



# Kurtun Dam oscillate characterization with landslide possible effect detection using InSAR observations

Fatih Celik<sup>1</sup> · Fusun Balik Sanli<sup>1</sup> · Kemal Celik<sup>2</sup> · Ayse Celik<sup>3</sup>

Received: 21 December 2024 / Accepted: 4 June 2025 / Published online: 18 June 2025  
© The Author(s) 2025

## Abstract

Observing and analyzing areas prone to landslides is crucial due to the extensive destructive capacity of landslides. To monitor landslide activities across diverse areas, remote sensing data and image processing methods are employed. This study proposes a method that integrates Multi-temporal Interferometric Synthetic Aperture Radar and advanced temporal tracking technologies to intensify surveillance of the Kurtun Dam and its valley. According to Sentinel-1 A data, the net displacement rates of the dam crest varied between  $-12$  and  $2$  mm/year (LOS). InSAR technology surveys the entire dam catchment area, detecting critical infrastructure such as slopes, spillways, and access roads. The crest of the Kurtun Dam experiences oscillatory deformation during filling activities, but the lateral slopes and downstream abutment remain stable. As reservoir water levels rise, the dam structure exhibits downstream deformations, whereas declining water level results in upstream displacements. Monitoring points located the opposite Ozkurtun settlement and within the reservoir area, both facing the dam, exhibited displacement rates of up to  $-50$  mm monthly. In regions susceptible to landslides, the greatest annual displacement rates were observed to be  $-54$  and  $-127$  mm/year. This study suggests that integrating 3D modeling with InSAR technology into dam monitoring systems can significantly enhance their effectiveness. At Kurtun Dam and other crucial locations within the catchment area, the integrated approach combined with topographic monitoring, ensures reliable landslide detection and analysis. By advancing monitoring technology for embankment dams, this strategy prioritizes safety and structural integrity assessments.

**Keywords** Landslide detection · Dam monitoring · Multi-temporal SAR · InSAR · Time series

---

✉ Fatih Celik  
fatih.celik1@std.yildiz.edu.tr

<sup>1</sup> Department of Geomatics Engineering, Yildiz Technical University, Istanbul 34220, Türkiye

<sup>2</sup> Department of Geomatics Engineering, Gumushane University, Gumushane 29100, Türkiye

<sup>3</sup> Department of Architecture and Urban Planning, Gumushane University, Gumushane 29600, Türkiye

## 1 Introduction

The increasing complexity of managing natural hazards and water resources, particularly in geologically sensitive and strategically important regions, has necessitated the advancement of monitoring technologies. Dams are critical infrastructures, serving multiple purposes including flood control, water supply, hydroelectric power generation and river navigation (Wang et al. 2023). With over 800,000 dams worldwide they play a key role in global water security, disaster resilience and the development of sustainable energy resources (Nasrat Adamo et al. 2019).

Despite their strategic value, many dams are located in high risk geological zones where natural hazards especially landslides pose significant threats to structural stability and downstream safety (Marchamalo-Sacristán et al. 2023, 2025). Historical disasters such as the 1928 Francis Dam collapse in the USA, the 1963 Vajont landslide in Italy, the 1975 Banqiao Dam failure in China and the 2024 Old Kijabe Dam collapse in Kenya have shown the devastating human and environmental consequences of inadequate dam monitoring (Dufaut 2013; Maina-Gichaba et al. 2013; Pang et al. 2023; Panizzo et al. 2005). Traditionally dam deformation monitoring has relied on terrestrial geodetic methods such as Global Navigation Satellite Systems (GNSS) and total stations. While these techniques offer high point specific accuracy. They are constrained by limited spatial coverage and logistical difficulties, especially in rugged or remote terrain (Barla et al. 2010; Scaioni et al. 2018). For instance the Atatürk Dam in Turkey was monitored using these methods to assess surface displacement (Milillo et al. 2016; Milillo et al. 2016a, b, c; Yavaşoğlu et al. 2018).

To overcome the limitations of ground based systems, satellite based Interferometric Synthetic Aperture Radar (InSAR) has emerged as a transformative solution. InSAR provides continuous high resolution surface deformation data over broad areas and under all weather and lighting conditions (Coskun et al. 2023; Ullo et al. 2019). It has been widely applied in the monitoring of earthquakes, mining subsidence, glacier movement and particularly in assessing the stability of dam structures and their surrounding environments (M. Wang et al. 2020a, b; Yang et al. 2023; Yuan et al. 2021). Among InSAR techniques Persistent Scatterer (PS-InSAR) and Small Baseline Subset (SBAS-InSAR) have proven particularly valuable for dam surveillance. PS-InSAR offers millimeter level precision by focusing on stable reflectors such as concrete surfaces and buildings while SBAS-InSAR is effective for capturing slow moving large-area deformations (Tonelli et al. 2023; Yuan et al. 2021; Zhang et al. 2023). Their complementary characteristics enable comprehensive monitoring of both localized and distributed displacement patterns.

Numerous studies have demonstrated the operational reliability of these methods. Conducted a time series InSAR analysis on the Oroville, Pong and Tehri Dams successfully detecting pre failure signals and post-event deformations (Verma and Vijay 2024). Thus confirming the value of InSAR for early warning systems. Similarly SBAS-InSAR to the Datengxia Water Conservancy Hub, where InSAR derived measurements strongly correlated with in situ data affirming its utility in both construction and operational phases (Ouyang et al. 2024). Beyond structural displacement detection InSAR has been used for deformation modeling and hazard forecasting. Wen et al., analyzed the impact of reservoir impoundment on landslide activity in the Wudongde Hydropower Station using InSAR highlighting a direct relationship between water level fluctuations and slope instability (Wen et al. 2025).

Das et al., introduced a spectral analysis based approach that successfully identified early signs of instability prior to the Brumadinho tailings dam disaster (Das et al. 2024).

Effective and integrated dam monitoring is essential not only for structural integrity and disaster mitigation but also for advancing sustainability objectives such as energy security, water management and climate resilience (Tu et al. 2023; Zhou et al. 2020). The Harsit Valley in Turkey's Black Sea region exemplifies these challenges with its complex geomorphology and vital hydropower infrastructure. This study focuses on the temporal deformation of the Kurtun Dam between January 2023 and March 2024 using an integrated approach that combines Sentinel-1 based InSAR analysis with traditional total station observations. The objective is to evaluate the effectiveness of this synergy in improving early warning capacity and long term structural resilience.

## 2 Study area and data

### 2.1 Study area

The Kurtun Dam and power plant is located on the Harsit Stream (formerly Dogankent Stream) in the Kurtun district (Fig. 1). Commissioned in 2002, the dam has been actively operating for over two decades. Playing a key role in regional hydroelectric energy production and water management. The installed capacity of the dam is 85 MWh making it the 177th largest power plant in Turkey and the fourth largest in Gumushane. It ranks as the 71st largest hydroelectric facility in the country. Generating an average of 198 GWh of electricity annually. Kurtun Dam and Hydroelectric Power Plant (HEPP) can supply the full

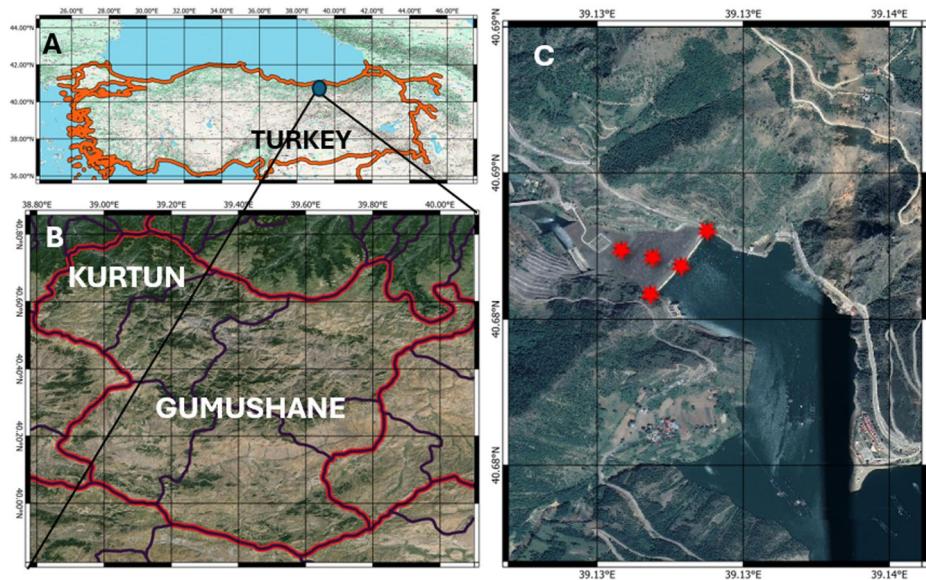


**Fig. 1** Overview map of the study area [(A) location of study area in Turkey, (B) surface land cover of the study area derived from the GoogleEarth, (C) location area of Kurtun Dam. Benchmark Points are shown with red star]

energy needs of approximately 41,798 people, including residential, industrial and public service demands. For residential consumption alone it can serve around 50,824 households. Structurally, the dam features a concrete face rock fill body with a total volume of 3 million cubic meters and stands 133 m above the riverbed. Under normal water levels the reservoir holds 108 hectometers cubed and covers a surface area of 2.62 km<sup>2</sup> (Web 1 [2024](#)) (Fig. 1).

## 2.2 Data introduction

Sentinel-1 satellite data were employed in this study to analyze large-scale structural stability from January 2023 to April 2024. Launched by the European Space Agency (ESA) in 2014, Sentinel-1 operates with a C-band Synthetic Aperture Radar (SAR) at an orbital altitude of 690 km and has a revisit cycle of 12 days. This study employed 46 ascending and 37 descending orbit images maintained over a 60-day temporal baseline and 200-meter vertical baseline. Single-look complex (SLC) data in the VV polarization mode using the Interferometric Wide (IW) mode were selected for Stack-InSAR processing. Although the Sentinel-1 archive spans nearly a decade this study specifically focused on the 2023–2024 period for two main reasons. First, the selected interval corresponds to a recent phase marked by hydrological variability and seasonal reservoir changes which are particularly relevant for detecting possible deformation signals. Second, only during this period were high resolution Total Station measurements simultaneously conducted allowing for consistent comparison between ground based measurements. By synchronizing the temporal windows of both data sources the study ensures methodological coherence and increases the reliability of the deformation assessment (Table 1).

Utilizing a 30-meter resolution DEM from the Shuttle Radar Topography Mission (SRTM) terrain feature parameters were determined. Overlay and shadow regions were identified and topographic effects were mitigated during InSAR processing. The main specifications are detailed in Table 1. Total Station was used to measure displacement for traditional positional measurements. Six reference stations were set up but only five of these, situated nearer to the dam were used for conventional geodetic measurements of angles and distances. Angles were accurately measured using complete sets and distances were assessed conjugately. From these measurements the coordinates of the object points were calculated to establish correlations among the reference stations. Water level data representing the total reservoir volume (hm<sup>3</sup>) and water level in meter was obtained from the State Hydraulic Works (DSI) affiliated with the Ministry of Agriculture and Forestry. These records cover the period from January 2023 to April 2024 and were used to assess seasonal fluctuations in water storage levels that may influence structural deformation patterns.

**Table 1** Sentinel-1 image specifications

| Platform     | Polarization | Path | Track | First      | Last       | Incident Angle | Number of Scenes |
|--------------|--------------|------|-------|------------|------------|----------------|------------------|
| Sentinel-1 A | VV           | 43   | 129   | 20,230,106 | 20,240,325 | 36.37          | 46               |
|              |              | 123  | 456   | 20,230,112 | 20,240,319 | 42.02          | 37               |

### 3 Methods

In this study, both PS-InSAR and SBAS-InSAR techniques were employed to comprehensively monitor dam and surrounding slope deformation. PS-InSAR is highly effective for detecting stable, coherent targets such as concrete dam structures or urban surfaces with high temporal correlation. However, it is less applicable in vegetated or decorrelated areas. Conversely, SBAS-InSAR is suitable for monitoring wider and more heterogeneous areas, including natural slopes and rural zones, by minimizing temporal and spatial decorrelation through small-baseline interferogram stacking. By combining both techniques, the study leverages the high-precision capabilities of PS-InSAR for dam panels and the broad coverage of SBAS-InSAR for adjacent slopes and landslide prone areas (Tonelli et al. 2023). This integrated approach enhances deformation interpretation and reduces observational uncertainty (Fig. 2).

#### 3.1 Multitemporal InSAR data processing

Multitemporal InSAR (MTI) processing, also known as time series analysis, strategically utilizes a series of SAR images along the same flight paths to enhance signal fidelity by minimizing distortions (Bayik et al. 2021; Liu et al. 2023). It primarily uses Persistent Scatterer and Small Baseline Subset methodologies (Han et al. 2023). These methods focus on extracting the most reliable signals from the core areas of persistent scatterers while simultaneously disregarding uncorrelated point targets (Han et al. 2023). In MTI, pixels' phase values are extracted by analyzing their sequence of images (Coskun et al. 2023). A pixel's phase value is determined by the combined reflection from scattering centers within its resolution cell.

The PS-InSAR surface settlement monitoring results were compared using total station measurements using three reference points covering the dam during the relevant period. The results from SBAS-InSAR processing were also compared with those from the PS method (Wu et al. 2019). This comparison validated the outcomes of the PS-InSAR technique's monitoring. The workflow of the processing technique is illustrated in Fig. 2. This study

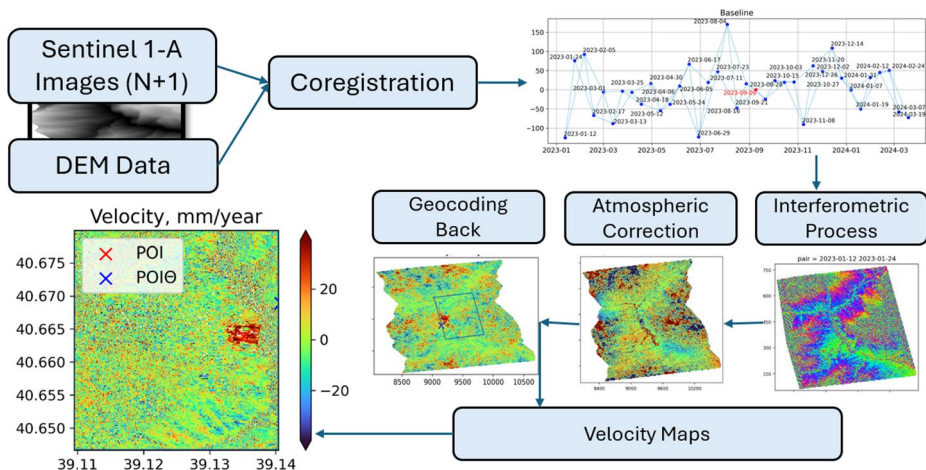


**Fig. 2** General flowchart of the InSAR processing

employed the Permanent Scatterer Interferometry (PSI) technique, utilizing StaMPS (Stanford Method for Persistent Scatterers) software to process data from Sentinel-1.

A single reference image was selected for coregistration with the dataset to maintain consistency and comparability across all scenes. These images were prepared using the Sentinel Application Platform (SNAP), enabling coregistration and interferogram generation (García-Lanchares et al. 2023). The interferograms produced were analyzed in detail using StaMPS software (Hooper et al. 2018). 45 interferograms were obtained from the ascending orbit and 36 from the descending orbit. Since both sets of interferograms were gathered from the same satellite during the same timeframe we can expect similarities in the findings from both orbital paths (Holden et al. 2020). The satellite's consistent observational geometry and environmental conditions based on its operational parameters underlie this expectation (Bayik et al. 2021). Using the PyGMTSAR software SBAS and PS Interferometry analyses were conducted directly within the Python environment with the application area fully recalculated. PyGMTSAR correctly processed data without the need for workarounds and excessive filtering (Pechnikov 2023). The results were then aggregated and merged.

The rate of deformation was measured in the direction perpendicular to the line of sight. For alignment with standard benchmark measurements it is essential to acquire LOS results across the north-south, east-west and vertical orientations (Hastaoglu et al. 2018). The displacement proportions in these directional LOS can be derived from both ascending and descending SAR images (Zheng et al. 2021). The precision of displacements in the polar direction is limited by the satellite's polar orbital movement. The calculation methods for displacements in the east-west and vertical directions are as follows:

$$\varphi_{LOS} = S^T \times D \quad (1)$$

$$S^T = (-\cos \eta \sin \theta \sin \eta \sin \theta \cos \theta) \quad (2)$$

Where  $\varphi_{LOS}$  represents the displacements in the line of sight,  $S$  denotes the satellite unit vector and  $D$  represents the surface displacement vector, including the incidence ( $\theta$  and azimuth angles ( $\eta$ )). To integrate the results from the ascending and descending LOS data. The LOS values were transformed into a grid with a resolution of approximately  $10 \times 10$  m (Bayik et al. 2021; Bayik and Abdikan 2021). Following this gridding procedure vertical and east-west displacements were determined using mathematical and geometrical principles.

## 4 Results

The technical evaluation of the Kurtun Dam was conducted using PS-InSAR and SBAS-InSAR methods, analyzing 83 scenes from the Sentinel-1 dataset covering the Kurtun valley of Gumushane province. This analysis also included corresponding precision orbit data and SRTM DEM data to improve the accuracy of the results (Du et al. 2021). To optimize the coherence of the dataset, the ascending image taken on July 5, 2023, was selected as the preliminary image. A total of 88 interferograms were generated for SBAS analysis using ascending orbit data. For the descending orbit, the image dated September 9, 2023, was chosen as the preliminary image. 70 interferograms were generated for SBAS analysis. Images

that extended beyond the designated study area were subsequently cropped to fit within the defined boundaries.

#### 4.1 Crest displacement detection using PS-InSAR

Within the study area, potential PS points were identified using two different methods: coherence coefficient threshold and amplitude deviation. This dual approach enabled comprehensive identification of PS candidates. The phase information for these points was then carefully extracted from the time series differential interferograms, providing crucial data for further analysis.

To assess the temporal displacement characteristics of the Kurtun Dam, several monitoring points were strategically positioned. In the dam's central top region (Point P3), displacement rates exceeded 17 mm/year (Fig. 3). Points P1 and P2, located on either side of the embankment, showed minimal displacement with rates not exceeding 3 mm/year. The midpoint of downstream slope (Point P4) exhibited a moderate yearly displacement rate of approximately 6 mm. Finally, point P5, situated at the foot of the dam slope, also showed a low displacement rate, with the annual rate remaining below 1 mm/year (Fig. 3).

Analysis of Figs. 4 and 5 shows a correlation between the displacement of the dam structure and reservoir water levels. Specifically, a rise in the water level is associated with a downward displacement of the dam, whereas a fall in the water level corresponds to an upward displacement of the dam structure. The observed phenomenon occurs because an increase in water level results in increased hydraulic pressure on the dam, causing the dam structure to oscillate in the downstream direction (Fig. 4).

As the water level drops, so does the hydraulic pressure on the dam, causing the upstream structure to oscillate. This indicates that the greatest oscillation of the dam typically occurs during periods of high water levels. The least displacement was observed during periods of low water (Fig. 5).

#### 4.2 Crest displacement detection using SBAS-InSAR

The monitoring results in this study are corroborated by the measurement of fixed ground points over the same period. In addition to the PS-InSAR results, the deformation moni-



**Fig. 3** The displacement rates at monitoring point P3 in dam crest, as observed through PS-InSAR analysis, are presented with descending LOS results in orange and ascending LOS results in blue

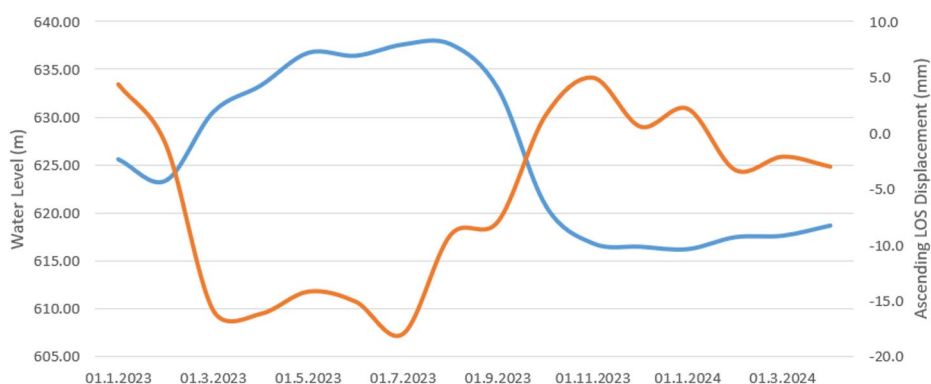


**Fig. 4** The displacement rates at monitoring point P3 in dam crest is presented with ascending LOS results in orange and water level measurement

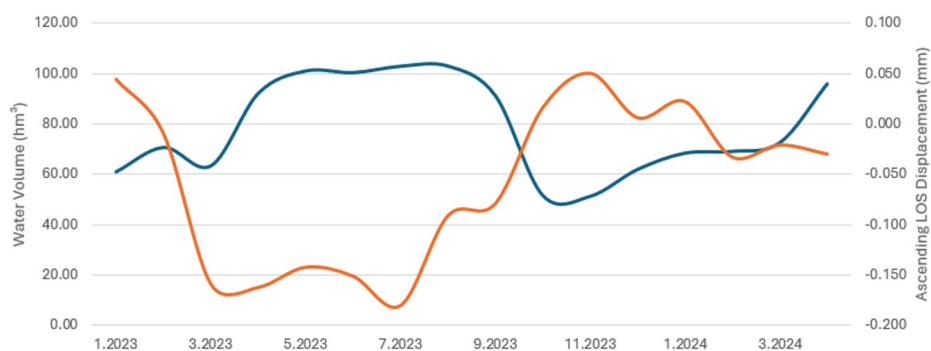


**Fig. 5** The displacement rates at monitoring point P3 in dam crest is presented with ascending LOS results in orange and water volume measurements in blue

toring results for the Kurtun Dam from January 2023 to April 2024 were analyzed. Both processing methods showed similar characteristics in terms of the deformation distribution along the satellite's line of sight.

The highest rate of deformation was recorded at the center and apex of the dam crest, with a gradual decrease toward the slopes on either side and downstream base. Comparative measurements from the reference points confirm this pattern, indicating an average annual deformation rate ranging from  $-12$  to  $2$  mm/year at the center of the ridge. The slopes on either side of the dam are relatively stable with deformation rates of approximately  $1$  mm/year. Most observed data points cluster within a deformation rate range of  $-0.8$  to  $2$  mm/yr, which is visually represented by blue dots on the maps in Fig. 6. The northern slope of the dam has an annual deformation rate less than  $-0.8$  mm/year, identical to the P1 benchmark's measurement (Fig. 6).

In regions where surfaces are less reflective, the distribution of monitoring points tends to be less dense and more dispersed, depending on the line of sight. The upper center of the dam exhibited the maximum deformation, as indicated by the dam surface deformation monitoring results. The average annual vertical displacement at P3 ranges from  $-9.6$  mm

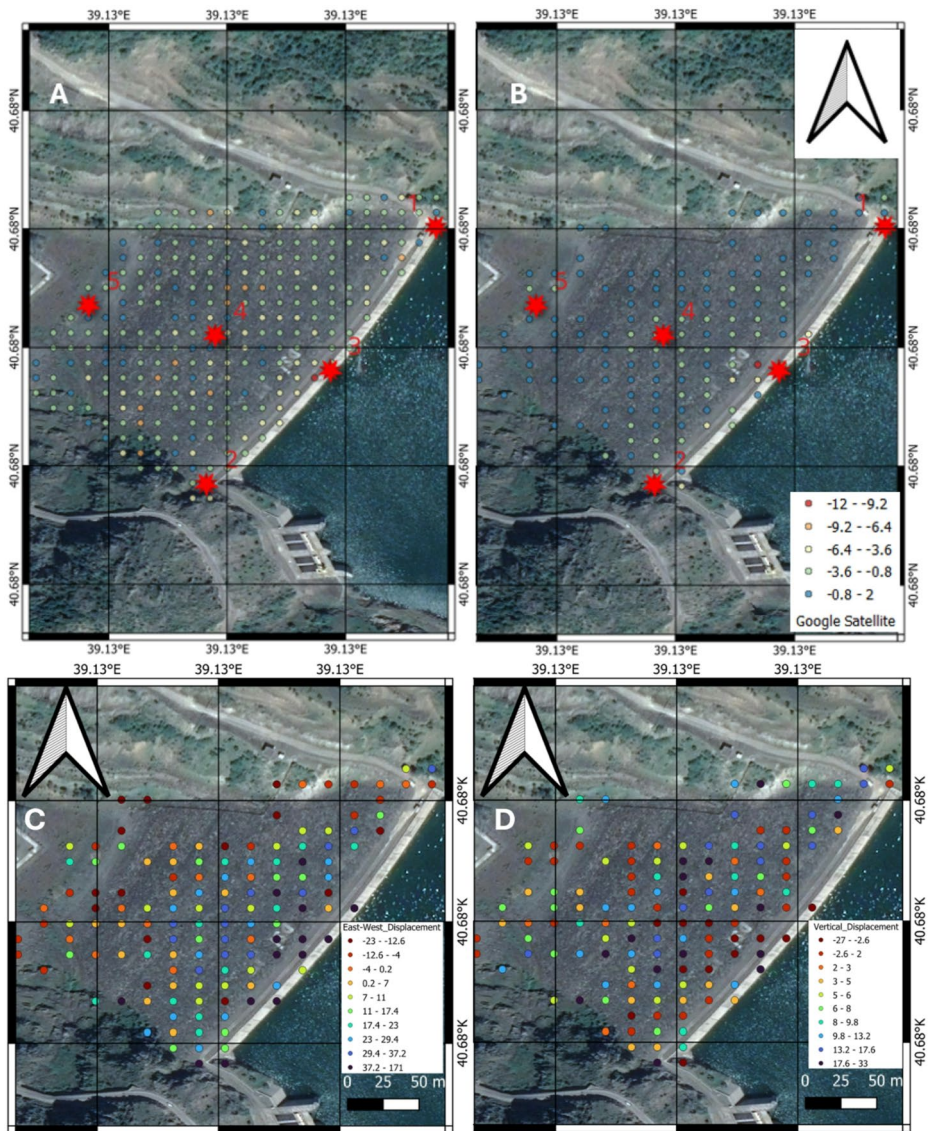


**Fig. 6** Dam SBAS-InSAR velocity results [(A) Ascending LOS direction, (B) Descending LOS direction, (C) East-West displacement map, (D) Vertical displacement map; Benchmark Points are shown with red star, rates in mm/year]

to 2.2 mm, with a maximum annual displacement of -11.6 mm. 1 mm/year or less is the rate of displacement at the dam's base near the embankment, signifying the stability of the foundation and embankment.

Figure 8 presents the displacement velocity maps of the dam body obtained using PS-InSAR analysis by combining ascending and descending LOS measurements. Panel (A) illustrates the east-west displacement component, while panel (B) shows the vertical dis-

placement component, with rates expressed in millimeters per year (mm/year). In the east–west direction (A), most deformation values range between  $-9$  mm/year and  $+12$  mm/year, indicating predominantly eastward motion in certain sections, particularly along the dam crest and right abutment, whereas other zones exhibit relatively stable behavior. In the vertical displacement map (B), subsidence dominates the dam body, with values reaching down to  $-48$  mm/yr, especially concentrated along the central and lower-left zones. Conversely, some localized uplift values up to  $+34$  mm/yr are detected near the upper dam shoulder. The spatial distribution of these displacements reveals heterogeneity in deformation behavior, which may relate to structural characteristics, load distributions, and varying foundation responses across the dam.

### 4.3 Ozkurtun landslide detection using InSAR in the reservoir area

Landslides within the study area were identified by combining PS-InSAR and SBAS-InSAR displacement data. The Ozkurtun landslide's displacement time series was acquired utilizing time series InSAR methods and positioned according to the slide's downward trajectory. Figure 6 depicts the average rate of deformation within the landslide, with the most intense deformation occurring predominantly in the central region, where the deformation rate reached up to 100 mm/year. The displacement is eastward, parallel to the dam's reservoir area.

Figures 7 and 8 show the location and annual displacement rate time series curves, respectively. These figures show that the central point of the area indicates the most active section of the landslide, as evidenced by the substantial cumulative displacements observed there. Between January 2024 and March 2024, the annual displacement rates at these central points exceeded 120 mm. In contrast, the deformation at the peripheral monitoring points was less prominent, with annual displacement rates of approximately 50 mm. Similar to the linear displacement trends observed in the upper parts of the landslide, the curves in the lower parts also show characteristics influenced by cyclical rainfall patterns and reservoir operations (Fig. 7).

Owing to the upward pressure of the reservoir water, the lower part of the landslide constantly deforms and has a higher displacement rate. As the water level in the reservoir gradually rises from January, the overall displacement of the landslide increases.

## 5 Discussion

InSAR technology possesses the capability to conduct deformation analysis with high precision and density over extensive areas. Although this technology has a dependent importance in capturing deformations depending on the coverage of the imagery, it plays a very effective role in monitoring dams in areas where data is available. The InSAR method is supported by traditional measurement techniques such as leveling and GNSS for monitoring dams. The InSAR method is ideal for monitoring extensive, slowly progressing landslides exhibiting diverse spatial deformation patterns (Wang et al. 2020a, b). Various studies have demonstrated the effectiveness of multi-temporal time series analysis in dam monitoring by comparing ground measurements with SBAS and PSI methodologies (Hooper et al. 2012; Milillo et al. 2016a, b, c; Milillo, Tapete, et al. 2016; Ruiz-Armenteros et al. 2018). Dam

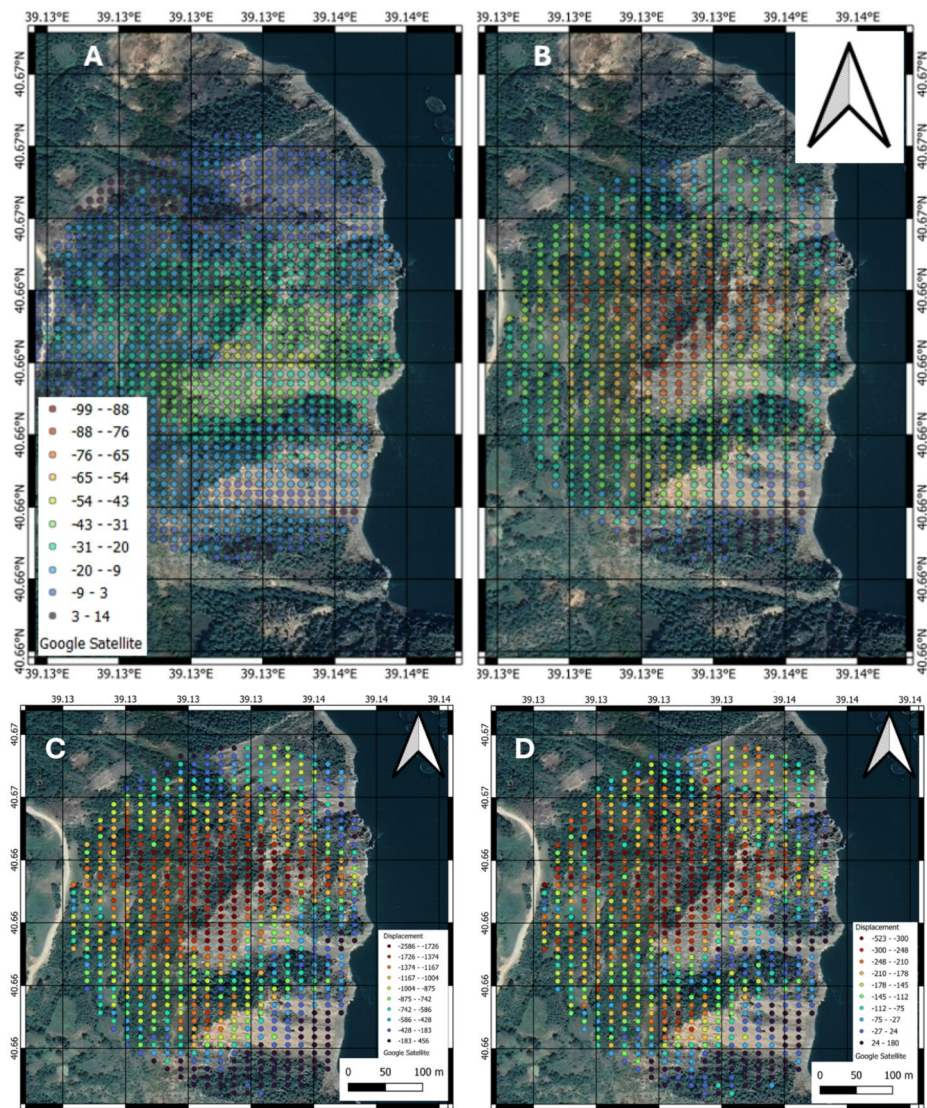


**Fig. 7** Landslide area SBAS-InSAR velocity results [(A) Descending LOS direction, (B) Ascending LOS direction, (C) East-West displacement map, (D) Vertical displacement map; rates in mm/year]

monitoring was performed using the Sentinel 1, ERS and TerraSAR-X satellites as documented in the literature (Holden et al. 2020) (Fig. 8).

Reservoir dam monitoring results can facilitate risk analysis and alert systems. InSAR deformation monitoring technology is particularly effective for obtaining high-precision and dense deformation results on concrete reservoir dam panels (Wang et al. 2023). Continuous monitoring of dam deformations is essential for assessing its safety conditions and ensuring the structural integrity of the dam (Cetin et al. 2000). Dam bodies undergo deformation as a result of factors such as self-weight, water pressure, temperature fluctuations

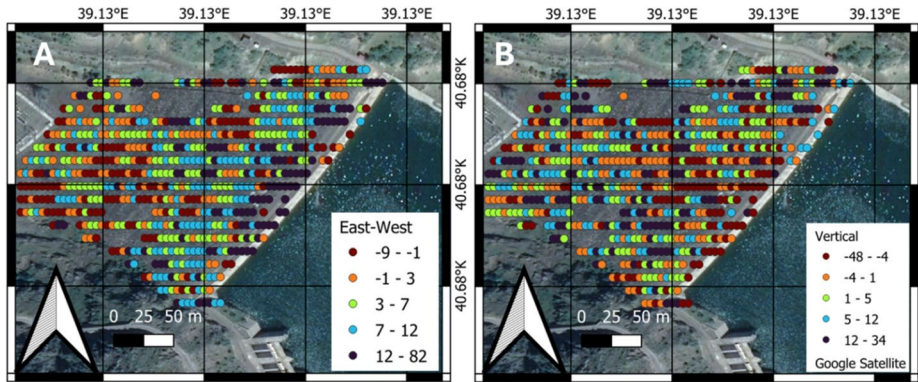


**Fig. 8** Dam PS-InSAR velocity results (A) East-West displacement map, (B) Vertical displacement map; rates in mm/year



**Fig. 9** The displacement rates at monitoring point in dam crest PS are presented with descending LOS results in orange, ascending LOS in green, and reservoir water volume measurements in blue

and the aging of materials. Periodic variations in water pressure and temperature induce transient deformations in dam structures, whereas self-weight and material aging contribute to long-term compaction and consolidation, leading to gradual increases in deformation over time. The deformation patterns of the dam slope and its base correlate with changes in water levels indicating a clear and significant relationship between displacement and water levels, indicating that the dam is generally in a stable condition (Fig. 9).

Between August and November 2023, a dry period with no rainfall led to a swift decrease in the reservoir level. Consequently, the displacement rates at all monitoring points on the landslide began to diminish averaging approximately 30 mm per month as depicted in Figs. 9 and 10. Owing to the lag effect of rainfall infiltration, the displacement rates in the upper sections of the landslide gradually reduced as the capacity and depth of rainfall infiltration increased, whereas moisture retention in the central areas of the landslide increased (Fig. 10).

During the period from April to September, when the reservoir water level was stabilized at 100  $\text{hm}^3$ , the landslide exhibited a slower rate of deformation. Subsequently, the delayed

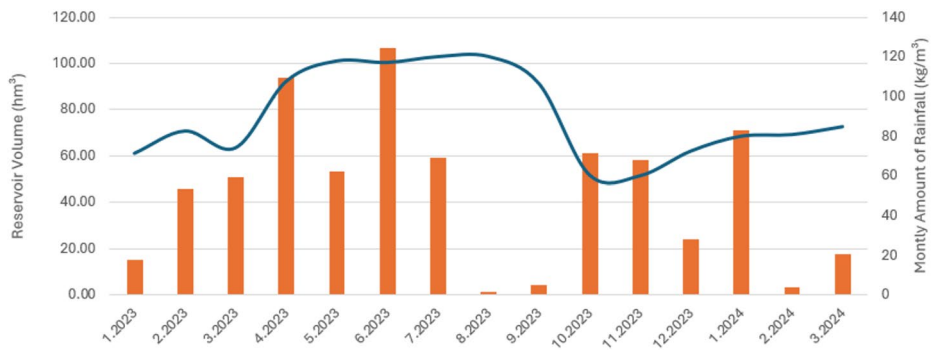


**Fig. 10** Rainfall amount and reservoir volume rates. Rainfall shows orange bars, and blue represents reservoir volume

infiltration effects of prior rainfall compounded by significant and continuous rainfall within the reservoir area, precipitated a phase of intensified deformation post-November. During this phase, some monitored displacement rates escalated to as much as 50 mm/month.

The substantial thickness and scale of the Ozkurtun landslide facilitate the infiltration of rainfall into the sliding surface, which can accelerate landslide activity. Previous research has established a correlation between reservoir landslides and rainfall events (Ouyang et al. 2024; Wang et al. 2023; Wen et al. 2025). These studies examined the relationship between landslide deformation and its environmental drivers, such as reservoir water levels and rainfall using long-term InSAR and benchmark point monitoring data from active landslide zones (Figs. 4 and 5). The findings from these studies corroborate the impact of changes in water levels and precipitation on landslide displacement trends aligning with the conclusions of this study. Furthermore, these outcomes affirm the efficacy of InSAR data in investigating the deformation mechanisms of landslides.

The results of the field investigation indicate that the deformation and collapse of the slope were influenced by the deteriorated slope conditions and structural features of the slope. Subjected to long-term gravitational forces, the slope exhibited creeping behavior by descending through a brittle mudstone layer. Over time, prestress accumulated leading to bending and downward displacement of the central and frontal parts of the slope. When the potential sliding surfaces of the bending segments approached each other the stored energy was suddenly released leading to collapse and rapid sliding.

InSAR technology offers a significant cost advantage for dam monitoring. Though documented in other studies, this benefit is limited to non-vegetated, non-waterlogged and stable regions. Multi-temporal InSAR analysis effectively monitors landslides, slopes, auxiliary infrastructures and dam bodies with consistent processing effort. The significance of this capability lies in its ability to maintain consistent frequency and precision throughout a dam's lifespan where traditional monitoring systems may falter. Effective dam modeling requires the availability of SAR data from the dam's construction period preferably during Sentinel-1. By combining conventional monitoring methods with InSAR the interferometric series can precisely detect and monitor the dam body and its associated structure deformation since their inception.

## 6 Conclusion

This research explores the application of the InSAR technique for extensive spatial monitoring and rapid detection of surface displacements in dam and reservoir areas. Additionally, it demonstrates the value of Sentinel-1 data for assessing the structural stability of large-scale engineering systems, taking advantage of the mission's wide spatial coverage and frequent C-band acquisitions at 12 day intervals.

Temporal variations observed in InSAR measured deformation and changes in surface morphology confirm the active nature of the landslide in the Ozkurtun settlement area. Maximum line-of-sight displacement rates reached up to 54 mm/yr and 127 mm/yr, with pronounced deformation in both vertical and east-west components particularly along the slope direction. Based on InSAR results and field observations, river erosion, reservoir volume fluctuations and gravitational forces appear to be the primary driving factors. While precipitation seems to have a minimal direct effect. It may still influence deformation patterns when interacting with other environmental factors. Specifically, the combined effects of rainfall, river erosion and reservoir water level changes may contribute to a more complex and seasonally modulated landslide behavior. These findings underline the need for continuous monitoring of the area to ensure the long term stability of both the landslide zone and the dam structure.

It is acknowledged that a comprehensive interpretation of dam and slope deformation ideally requires the integration of geological, geomorphological, and seismic background data. However, such information was not available for the Kurtun Dam region during the study period. Despite this limitation, the current analysis focuses on detecting and monitoring surface displacement using high-resolution InSAR techniques and conventional geodetic observations. The study thereby emphasizes the observed kinematic behavior rather than the full geotechnical mechanisms underlying the detected movements. Future research efforts incorporating subsurface investigations, geological mapping and seismic hazard analysis are essential for a more holistic assessment of slope stability and dam safety.

This study also highlights the advantages of integrating multiple remote sensing approaches to identify and characterize active landslides. The established interpretive framework presented herein facilitates the detection and mapping of unstable slopes across the Harsit Valley. Further field investigations and InSAR analyses should be conducted in parallel to estimate the volume of mass that may detach and potentially reach the reservoir basin. Evaluating the potential impact of mass movement into the reservoir, including the risk of wave overtopping or structural stress on the dam is crucial. Additionally, the potential displacement or reconfiguration of the rock-fill foundation should be assessed in the event of sudden hydrodynamic loads.

**Acknowledgements** We thank ESA's Research and Service Support team for their provision of InSAR data. We would like to thank the Turkish State Meteorology Service and Directorate General for State Hydraulic Works (DSI) institutions for data sharing.

**Author contributions** FC: literature review, in situ measurement, interferometric data process, data download, data analyses, and writing; FBS: literature review, interpretation of results, and writing; AC: literature review, interpretation of results, and writing; KC: literature review, measurement and data collection, interpretation of results. All authors read and approved the final manuscript.

**Funding** Open access funding provided by the Scientific and Technological Research Council of Türkiye (TÜBİTAK).

## Declarations

**Competing interests** The authors confirm having no competing interests.

**Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

## References

- Barla G, Antolini F, Barla M, Mensi E, Piovano G (2010) Monitoring of the Beauregard landslide (Aosta valley, Italy) using advanced and conventional techniques. *Eng Geol* 116(3–4):218–235. <https://doi.org/10.1016/j.enggeo.2010.09.004>
- Bayik C, Abdikan S (2021) Monitoring of small-scale deformation at sea-filled Ordu-Giresun airport, Turkey from multi-temporal SAR data. *Eng Fail Anal* 130. <https://doi.org/10.1016/j.engfailanal.2021.105738>
- Bayik C, Abdikan S, Ozdemir A, Arıkan M, Sanli B, F., Dogan U (2021) Investigation of the landslides in Beylikdüzü-Esenyurt districts of Istanbul from InSAR and GNSS observations. *Nat Hazards* 109(1):1201–1220. <https://doi.org/10.1007/s11069-021-04875-7>
- Cetin H, Laman M, Ertunç A (2000) Settlement and slaking problems in the world's fourth largest rock-fill dam, the Atatürk Dam in Turkey. In / *Engineering Geology* 56. [www.elsevier.nl/locate/enggeo](http://www.elsevier.nl/locate/enggeo)
- Coskun S, Bayik C, Abdikan S, Gorum T, Sanli FB (2023) International archives of the photogrammetry. 48(M):497–502. *Remote Sensing and Spatial Information Sciences - ISPRS Archives* <https://doi.org/10.5194/isprs-archives-XLVIII-M-1-2023-497-2023>. MONITORING THE SLOWLY DEVELOPING LANDSLIDE WITH THE INSAR TECHNIQUE IN SAMSUN PROVINCE, NORTHERN TURKEY
- Das S, Priyadarshana A, Grebby S (2024) Monitoring the risk of a tailings dam collapse through spectral analysis of satellite InSAR time-series data. *Stoch Env Res Risk Assess* 38(8):2911–2926. <https://doi.org/10.1007/s00477-024-02713-3>
- Du Q, Li G, Chen D, Zhou Y, Qi S, Wu G, Chai M, Tang L, Jia H, Peng W (2021) SBAS-InSAR-Based analysis of surface deformation in the Eastern Tianshan mountains, China. *Front Earth Sci* 9. <https://doi.org/10.3389/feart.2021.729454>
- Duffaut P (2013) The traps behind the failure of malpasset arch dam, france, in 1959. *J Rock Mech Geotech Eng* 5(5):335–341. <https://doi.org/10.1016/j.jrmge.2013.07.004>
- García-Lanchares C, Marchamalo-Sacristán M, Fernández-Landa A, Sancho C, Krishnakumar V, Benito B (2023) Analysis of deformation dynamics in Guatemala City metropolitan area using persistent scatterer interferometry. *Remote Sens* 15(17). <https://doi.org/10.3390/rs15174207>
- Han Y, Liu G, Liu J, Yang J, Xie X, Yan W, Zhang W (2023) Monitoring and analysis of land subsidence in Jiaozuo City (China) based on SBAS-InSAR technology. *Sustain (Switzerland)* 15(15). <https://doi.org/10.3390/su15151737>
- Hastaoglu KO, Poyraz F, Turk T, Yılmaz I, Kocbulut F, Demirel M, Sanli U, Duman H, Balik Sanli F (2018) Investigation of the success of monitoring slow motion landslides using persistent scatterer interferometry and GNSS methods. *Surv Rev* 50(363):475–486. <https://doi.org/10.1080/00396265.2017.1295631>
- Holden D, Donegan S, Pon A (2020) Brumadinho dam InSAR study: analysis of TerraSAR-X, COSMO-SkyMed and Sentinel-1 images preceding the collapse. 293–306. [https://doi.org/10.36487/acg\\_repo/2025\\_15](https://doi.org/10.36487/acg_repo/2025_15)
- Hooper A, Bekaert D, Spaans K, Arikian M (2012) Recent advances in SAR interferometry time series analysis for measuring crustal deformation. In *Tectonophysics* 514–517:1–13. <https://doi.org/10.1016/j.tecto.2011.10.013>
- Hooper A, Bekaert D, Hussain E, Spaans K (2018) StaMPS/MTI Manual Version 4.1b

- Liu H, Huang S, Xie C, Tian B, Chen M, Chang Z (2023) Monitoring roadbed stability in permafrost area of Qinghai–Tibet railway by MT-InSAR technology. *Land* 12(2). <https://doi.org/10.3390/land12020474>
- Maina-Gichaba C, Kipseba EK, Masibo M (2013) Overview of Landslide Occurrences in Kenya. Causes, Mitigation, and Challenges. In *Developments in Earth Surface Processes* 16:293–314). Elsevier B.V. <https://doi.org/10.1016/B978-0-444-59559-1.00020-7>
- Marchamalo-Sacristán M, Ruiz-Armenteros AM, Lamas-Fernández F, González-Rodrigo B, Martínez-Marín R, Delgado-Blasco JM, Bakon M, Lazecky M, Perissin D, Papco J, Sousa JJ (2023) MT-InSAR and dam modeling for the comprehensive monitoring of an Earth-Fill dam: the case of the Benínar dam (Almería, Spain). *Remote Sens* 15(11). <https://doi.org/10.3390/rs15112802>
- Marchamalo-Sacristán M, Ruiz-Armenteros AM, Lamas-Fernández F, González-Rodrigo B, Martínez-Marín R, Delgado-Blasco JM, Bakon M, Lazecky M, Perissin D, Papco J, Sousa JJ (2025) Correction: Marchamalo-Sacristán MT-InSAR and Dam Modeling for the Comprehensive Monitoring of an Earth-Fill Dam: The Case of the Benínar Dam (Almería, Spain). *Remote Sens*. 2023, 15, 2802. *Remote Sensing*, 17(7):1234. <https://doi.org/10.3390/rs17071234>
- Milillo P, Bürgmann R, Lundgren P, Salzer J, Perissin D, Fielding E, Biondi F, Milillo G (2016a) Space geodetic monitoring of engineered structures: the ongoing destabilization of the Mosul dam. *Iraq Sci Rep* 6. <https://doi.org/10.1038/srep37408>
- Milillo P, Perissin D, Salzer JT, Lundgren P, Lacava G, Milillo G, Serio C (2016b) Monitoring dam structural health from space: insights from novel InSAR techniques and multi-parametric modeling applied to the Pertusillo dam basilicata, Italy. *Int J Appl Earth Obs Geoinf* 52:221–229. <https://doi.org/10.1016/j.jag.2016.06.013>
- Milillo P, Tapete D, Cigna F, Perissin D, Salzer J, Lundgren P, Fielding E, Burgmann R, Biondi F, Milillo G, Serio C (2016c) Structural health monitoring of engineered structures using a space-borne synthetic aperture radar multi-temporal approach: from cultural heritage sites to war zones. *SAR Image Anal Model Techniques XVI* 10003:100030N. <https://doi.org/10.1117/12.2241620>
- Nasrat Adamo N, Al-Ansari V, Sissakian J, Sven Knutsson (2019) Mosul dam: geology and safety concerns. *J Civil Eng Archit* 13(3). <https://doi.org/10.17265/1934-7359/2019.03.001>
- Ouyang Y, Feng T, Feng H, Wang X, Zhang H, Zhou X (2024) Deformation monitoring and potential risk detection of In-Construction dams utilizing SBAS-InSAR Technology—A case study on the Datengxia water conservancy hub. *Water (Switzerland)* 16(7). <https://doi.org/10.3390/w16071025>
- Pang Z, Jin Q, Fan P, Jiang W, Lv J, Zhang P, Cui X, Zhao C, Zhang Z (2023) Deformation monitoring and analysis of reservoir dams based on SBAS-InSAR Technology—Banqiao reservoir. *Remote Sens* 15(12). <https://doi.org/10.3390/rs15123062>
- Panizzo A, De Girolamo P, Risio M, Di, Maistri A, Petaccia A (2005) Natural Hazards and Earth System Sciences Great landslide events in Italian artificial reservoirs. In *Natural Hazards and Earth System Sciences* 5.
- Pechnikov Alexey (2023) PyGMTSAR
- Ruiz-Armenteros AM, Lazecky M, Hlaváčová I, Bakoň M, Manuel Delgado J, Sousa JJ, Lamas-Fernández F, Marchamalo M, Caro-Cuenca M, Papco J, Perissin D (2018) Deformation monitoring of dam infrastructures via spaceborne MT-InSAR. The case of La Viñuela (Málaga, Southern Spain). *Procedia Comput Sci* 138:346–353. <https://doi.org/10.1016/j.procs.2018.10.049>
- Scaioni M, Marsella M, Crosetto M, Tornatore V, Wang J (2018) Geodetic and remote-sensing sensors for dam deformation monitoring. In *Sensors (Switzerland)* 18(11). MDPI AG. <https://doi.org/10.3390/s18113682>
- Tonelli D, Caspani VF, Valentini A, Rocca A, Torboli R, Vitti A, Perissin D, Zonta D (2023) *Remote Sens* 15(21). <https://doi.org/10.3390/rs15215242>. Interpretation of Bridge Health Monitoring Data from Satellite InSAR Technology
- Tu K, Ye S, Zou J, Hua C, Guo J (2023) InSAR displacement with High-Resolution optical remote sensing for the early detection and deformation analysis of active landslides in the upper yellow river. *Water (Switzerland)* 15(4). <https://doi.org/10.3390/w15040769>
- Ulló SL, Addabbo P, Martire D, Di, Sica S, Fiscante N, Cicala L, Angelino CV (2019) Application of DInSAR technique to high coherence Sentinel-1 images for dam monitoring and result validation through in situ measurements. *IEEE J Sel Top Appl Earth Observations Remote Sens* 12(3):875–890. <https://doi.org/10.1109/JSTARS.2019.2896989>
- Verma D, Vijay S (2024) Time-Series analysis of dam deformation using Satellite-Based InSAR technique: case studies from oroville, pong, and Tehri dams. 11136–11140. <https://doi.org/10.1109/igarss53475.2024.10642554>
- Wang M, Yang S, Zhang J, Li X (2020a) Risk assessment of landslide-induced surge disaster of river type reservoir in mountainous area. *Syst Sci Control Eng* 8(1):454–461. <https://doi.org/10.1080/21642583.2020.1788469>

- Wang QQ, Huang QH, He N, He B, Wang ZC, Wang YA (2020b) Displacement monitoring of upper Atbara dam based on time series InSAR. *Surv Rev* 52(375):485–496. <https://doi.org/10.1080/00396265.2019.1643529>
- Wang Q, Gao Y, Gong T, Liu T, Sui Z, Fan J, Wang Z (2023) Dam surface deformation monitoring and analysis based on PS-InSAR technology: A case study of Xiaolangdi reservoir dam in China. *Water (Switzerland)* 15(18). <https://doi.org/10.3390/w15183298>
- Web 1 Kürtün Barajı ve (2024) Hidroelektrik Santrali Projesi, Access Date: 13/06/2024, <https://www.nuroli.nsaat.com.tr/portfolio/kurtun-baraji-ve-hidroelektrik-santrali-projesi>
- Wen F, Song C, Li Z, Yu C, Chen B, Du J, Liu Z, Wen Y (2025) Landslide detection and deformation control analysis in the reservoir area of Wudongde hydropower station by InSAR observations. *Earth Space Sci* 12(4). <https://doi.org/10.1029/2024EA004002>
- Wu Q, Jia C, Chen S, Li H (2019) SBAS-InSAR based deformation detection of urban land, created from mega-scale mountain excavating and Valley filling in the loess plateau: the case study of yan'an City. *Remote Sens* 11(14). <https://doi.org/10.3390/rs11141673>
- Yang F, An Y, Ren C, Xu J, Li J, Li D, Peng Z (2023) Monitoring and analysis of surface deformation in alpine Valley areas based on multidimensional InSAR technology. *Sci Rep* 13(1). <https://doi.org/10.1038/s41598-023-39677-3>
- Yavaşoğlu HH, Kalkan Y, Tiryakioğlu, Yigit CO, Özbey V, Alkan MN, Bilgi S, Alkan RM (2018) Monitoring the deformation and strain analysis on the Atatürk dam, turkey. *Geomatics. Nat Hazards Risk* 9(1):94–107. <https://doi.org/10.1080/19475705.2017.1411400>
- Yuan M, Li M, Liu H, Lv P, Li B, Zheng W (2021) Subsidence monitoring base on sbas-insar and slope stability analysis method for damage analysis in mountainous mining subsidence regions. *Remote Sens* 13(16). <https://doi.org/10.3390/rs13163107>
- Zhang Z, Hu C, Wu Z, Zhang Z, Yang S, Yang W (2023) Monitoring and analysis of ground subsidence in Shanghai based on PS-InSAR and SBAS-InSAR technologies. *Sci Rep* 13(1). <https://doi.org/10.1038/s41598-023-35152-1>
- Zheng H, Shi Z, Shen D, Peng M, Hanley KJ, Ma C, Zhang L (2021) Recent Advances in Stability and Failure Mechanisms of Landslide Dams. In *Frontiers in Earth Science* (Vol. 9). Frontiers Media S.A. <https://doi.org/10.3389/feart.2021.659935>
- Zhou C, Cao Y, Yin K, Wang Y, Shi X, Catani F, Ahmed B (2020) Landslide characterization applying sentinel-1 images and Insar technique: the Muyubao landslide in the three Gorges reservoir area, China. *Remote Sens* 12(20):1–20. <https://doi.org/10.3390/rs12203385>

**Publisher's note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.