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High-Precision Dam Deformation Monitoring Using Advanced InSAR Techniques: A Review

Sachi Anand*, Mulk Raj Anand, Ashutosh Narayan Srivastava, Saket Rusia

Department of Civil Engineering, Rajkiya Engineering College Mainpuri, Uttar Pradesh, India.
B. Tech Student, sachianand.2304@gmail.com; Assistant Professor, mulkraj53@gmail.com;
Assistant Professor, ashutoshrivastv@gmail.com; Assistant Professor, saket@recmainpuri.in

** Correspondence: mulkraj53@gmail.com*

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Abstract Interferometric Synthetic Aperture Radar (InSAR) has become a key technology for high-precision dam deformation monitoring, offering millimeter-level accuracy, broad spatial coverage, and all-weather operability. This review systematically synthesizes advancements in several InSAR techniques, including DInSAR, PS-InSAR, SBAS-InSAR, MT-InSAR, and GB-SAR, and illustrates their applications across various dam types through case studies of the Xiaolangdi, Banqiao, Pertusillo, Shuibuya, La Viñuela, Liuduzhai, and Enguri dams. These studies highlight InSAR's effectiveness in detecting crest deformation, slope instability, settlement patterns, and hydrostatic-thermal responses, with results validated against GNSS and levelling benchmarks. Despite challenges such as atmospheric noise and decorrelation, integrating InSAR with numerical modeling and multi-sensor data fusion has significantly improved diagnostic reliability. With the advent of new satellite missions and artificial intelligence-based time-series analysis, InSAR is poised to become a cornerstone of modern dam safety frameworks, enabling proactive risk management through near-real-time deformation intelligence.
Keywords: InSAR; Dam deformation monitoring; Advanced InSAR techniques; Safety assessment

1. Introduction

Dams serve as crucial elements of the national water infrastructure, facilitating hydropower generation, irrigation, flood mitigation, and municipal water provision. Guaranteeing their structural soundness is of utmost importance, as deformation, whether induced by hydrostatic loading, thermal variations, material deterioration, or seepage processes, can develop gradually and pose a threat to long-term stability. Conventional monitoring methods, such as leveling, plumb lines, and total stations, offer high precision but are spatially discrete and temporally restricted. Consequently, they are inadequate for comprehensively capturing the complexity of deformation patterns across extensive dam surfaces, abutments, and surrounding slopes (Pang et al., 2023).

Interferometric Synthetic Aperture Radar (InSAR) has emerged as a highly competent alternative due to its capacity to measure millimeter-scale displacements over large areas, independent of lighting or meteorological conditions. Recent research has demonstrated its efficacy across various dam types. Persistent Scatterer InSAR (PS-InSAR) analysis at the Xiaolangdi Dam identified crest displacements ranging from -18 to -36 mm/yr, revealing a distinct correlation with reservoir-level fluctuations (Wang et al., 2023). Small BAseline Subset InSAR (SBAS-InSAR) applied to the Banqiao Dam detected both minor, stable dam-body movements and significant subsidence in adjacent floodplain areas, with the results verified through BeiDou Global Navigation Satellite System (GNSS) measurements (Pang et al., 2023). Similarly, L-band InSAR successfully captured over 100 mm of settlement at the Shuibuya Concrete-Faced Rockfill Dam (CFRD), showing strong consistency with leveling observations (Zhou et al., 2016).

In addition to displacement measurements, InSAR also aids in comprehending deformation mechanisms. At the Liuduzhai Dam, InSAR time-series analysis revealed substantial pre-reinforcement consolidation caused by seepage, followed by a notable reduction in deformation after the installation of a cut-off wall (Liu et al., 2023). At the Enguri arch dam, a combined Ground-Based Synthetic Aperture Radar (GB-SAR) and GNSS framework effectively resolved long-term phase-unwrapping inconsistencies, enhancing the accuracy of continuous monitoring (Rebmeister et al., 2025).

Today, the studies demonstrate the increasing significance of InSAR as an essential tool for dam safety assessment. It can capture subtle deformation trends, diagnose underlying mechanisms, and complement traditional monitoring systems. This review assesses key InSAR methodologies, corresponding satellite missions, representative case studies, and emerging technological directions that will influence the future of dam deformation monitoring.

2. Overview of InSAR Techniques for Dam Deformation Monitoring

In response to the escalating demand for reliable and spatially comprehensive deformation measurements, Interferometric Synthetic Aperture Radar (InSAR) has emerged as one of the most influential technologies in contemporary dam monitoring. InSAR operates by comparing the phase information of radar signals obtained from repeated satellite passes to detect subtle alterations in surface elevation or displacement. Owing to the ability of these radar signals to penetrate atmospheric conditions and function independently of sunlight, InSAR offers an uninterrupted monitoring capability that traditional ground-based instruments are unable to achieve.

Diverse variants of InSAR have been developed to address the distinct structural behaviors of dams and the environmental challenges they face. Differential InSAR (DInSAR) represents the most fundamental form and is capable of detecting substantial deformations occurring between two acquisition dates. Nevertheless, its susceptibility to atmospheric noise and temporal decorrelation restricts its reliability on vegetated or highly dynamic dam surfaces (Aswathi et al., 2022). More advanced time-series techniques have become the norm. Permanent Scatterer InSAR (PS-InSAR) focuses on stable, highly reflective points, commonly found on concrete faces, spillways, and abutments, facilitating long-term, millimeter-level tracking of structural movement. This method has proven to be particularly effective at Xiaolangdi Dam, where persistent scatterers enabled detailed mapping of crest displacement patterns (Wang et al., 2023).

For earth-fill and rockfill dams, where surface roughness and vegetation often reduce coherence, the Small Baseline Subset (SBAS-InSAR) offers a more robust solution. By forming interferograms solely from image pairs with minimal temporal and geometric separations, the SBAS maintains coherence and allows for broader coverage of earthen structures. Its efficacy was demonstrated at Banqiao Dam, where SBAS successfully distinguished between small dam-body movement and larger external subsidence zones (Pang et al., 2023).

An extension of these methods, Multi-Temporal InSAR (MT-InSAR) integrates both PS and SBAS concepts to construct long-term deformation histories from multiple satellite missions. This approach was crucial in reconstructing the 26-year deformation behavior of the La Viñuela Dam, revealing its long-term consolidation trends (Ruiz-Armenteros et al., 2018). MT-InSAR is increasingly valued for its capacity to merge archival datasets and modern acquisitions into continuous structural records.While satellite-based systems provide regional coverage, Ground-Based SAR (GB-SAR) offers extremely high temporal resolution for the focused monitoring of critical sections of a dam. GB-SAR systems can acquire images every few minutes, enabling near-real-time deformation tracking during extreme loading conditions and suspected instability events. The precision of this method was further enhanced in (Rebmeister et al., 2025), where the integration of GB-SAR with GNSS measurements corrected unwrapping inconsistencies and improved long-term accuracy.

Collectively, these techniques form a comprehensive set of tools, each suitable for a specific combination of dam type, surface conditions, monitoring objectives, and time constraints. Their combined development represents a significant transition from point-based monitoring to fully spatial, time-resolved deformation assessment, which is an essential advancement for ensuring dam safety in increasingly uncertain environmental conditions. The general processing framework of the PS-InSAR technique, encompassing image co-registration, interferogram generation, phase filtering, permanent scatterer selection, atmospheric correction, and deformation time-series estimation, is illustrated in Figure 1.

3. Sar Satellite Missions Used in Dam Deformation Studies

The performance of InSAR-based dam monitoring is significantly influenced by the characteristics of the satellite missions employed, especially the radar wavelength, revisit frequency, incidence angle, and spatial resolution. Over the past three decades, a diverse constellation of SAR satellites has facilitated the high-precision monitoring of dams globally, each offering distinct advantages based on its sensor specifications.

C-band missions, such as Sentinel-1A/B, are the most extensively utilized for operational dam monitoring. This is due to their free accessibility, 6-12-day revisit cycle, and strong coherence across diverse terrain conditions. Sentinel-1 data have underpinned numerous deformation studies. For instance, PS-InSAR analysis was conducted at a certain location (Wang et al., 2023) using 62 ascending-orbit images from 2020 to 2022, and SBAS monitoring of Banqiao Dam was carried out using 80 images acquired between 2020 and 2022. These datasets enabled the detailed extraction of time-series, revealing crest deformation, slope instability, and time-lagged hydro-mechanical responses.

L-band missions, like ALOS-1 PALSAR, exhibit superior penetration through vegetation and rough earth-fill surfaces because of their longer wavelengths. This renders them particularly effective for monitoring large vegetated or rockfill dams. For example, the application of L-band SBAS to the Shuibuya CFRD achieved high coherence and successfully captured cumulative settlements exceeding 100 mm. Validation against levelling indicated a strong correlation of 0.93. Similarly, ALOS-1 was employed in the pre-reinforcement monitoring of the Liuduzhai Dam, where it detected significant consolidation-driven deformation of up to -22.5 mm/yr.

X-band missions, including COSMO-SkyMed and TerraSAR-X, provide higher spatial resolutions (as fine as 1-3 m) and shorter revisit intervals. This makes them ideal for detecting subtle short-wavelength deformations and capturing the detailed structural responses of concrete dams. At the Pertusillo Dam, X-band data from COSMO-SkyMed and TerraSAR-X were integrated with L-band ALOS observations, enabling the detection of seasonal horizontal displacements (with an amplitude of approximately 10 mm) and the separation of hydrostatic and thermal deformation components.

Legacy missions, ERS-1/2 and Envisat, laid the foundation for long-term monitoring through MT-InSAR. These multi-decade archives enabled the reconstruction of historical deformation trends, as exemplified by the La Viñuela Dam study, which generated a 26-year deformation record using ERS, Envisat, and Sentinel-1 datasets.

Across these missions, the diversity of radar wavelengths—C-band (5.6 cm), L-band (23.6 cm), and X-band (3.1 cm)—offers complementary sensitivity to different dam materials and surface conditions of the dams. Multi-mission integration has become increasingly prevalent, enhancing the temporal density, coherence stability, and overall robustness of deformation estimates. Collectively, these satellite platforms form a comprehensive observational framework that supports high-precision, continuous dam safety assessments across various dam types and environmental conditions.

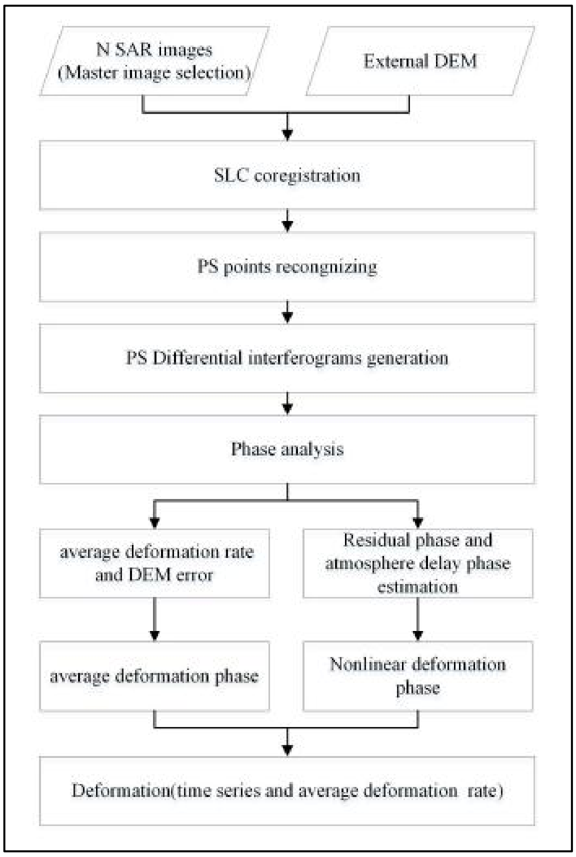

Figure 1. Flow chart of ps-insar technology (revised from Wang et al., 2023)..

4. Applications of Insar in Dam Monitoring

The utilization of Interferometric Synthetic Aperture Radar (InSAR) in dam safety assessment encompasses a broad range of aspects related to structural, hydrological, and geotechnical behaviors. Due to its millimeter-level sensitivity and dense spatial coverage, InSAR empowers engineers to detect and analyze deformation patterns that are often overlooked by traditional point sensors. One of the most notable applications is the monitoring of dam crest deformation. Even minor displacements at the crest can signify stress redistribution, the effects of hydrostatic loading, or long-term material deformation. Persistent Scatterer InSAR (PS-InSAR) analysis of the Xiaolangdi Dam identified significant crest deformation ranging from -18 to -36 mm/yr, with deformation patterns being closely correlated with seasonal reservoir-level fluctuations. These results emphasize InSAR's ability to uncover periodic hydro-mechanical responses that are undetectable by sparse geodetic networks.

InSAR is also highly effective in monitoring the stability of slopes and abutments, particularly for earth-fill and clay-core dams. In these dams, percolation, erosion, and consolidation can lead to heterogeneous movements. Small BAseline Subset InSAR (SBAS-InSAR) applied to the Banqiao Dam revealed stable dam body motions (-1 to -4 mm/yr), but significant subsidence hotspots exceeding -25 mm/yr were detected in adjacent river channels and slopes. These findings illustrate the value of InSAR in distinguishing between the structural deformation of the dam itself and broader geomorphic instabilities in the surrounding area. Another major application is the detection of settlements in high rockfill and concrete-faced rockfill dams (CFRDs). Due to their large heights and complex material behaviors, CFRDs often experience substantial consolidation during the early stages of operation. L-band InSAR monitoring of the Shuibuya Dam captured cumulative settlements exceeding 100 mm, with distinct spatial patterns indicating larger deformations in the upper fill zones. These results were in good agreement with levelling measurements, with a correlation coefficient of 0.93. Such large-scale settlement mapping is nearly unachievable using only conventional instrumentation.

InSAR time-series data also serves as a diagnostic instrument for evaluating the effectiveness of rehabilitation and structural upgrades. At the Liuduzhai Dam, pre-reinforcement monitoring detected severe consolidation-driven deformation with velocities reaching up to -22.5 mm/yr. In contrast, post-reinforcement PS-InSAR observations showed significantly reduced deformation rates (-0.4 to -1.2 mm/yr) and a transition from cumulative to purely seasonal elastic behavior. This clear pre-and post-comparison highlights the usefulness of InSAR in verifying the success of seepage control measures and cutoff wall installations.

For concrete arch dams, where deformation is typically dominated by hydrostatic and thermal effects rather than settlement, InSAR enables the separation of these multi-physical influences. Multi-sensor PS-InSAR applied to the Pertusillo Dam identified deformation characterized by horizontal seasonal oscillations (~10 mm) associated with temperature-driven expansion and reservoir level variability. By integrating InSAR with hydrostatic-thermal modelling, researchers were able to distinguish reversible seasonal movements from potential long-term ageing effects, which are crucial for high-arch dam safety assessments.

Finally, InSAR applications have extended to data fusion and hybrid monitoring systems, especially in combination with Ground-Based Synthetic Aperture Radar (GB-SAR) and Global Navigation Satellite System (GNSS). At the Enguri Dam, the integration of GNSS with high-frequency GB-SAR corrected long-gap phase-unwrapping errors and aligned relative measurements to absolute displacements, reducing model offsets from 8.3 mm to 0.4 mm. This demonstrates the emerging ability of InSAR to complement and enhance traditional monitoring networks.

Overall, InSAR enables comprehensive structural assessments by capturing dam crest deformation, slope instability, settlement trends, hydrostatic-thermal cycles, and the performance of rehabilitation measures. As such, it is one of the most versatile and powerful tools for modern dam safety monitoring.

5. Recent Case Studies from Literature

Several recent InSAR-based investigations have provided compelling evidence of the reliability and diagnostic value of this technique for dam deformation monitoring. The following case studies covering concrete, rockfill, earth-fill, and arch dams illustrate the breadth of applications and diversity of deformation behaviors captured by modern InSAR techniques.

5.1 Xiaolangdi Dam, China- PS-InSAR (Sentinel-1)

PS-InSAR monitoring of the Xiaolangdi rockfill dam revealed significant crest deformation ranging from -18 to -36 mm/yr, with the highest displacements concentrated near the central crest region. Time-series analysis demonstrated a clear seasonal pattern driven by reservoir-level fluctuations, with downstream movement during high-water periods and a partial rebound as water levels receded. These results highlight the sensitivity of PS-InSAR to hydro-mechanical loading and its capability to capture subtle seasonal kinematics that traditional geodetic systems may overlook.

The spatial distribution of deformation across the Xiaolangdi Dam surface is presented in Figure 2 where PS-InSAR results indicate maximum displacement concentrated at the dam crest, reaching deformation rates between -18 and -36 mm/yr, while the abutment and slope regions remain relatively stable.

A clear relationship between seasonal deformation and reservoir water-level variation is observed in Figure 3, where downstream movement increases during high-water periods and partially recovers during drawdown, highlighting the hydro-mechanical response of the dam structure.

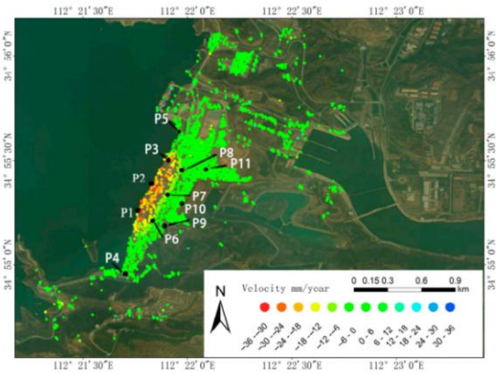

Figure 2. Deformation Rate Map of Xiaolangdi Dam(revised from Wang et al., 2023).

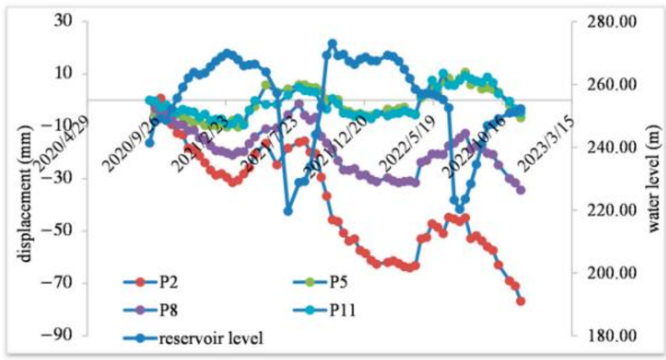

Figure 3. Deformation Time Series vs Reservoir Water Level(revised from Wang et al., 2023).

5.2 Banqiao Dam, China- SBAS-InSAR (Sentinel-1) + GNSS Validation

SBAS-InSAR applied to the Banqiao clay-core dam captured small but consistent dam-body displacements (approximately -1 to -4 mm/yr) while simultaneously identifying severe subsidence hotspots exceeding -25 mm/yr in the adjacent riverbank and floodplain areas. The deformation patterns showed a ~35-day lag behind the reservoir-level changes, indicating a delayed hydrological response. Validation with BeiDou GNSS stations produced an RMSE of ~1.1 mm, confirming the high accuracy of the SBAS for monitoring earth-fill dams and surrounding geomorphic features.

The SBAS-InSAR-derived subsidence pattern for the Banqiao Dam and its surrounding environment is illustrated in Figure 4, showing relatively small deformation within the dam body (-1 to -4 mm/yr) but significant subsidence in adjacent slopes and floodplain areas reaching up to -27 mm/yr.

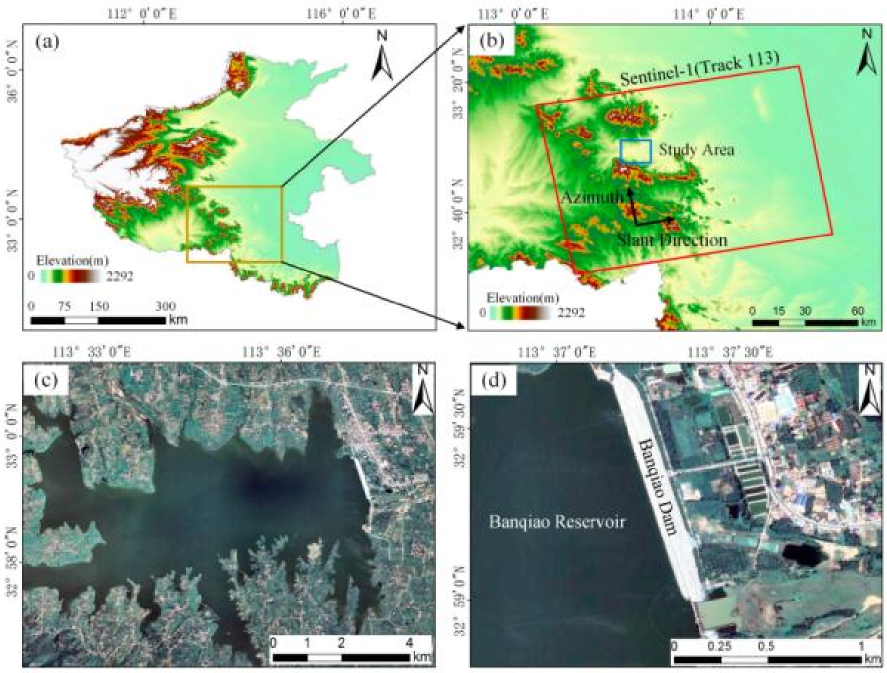

Figure 4. Subsidence Map of Banqiao Dam and Surrounding Area(revised from Pang et al., 2023)

5.3 Shuibuya Dam, China- L-Band InSAR for High CFRDs

Shuibuya, the world's highest concrete-faced rockfill dam (233.5 m), was monitored using L-band ALOS PALSAR imagery, which maintains high coherence over rockfill surfaces. The analysis recorded cumulative settlements exceeding 100 mm, with deformation concentrated in the upper rockfill zones, where material compaction and creep are dominant. A comparison with 11 levelling stations showed strong agreement (correlation 0.93), demonstrating the superior performance of the L-band for tall, rough-surfaced dams undergoing long-term settlement.

The long-term settlement behaviour of the Shuibuya concrete-faced rockfill dam is shown in Figure 5, where L-band InSAR measurements reveal cumulative settlement exceeding 100 mm, with deformation primarily concentrated in the upper and middle rockfill zones.

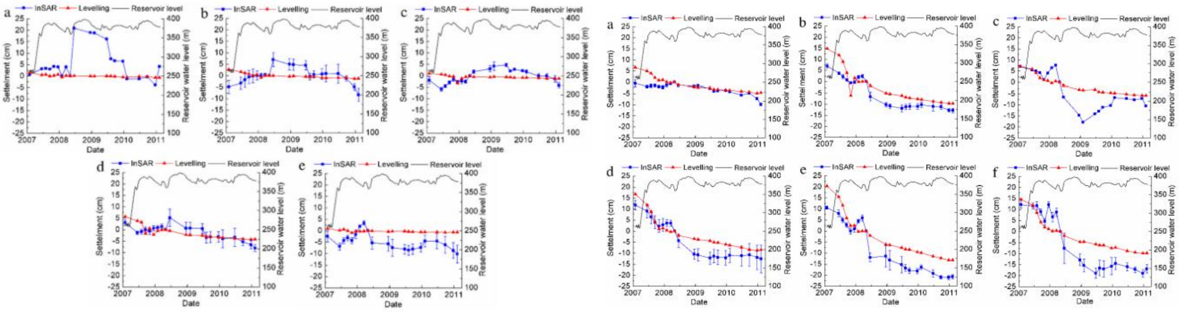

Figure 5. Shuibuya Settlement Time Series (>100 mm)(revised from Zhou et al., 2016)

5.4 Pertusillo Dam, Italy- Multi-Sensor InSAR + Hydro-Thermal Modelling

A multi-frequency, multi-sensor InSAR analysis combining COSMO-SkyMed (X-band), TerraSAR-X (X-band), and ALOS (L-band) provided detailed deformation insights into the Pertusillo arch dam. The dam exhibited seasonal oscillations of approximately 10 mm, primarily dominated by thermal expansion and hydrostatic pressure variations. By integrating InSAR observations with hydrostatic-thermal-time (HST/HTT) models, this study successfully distinguished reversible seasonal behavior from potential long-term structural aging, demonstrating the potential of model-assisted InSAR for advanced dam diagnostics.

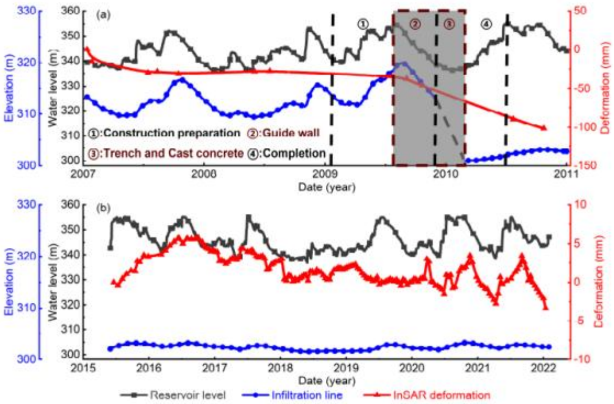

Figure 6. Pre- and Post-Reinforcement Deformation at Liuduzhai Dam(revised from Liu et al., 2023)

5.5 Liuduzhai Dam, China- Pre- and Post-Reinforcement Assessment Using InSAR

A comprehensive analysis integrating Small BAseline Subset (SBAS) InSAR technique using ALOS-1 data and Persistent Scatterer InSAR (PS-InSAR) technique with Sentinel-1 data for the Liuduzhai Dam offered a valuable pre-post comparison of the effectiveness of its rehabilitation. Prior to the reinforcement work, the dam underwent severe settlement, with deformation rates reaching up to -22.5 mm/yr, primarily induced by seepage-triggered consolidation. Subsequent to the installation of a plastic concrete cut-off wall, the deformation rates declined to the range of -0.4 to -1.2 mm/yr. Moreover, the deformation behavior shifted from cumulative plastic settlement to minor, reversible elastic movement regulated by reservoir water level fluctuations. This case study underscores the potential of InSAR technology in assessing the success of remediation efforts and diagnosing seepage mechanisms.

The efficacy of the reinforcement measures implemented at the Liuduzhai Dam is clearly manifested in Figure 6. The deformation rates decreased from a peak of -22.5 mm/yr before the rehabilitation to less than -1.2 mm/yr after the installation of the cut-off wall, signifying a transition from consolidation-driven settlement to stable elastic behavior.

5.6 Enguri Dam, Georgia-GNSS-Assisted GB-SAR for Absolute Accuracy

At the 271.5 m high Enguri arch dam, a hybrid monitoring system integrating GB-SAR with GNSS was deployed to overcome the long-term phase-unwrapping errors. Following a multi-month acquisition gap, GNSSguided correction reduced displacement map offsets from -8.3 mm to 0.4 mm relative to the numerical model, demonstrating that fusing absolute (GNSS) and relative (GB-SAR) measurements significantly improves long-term reliability. This represents a major advancement in next-generation dam-safety monitoring frameworks.

6. Advantages and Limitations of Insar Techniques

InSAR technology offers compelling advantages for dam monitoring, including wide-area, high-density coverage with millimeter-level accuracy, weather-independent operation, and the ability to capture long-term deformation trends—even enabling quantitative assessment of rehabilitation effectiveness. Yet these strengths are accompanied by notable limitations. Atmospheric disturbances, coherence loss over vegetated or rough terrain, and the inherent difficulty of separating vertical from horizontal motion due to line-of-sight measurements can constrain interpretation. Phase unwrapping errors, reduced sensitivity over water surfaces, and reliance on satellite revisit intervals further complicate application. Recognizing both the capabilities and the constraints of InSAR is essential for leveraging its full potential while mitigating its weaknesses through integration with complementary monitoring techniques.

6.1 Advantages

(1) **Wide-Area, High-Density Coverage**
InSAR provides thousands of measurement points across the dam body, abutments, and surrounding terrain, enabling a detailed spatial assessment, unlike traditional point-based tools such as plumb lines or levelling networks.

(2) **Millimetre-Level Accuracy**
Advanced InSAR techniques achieve millimeter-scale precision, as demonstrated at Xiaolangdi, where PS-InSAR detected crest deformation between -18 and -36 mm/yr [], and at Banqiao, where SBAS-InSAR achieved an RMSE of ~1.1 mm when validated with BeiDou GNSS.

(3) **Independence from Weather and Illumination**
Because SAR sensors operate in the microwave spectrum, InSAR remains effective under all weather conditions and during both day and night, ensuring consistent monitoring in remote and cloudy regions.

(4) **Capability to Capture Seasonal, Hydrostatic, and Thermal Behaviour**
InSAR time-series analyses reveal complex interactions, such as reservoir-level-driven deformation, thermal expansion, and long-term material behavior. At the Pertusillo Dam, multi-sensor InSAR identified seasonal horizontal oscillations of approximately 10 mm linked to hydrostatic and thermal loading.

(5) **Long-Term Historical Reconstruction**
MT-InSAR supports multi-decade monitoring by using archival datasets. For La Viñuela Dam, a continuous 26-year deformation record was created using ERS, Envisat, and Sentinel-1 missions, revealing persistent consolidation rates of -4 to -7 mm/yr at the dam.

(6) **Assessment of Rehabilitation Effectiveness**
InSAR can quantitatively assess the effects of structural upgrades. At the Liuduzhai Dam, pre-reinforcement settlement rates of -22.5 mm/yr were reduced to -0.4 to -1.2 mm/yr following the installation of a cut-off wall, clearly demonstrating the success of the intervention.

6.2 Limitations

(1) **Atmospheric and Environmental Noise**
InSAR signals are affected by atmospheric water vapor variations and temperature gradients, which can distort displacement measurements. Several studies, including those conducted at the Enguri Dam, require specialized atmospheric correction procedures to maintain accuracy.

(2) **Coherence Loss in Vegetated or Rough Terrain**
Earth-fill and rock-fill dams often experience coherence degradation due to vegetation, permeable materials, and rough surfaces. L-band SAR (e.g., ALOS) offers improved performance in such environments, as shown in the Shuibuya CFRD study.

(3) **Challenges in Distinguishing Vertical and Horizontal Motion**
Because InSAR primarily measures line-of-sight displacement, separating vertical settlement from horizontal deformation is difficult unless both ascending and descending datasets or numerical models are available for comparison.

(4) **Phase Unwrapping Errors in Long Time-Series**
Gaps in data acquisition or rapid deformations can cause unwrapping inconsistencies. At the Enguri Dam,

such errors were detected once the monitoring system experienced a multi-month data interruption, and GNSS integration was required for correction.

(5) **Limited Sensitivity Over Water and Smooth Surfaces**
SAR coherence is low over water bodies or extremely smooth concrete surfaces, reducing the measurement density in spillways, reservoirs, or newly constructed dam sections.

(6) **Dependence on Satellite Revisit Periods**
Satellites such as Sentinel-1 have revisit intervals of 6-12 days, which may be insufficient for detecting rapid deformation in early warning scenarios, although GB-SAR can supplement in such cases.

7. Future Scope of Insar-Based Dam Monitoring

The rapid evolution of radar remote sensing, numerical modelling, and data fusion techniques is expanding the potential of InSAR in dam safety management. Although current applications have demonstrated high accuracy and broad coverage, several emerging directions are expected to significantly enhance the reliability, temporal resolution, and diagnostic power of InSAR-based monitoring systems.

A major future advancement lies in the integration of multisensor datasets, including InSAR, GNSS, GB-SAR, UAV photogrammetry, and in-situ geotechnical sensors. Studies such as the Enguri Dam investigation have already demonstrated that GNSS-assisted correction can resolve long-term phase-unwrapping ambiguities in GB-SAR time series, reducing displacement offsets from -8.3 mm to 0.4 mm. Such hybrid frameworks are likely to become standard practice, ensuring absolute displacement accuracy while retaining the spatial coverage of InSAR.

Upcoming satellite missions, including NASA-ISRO's NISAR, ALOS-4, and next-generation commercial X-band constellations, are expected to deliver higher temporal frequency, improved radiometric stability, and enhanced coherence over vegetated and rough surfaces. This will substantially benefit earth-fill and rockfill dams, where L-band systems such as ALOS have already proven effective (e.g., Shuibuya CFRD). Continuous multi-band observations will also strengthen the ability to separate the vertical and horizontal displacement components, thereby reducing the geometric ambiguity in the deformation analysis. The future also points toward a deeper integration of InSAR with numerical modelling and geotechnical interpretation. The Liuduzhai Dam study showed how InSAR combined with seepage modelling could identify shifts from consolidation-driven deformation to elastic behavior after rehabilitation. Such approaches could be expanded to incorporate finite element modelling of stress distribution, seepage pathways, and material degradation, enabling predictive hazard assessment rather than solely diagnostic monitoring.

Furthermore, machine learning and AI-based deformation forecasting offer promising avenues for early warning systems. With rich multi-year time-series data available from MT-InSAR (e.g., the 26-year La Viñuela record), data-driven models can be trained to detect anomalies, classify deformation signatures, or predict failure-prone trends before they escalate. AI-assisted classification may also help to automatically differentiate hydrological, thermal, and structural deformation components.

Finally, as InSAR infrastructure moves closer to real-time data processing pipelines, especially through cloud computing and automated workflows, dam operators may soon access near-real-time deformation dashboards integrating satellite, GB-SAR, and GNSS data. Such systems will enable continuous safety evaluation, more frequent risk assessments, and rapid response to abnormal deformation patterns, marking a major shift toward proactive dam health management.

8. Conclusion

Interferometric Synthetic Aperture Radar (InSAR) has emerged as one of the most potent technological advancements in contemporary dam safety monitoring. It provides millimeter-level precision, extensive spatial coverage, and the capacity to capture intricate structural behaviors that traditional point-based instruments frequently fail to detect.

In various types of dams, such as rockfill dams, earth-fill dams, Concrete-Faced Rockfill Dams (CFRD), and arch dams, recent research has consistently shown that InSAR can map crest deformation, settlement patterns, slope instabilities, and reservoir-induced kinematics with high reliability. For example, the Permanent Scatterer InSAR (PS-InSAR) at Xiaolangdi detected significant crest displacements associated with hydro-mechanical loading. Meanwhile, L-band observations at the Shuibuya CFRD successfully reproduced large settlements that are typically only measurable via leveling benchmarks. Furthermore, modern InSAR applications extend beyond deformation detection to encompass interpretation and validation. Long-term Multi-Temporal InSAR (MT-InSAR) reconstructions, like the 26-year record of La Viñuela, reveal slow consolidation trends and material behavior over several decades. Integrated methods that combine InSAR with Global Navigation Satellite System (GNSS), Ground-Based Synthetic Aperture Radar (GB-SAR), or numerical modeling further enhance accuracy and facilitate a mechanistic understanding, as evidenced by the case studies of Enguri and Liuduzhai. These examples underscore the increasing role of InSAR not only as a monitoring tool but also as an analytical framework capable of evaluating the success of rehabilitation, differentiating between structural and environmental effects, and supporting predictive risk assessments. Overall, InSAR is evolving from a supplementary technique to a core component of dam safety management.

With upcoming satellite missions, improved temporal resolution, the integration of hybrid sensors, and the development of automated processing, InSAR-based monitoring is expected to provide near-real-time and highly reliable deformation information. As dams age and climate-related pressures increase, such capabilities will be essential for ensuring the long-term security and resilience of critical infrastructure. .

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