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InSAR as a tool for monitoring hydropower projects: A review

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ABSTRACT

This paper provides a review of using Interferometric Synthetic Aperture Radar (InSAR), a microwave remote sensing technique, for deformation monitoring of hydroelectric power projects, a critical infrastructure that requires consistent and reliable monitoring. Almost all major dams around the world were built for the generation of hydropower. InSAR can enhance dam safety by providing timely settlement measurements at high spatial-resolution. This paper provides a holistic view of different InSAR deformation monitoring techniques such as Differential Synthetic Aperture Radar Interferometry (DInSAR), Ground-Based Synthetic Aperture Radar (GBInSAR), Persistent Scatterer Interferometric Synthetic Aperture Radar (PSInSAR), Multi-Temporal Interferometric Synthetic Aperture Radar (MTInSAR), Quasi-Persistent Scatterer Interferometric Synthetic Aperture Radar (QPSInSAR) and Small BAseline Subset (SBAS). PSInSAR, GBInSAR, MTInSAR, and DInSAR techniques were quite commonly used for deformation studies. These studies demonstrate the advantage of InSAR-based techniques over other conventional methods, which are laborious, costly, and sometimes unachievable. InSAR technology is also favoured for its capability to provide monitoring data at all times of day or night, in all-weather conditions, and particularly for wide areas with mm-scale precision. However, the method also has some disadvantages, such as the maximum deformation rate that can be monitored, and the location for monitoring cannot be dictated. Through this review, we aim to popularize InSAR technology to monitor the deformation of dams, which can also be used as an early warning method to prevent any unprecedented catastrophe. This study also discusses some case studies from southern India to demonstrate the capabilities of InSAR to indirectly monitor dam health.

1. Introduction

Remote sensing is the technique used to obtain information about the Earth's surface (both land and water) and atmosphere using sensors on-board terrestrial, airborne (aircraft, balloons) or space-borne (satellites, space shuttles) platforms (Navalgund et al., 2007; Bouali et al., 2017). Remote sensing is an effective technique for studying change detection, which is the process of identifying and assessing changes in a variety of surface phenomena over time (Mouat et al., 1993; Mishra et al., 2017). There are different types of remote sensing techniques that utilize sections of the electromagnetic spectrum (e.g., optical, LiDAR, radar), of which microwave radar remote sensing has the advantages of being able to monitor earth surface resources day and night, and can penetrate cloud cover (Khoram et al., 2016). Of the different imaging techniques employed in microwave remote sensing, Synthetic Aperture Radar (SAR) is widely used to produce fine resolution images (Chan and Koo, 2008; Bouali et al., 2017).

Interferometric Synthetic Aperture Radar (InSAR) is a powerful tool for mapping ground movements using SAR data. Graham (1974) conducted the first InSAR experiment for topographic mapping, whereas Zebker and Goldstein (1986) reported the first practical findings using side-looking airborne radar (SLAR). One of

; InSAR, Interferometric Synthetic Aperture Radar; RADAR, Radio Detection and Ranging.

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the most mature applications of space-borne InSAR technology is deformation monitoring (Jianjun et al., 2017). InSAR performs high-density measurements across wide regions by utilizing radar signals from Earth-orbiting satellites to monitor changes in land-surface height at high resolution and spatial detail (Galloway et al., 2000). InSAR methods can be improved to mm sensitivity by analysing lengthy sequences of SAR images, and may be utilized to efficiently monitor ground movements and minute displacements of structures like dams, buildings, and bridges (Perissin, 2016). InSAR research was expanded with the deployment of the ERS-1 and ERS-2 satellites. By the deployment of new satellites, the number of scientific studies using InSAR technology has also increased (Aydoner et al., 2004). And with more satellites with on-board microwave sensors orbiting the Earth, the potentiality of using InSAR data is on the rise.

InSAR has different deformation monitoring methods viz., Differential Interferometric Synthetic Aperture Radar (DInSAR) (Gabriel et al., 1989), Ground-Based Interferometric Synthetic Aperture Radar (GBInSAR) (Tarchi et al., 1999), Persistent Scatterer Interferometric Synthetic Aperture Radar (PSInSAR), (Ferretti et al., 2000, 2001), Multi-Temporal Interferometric Synthetic Aperture Radar (MTInSAR) (Feretti et al., 2001), Quasi-Persistant Scatterer Interferometric Synthetic Aperture Radar (QPSInSAR) (Kuri et al., 2018) and Small BAseline Subset (SBAS) (Berardino et al., 2002) (Fig. 1).

This paper showcases a review on the uses of InSAR in monitoring hydroelectric power projects, one of the most critical infrastructures that need consistent and reliable monitoring. InSAR technologies enhance dam safety by providing timely settlement measurements at high spatial resolution and have been validated in several studies (Tarchi et al., 1999; Altinbilek, 2002; Honda et al., 2012; Lazecký et al., 2015; Roque et al., 2015; Di Martire et al., 2015; Lier et al., 2015; Di Pasquale et al., 2018; Hooper, 2018; Ullo et al., 2019; Wang et al., 2019; Qiu et al., 2020). Nearly all major dams in the world were built for hydroelectric power. Dams were first used for hydroelectric power around 1890. Hundreds of major

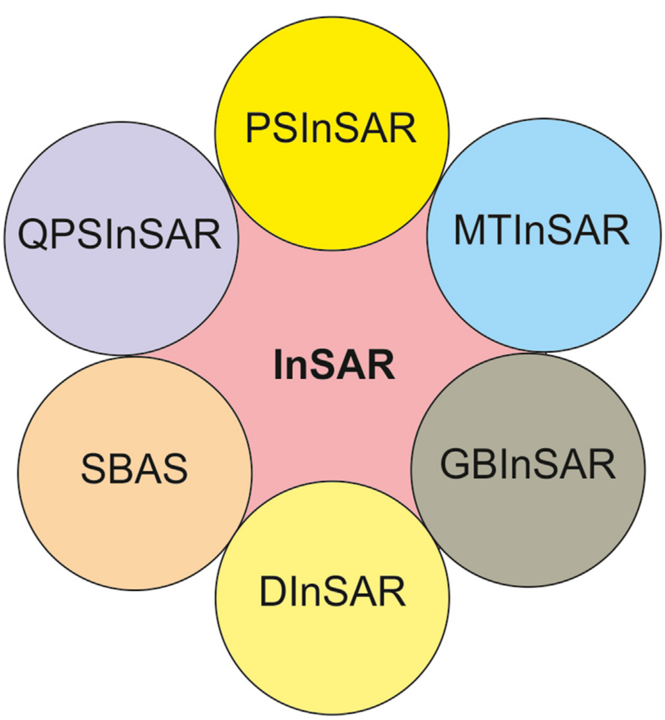

Fig. 1. Types of InSAR techniques.

dams had been constructed worldwide by the end of 1900 (Altinbilek, 2002). According to the World Commission on Dams (WCD, 2000), hydropower accounts for 19% of the total electricity supply. It is employed in over 150 nations since it is the most plentiful renewable energy resource.

Dams are essential infrastructures that aid in irrigation, navigation, flood control and hydropower (Huang and Yan, 2009). Dams are often located in hilly areas where ground movements are caused by natural geodynamics or induced by changes in ground stress (Raventos et al., 2019). Several dams collapsed, resulting in massive losses of life and a severe impact on the environment (Cheng et al., 2019). For example, on July 23, 2018, a saddle dam in the Xe Pian-Xe Namnoy hydropower dam under construction in Attapeu Province, southern Laos, collapsed, causing serious damage to the villages downstream that killed at least 48 people, leaving 23 others missing, and displacing over 7000 people. Another major dam collapse occurred during 1928 March 12–13, the St. Francis Dam of Los Angeles that catastrophically killed 450 in the San Francisquito and Santa Clara River Valleys. It was considered as the greatest man-made disaster in California history.

Hence, precise and regular monitoring of dams and their surroundings is essential for averting catastrophic infrastructure damage and maintaining the safety of downstream communities (Cheng et al., 2019; Ruiz-Armenteros et al., 2018). A cost-effective method of monitoring dams and their environs at a regional scale would allow for more efficient planning of more localized monitoring tasks (Roque et al., 2015). Compared to traditional/conventional surveying methods, InSAR offers the benefit of providing a high density of measurement points over large areas, including regions that are dangerous or difficult to access. Time-series InSAR techniques provide high-precision time-series of movement that may be used to quantify mm-level displacements on the Earth's surface at a regional scale over time, and seasonal uplift/subsidence cycles (Roque et al., 2015; Lu et al., 2010). This technique is a cost-effective way for deformation monitoring of dams and can be used as an early warning system for the safety of structures and their environs (Cheng et al., 2019; Massonnet and Feigl, 1998; Roque et al., 2015; Lu et al., 2010).

2. Commercial and other future missions

The first commercial SAR satellite is ICEYE constellation, which was launched in January 2018 and equipped with the first operational microsatellite-based X-band SAR sensors. This commercial constellation currently consists of 3 s-generation X-band SAR satellites, which provide nearly daily access to any location on the planet (Krieger and Moreira, 2006; Ignatenko et al., 2020). The ability to operate a large number of spacecraft at a low cost is the main advantage. The instrument had a pulse bandwidth of 60 MHz, with a resolution of 5–10 m. ICEYE-X2, a representative instrument of the ICEYE constellation, is now in a sun-synchronous polar orbit with a ground track repetition cycle of 17 days and 15 imaging orbits each day (Ignatenko et al., 2020). The ICEYE SAR satellites are active phased array antenna-based side-looking SAR sensors with Stripmap, Spotlight, and ScanSAR imaging modes as well as left- and right-looking acquisitions. When compared to a continuous Stripmap mode, Spotlight mode uses mechanical antenna steering in the azimuth direction to enhance the illumination period, resulting in a larger synthetic aperture and hence, greater azimuth resolution (Lukosz et al., 2021; Ignatenko et al., 2020). The utilization of multiple multistatic acquisition modes with synchronised transmit signals is one of the future developments. This should allow for a more flexible imaging geometry that can be dynamically modified to different operational SAR applications (Antropov et al., 2018; Krieger and Moreira, 2006; Ignatenko et al., 2020).

The future SAR satellites include NISAR, Tandem-L and ALOS-4. NISAR is a NASA-ISRO (Indian Space Research Organization) Earth-observing mission, a dual frequency SAR satellite with the goal of measuring the causes and consequences of land surface changes on a global scale (Jones et al., 2021; NISAR, 2020). Ecosystem disturbances, ice sheet collapse, and natural hazards are all potential research topics (NISAR, 2020). The NISAR mission is NASA's first L-band SAR mission in orbit. NISAR, which is scheduled to launch in 2022, will collect wall—to—wall L-band data (and S-band data in some regions) globally, repeating its orbit every 12 days over the course of its three-year mission, providing high-resolution data. The NISAR mission is designed to detect subtle changes in the Earth's surface caused by motions in the crust and ice surfaces. NISAR will advance our understanding of natural hazards and improve our understanding of key impacts of climate change (Silva et al., 2021; Jones et al., 2021).

Tandem-L is a ground-breaking radar satellite mission to track dynamic processes on the Earth's surface with mm accuracy for earthquake, volcano, and landslide research, as well as risk assessment and mitigation (Moriera et al., 2015). Tandem-L is planned by the German Aerospace Center in collaboration with numerous Helmholtz research groups and German space businesses (Kreiger et al., 2009). Two completely polarimetric radar satellites will provide monostatic and bistatic SAR pictures as part of the mission concept. The provision of large antenna apertures in space and flexible operation via reconfigurable feed electronics are the key advantages of this novel SAR system concept. For the first time, a continuous 350 km wide swath with a 7 m azimuth resolution, good noise equivalent sigma zero, and ambiguity suppression can be mapped (Kreiger et al., 2014; Huber et al., 2018).

The Advanced Land Observing Spacecraft-4 (ALOS-4) is a Japanese Aerospace Exploration Agency (JAXA) land observation satellite with L-band SAR (Motohka et al., 2017). ALOS-4's goals are to continue and improve the ALOS-2 mission, which includes disaster monitoring in all weathers, forest monitoring, sea ice monitoring, and ship and ocean monitoring and using time-series observations to investigate novel applications such as minor movement detection of big infrastructures (Motohka et al., 2019). It has a designed life time of 7 years with PALSAR-3 and has a revisit cycle of 12 days (Motohka et al., 2019). The satellites hosting microwave sensors (operational, future projects and dysfunctional) are provided in Fig. 2 and Table 1.

3. Need for dam monitoring

Dam has several components (Fig. 3) and hence, deformation of a dam occurs for several reasons. Thermal forces owing to air temperature and sun warming, and hydrostatic water pressure from the basin (Oro et al., 2016) are examples of external inputs that can change the geometry of a dam. Seismic occurrences (Siyahi and Aslan, 2008), and changes in the geotechnical characteristics of the substrate (Kasana et al., 2015) are two of the most uncommon causative factors for dam deformation. Inner factors, such as changes in the strain-stress curve of structural materials (e.g., due to plasticity processes), local sinking or sliding of the dam body with respect to the bedrock, and water seepage in earth-filled dams, can all also cause deformation (Scaioni et al., 2018). External forces generally cause horizontal movements, and they can be quite severe near the dam's crest. Vertical displacements may be seen on the dam's upper crown, internal inspection tunnels, foundations, and bedrock contact on the valley's lateral sides (Scaioni et al., 2018).

3.1. *InSAR methods for dam monitoring*

Accurate deformation monitoring of dams and their surroundings is of utmost importance to detect instability and avert catastrophic loss of infrastructure and lives (Oommen et al., 2021). Assessment would allow for the early detection of potentially unstable locations, acting as a safety warning system and identifying areas that would require more precise and targeted monitoring activities (Roque et al., 2015). A dam may fail when loading exceeds resistance against overtopping, internal erosion, slope instability, sliding/overturning, and excessive deformation (Zhang et al., 2009). Different InSAR techniques used for monitoring dams are discussed here.

3.1.1. *Monitoring using DInSAR*

DInSAR was the first radar interferometry method used for ground deformation monitoring. DInSAR is a technique for processing SAR images that are based on combining one or more pairs of satellite images with known orbital characteristics (Ullo et al., 2019). An interferogram is created by combining two SAR images acquired from the same orbit but with an orbital baseline difference (Ullo et al., 2019; Pepe and Calò, 2017).

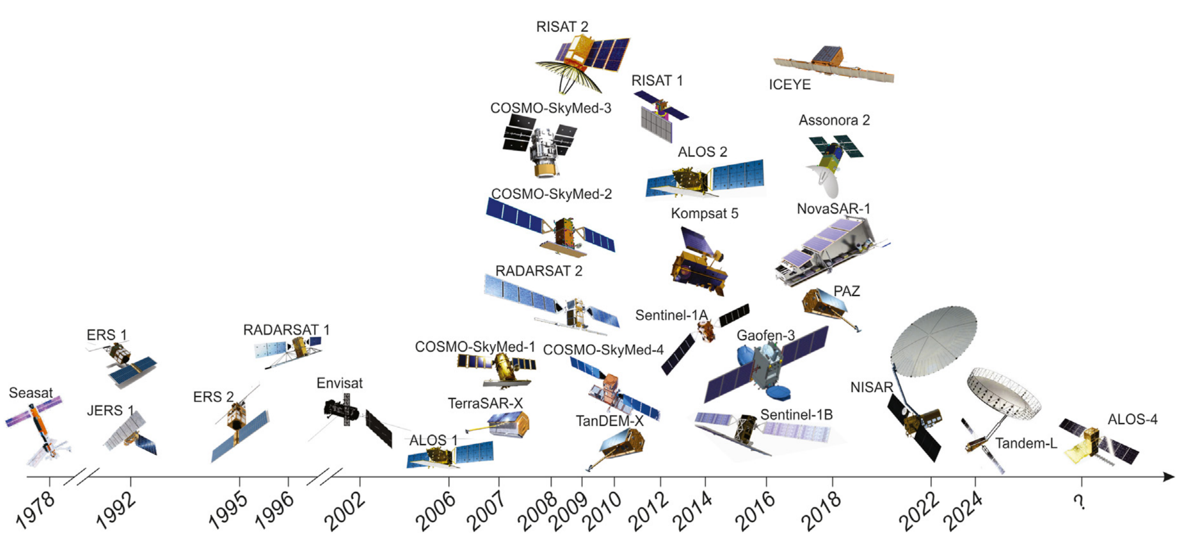

Fig. 2. List of satellites hosting microwave sensors (satellite images were collected from different sources).

Table 1
Details of satellite-based radar systems.

Satellite	Sensor	Bands	Spatial resolution (m)	Repeat cycle	Accessibility	Operational/defunct	Agency
Seasat	SAR	L	25	17 days	Freely available in ASF	Defunct (1978–1978)	National Aeronautics and Space Administration (NASA)
JERS-1	SAR	L	18	44 days	Freely available in ASF	Defunct (1992–1998)	Japan Aerospace Exploration Agency (JAXA)
ERS-1	AMI	X	25	35 days	Freely available in ASF	Defunct (1991–2000)	European Space Agency (ESA)
ERS-2	AMI	X	25	35 days	Freely available in ASF	Defunct (1995–2011)	European Space Agency (ESA)
RADARSAT-1	SAR	C	8–100	24 days	Freely available in ASF	Defunct (1995–2013)	Canadian Space Agency (CSA)
Envisat	ASAR	C	12.5	35 days	Freely available in ESA	Defunct (2002–2012)	European Space Agency (ESA)
ALOS-1	PALSAR	L	10–100	46 days	Freely available in ASF	Defunct (2006–2011)	Japan Aerospace Exploration Agency (JAXA)
TerraSAR-X	SAR	X	1–16	11 days	Freely available in ESA	Operational (from 2007)	German Aerospace Center (DLR)
COSMO-SkyMed-1	SAR-2000	X	1–100	16 days	Freely available in ESA	Operational (from 2007)	Italian Space Agency (ASI)
RADARSAT-2	SAR	C	3–100	24 days	Freely available in ESA, ASF	Operational (from 2007)	Canadian Space Agency (CSA)
COSMO-SkyMed-2	SAR-2000	X	1–100	16 days	Freely available in ESA	Operational (from 2007)	Italian Space Agency (ASI)
TanDEM-X	SAR	L	1–16	11 days	Freely available in ESA	Operational (from 2010)	German Aerospace Center (DLR)
RISAT-1	SAR	C	1–50	25 days	Freely available in ESA	Defunct (2012–2016)	Indian Space Research Organization (ISRO)
COSMO-SkyMed-3	SAR-2000	X	1–100	16 days	Freely available in ESA	Operational (from 2019)	Italian Space Agency (ASI)
COSMO-SkyMed-4	SAR-2000	X	1–100	16 days	Freely available in ESA	Operational (from 2019)	Italian Space Agency (ASI)
Sentinel-1A	SAR	C	5–40	12 days	Free in ASF, Copernicus open access hub	Operational (from 2014)	European Space Agency (ESA)
KOMPSAT-5	COSI	X	1–20	28 days	Freely available in ESA	Operational (from 2013)	Korea Areospace Research Institute (KARI)
ALOS-2	PALSAR-2	L	1–100	30 days	Freely available in ASF	Operational (from 2014)	Japan Aerospace Exploration Agency (JAXA)
Sentinel-1B	SAR	C	5–40	12 days	Freely in ASF, Copernicus open access hub	Operational (from 2016)	European Space Agency (ESA)
Gaofen-3	SAR-C	C	1–500	29 days	Freely available in ESA	Operational (from 2016)	China National Space Administration (CNSA)
SAOCOM-1A	SAR	L	7–100	16 days	NA	Operational (from 2018)	ComisiónNacional de ActividadesEspaciales (CONAE) (Argentina's Space agency)
PAZ	SAR-X	X	1–16	11 days	NA	Operational (from 2018)	Instituto National de TécnicaAeroespacial (INTA) (Space agency of Spain)
NovaSAR-1	S-SAR	S	6–400	16 days	NA	Operational (from 2018)	Surrey Satellite Technology Limited (SSTL)
Asnaro-2	XSAR	X	1–16	12 days	NA	Operational (from 2018)	Japan Aerospace Exploration Agency (JAXA)
SAOCOM-1B	SAR	L	7–100	12 days	NA	Operational (from 2020)	ComisiónNacional de ActividadesEspaciales (CONAE) (Argentina's Space agency)
Commercial satellite							
ICEYE constellation	XSAR	X	5–10	17 days	Available in ESA	Operational (from 2018)	European Space Agency (ESA)
Future projects							
NISAR	SAR	L,S	3–10	12 days	NA	Scheduled for 2022	Indian Space Research Organization (ISRO) and National Aeronautics and Space Administration (NASA)
Tandem-L	SAR	L	7	16 days	NA	Scheduled for 2024	German Aerospace Center
ALOS- 4	SAR	L	10	12 days	NA		Japanese Aerospace Exploration Agency (JAXA)

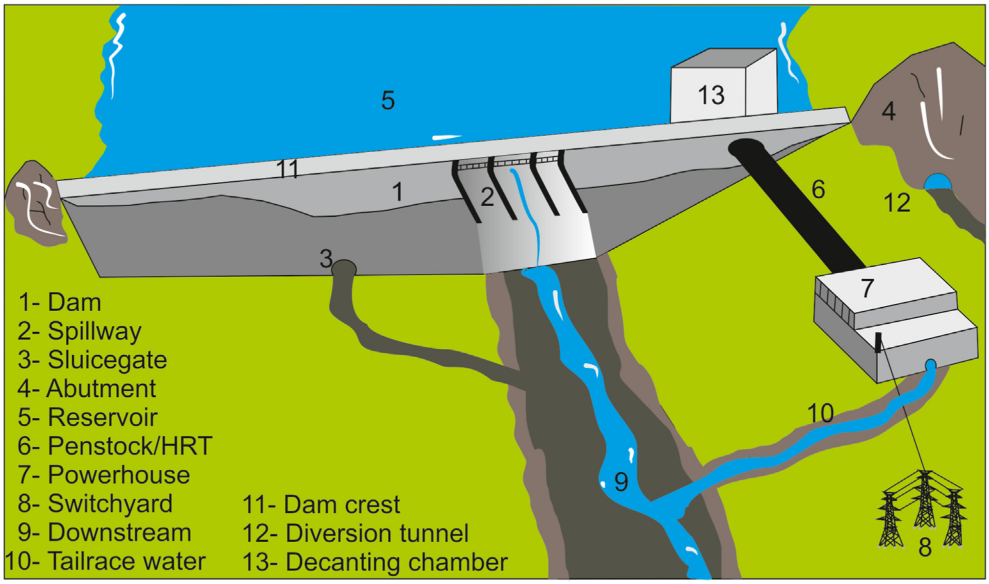

Fig. 3. Sketch map showing the major components of a dam.

Initial applications of space-borne DInSAR include evaluating ground subsidence over large areas and detecting earthquake-induced deformations (Rosen et al., 2000). Honda et al. (2012) monitored the stability of an earth-fill dam, the Taiho Subdam in Okinawa Prefecture, Japan, using DInSAR. They measured the exterior deformation of earth-fill dams using ALOS PALSAR from 6th December 2006 to 17th December 2010. The results of DInSAR measurements were compared with the GPS measurements and showed 80% accuracy. Another comparative study between DInSAR and ground data was conducted by Di Martire et al. (2015) using 51 images of Envisat-ASAR (29th November 2002 to 30th July 2010) of Conza Dam, located in the southern Apennines (Italy), which is quite close to the epicenter of the large earthquake (Mw = 6.9) that struck on November 23rd, 1980. These results show that this method is reliable for accurate monitoring of civil facilities, particularly dams with a large exposure factor and associated risk. DInSAR workflow is very much effective for deformation monitoring of large reservoirs, for example, two large reservoirs in Italy: the Campolattaro and Campotosto were monitored using Sentinel-1A images, and these reservoirs combine to form one of the largest reservoir systems in Europe, impounded by three dams: Poggio Cancelli, Sella Pedicate, and Rio Fucino (Ullo et al., 2019). From the derived differential interferograms and the relative displacements for these dams, the most affected one was the Poggio Cancelli earth dam, closest to the earthquake zone with a vertical velocity of -13 to -18 cm/y, followed by velocities for the Rio Fucino Dam (-15 cm), and comparatively least for the SellaPedicate Dam (about -8 cm). And results from SAR and high-precision levelling show an increasing trend in displacement.

3.1.2. Monitoring using GBInSAR

Tarchi et al. (1999) proposed ground-based interferometry principles to monitor structures. GBInSAR is an advanced, high-precision, low-cost, and continuous monitoring system (Pieraccini et al., 2006). This technique has the ability to set the sampling frequency on its own (Qiu et al., 2020).

The displacement of a dam, induced by variations in water level and temperature over a length of time, was studied by Tarchi et al. (1999). The findings have been compared with data collected by a network of traditional sensors put on the structure. Local displacement data has been collected using a displacement monitoring system based on a network of pendulums and extensometers installed inside the barrage of the dam. Accuracy in the order of a fraction of one mm has been obtained for the study. Di Pasquale et al. (2018) attempted to describe displacement measurements of earth dam surfaces and whole dam infrastructures, including bridges, chalice-shaped spillway and other concrete structures using GB-InSAR. For this study, SAR is used to measure earth dam surface displacements and Real Aperture Radar (RAR) is used for the vibration frequencies of concrete structures. They put forward two different methodologies, for the acquisition of SAR data and for the rendering of results. A geometrical correction factor is derived to correct the Line-of-Sight (LoS) displacement measurements and provide real dam displacement vectors. Also, Ku-band ground-based radar has been used to acquire RAR data, measure their displacements and visualize the corresponding frequency spectra of dam concrete structures. Here, four case studies were examined using radar acquisition strategies, specifically developed to monitor earth dams located in the Apulia and Campania regions, in southern Italy. Structural engineers may use the two techniques proposed in this work to get geolocated displacement vectors over downstream and upstream dam surfaces, as well as displacement time series and vibration spectra for whole infrastructures (Ullo et al., 2019). In case, continuous GBInSAR data of the dam surface and concrete structures are obtained, it might offer up new possibilities for dam modelling during seismic events, at least for the larger and most significant dams in seismically prone areas (Ullo et al., 2019). Another GBInSAR study to monitor the surface deformation of a large reservoir dam was conducted by Wang et al. (2019). Using consecutive GBInSAR image sequences, a multi-threshold method was used to select coherent point targets (CPTs), and using differential GBInSAR with image subsets based on CPTs, the deformation of a huge reservoir dam was measured. The efficiency and accuracy of these methods were verified by comparing the results with measurements by a reversed pendulum monitoring system. So, the GBInSAR technique can be used for areal deformation monitoring and early warning systems for dams, supported slopes, rock slopes, and landslides. Recently, a study on structure deformation monitoring of Geheyan Dam from 29th July to 1st August 2020 using GBSAR data has been conducted (Qiu et al., 2020). The deformation of the dam spillway gates is observed greater than that of the dam body, and the displacement gradually increases in the direction of water flow as the water level in the reservoir area rises.

From these studies, it is clear that GB-InSAR allows for continuous monitoring of areal deformation, allowing for near-real-time management of the overall status of dam surfaces.

3.1.3. Monitoring using PSInSAR

Persistent Scatterer Interferometry (PSI) is a radar-based method that belongs to the ADInSAR group and has been used for geophysical monitoring of natural hazards and ground motion (Roque et al., 2015; Cheng et al., 2019). PSI is a powerful remote sensing technology that has acquired huge popularity for measuring deformation in man-made structures and can measure and monitor surface displacements in mm level accuracy using a stack of single look complex (SLC) SAR images taken at the same place over time (Crosetto et al., 2011; Ferretti et al., 2000; Pooja et al., 2021; Rajaneesh et al., 2021; Sajinkumar et al., 2020).

Structural health monitoring of dams using ADInSAR has been conducted by Mazanti et al. (2015), mainly over three dams viz., the Three Gorges Dam (China), the Plover Cove Dam (Hong Kong), and the San Liberato Dam (Italy), using both recent high-resolution SAR images and past low-resolution images.

The structure and surrounding areas were monitored for the Three Gorges Dam with the aid of two sets of COSMO-SkyMed images stacks (ascending and descending), where 29 images acquired from February to August 2011 were used to retrieve the terrain deformation. PSI analyses were performed in both datasets. The result shows a strong deformation on the southwest side of the dam. The main challenge of the study was the unfeasibility of separating seasonal movements from linear displacement due to the short experimental time (less than one year). Deformation for the Plover Cove Dam in Hong Kong has been monitored using recent SAR images. Sixty-two TerraSAR-X and eleven TanDEM-X (German Space Agency - DLR) strip map images, acquired in ascending orbital geometry, covering October 2008 and June 2012 have been used. The correlation of obtained PS points with water level data gave cyclic deformation and cyclic water level fluctuations (cyclic stress). The stability of the San Liberto Dam of Umbria region, Central Italy, has been monitored and thereby structural health assessment of the dam was carried out using 93 Envisat satellite SAR images acquired from 16th November 2002 to 8th October 2010 (Tomás et al., 2013). From the results, the permanent deformation of the dam during the period 2002–2010 is low. Only a few mm of seasonal deformations were identified in the crest, related to temperature variations and characterized by metallic elements.

Lazecký et al. (2015) reported three examples of PSI applications to monitor deformations of three different types of dams, using SAR data sources: the Charvak Dam in Uzbekistan based on ENVISAT-ASAR data, the Three Gorges Dam in China based on Cosmo-SkyMed data, and the Plover Cove Dam in Hong Kong based on TerraSAR-X data. A deformation study has been conducted over Charvak Dam, Uzbekistan using StaMPS Toolbox and SarProz PSI, the two alternative implementations of the PSI approach (Hooper, 2008). Both produced comparable outcomes. Over the dam body, a constant deformation of 5 mm/y was observed throughout the whole ENVISAT dataset acquired from April 2003 to May 2010. The deformation study of the Three Gorges Dam was conducted using a combination of QPSInSAR and PSI. The Three Gorges Dam, the biggest hydroelectric plant in the world, has four main parts—the central one, the spillway and the two power plants. The displacement study shows that in the first three years, a slight seasonal trend was observed, likely associated with the pressure of the water, changing its level seasonally. Plover Cove Dam is a long marine dam, made primarily of sand and gravel. SarProz PSI processing of 62 TerraSAR-X and 11 TanDEM-X stripmap acquisitions from October 2008 to September 2012 was used for monitoring. PSInSAR has identified extremely shallow movements. The dam bank closest to the reservoir subsides slightly quicker (1–2 mm/y) than the other side. However, the total subsidence does not surpass 1.5 cm. Other motions induced by water pressure from the reservoir, and small motions due by tidal variations have been recorded. These motions are periodic and do not result in long-term effects such as subsidence. Perissin et al. (2009) conducted a study on the results obtained within the Dragon project, cooperation program between the European Space Agency (ESA) and the National Remote Sensing Center of China (NRSCC), for monitoring the terrain motion in urban areas, measuring the city growth rate and evaluating the stability of manmade structures. The main results were obtained in the test sites of Shanghai, Tianjin and Three Gorges Dam. InSAR, PSInSAR, and a combination of coherent-incoherent analyses has been used to process the data. Similarly, Roque et al. (2015) carried out a method to evaluate the safety of dams and their surroundings by using time-series InSAR techniques on Earth dams Alamos 1, 2, and 3 in Portugal. Alamos dams are linked to Alqueva, a concrete arch dam that is well equipped and well-monitored, and were selected for testing the proficiencies of PSInSAR for dam safety. Sixteen ALOS-1 PALSAR images between 2004 and 2010 were used for the process. Displacement for Alamos 2 is observed as -15.4 mm/y and for Alamos 1 is -4.7 mm/y. Moreover, they compared these results with the geodetic method, and comparison showed differences in average displacement rate between 0.2 mm/y and 3.2 mm/y. The discrepancy is due to neglecting the planimetric displacements and using fewer images for PSInSAR processing. The study concluded with a suggestion to install artificial corner reflectors in critical areas where persistent scatterer (PS) was not available. These structures will show a stable reflective behaviour, identified as PS, and allow for displacement analysis. De souse et al. (2015) carried out dam deformation monitoring of three dams (Paradela, Raiva and Alto Ceira) in Portugal using PSInSAR. The estimation was done using several sets of ERS and ENVISAT C-band SAR data. For the Raiva Dam, instability was noted at the southern slope, and no conclusion was made for the rest of the areas because of the low quality of PS points obtained. In the case of the Alto Ceira Dam, upward movement near the crest and centre of the dam was observed. PSInSAR estimations for Paradela Dam show the dam's top-centre part slowly inclining towards the reservoir, linearly with time. The deformation trend is observed as less than 2 mm/y on the lower part of the dam and up to 5 mm/y on the upper part of the dam. These results were compared with the geodetic measurements like levelling, which has been obtained from Geodetic Observing System (GOS). The number of images used for this study is relatively small, and the resolution (30 m) is not appropriate for dam monitoring. Raventos et al. (2019) monitored slope stability over a dam reservoir in the Spanish Pyrenees using PSInSAR. Two types of studies were conducted: firstly, a historical study with the C-Band sensor ENVISAT, covering the period between 2003 and 2010, and a monitoring study with the C-band sensor Sentinel-1A covering from October 2014 to August 2016. Results from the historical study showed the main ground displacement patterns at the dam surrounding slopes. The Eastern area results show a general ground movement of 5 mm/y at the west faced slope with specific movements of accumulated 4.5 cm during the time studied with a yearly velocity of 6.5 mm/y. Also, a further study was conducted with Sentinel-1A data resulting in a database with a higher density of measurement points to analyse the ground motion that occurred around the reservoir. These results show general stability of slopes with localized ground motion, affecting small areas with an averaged motion of 10–15 mm during monitoring time (from February 2015 to September 2016). Because this movement affects the whole slope extension, the most noticeable ground motions are found on the slopes' east and north of the reservoir. The data reveal that the motion originally identified is still present in the reservoir's eastern region. With magnitudes of 20 mm/y, ground motion is concentrated in the lower parts of the slopes, near the ravines, with magnitudes concentrating in summer and autumn. In conclusion, movements are slower in this time than in the historical research; the area appears to have become more stable. Hence, from the first historical study, the time-series obtained with PSInSAR analysis allows for a better understanding of the trigger of the movements and the accelerations due to a change in the border conditions. The second study assisted in understanding whether the triggering parameters have changed with time to correlate the difference in the trend of displacements with the hydraulic and/or rainfall. Cheng et al. (2020) analysed the deformations of the Saddle Dam, one of the Xe-Pian Xe-Namnoy hydroelectric power projects in Laos using the PSInSAR technique. InSAR technology was used with Sentinel-1A SAR images to investigate the spatial and temporal deformation before and after the dam's collapse. Analysis has been done using the images between 30th July 2017 and 25th July 2018. Results show that a small dam area is unstable and shows deformation of -25 to -10 mm/y. However, a different study has been carried out by Yazici and Tunc (2020). They monitored the existing landslides and found new unstable areas in the dam reservoir of Havuzlu village in Artvin/Turkey using PSInSAR method and compared them with different validation methods to test the efficiency of the PSInSAR technique. The validation was carried out using the displacements quantified by GPS and optical levelling methods, and found high correlation. One of the important river basins in northeastern Turkey, the Coruh river basin, encompasses five big dams, and this study has been conducted in the Artvin Dam area. Landslides in dam reservoirs are one of the main causes of dam failures in the world. Thus, monitoring and determining landslides in dam reservoirs is considered very crucial. Sentinel-1A images between January 3, 2018 and December 17, 2018 were used for the process. The total displacements of PS points in Havuzlu are found between -25 mm/y and +28 mm/y. For the validation of PSInSAR technique, the reference points measured by Electronic Distance Measurement (EDM) are used, since GPS ground control points are not available in this area. It was concluded that the displacements found by PSInSAR method are comparable with the reference points' displacements measured in the study area. From the results, the points with the highest velocity are located around the border of the landslide where the unstable area starts in the dam reservoir. Thus, the PSInSAR method is successful in PS analysis of landslide applications in dam areas and thus, detecting the existing landslides. Thus, it is clear from these studies that the PSInSAR technology for deformation monitoring of dams can be used as an early warning method.

3.1.4. Monitoring using QPSInSAR

Perissin et al. (2011) introduced QPSInSAR, a method that improves the spatial distribution of points by extracting information from partly coherent targets, allowing phase and space-time coherence analyses (Zhou et al., 2019).

The deformation of Langya Dam in Qian'an Country, Jilin, China, has been studied using QPS-InSAR method and 21 Sentinel–1B images (C-band) acquired during September 2017–May 2018 by Zhou et al. (2019). From the results, it is observed that the Langya Dam trended upward during the monitoring period (September 25, 2017 to October 31, 2017) with an average deformation rate of 6.9 cm/y and the deformation in the west was greater than that in the east, and the surface was relatively stable. The uplift of the dam is associated with soil frost heaving caused by the gradual decrease of temperature and groundwater recharge.

3.1.5. Monitoring using MTInSAR

MTInSAR has matured to the point that it may now be utilized to measure small deformations produced by natural events or manmade structures. Dam structural health monitoring using MTInSAR is not yet a widespread procedure. However, these findings led to the conclusion that MTInSAR approaches can aid the development of new and more effective methods of monitoring and evaluating dam health and provide low-cost redundancy to support and assist warning systems (Ruiz et al., 2018).

Ruiz et al. (2018) monitored the La Vinuela Dam (Malaga, Spain), a 96 m height earth-fill dam, built during 1982–1989, using MTInSAR method. The datasets selected for the study are from the European satellites ERS-1/2 (1992–2000), ENVISAT (2003–2008), and Sentinel-1A/B (2014–2018). Maximum deformation rates were measured in the initial period (1992–2000), around -7 mm/y (LoS direction) on the crest of the dam. Low deformation rates were obtained during 2003–2008, around -4 mm/y. The obtained results confirm that the Lavinuela Dam has been deforming since its construction as an earth-fill dam. Monitoring using Sentinel-1A/B shows that the deformation is still active in 2014–2018 in the central upper part of the dam, with a maximum velocity reaching -6 mm/y. Thus, MT-InSAR techniques could support new and more effective means of monitoring and analysing the health of dams accompanying actual dam surveillance systems.

3.1.6. Monitoring using SBAS

The Small BAseline Subset (SBAS) technique is a DInSAR approach that detects and analyses Earth's surface deformation over time (Berardino et al., 2007). It relies on the utilization of a large number of SAR acquisitions and implements a simple combination of multi-look DInSAR interferograms, which are computed from these data and then used to generate mean deformation velocity maps and time-series (Berardino et al., 2002; Lanari et al., 2007).

A deformation study has been conducted by Voege et al. (2012), who investigated the viability of applying satellite-based SAR interferometry to monitor deformations at dams and reservoir slopes. The area of interest is the Svartevatn Dam in southwest Norway, an earth-rockfill dam. A set of 76 (descending mode) and 59 (ascending mode) ERS-1/2 scenes covering 1992–2000 had been used. The displacement estimation has been carried out using the Small Baseline Subset (SBAS) algorithm with the GSAR software. Results show that maximum displacement velocity observed near the centre of the crest and the subsidence near the crest is getting weaker between 1995 and 2000 compared to earlier. The authors concluded that the historic SAR data could be used to monitor deformations at the dam with a resolution similar to geodetic measurements. Also, from the results, it is clear that SAR interferometry allows the mapping of very local displacements at the dam and displacements on a regional scale around the reservoir. A similar study using SBAS has been conducted for Masjed Soleiman Dam, a hydropower dam situated in South West of Iran (Aminjafari, 2017). 19 ASAR images of ENVISAT sensor acquired from August 22, 2003 to May 7, 2010 were used for the InSAR analysis. Results from InSAR processing showed a maximum velocity of 11 mm/y. They concluded that the middle part of dam moves faster than other parts (3.5 mm/y) and the displacement rate at lateral sides has declined to 1 mm/y. The deformations derived from InSAR have been used as an initial condition in Finite Element Modelling (FEM). The authors compared these results with geodetic surveying operations at four points on the dam, and it shows a good agreement between the results. In both these studies, the authors compared the results from SBAS with geodetic measurements and proved that SBAS is a successful tool to monitor the deformation of dams. Later, Darvishi et al. (2020) found out the hydrology-induced ground deformation surrounding Lake Mead as well as the displacement of Hoover Dam. Lake Mead provides water and hydropower to millions of people in Las Vegas, Los Angeles, and the southern United States. Rising temperatures, increased evaporation, and decreased precipitation have significantly reduced water levels in recent years, probably altering the surrounding groundwater and surface as well. SBAS technique was used for the reservoir, which included 138 SAR data from ERS1/2, Envisat, ALOS PALSAR, and Sentinel-1A/B, covering 1995 to 2019. Then, they applied the SBAS approach with descending and ascending modes of Sentinel-1A/B imageries for the dam study from 2014 to 2019. Around the lake, there observed two primary deformation patterns linked to water level fluctuations. ERS and Sentinel-1A data first revealed a ground deformation that began as a subsidence pattern in 1995 and progressively transformed to uplift until 2019. Second, the relationship between deformation and changes in water levels has shifted from negative to positive, with a changeover point around March 2008. So, until March 2008, the ground reacted to water fluctuations in the reservoir, but after that, it no longer played a significant role in the deformation around the lake.

3.1.7. Monitoring using multiple InSAR techniques

The cross-correlation of data from several sensors in order to maximize their potential and efficiency is a fascinating element of sensor/data integration. A few of the instances are mentioned in this study. Alba et al. (2008) used the GBInSAR technique to measure the daily deformations of the Cancano Dam (Alta Valtellina, Italy), an arch-gravity dam. And, a new radar system called Image by Interferometric Survey (IBIS) was introduced, to monitor the dynamic and static response of many points on a structure with a displacement sensitivity of up to 10–20 μm (Alba et al., 2008). IBIS is a ground-based microwave interferometer with active imaging capabilities that are used to monitor illuminated objects movement across long distances (Berardini et al., 2007, Qiu et al., 2016). In this work, the IBIS sensor was used to monitor the displacement of several points on a large structure along with the GBInSAR. For validation purposes, the displacement measurements were compared to measurements acquired by a coordinate meter mounted on the dam's core section; a good agreement between novel radar techniques and well-tested monitoring sensors was attained. A similar study has been conducted by Qui et al. (2016), where they tested the GBInSAR technique's capacity to measure the deformation of Hegeyan Dam, built on Qing River, Hubei Province, China. The structure was subjected to constant monitoring during the year 2013. The obtained displacement map has been compared with vertical monitoring results such as IBIS, a ground-based microwave interferometer with active imaging capabilities that are used to monitor illuminated object's movement across long distances. IBIS-L is new radar that uses microwave interferometry to operate (Qiu et al., 2016). The monitoring precision of GBInSAR technology allows it to be used in deformation monitoring for major projects like dams. Mascolo et al. (2014) and Nico et al. (2015) used GBInSAR with a space-borne ADInSAR analysis of Cosmo-SkyMed data to examine horizontal and vertical displacements of ancient embankment dams. The former was used to measure horizontal displacement vectors, whereas the latter was used to measure vertical displacement vectors. Gama et al. (2019) combined ADInSAR techniques such as SBAS and PSI to detect and monitor the surface motions in the Germano iron mining complex region (Mariana, Brazil), after the collapse of the Fundao tailing dam that occurred on November 5, 2015. The analysis was carried out using 46 TerraSAR-X images, yielding the following results: techniques were used to assess the stability conditions of the Germano mining assets, particularly the main structures of the Germano Dam and the detection of small settlements in the mining tailings storage, indicating that these may be important components for open-pit mine risk management.

Another study has been carried out by Praveen et al. (2021) to monitor the hill slopes during excavations in a concrete gravity dam site of the Punatsangchhu River in western Bhutan. The Image By Interferometric Survey–Frequency Modulated (IBIS–FM) Radar System, a GBInSAR designed to remotely measure slow displacements with an accuracy of a tenth of a mm, was installed during July 2018 at the Punatsangchhu Hydroelectric project's left bank to monitor the displacement of the unstable right bank. The method entails obtaining a radar image of the ground surface, which is then compared to images acquired at various time periods to determine relative ground displacement. The hill slope displacement is analysed using IBIS–FM method, which monitors point locations as well as areas and assigns distinct threshold values for timely alarms. This real-time monitoring was successful in detecting the reactivation of the landslide. As a result, this study demonstrates the effectiveness of the IBIS-FM radar in monitoring slope instability in near real-time with sub-mm accuracy.

4. A few site-specific case studies

Deformation study was conducted over three dams of south India: Idamalayar Dam, Malankara Dam, and Upper Sholayar Dam using 23 Sentinel-1A radar images—acquired in Stripmap mode between 21st February 2016 and 3rd June 2017 at a spatial resolution of 22 m using PSI and ENVI SARscape software. PSI results are shown as velocity measurements: negative values indicate deformation away from the satellite while positive values indicate deformation towards the satellite.

Idamalayar Dam is a multipurpose concrete gravity dam located in the Ernakulam District in Kerala, India (Fig. 4). The structure was completed in 1985 and has a length of 373 m and height of 102.8 m. The dam creates a 28.3 km^2 reservoir that was used for power generation and a proposed irrigation program. 112 PS points were obtained on the Idamalayar Dam, of which 103 are located within the middle, tallest portion of the dam (Fig. 4A–B). Deformation rates across the concrete structure range from 7 mm/y to -10 mm/y (Fig. 4D shows −10 mm/y PS point), with the greatest velocities measured along the dam flanks. A Kriging interpolation of the PS velocity (Fig. 4C) demarks the reservoir side of Idamalayar Dam as undergoing slight subsidence (-2 mm/y contour located north of the east flank) and south side as relatively stable (0 mm/y contour located south of the structure). Although three PS points along the dam flanks measure cm-scale movements, most of the data show the dam is relatively stable. 109 PS points measure velocities at less than 5 mm/y in either direction. The Kriging interpolation also indicates the dam is moving at an average velocity of -1 mm/y (the -1 mm/y contour line is parallel to the length of the dam). PS points such as that shown in Fig. 4D should not be dismissed. However, as this displacement time-series implies there may be a localized structural health issue (e.g., Kang et al., 2017).

Malankara Dam is a gravity dam, built in 1994, across the Thodupuzha river with a height of 42 m and length of 460 m in Kerala, India (Fig. 5). The dam was built to provide irrigation to the region, but is also a tourist destination because it is open year-round and its 153.5 km^2 artificial lake supports boating and fishing activities. 111 PS points are obtained within the Malankara Dam region (Fig. 5A): 77 PS points on the gravity dam itself and 34 PS points within the building complex on the property to the northwest. 107 PS points exhibit downward deformation; the remaining four PS points measure ground movements between 0 mm/y and 2 mm/y. The

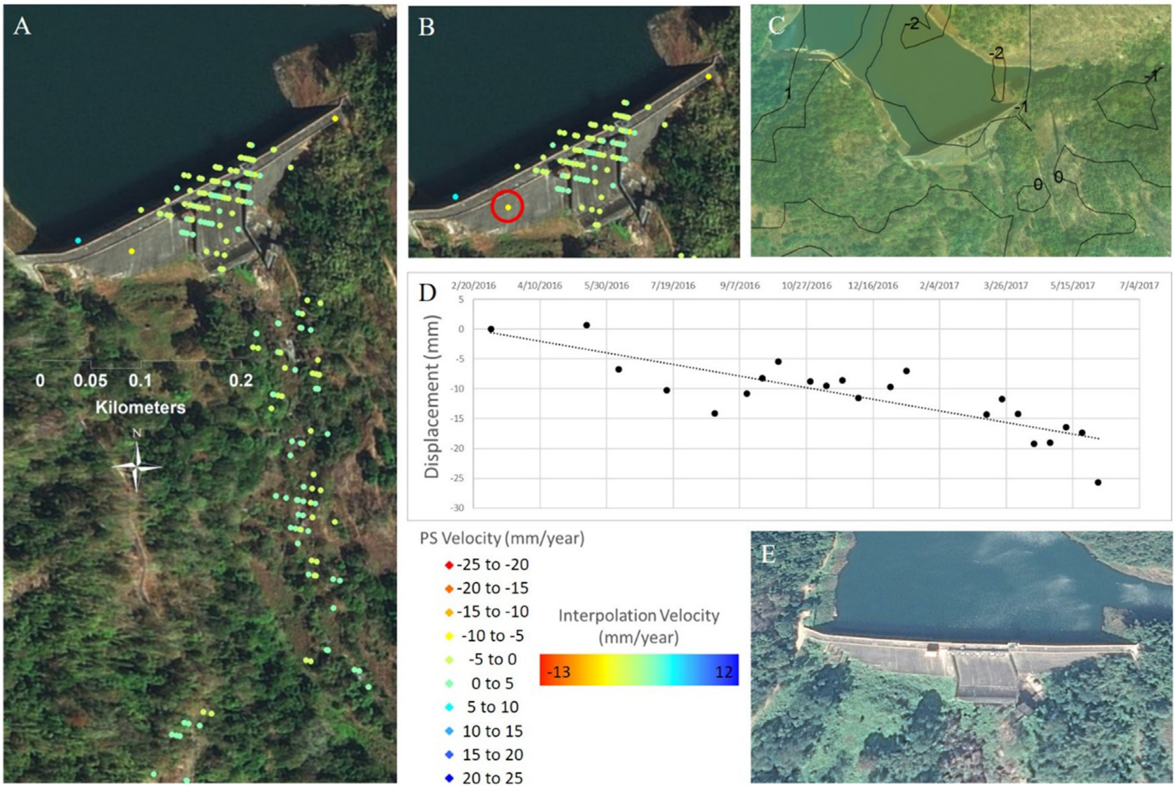

Fig. 4. Idamalayar Dam. (A) Results from PSI technique. PS are individual points measuring velocity (mm/year) ranging from -25 mm/year (red) to 25 mm/year (blue). (B) Close-up of PS points on Idamalayar Dam. (C) Kriging interpolation of PSI results (contour interval = 1 mm/year). Interpolation velocity ranges from -13 mm/year (red) to 12 mm/year (blue). (D) Displacement-time series of PS point in red circle from Fig. 4(B). (E) Google Earth view of the Idamalayar Dam.

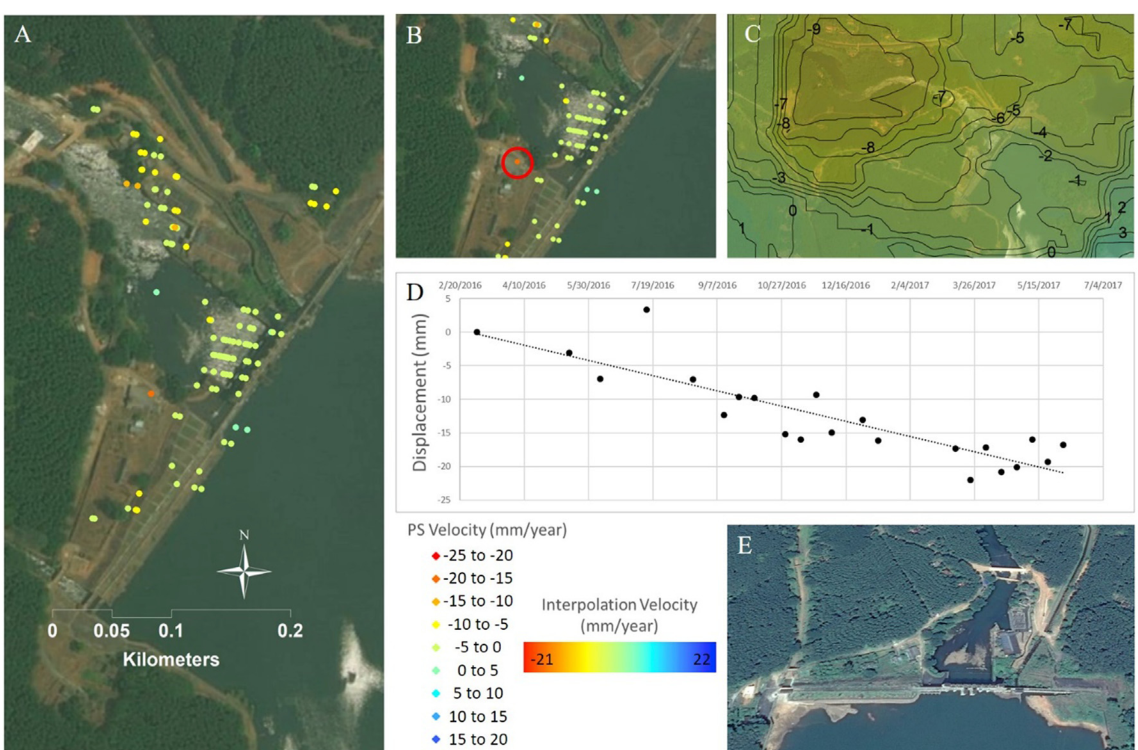

Fig. 5. Malankara Dam. (A) Results from PSI technique. PS are individual points measuring velocity (mm/year) ranging from -25 mm/year (red) to 25 mm/year (blue). (B) Close-up of PS points on Malankara Dam. (C) Kriging interpolation of PSI results (contour interval = 1 mm/year). Interpolation velocity ranges from -21 mm/year (red) to 22 mm/year (blue). (D) Displacement-time series of PS point in red circle from (B). (E) Google Earth view of the Malankara Dam.

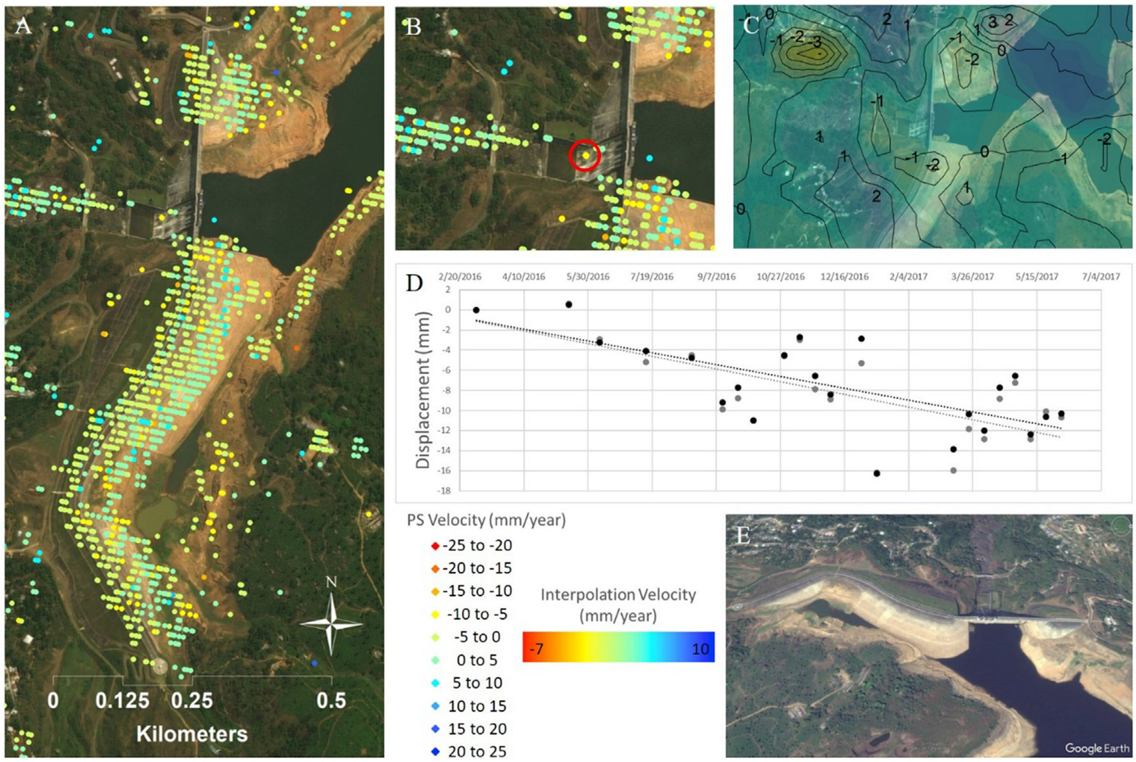

Fig. 6. Upper Sholayar Dam. (A) Results from PSI technique. PS are individual points measuring velocity (mm/y)ranging from -25 mm/y (red) to 25 mm/y (blue). (B) Close-up of PS points on Upper Sholayar Dam. (C) Kriging interpolation of PSI results (contour interval = 1 mm/y). Interpolation velocity ranges from -7 mm/y (red) to 10 mm/y (blue). (D) Displacement-time series of two PS points in red circle from (B). (E) Google Earth view of Upper Sholayar Dam.

Malankara Dam is experiencing variable rates of subsidence. The 53 PS points located on the middle crest and berm portion of the dam indicate an average velocity of -3 mm/y. The southwest embankment is moving at a velocity as high as -16 mm/y (red circle in Fig. 5B; D) and the north embankment is moving between -5 mm/y and -9 mm/y. Fig. 5C provides the Kriging interpolation of the PS velocity, which shows the entire Malankara Dam lies between the -2 mm/y and -7 mm/y contours, with subsidence rates increasing towards the northwest. Presence of regional subsidence—not exclusively on Malankara Dam—may mean the structure is not failing. Instead, there may be geological factors (e.g., sediment compaction or tectonic activity) or other anthropogenic factors (e.g., subsurface groundwater extraction) causing apparent subsidence near Malankara Dam.

Upper Sholayar Dam is a concrete masonry dam built in 1965 to aid in the generation of hydroelectric power (Fig. 6). The dam has a height of 66 m, a length of 430.6 m, and creates a 71.3 km^2 reservoir. Since reservoir levels were relatively low in 2016 and 2017, ~918 PS points were identified on the Upper Sholayar Dam, mostly on the two large embankments flanking the concrete dam (Fig. 6A). The entire structure is experiencing subsidence. Velocity values on both the north and south embankments range between 5 mm/y and -10 mm/y (Fig. 6A–C), and deformation on the concrete structure is as high as -7 mm/y (Fig. 6A–D). Kriging interpolation shows small subsidence bowls on each embankment and also due west of the concrete dam. The most dramatic subsidence bowl (northwest corner of Fig. 6C) covers a small neighbourhood in Sholayar Dam City. Presence of these subsidence bowls indicating no background deformation in the surrounding area, unlike around Malankara Dam, also implies the occurrence of subsidence on the Upper Sholayar Dam.

5. Discussion and conclusion

With all these prominent advantages mentioned, InSAR techniques also have limitations, especially for displacement monitoring. One of the limitations of employing InSAR for dam monitoring is that the side slopes is foreshortened, resulting in an underestimate of the deformation magnitude. Images of objects in SAR images are projected to the radar beam's LoS. As a result, depending on the SAR geometry and slope aspect, the distances between dam slopes and crests appear to be a factor shorter than their real values (Husseinawi et al., 2018). Other limitation of the InSAR based monitoring is that the maximum detectable deformation is half its wavelength. If the deformation rate exceeds this value at a site the images would be incoherent. Therefore, the InSAR based monitoring is suitable for small movements and not for large deformations. Furthermore, another limitation is that the location of the PS points cannot be pre-determined before processing the images.

But, monitoring the deformation of large dams using SAR data is a topic of great relevance. Continuous monitoring of dams plays an important role in securing their structural integrity and maintaining their longevity (Mazanti et al., 2015). In recent years, remote sensing techniques have been used to monitor dams. Comparing with other traditional methods, InSAR technology is favoured for its capability to provide monitoring data all-time, with all-weather conditions and particularly for wide-areas with high accuracy (Curlander and McDonough, 1991; Mazzanti et al., 2015). InSAR techniques are suggested for monitoring dam and surrounding slope movements because of their great sensitivity, which allows them to properly assess the effect of diverse deformation sources such as water pressure in dammed reservoirs. It is feasible to identify dam movements clearly, both continuously and monthly, using adequate datasets in terms of temporal and spatial resolution as well as the orientation of the satellite LoS towards the dam (Lazecky et al., 2015). This paper has presented a literature review on the case studies on deformation monitoring of dams using InSAR technologies, mostly using PSInSAR, GBInSAR, MTInSAR, DInSAR, QPSInSAR, and SBAS techniques. Some authors compared the results with geodetic measurements while others compared deformations obtained from InSAR to the deformation obtained with other sensors like GPS measurements, statistical comparison, coordinate meter, and pendulum monitoring.

PSInSAR study of three dams from southern India reveals a relatively stable Idamalayar Dam that may have localized deterioration, regional instability around Malankara Dam, and subsidence of Upper Sholayar Dam embankments. A high density of PS points proximal to assets allows agencies to utilize this technology for supplementation of in-situ instruments. Therefore, InSAR can be used as a cost-effective method for long-term dam monitoring together with in-situ instrumentation to understand structural and regional stability.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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