 2014). Gabriel et al. (1989) were the first to apply DInSAR to localize small movements (magnitude ≤ 1 cm) of the surface elevation of large regions (50 km ranges), originating from seismic events, via Seasat SAR images. Subsequently, it became more popular in the early 1990s with the studies by Goldstein et al. (1988) and Massonnet et al. (1993).

In a simplified way, the DInSAR technique is based on the calculation, on a pixel-by-pixel basis, of the phase difference relative to, at least, a pair of SAR images, acquired at different times and satellite positions. Assuming that the reflectivity of the target and the behavior of the atmosphere are constant in the analyzed acquisitions, and that the system noise is negligible, the phase values of an interferogram are proportional to the displacement of the target between the two acquisitions.

It is important to point out that the classic DInSAR technique normally employs a Digital Elevation Model (DEM) of good accuracy so that a phase corresponding to the DEM is simulated in the acquisition geometry of the SAR sensor.

Errors induced by atmospheric phase components, residual phase due to orbit errors, and system noise and speckle are disregarded in the DInSAR technique, as a statistical analysis of a temporal series of images is needed to understand these phase components (Paradella et al., 2021). Due to this, the application of DInSAR is limited to detection of deformation in the centimeter to metric order, being recommended to analyze significant surface variations.

3.3.2 Advanced SAR differential interferometry (A-DInSAR)

From the limitations of the DInSAR technique, a series of techniques were developed that use the processing of several SAR acquisitions for the detection and construction of time series of signals with backscattering similar to that of punctual targets, improving accuracy, range coverage and the ability to detect temporal changes of surface deformation phenomena.

These techniques are part of the group named as Advanced Differential SAR Interferometry (A-DInSAR), and can be highlighted: Persistent Scatter Interferometry SAR (PSInSAR) – Ferretti et al. (2000) and Ferretti et al. (2001); Small Baseline Subset (SBAS) – Berardino et al. (2002); and SqueeSAR Technology – Ferretti et al. (2011).

A-DInSAR make use of multi-scenes, at least 15, making it possible to filter out undesirable phase components (decorrelation) and to model the monitoring of surface deformation phenomena with a precision of centimeters to millimeters, using, for the most part, sensors in the bands C and X (Macedo et al., 2011; Gama et al., 2013). The Chart 1 shows the main characteristics of each processing technique and summarizes relevant aspects (Gama et al., 2013).

4. Revelant aspects of InSAR technology

4.1 Advantages

As main advantages of InSAR we can mention the coverage of large areas (images of 250 km by 250 km, in the case of the Sentinel-1A/B satellite, of the European Space Agency); regular image acquisition, that is, high temporal resolution and long-term monitoring; operation under any atmospheric conditions, without the need for sunlight (unlike optical sensors) and allowing to observe most of the structures visible in this image (Patrício, 2018; Lin, 2022).

Chart 1. Comparative between the main InSAR techniques (Gama et al., 2013).

Technique	Main Characteristics
DInSAR	Interferometry with DEM removed; Qualitative information, distributed on soil deformation; Severely affected by atmospheric and noise effects; It does not predict any time series.
PSInSAR	Exploits stable ground targets – Permanent Scatterers (PS); Estimates atmospheric effects and their removal; Provides a time series; It does not provide measurements of the homogeneous distributed scatterers (DS); It needs at least 20 images.
SqueeSAR	Exploits stable ground targets – PS; Provides DS measures; Estimates atmospheric effects and their removal; Provides a time series; It needs at least 20 imagens.
SBAS	Exploits stable ground targets – PS; Estimates atmospheric effects and their removal; Provides a time series; Does not provide DS measures; It needs at least 8 images.

In addition, the possibility of InSAR measuring past displacements, through historical SAR images, allows the performance of studies of surface variations that may not be available through other data sources (Souza, 2022). The space-time capacity of the InSAR data has a larger field of observation, which allows better interpretation of the displacements and areas with different levels of criticality, helping in the implementation of other instruments, in the definition of the best position and in the collaboration of the improvement of the follow-up of the behavior of the region studied (Intrieri & Gigli, 2016).

Allied to these characteristics, the diagnostic analysis obtained through the spatial observables of InSAR data and information from other instruments of a punctual nature, makes decision-making more assertive. As the composition of a monitoring program, in principle, combines different information, such as rainfall data, surface and subsurface displacements, the possibility of integrating this information allows significant gains in understanding the evolution and mechanisms of action of the object of study (McCormack et al., 2011).

New processing techniques have allowed better accuracy of InSAR data. A-DInSAR techniques such as PSInSAR and SBAS are used to monitor surface deformation with an accuracy of centimeters or subcentimeters when using sensors in the C and X band, and accuracy of a few centimeters with sensors in the L band (Gama et al., 2013; Du et al., 2022).

4.2 Limitations

Due to the operating characteristics of the InSAR technology, some limitations are inherent to the system. The operating method of orbital platforms where the image acquisition radars are on board, operate according to predefined orbits. Thus, each satellite mission has a different revisit time. Due to this time, which can take days, monitoring sensitive areas such as unstable slopes, dams and mining environments make it impossible to monitor in real time and create alert systems based only on InSAR data. In addition, the time required to process the SAR images and make the displacement data available directly impacts the observational capacity of the studied phenomena in a monitoring program (Höser, 2018).

Another important factor concerns the aspects related to the operation of the satellites, as the orbits have a polarized nature, it is possible to capture displacements that occur in the east-west direction. However, ground displacements oriented in the north-south direction cannot be perceived in the satellite image direction and, therefore, InSAR is not able to detect them (McCormack et al., 2011).

Factors associated with image acquisition, for example, temporal and geometric miscorrelation, result in loss of coherence and accuracy of the results (Antunes, 2015). Temporal decorrelation has a great impact on interferometric measurements in areas of vegetation or in areas composed of targets whose electrical properties change over time. Also, variations in reflectivity due to the angle of incidence (geometric decorrelation) restrict the number of pairs suitable for interferometric use (Negrão et al., 2017).

5 Applications

Interferometry makes it possible to explore aspects related to the geometry of the relief, such as DEM, displacement measurements and monitoring of large areas and/or engineering constructions. Among the applications some stand out, like the monitoring of slopes (natural slopes, mining slopes, road slopes), land subsidence, constructions such as dams, bridges and highways. In this article, four cases of InSAR applications with emphasis on slope monitoring were analyzed. The review of these examples allows an approach to the characteristics of SAR interferometry, contributing to the discussion of the topic of this article.

5.1 Unoccupied natural slope - Carlà et al. (2019)

The article by Carlà et al. (2019) shows the monitoring of an alpine slope in Bosmatto, alp region in northwest Italy, which suffered a sudden movement reactivation on October 15, 2000, after intense and prolonged rain. Monitoring included InSAR acquisitions from the Sentinel-1 satellite constellation (in the ascending and descending orbits), information from GBInSAR (Ground-Based InSAR) and readings from two GNSS stations (Global Navigation Satellite System) for continuous monitoring and five GNSS stations for campaign measurements (manually operated).

About the analyzed area, the satellite constellation operating in C-band Sentinel-1 acquired 130 IW (wide-band interferometric) scenes in descending orbit, as well as another 130 IW scenes in ascending orbit, between October 10, 2014 and February 22, 2018. InSAR products, with a spatial resolution of 4 × 14 m, were processed using the SqueeSAR algorithm.

As a result, the authors stated that the acquisition of images in the descending orbit presented more satisfactory results than in the ascending orbit, this happened because the movement of the slope studied occurs predominantly in the direction parallel to the displacement of the satellite.

Depending on the ascending and descending orbits, it is possible to decompose the movement into vertical and horizontal. In this case it was calculated the annual velocity measured in both directions. The landslide has comparable values of maximum vertical and east-west velocity (where negative east-west velocity means westward movement), varying from 20 mm/year to 38.5 mm/year in the southeast sector of instability.

Regarding GBInSAR, the results presented were not consistent with those obtained by GNSS and InSAR, which suggests that there was some bias in the acquisition of information. Since it is an alpine slope, subjected to the presence of snow in its different phases, the results showed a sensitivity of GBInSAR to the detection of snow movements, which are not representative of the slope.

The points obtained from the decomposition of the satellites' ascending and descending InSAR datasets were compared with the GNSS measurements, showing remarkably consistent results, especially with regard to the movements of the vertical component. As expected, there are discrepancies between the velocities in the East-West direction of InSAR and the horizontal velocities of the GNSS stations, due to the absence of the North-South component in InSAR.

Carlà et al. (2019) highlighted the importance of GNSS monitoring and conventional techniques, such as topography, to accurately define slope displacements, even if in a rare manner, especially for movements with predominant North-South direction. In the case of alpine slopes, the authors stated that these techniques are relevant for monitoring during the winter months, when interferometric images may show loss of coherence due to the presence of snowe.

Through the better spatial coverage and measurement accuracy, the InSAR satellite technique could therefore be essential for improving the monitoring of landslides similar to those of the Bosmatto Alpines. The authors concluded that the GNSS and InSAR datasets should be used together, overcoming individual limitations, given the different characteristics and acquisition modes.

5.2 Open pit mine slope - Intrieri et al. (2019)

The study deals with the use of InSAR data to show the potential of new generations of satellites in detecting instability limits and predicting failure times in open pit mines. To do this, an analysis was performed using interferometry with C-band SAR images acquired by the Sentinel satellite constellation (revisit time of 6 days) for the period from March 2, 2016 to November 21, 2016, considering the acquisition of ascending (47 images) and descending (49 images) geometry images (Intrieri et al., 2019).

Intrieri et al. (2019) point out that the analysis of the displacement data was based on the respective absolute values, trends, acquisition geometry and spatialization of the data, as well as the geomorphology related to the slope. In the study, the authors also highlight the data analysis according to the inverse velocity method, based on the accelerated creep theory. In this method, it is possible to establish the failure time as the intersection between the inverse of the velocity and the time axis, considering that as the velocity increases and, theoretically, tends to infinity at the moment of collapse, its inverse will tend to zero.

The annual velocity result obtained for the area obtained from the images in ascending orbit show annual velocity ranging from -365 to -100 mm/year, indicative of the zone of higher displacements. According to the authors, in this area, the accelerated creep behavior started in the central portion of the landslide and propagated until the occurrence of the collapse.

According to the authors, the results of the displacement readings obtained over time show a slight linear trend with values close to 34.5 mm of displacement from February 19, 2016 to October 10, 2016. Then, the data presents a accelerated behavior that reaches a total displacement of 110.2 mm on November 15, 2016, the last acquisition before the failure recorded on November 17, 2016. In the analysis, the behavior of the slowed velocity (mm/day) it is possible to identify a change in the behavior pattern of displacement data from October 10, although the reading interval did not allow systematic monitoring of the evolution of displacements in the vicinity of the rupture.

Intrieri et al. (2019) highlight that the linear adjustment formed by the inverse velocity values shows an intersection with the date axis (collapse) around November 26, 2016 (after the collapse). In similar way, the authors highlight that if the last measurement were discarded, the linear adjustment would be better and the predicted failure date would be November 16, 2016, one day before the actual failure. In this sense, the authors draw attention to the fact that even with different adjustments, the analysis clearly identified the ongoing failure process.

Intrieri et al. (2019) concluded that InSAR is effective for monitoring unstable areas, targeting areas where equipment for in loco monitoring should be installed, and reconstructing the geometry of landslide areas surfaces. However, it should be noted that the satellite revisit time may not be enough to observe the beginning of displacement acceleration, compromising the need for quick responses within the framework of an early warning system.

5.3 Natural occupied slope - Ciampalini et al. (2021)

In this case, MT-InSAR (multi-temporal InSAR data) were used to evaluate the displacements that occurred in an area of rugged relief (occupied natural hillside) located in the north-western part of the region of Tuscany (central Italy) between 1992 and 2020 Data from the ERS 1/2 (from 1992 to 2000) satellites of the C band, Envisat (from 2003 to 2010) and COSMO-SkyMed (CSK) satellites of the X band from 2011 to 2014 were used to analyze the conditions of the long displacement term, aiming to identify the best location for the installation of geotechnical instruments (extensometers and inclinometers) (Ciampalini et al., 2021). The authors also used satellite images Sentinel-1A (from 2016 to 2017) and Sentinel-1B (from 2017 to 2020), in a combined analysis, between SAR data and displacements acquired by geotechnical sensors.

The results of the CSK satellite images (2010-2014) were compared with a inventory areas of landslides that occurred over time. The temporal analysis revealed that between 2010 and 2014 there was an increase in the maximum displacement rate with values of around 20.3 mm/year and an average rate of 6.4 mm/year. The highest displacement rates were measured in the southwest part of the village, where seven extensometers and one inclinometer were installed in April 2016.

MT-InSAR data were compared with deformation recorded by geotechnical instruments. Regarding the spatial distribution, there is an agreement between the points of faster movement of the descending data from Sentinel-1 and the movement points registered by the geotechnical sensors, while the extensometers that present stability are surrounded by stable or extremely slow-moving interferometric points.

Sentinel-1 data were compared with deformations recorded by geotechnical monitoring instruments, as well as with rainfall records obtained between 2016 and 2020. The results obtained demonstrate that all geotechnical sensors correctly identified deformation trends and periods of landslide acceleration. The inclinometer recorded a sliding surface at a depth of 23 meters, with a maximum displacement of up to 20 mm between 2017 and 2020, and a second sliding surface at a depth of 5 meters from the ground, resulting in an accumulated surface displacement of about 36 mm during the same period.

According to Ciampalini et al. (2021), the changes observed in the inclinometer confirm that prolonged rainfall increases the displacement rate, a behavior that is recorded by all sensors in the monitoring system.

The authors point out that the spatial and temporal distribution of deformations shows good agreement between both monitoring systems, with a satisfactory correlation. The comparative analysis between deformation and precipitation data suggests that the accelerations identified in the landslide deformation rate can be attributed to rainfalls.

Ciampalini et al. (2021) concluded that InSAR data can be used to select the ideal location for installing in situ sensors, especially when considering the spatial distribution of slope deformations over long periods of time. As they can also be used to confirm and validate measurements of geotechnical instrumentation data. In cases where validation is possible, and there is no need to install warning systems, it is possible to monitor the evolution of deformations, even in the absence of in situ sensors.

5.4 Coastal region slope - Traglia et al. (2018)

The area under study is a volcanic slope in a coastal region, with part of it in an underwater environment. Located in the Aeolian archipelago, it belongs to a large volcanic complex, on the southern coast of Italy. The study employs InSAR for long-term assessment of submarine slope stability in volcanic systems. For this purpose, SAR images were used considering the CSK constellation (84 images, X band) between February 2010 and December 2014 and the Sentinel-1A constellation (47 images, band C) between February 2015 and October 2016.

The authors analyzed a section of the northwest side of the slope, where scars from landslides can be seen up to 700 m below sea level. To characterize the bottom morphology of the study area, Traglia et al. (2018) performed a bathymetric survey with a sonar-type device at depths between -20 and -500 m, in order to obtain a DEM of the underwater part of the area. Since it is a volcanic environment, thermographic surveys were also performed using a thermographic camera, with the aim of analyzing the patterns of thermal behavior and fracturing of the lava delta.

Traglia et al. (2018) highlighted that thermography data indicated rapid cooling since the last eruption and no evidence of fracturing processes related to delta instability. Regarding bathymetry, the authors point out that the lava delta has a difference in level >40º and a rough surface. According to the authors, the InSAR data identified a stable area in the northern portion of the lava delta and instability in the southern portion of the area. The displacement results of the CSK data show the evolution of the displacements, with a pattern of the unstable portion of the order of -200 mm between 2010 and 2014 and Sentinel-1A data with displacement values greater than -200 mm between 2015 and 2016, with a total value towards the end of the period of more than 400 mm of displacement.

The authors also selected four points (CSK and Sentinel-1A data) within the area of the lava delta, in order to show the behavior of the displacement in the period between February 22, 2010 and October 15, 2016. The results of the displacements from the CSK data (February 22, 2010 to December 18, 2014) show a trend change in the final period of the series (period of explosions and occurrence of lava flows in the area), which according to the authors the highest velocity of the order of 70 mm/year.

Traglia et al. (2018) also show LOS displacement results according to Sentinel-1A data (from February 23, 2015 to October 15, 2016) for the same positions of points identified in the CSK dataset. The results show a change in displacement trends in 2016, the points positioned in the central region of the lava delta show a reduction in velocity of 180 mm/year and 70 mm/year, tending towards stability. Some results show small oscillations and their location is outside the central region os the lava delta.

For the authors, the InSAR data made it possible to identify the instability zones of the lava delta, in addition to changes in the patterns of the displacement series demonstrating a relationship with lava flows from previous eruptions, which influenced the behavior of the instability zones along the slope. In addition, the displacement time series along the study region confirmed an internal subdivision of the lava delta, which showed abrupt changes in displacement trends in the unstable portion of the slope.

6 Final considerations

This article has partial results of a master's thesis research, developed by the Geotechnical Engineering Group for Slopes, Plains and Disasters (the acronym in Brazilian Portuguese is GEGEP) of the Federal University of Pernambuco (UFPE) under the supervision of the first author. Characteristics, concepts, principles, some advantages and limitations of the InSAR technique were presented, with emphasis on the potential for applications in the monitoring of slopes (natural and artificial), which can be applied to land subsidence, dams, bridges and highways. The technique has allowed a good contribution in the detection of information about the Earth's surface, such as obtaining DEM, measuring displacements and the possibility of monitoring large areas.

The time series obtained by InSAR are able to provide displacement information with good accuracy, in addition to being able to strategically direct the deployment of traditional monitoring equipment within the area of interest, making it possible to obtain an integrated monitoring network. Furthermore, the InSAR data can be checked and validated using other equipment (GNSS, total station), ensuring better assertiveness in the diagnosis of areas with the presence of movement.

However, there are limitations regarding the acquisition of information by InSAR, especially for short periods of time. Radars on board satellite platforms have a long revisit time, which does not allow for real-time observation of displacements. This condition makes it difficult to make decisions based only on InSAR information, requiring data from other equipment (inclinometers, tiltmeters, extensometers). Although, it should be noted that technology has advanced, with the emergence of new ground-based interferometric radars, which have managed to reduce the acquisition time and increase the accuracy and reliability of the technique.

Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have noted and affirmed the content of the article and there is no financial interest to report.

Authors' contributions

Roberto Quental Coutinho: supervision, guidance, project management. Jailson Silva Alves: research, data analysis, writing of the manuscript. Hanna Barreto de Araújo Falcão Moreira: research, data analysis, writing of the manuscript. Júlia Isabel Pontes: research, conceptualization, writing of the manuscript. Wilson Ramos Aragão Júnior: research, conceptualization, methodology, writing of the manuscript.

Data availability

No data sets were generated in the course of the current study; therefore, data sharing is not applicable.

List of symbols

R	Inclined Distance
φ	Fase
λ	Spectrum Range

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