

Research Article

Integrated Earthquake-Induced Stability Assessment of Lam Chae Earth Dam using Sentinel-1 DInSAR and Field Instrumentation

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ABSTRACT

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The Mw 7.7 Myanmar earthquake of 28 March 2025 generated ground shaking across several regions of Thailand, including Nakhon Ratchasima Province, where the Lam Chae Earth Dam is located. Rapid and reliable assessment of dam stability following seismic events is essential for ensuring public safety and supporting reservoir operation. In this context, Sentinel-1 Differential Interferometric Synthetic Aperture Radar (DInSAR) provides spatially continuous deformation measurements over large areas and complements conventional point-based field monitoring instruments. This study presents an integrated assessment of earthquake-induced dam stability using Sentinel-1 DInSAR together with field instrumentation, including inclinometers and piezometers. Sentinel-1 synthetic aperture radar (SAR) images acquired during the pre-seismic, co-seismic, and post-seismic periods were processed to derive line-of-sight (LOS) surface deformation and compared with in-situ monitoring data. The DInSAR analysis revealed a maximum cumulative LOS displacement ranging from approximately - 27 to - 30 mm during the co-seismic period, whereas inclinometer measurements indicated internal deformation ranging from - 1.258 to - 3.980 mm. Piezometer observations confirmed that pore-water pressure remained within the normal operating range throughout the monitoring period. Although DInSAR measurements are subject to uncertainties associated with atmospheric delay, temporal decorrelation, and vegetation-induced coherence loss, the observed deformation patterns were consistent with field measurements, providing complementary evidence for assessing dam behaviour. This study demonstrates the applicability of integrating satellite-based DInSAR with conventional geotechnical instrumentation for post-earthquake dam safety assessment in Thailand, where such integrated applications remain limited. The integrated interpretation of satellite- and ground-based monitoring indicates that the Lam Chae Earth Dam remained structurally stable following the earthquake and provides a practical framework for long-term structural health monitoring of earth dams.

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1. Introduction

Earth dams are among the most important civil infrastructures for water resources management, providing irrigation water, domestic water supply, flood mitigation, and hydropower generation. Because these structures retain large volumes of water, their structural integrity is directly associated with downstream public safety, environmental protection, and economic sustainability. Throughout their service life, earth dams are subjected to various external loads, including floods, earthquakes, and climate-related hazards, as well as internal

forces such as hydrostatic pressure and self-weight. These factors may gradually induce deformation, material deterioration, or structural instability if not properly monitored. Therefore, continuous monitoring and periodic stability assessment are fundamental components of modern dam safety management.

Among these hazards, earthquakes are of particular concern because seismic loading can induce settlement, cracking, internal deformation, liquefaction, and changes in pore-water pressure within earth-fill dams. Although many modern dams

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are designed to resist seismic loading, post-earthquake assessment remains essential to verify structural integrity, identify potential damage, and support operational decision-making. Consequently, integrating multiple sources of monitoring data has become increasingly important for improving the reliability of dam safety evaluation, particularly after significant seismic events.

On 28 March 2025, the Mw 7.7 Myanmar earthquake generated ground shaking across several regions of Thailand, including Nakhon Ratchasima Province, where Lam Chae Earth Dam is located. Although the seismic intensity at the dam site was approximately Modified Mercalli Intensity (MMI) III, representing weak shaking, engineering assessment was still considered necessary because even low-to-moderate seismic loading may influence the deformation behaviour of earth-fill embankments. Lam Chae Dam is a homogeneous rolled earth-fill embankment constructed across the Lam Chae River. The dam has a maximum height of 29.50 m, a crest length of 2,400 m, and a storage capacity of approximately 275 million m³, supplying irrigation water to Khon Buri District and surrounding agricultural areas while also supporting fisheries, public water supply, and tourism. Owing to its strategic importance, evaluating the dam's structural response following the earthquake is essential for ensuring long-term operational safety.

Conventional dam safety monitoring primarily relies on field instrumentation, including inclinometers, piezometers, and water level indicators. These instruments provide accurate point-based measurements of internal deformation and pore-water pressure; however, they are limited in spatial coverage and cannot directly represent deformation over the entire dam surface. Satellite-based Differential Interferometric Synthetic Aperture Radar (DInSAR) has therefore emerged as an effective complementary technique because it enables spatially continuous deformation monitoring over large areas without requiring direct site access. When integrated with conventional geotechnical instrumentation, DInSAR provides a more comprehensive understanding of dam behaviour by combining wide-area surface deformation with internal structural responses.

Previous studies have demonstrated the successful application of InSAR techniques for monitoring deformation of dams and other geotechnical infrastructures in various countries. Satellite observations have been applied to monitor deformation at the Pertusillo Dam, Mosul Dam, Hoover Dam, and several reservoirs in Europe and Asia, demonstrating the capability of InSAR to detect long-term deformation and complement conventional field monitoring. Recent studies have also highlighted the advantages of integrating satellite observations with in-situ measurements to improve the interpretation of structural behaviour and support infrastructure safety assessment. Nevertheless, most previous investigations

have focused on long-term deformation monitoring under normal operating conditions, whereas studies addressing earthquake-induced deformation of earth dams using integrated satellite and field observations remain relatively limited, particularly in Southeast Asia and Thailand. Furthermore, operational frameworks that combine Sentinel-1 DInSAR with conventional geotechnical instrumentation for continuous dam safety assessment and post-earthquake monitoring have not yet been widely established.

Therefore, this study aims to evaluate the earthquake-induced stability of Lam Chae Earth Dam by integrating Sentinel-1 DInSAR observations with inclinometer and piezometer measurements. Sentinel-1 SAR images acquired during the pre-seismic, co-seismic, and post-seismic periods were analysed to estimate surface deformation and compared with field monitoring data to evaluate the dam's structural response. The novelty of this study lies in the integration of satellite-based DInSAR with conventional geotechnical instrumentation for post-earthquake assessment of an earth-fill dam in Thailand. This integrated approach provides a more comprehensive interpretation of both surface and internal deformation and demonstrates a practical framework for long-term dam safety monitoring and structural health assessment following seismic events.

1.1 Literature review

Theory

1. The Differential Interferometric Synthetic Aperture Radar (DInSAR) technique is an advanced form of the Interferometric Synthetic Aperture Radar (InSAR) method. It is based on comparing the phase of radar backscattered signals from two satellite SAR images acquired over the same area at different times, in order to analyze the change in the distance between the satellite and the Earth's surface along the Line of Sight (LOS) direction. This technique is capable of detecting ground surface displacements at the millimeter scale.

The DInSAR method determines the phase difference after removing the topographic contribution, thereby isolating only the displacement caused by physical processes. The fundamental equation of DInSAR is expressed as:

$$\Delta d = \frac{\lambda \Delta \phi}{4\pi} \quad (1)$$

where λ represents the radar wavelength, $\Delta \phi$ denotes the phase difference of the backscattered signals between the two acquisition times, and Δd is the LOS displacement.

2. The Sentinel Application Platform (SNAP) is a free and open-source software developed by the European Space Agency (ESA) for the processing and analysis of satellite data. The platform provides a comprehensive suite of tools for Synthetic Aperture Radar (SAR) data processing, encompassing key procedures such as orbit file application, subsetting,

interferogram formation, topographic phase removal, filtering, and phase unwrapping.

These integrated tools enable users to systematically derive Line-of-Sight (LOS) displacement results from SAR imagery, facilitating a standardized and reproducible workflow for interferometric data processing without any licensing cost.

3. Dam instrumentation refers to a series of engineering instruments designed to monitor, observe, and evaluate the behavior of dams during both the construction and operational phases. The primary objective of such instrumentation is to ensure continuous assessment of the dam's stability and safety. These instruments record physical changes occurring within the dam structure, such as ground displacement, pore-water pressure, and reservoir water level, which are critical parameters for evaluating dam stability and preventing potential failures in earthfill structures.

The main instruments utilized in this study include: Inclinator, which measures internal horizontal and vertical displacements within the dam body by detecting changes in the inclination angle of a casing embedded inside the dam. The variation in inclination is then converted into the actual displacement values.

Piezometer, which monitors pore-water pressure within the soil to evaluate the groundwater level and internal drainage condition of the dam. An unusual increase in pore pressure may indicate excess hydraulic pressure, which could affect the stability of the earth dam.

Water Level Indicator, which records variations in the reservoir water level to examine its relationship with pore-water pressure and the overall deformation behavior of the dam.

This integrated monitoring system provides essential data for assessing the dam's performance and supports early detection of abnormal conditions that may compromise structural safety.

1.2 Related works

1. Cigna *et al.* (2019) conducted a study entitled "Satellite InSAR Monitoring of Dam Stability: A Review of Cases and Approaches." The research explored the potential of differential and time-series InSAR techniques for monitoring dam deformation and related structural components. The authors proposed an operational monitoring framework to support dam management authorities and emphasized the importance of integrating field-based measurements to validate and enhance the reliability of InSAR-derived results.

2. Ruiz-Armenteros *et al.* (2020) conducted a study entitled "DInSAR Monitoring of Mosul Dam Deformation and Its Correlation with Water Level Variations." The research applied the Differential Interferometric Synthetic Aperture Radar (DInSAR) technique to analyze deformation at the Mosul Dam, which is located in an area susceptible to seismic activity and gypsum dissolution. The results revealed surface displacements consistent with ground-based observations, confirming that DInSAR is an effective tool for detecting small-scale structural

changes in dams, even under complex topographic and geological conditions.

3. Wang *et al.* (2020) conducted a study entitled "Application of Sentinel-1 DInSAR in Assessing Seismic Deformation of Hydropower Dams." This research employed the DInSAR technique to detect deformation of dams and reservoirs following seismic events. The results revealed small but significant deformations that correlated with seismic vibrations. The authors also proposed a practical framework for organizing co-seismic and post-seismic image pairs, enabling clearer temporal interpretation of deformation patterns.

4. Liu *et al.* (2021) conducted a study entitled "Monitoring of Reservoir Dams in Asia Using Sentinel-1 InSAR Time-Series Analysis." The research applied time-series InSAR techniques, including Small Baseline Subset (SBAS) and Persistent Scatterer (PS) methods, to monitor multiple dams across Asia. The results demonstrated that millimeter-scale annual displacements could be effectively detected and correlated with reservoir water level variations. The study highlighted that Sentinel-1 data are highly suitable for establishing regional-scale dam monitoring systems, supporting continuous assessment of dam stability.

5. Darvishi *et al.* (2021) conducted a study entitled "Correlation Between Groundwater Level Changes and Ground Deformation Using InSAR: Case Study of Lake Mead and Hoover Dam, USA." The research employed time-series InSAR analysis based on Sentinel-1 satellite data to investigate the relationship between reservoir water-level variations and ground deformation around Lake Mead and the Hoover Dam in the United States. The results indicated that a decline in reservoir water levels caused uplift of the surrounding crust at a rate of several millimeters per year, reflecting the geological response to changes in subsurface pore-water pressure. This study demonstrated the strong potential of InSAR techniques for monitoring the interaction between hydrological changes and surface deformation in dam environments.

6. Ladawadee *et al.* (2022) conducted a study entitled "A Study of the Relationship Between Groundwater Pressure Change and Land Subsidence Rate Using InSAR Time-Series Technique." The research investigated land subsidence in Nakhon Pathom and Samut Sakhon Provinces, Thailand, by analyzing Sentinel-1 satellite data through the InSAR time-series technique. The results revealed that most areas within the study region experienced ground subsidence. When compared with groundwater level data, it was found that areas with intensive groundwater extraction exhibited higher subsidence rates. The analysis confirmed a strong correlation between groundwater pressure variations and land deformation detected by InSAR, demonstrating the consistency and reliability of the InSAR-based monitoring approach.

7. Soralump *et al.* (2024) applied Sentinel-1 DInSAR to monitor slope movement in the Doi Chang landslide area, northern Thailand. The results showed LOS displacement rates

of -10 to -25 mm/year, consistent with inclinometer data and correlated with rainfall patterns. The study confirmed that Sentinel-1 DInSAR is effective for detecting small-magnitude ground deformation in complex mountainous terrain and can support landslide early-warning and risk-management systems.

2. Materials and Methods

2.1 Study area

Lam Chae Earth Dam is located in Khon Buri District, Nakhon Ratchasima Province, northeastern Thailand (Figure 1). The dam was constructed across the Lam Chae River as part of the Lam Mun River Basin Development Project to provide irrigation water, domestic water supply, flood mitigation, fisheries, and environmental conservation. Operated by the Royal Irrigation Department (RID), Lam Chae Dam is one of the major water resource infrastructures supporting agricultural production and socio-economic development within the region. Owing to its strategic importance, continuous structural monitoring and periodic safety assessment are essential to ensure long-term operational reliability and to minimize potential risks associated with structural deterioration and natural hazards.

Lam Chae Dam is a homogeneous rolled earth-fill embankment with a maximum height of 29.50 m, a crest length of approximately 2,400 m, and a total storage capacity of approximately 275 million m^3 . As with other earth-fill dams, its structural behaviour may be influenced by hydraulic loading, environmental conditions, and external dynamic loading such as earthquakes. Consequently, continuous monitoring of both surface and internal deformation is necessary to support dam safety evaluation and long-term infrastructure management.

On 28 March 2025, a moment magnitude (M_w) 7.7 earthquake occurred in central Myanmar and generated ground shaking across several regions of Thailand, including Nakhon

Ratchasima Province, where Lam Chae Dam is located. Although the estimated seismic intensity at the dam site was approximately Modified Mercalli Intensity (MMI) III, corresponding to weak ground shaking, engineering assessment was considered necessary because even low-to-moderate seismic loading may influence the deformation behaviour of earth-fill embankments. Post-earthquake deformation monitoring therefore provides valuable information for verifying structural performance and supporting dam safety management.

This study investigated the deformation behaviour of Lam Chae Earth Dam during the pre-seismic, co-seismic, and post-seismic periods associated with the 28 March 2025 Myanmar earthquake. This temporal classification enabled the evaluation of deformation characteristics before the earthquake, the immediate structural response during the seismic event, and the subsequent evolution of deformation after the earthquake. The post-seismic assessment focused on determining whether any progressive deformation persisted following the earthquake or whether the observed deformation remained stable within the uncertainty of the monitoring measurements, rather than assuming structural recovery or elastic rebound.

To improve the reliability of the assessment, satellite-derived deformation obtained from Differential Interferometric Synthetic Aperture Radar (DInSAR) was integrated with conventional geotechnical monitoring data, including inclinometer measurements, piezometer observations, reservoir water level records, and rainfall data. The combination of spatially continuous satellite observations with point-based field measurements provides complementary information for evaluating both surface and internal deformation of the dam, thereby reducing interpretation uncertainty and improving confidence in the assessment of structural behaviour following the earthquake.

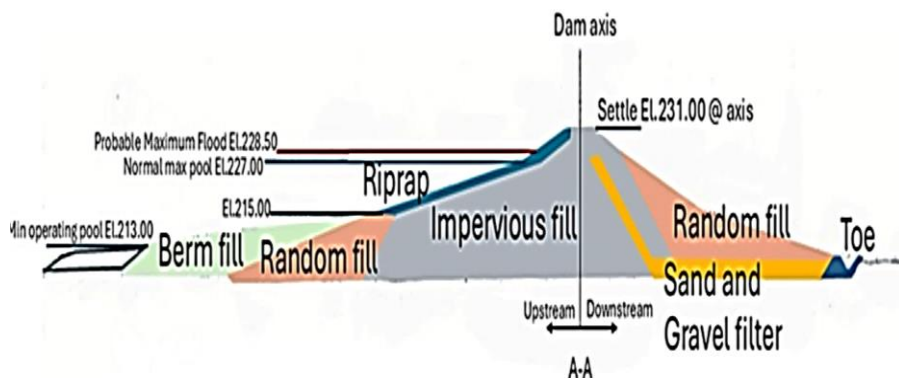


Figure 1 Cross-section of Lam Chae Dam.

2.2 Data used

1. Sentinel-1 Synthetic Aperture Radar (SAR) imagery, provided by the European Space Agency (ESA), was employed as the primary dataset for DInSAR analysis. The SAR images were obtained from the Copernicus Open Access Hub and acquired in the Interferometric Wide (IW) swath mode with dual

polarization (VV and VH). All SAR scenes were acquired from the same ascending orbit, Path 99, and Frame 1225, thereby ensuring identical acquisition geometry and complete spatial overlap throughout the study period.

The use of a single orbit direction together with identical path and frame minimizes geometric inconsistencies and reduces the

influence of look-angle differences during interferometric processing. Furthermore, maintaining consistent acquisition geometry helps minimize geometric decorrelation, ensuring that the detected interferometric phase differences primarily represent ground surface deformation rather than variations caused by imaging geometry. Consequently, the reliability and consistency of the displacement measurements are significantly improved.

The Sentinel-1 images were selected to cover the pre-seismic, co-seismic, and post-seismic periods associated with the 28 March 2025 Myanmar earthquake, allowing the temporal evolution of dam deformation to be investigated before, during, and after the seismic event. The acquisition dates and characteristics of all Sentinel-1 datasets used in this study are summarized in Table 1. The spatial coverage of the Sentinel-1 SAR imagery over the study area is illustrated in Figure 2.

Sentinel-1 operates in the C-band with a radar wavelength of approximately 5.6 cm, enabling day-and-night observations under nearly all weather conditions regardless of cloud cover. These capabilities make Sentinel-1 particularly suitable for long-term deformation monitoring of large civil engineering infrastructures, including earth dams, where continuous and spatially extensive observations are required.

Table 1 Time periods of Sentinel-1 SAR data used for pre-, co-, and post-seismic analysis.

Period	Date range (start–end)
Pre-seismic	15-03-2025 – 17-03-2025
Co-seismic	17-03-2025 – 29-03-2025
Post-seismic	29-03-2025 – 10-04-2025
Recent	15-07-2025 – 27-07-2025

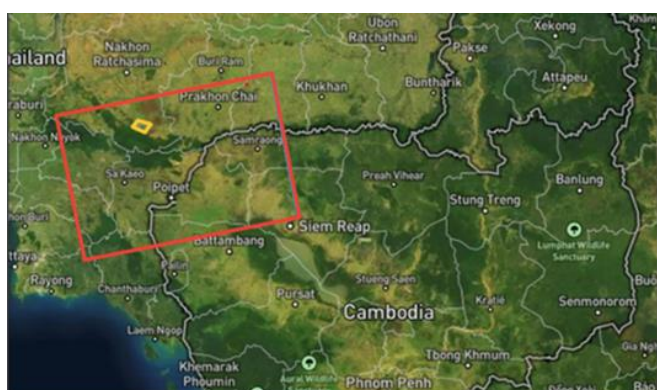


Figure 2 Sentinel-1 satellite image coverage area.

2. **Field data:** Field data were obtained from the dam instrumentation system installed at Lam Chae Dam. The instruments include Inclinoimeters, Piezometers, and Water Level Indicators, which are used to monitor dam behavior and internal conditions.

Four Inclinometers are installed along the dam crest at chainages 0+600, 1+000, 1+500, and 2+000 km, to measure horizontal displacement and percentage shear strain within the embankment.

The Water Level Indicator records the reservoir water level, which was monitored between January and April 2025.

The Piezometer system consists of two types:

Embedded Piezometers, which directly measure pore-water pressure within the soil, with two borehole locations at chainages 0+730 and 1+180 km, comprising a total of 33 sensors.

Open-end Standpipe Piezometers, which measure water pressure through the water level rise inside the standpipe, installed at six locations along the dam crest 0+500, 0+750, 0+925, 1+500, 1+820, and 1+900 km with a total of 12 sensors.

Each location includes instruments installed at both the embankment and foundation levels. The layout and cross-sectional arrangement of these instruments are illustrated in Figures 3, 4, and 5.

The overall methodology adopted in this study is illustrated in Figure 6. The workflow consists of four major stages: (1) acquisition and preprocessing of Sentinel-1 SAR imagery, (2) DInSAR processing using SNAP version 12, (3) collection and analysis of field monitoring data, and (4) integration of satellite-derived surface deformation with conventional geotechnical observations for post-earthquake dam stability assessment.

1. DInSAR data processing: Sentinel-1 SAR images were processed using the Sentinel Application Platform (SNAP version 12) developed by the European Space Agency (ESA). A conventional Differential Interferometric Synthetic Aperture Radar (DInSAR) workflow was implemented to estimate Line-of-Sight (LOS) surface deformation associated with the 28 March 2025 Mw 7.7 Myanmar earthquake.

The processing sequence consisted of Apply Orbit File, TOPSAR Split, Back-Geocoding, Enhanced Spectral Diversity, Interferogram Formation, TOPSAR Deburst, Topographic Phase Removal, Goldstein Phase Filtering, phase unwrapping using the Statistical-Cost Network-Flow Algorithm for Phase Unwrapping (SNAPHU), Range-Doppler Terrain Correction, and generation of the final geocoded displacement products.

During the terrain correction stage, the SRTM 3Sec Digital Elevation Model (Auto Download) was employed to remove topographic distortions and geocode the interferometric products. Both DEM resampling and image resampling were performed using the bilinear interpolation method, and the final products were projected into the WGS 84 / UTM Zone 48N coordinate reference system for subsequent spatial analysis.

To improve interferometric phase quality, Goldstein Phase Filtering was applied before phase unwrapping. The filtering parameters consisted of an Adaptive Filter Exponent of 1.0, FFT size of 64, window size of 3, and coherence threshold of 0.2. This filtering process effectively reduced phase noise while preserving the interferometric fringes required for reliable phase unwrapping.

Phase unwrapping was subsequently performed using the SNAPHU algorithm. The wrapped interferometric phase generated in SNAP was exported to SNAPHU for phase

unwrapping and subsequently imported back into SNAP. This procedure converts the wrapped phase into a continuous phase surface, thereby enabling the calculation of Line-of-Sight (LOS) displacement.

The interferometric coherence generated during processing was used as a quality indicator to evaluate the reliability of the interferometric phase prior to phase unwrapping. Areas exhibiting relatively low coherence, particularly those covered by dense vegetation, were interpreted cautiously because temporal decorrelation may reduce the accuracy of

displacement estimation. Furthermore, atmospheric delay and other interferometric uncertainties were considered during the interpretation of the DInSAR results by comparing the satellite-derived deformation with field monitoring observations.

Finally, the geocoded LOS displacement maps were exported in GeoTIFF format and imported into QGIS for spatial analysis. Surface displacement values corresponding to the locations of the monitoring instruments installed on Lam Chae Earth Dam were extracted for subsequent comparison with field monitoring data.

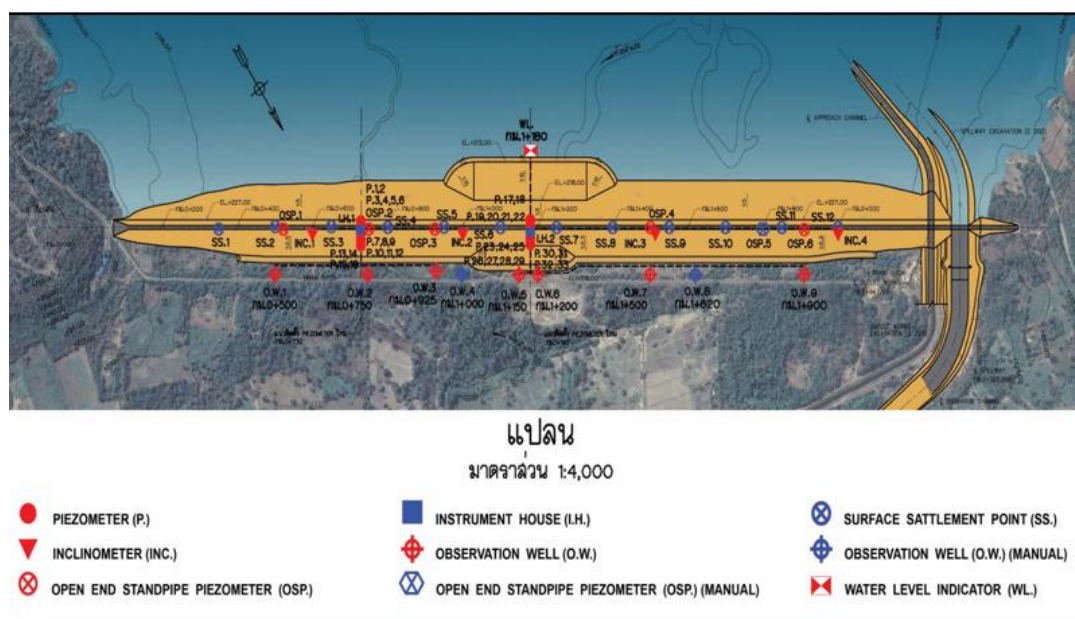


Figure 3 Plan view of Lam Chae Dam instrumentation installation.

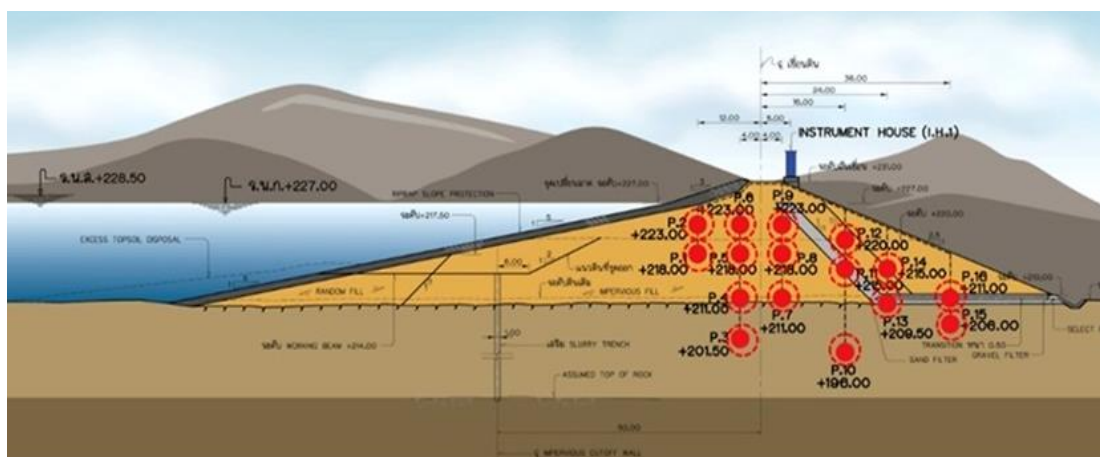


Figure 4 Cross-section of the installation of Piezometer at location 0+730.

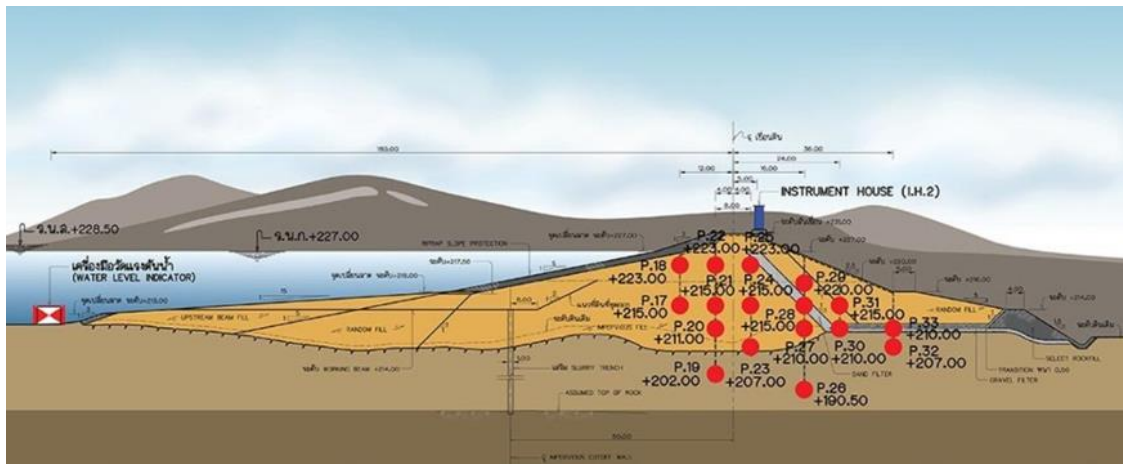


Figure 5 Cross-section of the installation of Piezometer at location 1+180.

Methodology

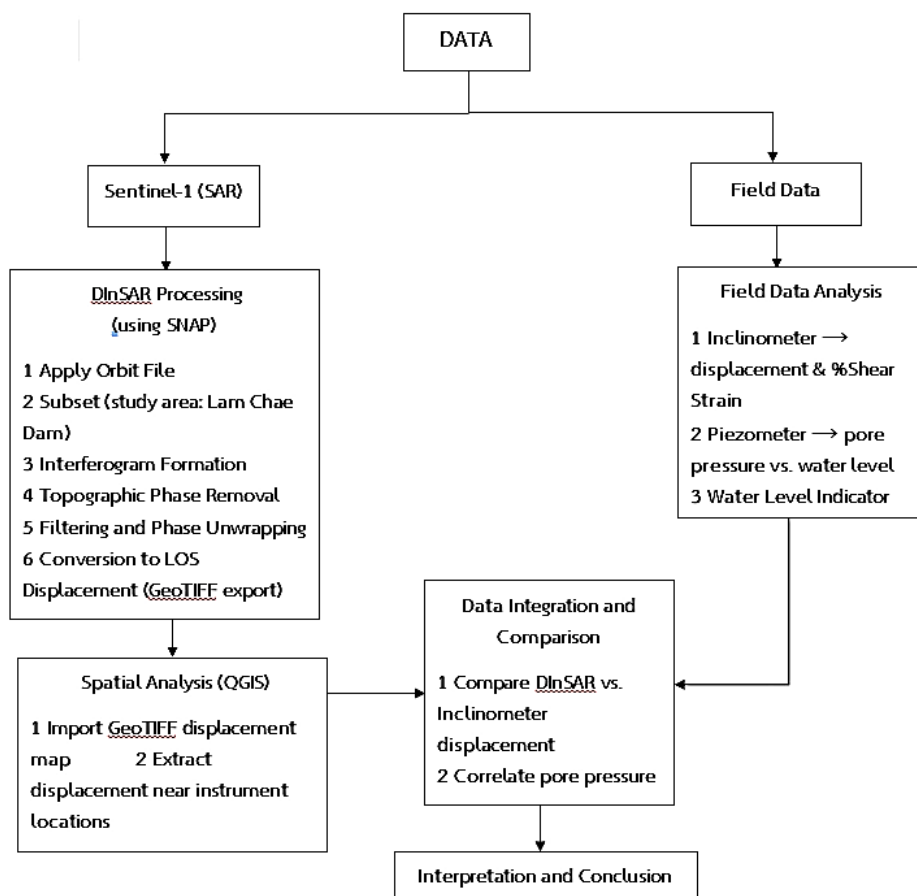


Figure 6 Diagram showing the sequence of research procedures.

2. Field monitoring data analysis: Field monitoring data were obtained from the Dam Safety Division, Royal Irrigation Department (RID), Thailand, and consisted of inclinometer measurements, piezometer observations, and reservoir water level records. These datasets were analysed together with the Line-of-Sight (LOS) displacement derived from the DInSAR analysis to investigate the structural response of Lam Chae Earth Dam during the pre-seismic, co-seismic, and post-seismic periods associated with the 28 March 2025 Mw 7.7 Myanmar earthquake.

Inclinometers installed along the dam crest were used to monitor the internal displacement within the Lam Chae Earth Dam embankment. The displacement values were derived from cumulative movements measured along the A-axis and B-axis, which are two mutually perpendicular directions recorded by the instrument. The displacement changes along each axis are denoted as ΔA (displacement change along the A-axis) and ΔB (displacement change along the B-axis).

Since the two axes are orthogonal, the resultant displacement at each measurement depth was determined from the vector

sum of the displacement components, representing the magnitude of the deviation of the inclinometer casing from its original vertical alignment.

The inclinometer data collected between January and April 2025 were analysed together with the DInSAR-derived Line-of-Sight (LOS) displacement. In addition, the percentage shear strain (% Shear Strain) recorded by the inclinometer was analysed to evaluate variations in embankment deformation during the pre-seismic, co-seismic, and post-seismic periods. For consistency with the DInSAR observations, the analysis focused on Depth Level #1, corresponding to the shallowest monitoring interval nearest to the ground surface.

Figure 7 presents an example of the inclinometer monitoring data used in this study.

Reservoir water level records covering the period from January to April 2025 were analysed to evaluate hydraulic loading conditions throughout the monitoring period. The temporal variation in reservoir water level was subsequently compared with pore-water pressure measurements to support the interpretation of hydraulic conditions within the embankment and their potential influence on the observed deformation behaviour.

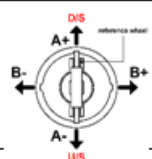
Piezometer Monitoring Pore-water pressure within the embankment was monitored using two types of piezometers: embedded piezometers and open-end standpipe piezometers.

Four embedded piezometer heads (P.5, P.8, P.21, and P.24) were selected for analysis. Piezometers P.5 and P.8 are located at chainage 0+730 km, whereas P.21 and P.24 are located at chainage 1+180 km, representing both the dam core and downstream sections.

In addition, four open-end standpipe piezometers located near the inclinometer stations at chainages 0+750, 0+925, 1+500, and 1+900 km were included in the analysis, resulting in a total of eight piezometer monitoring points.

The pore-water pressure data collected between January and April 2025 were analysed together with the corresponding reservoir water level records. Time-series graphs were subsequently constructed to examine the relationship between pore-water pressure and reservoir water level, thereby supporting the interpretation of the hydraulic response of the embankment and the stability condition of Lam Chae Earth Dam throughout the monitoring period 2.

Monitoring Record
(In-Place Inclinometer)



Monitoring Data			Horizontal Displacement		%Shear strain	
			A-axis	B-axis	A-axis	B-axis
Sensor ID	Elevation	Depth	Cumulative Displacement Relative to Initial Reading	Cumulative Displacement Relative to Initial Reading		
	(m MSL)	(m)	(mm)	(mm)	(%)	(%)
	+227.499	0.00				
INC.1#1	+226.159	1.34	-31.9110	8.5970	1.7240	-0.2410
INC.1#2	+222.659	4.84	-92.2500	18.0410	-0.3080	0.0340
INC.1#3	+219.159	8.34	-81.3370	17.1200	-0.3490	0.0270
INC.1#4	+215.659	11.84	-69.1600	15.9650	-0.2890	0.0270
INC.1#5	+212.159	15.34	-58.8700	15.2260	-0.4590	0.0370
INC.1#6	+208.659	18.84	-43.0530	13.7410	-0.4890	0.0760
INC.1#7	+205.159	22.34	-25.6610	11.5840	-0.2150	0.0970
	+193.239	34.26	0.0000	0.0000	0.0000	0.0000

Figure 7 Example of data recorded from the Inclinometer instrument.

3. Data integration: A comparative analysis was performed by plotting graphs of displacement values obtained from the DInSAR technique and inclinometer measurements to examine the consistency and correlation of displacement trends between the two datasets.

3. Results and Discussion

1. DInSAR displacement analysis results: The DInSAR analysis successfully detected spatial and temporal variations in the Line-of-Sight (LOS) displacement of Lam Chae Earth Dam before, during, and after the 28 March 2025 Mw 7.7 Myanmar earthquake. The reported values represent cumulative LOS

displacement for each observation period derived from Sentinel-1 interferometric image pairs. The spatial distribution of cumulative LOS displacement during the pre-seismic, co-seismic, post-seismic, and recent periods is presented in Figure 8.

During the pre-seismic period (5–17 March 2025), the cumulative LOS displacement remained relatively small, ranging from approximately -10 to -15 mm along most sections of the dam crest, indicating relatively stable surface conditions before the earthquake. In contrast, the co-seismic period (17–29 March 2025) exhibited the largest cumulative LOS displacement, ranging from approximately -27 to -32 mm, indicating that the earthquake produced a measurable surface deformation response. Compared with the pre-seismic observations, the co-seismic interferometric results clearly demonstrate an increase in deformation magnitude associated with the occurrence of the earthquake. These findings indicate that DInSAR successfully captured the transient response of the dam surface to seismic loading (Figure 8).

During the post-seismic period (29 March–10 April 2025), the cumulative LOS displacement decreased to approximately -5 to -10 mm, which is considerably smaller than that observed during the co-seismic period. The reduction in displacement magnitude indicates that the observable surface deformation diminished after the earthquake. However, this reduction should not be interpreted as evidence of complete structural recovery. Instead, the post-seismic observations indicate that no progressive increase in surface deformation was detected following the earthquake, and the measured displacement gradually approached the baseline level observed before the seismic event. The deformation pattern remained generally consistent during the recent period (15–27 July 2025), with no evidence of continuously increasing displacement, suggesting that the deformation induced by the earthquake did not continue to develop during the subsequent monitoring period (Figure 8).

To further evaluate whether the deformation behaviour observed at Lam Chae Earth Dam was consistent with that of other earth-fill dams subjected to seismic loading, an additional case study was conducted using Mae Kuang Udom Thara Dam, Chiang Mai Province, following the 20 October 2022 Mw 4.1 earthquake. The same DInSAR processing workflow was applied to analyse cumulative LOS displacement during the pre-seismic, co-seismic, post-seismic, and recent periods. As shown in Figure 9, the deformation profiles of Mae Kuang Dam exhibited a temporal pattern similar to that observed at Lam Chae Dam. The largest cumulative LOS displacement occurred during the co-seismic period (approximately -51 to -53 mm), followed by a substantial reduction during the post-seismic period, while the recent observations approached the deformation level recorded before the earthquake. No evidence of progressive deformation was identified after the seismic event.

The comparable deformation behaviour observed at both Lam Chae Earth Dam and Mae Kuang Udom Thara Dam suggests that DInSAR is capable of capturing the transient surface response of earth-fill dams to earthquake loading. In both case studies, the largest cumulative LOS displacement occurred during the co-seismic period, whereas the displacement magnitude decreased during the post-seismic period without exhibiting a continuous increase thereafter. These observations indicate that the detected deformation represents a temporary response to seismic loading rather than progressive structural deterioration. Nevertheless, DInSAR measurements should be interpreted together with field monitoring observations because the technique measures deformation only along the satellite Line-of-Sight (LOS) direction and may be affected by atmospheric delay, vegetation-induced decorrelation, and other interferometric uncertainties.

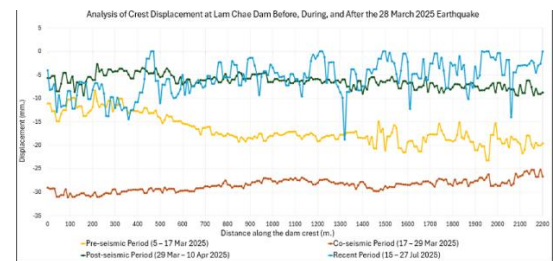


Figure 8 Analysis of the displacement of Lam Chae Dam using data from the DInSAR technique before, during, and after the earthquake event on March 28, 2025.

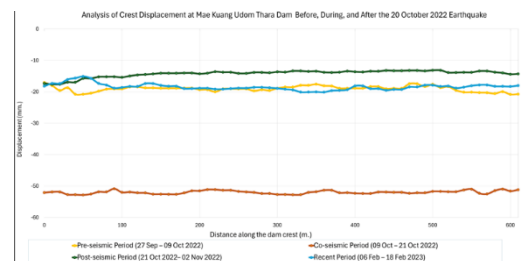


Figure 9 Analysis of the displacement of Mae Kuang Udom Thara Dam using data from the DInSAR technique before, during, and after the earthquake event on October 20, 2022.

2. The field monitoring data were analysed to evaluate the internal deformation and hydraulic behaviour of Lam Chae Earth Dam before, during, and after the 28 March 2025 Mw 7.7 Myanmar earthquake. The monitoring system consisted of four in-place inclinometers installed along the dam crest, together with piezometers and reservoir water level measurements. These complementary datasets were used to verify whether the deformation detected by DInSAR was accompanied by significant internal deformation or abnormal changes in pore-water pressure.

The inclinometer measurements indicated that the internal displacement of the dam increased during the co-seismic period but remained relatively small throughout the monitoring period. During the pre-seismic period, the measured displacement

ranged from approximately -0.528 to -1.835 mm, whereas the co-seismic period exhibited the largest displacement, ranging from approximately -1.258 to -3.980 mm. Following the earthquake, the displacement decreased to approximately -0.189 to -1.689 mm, approaching the pre-seismic level (Figure 10). These observations indicate that although the earthquake produced a measurable response within the embankment, no progressive increase in internal deformation was observed after the seismic event.

To further assess the structural response of the embankment, the measured shear strain was evaluated using the inclinometer data. As illustrated in Figure 11, the calculated shear strain remained below 2% for both the A-axis and B-axis throughout the pre-seismic, co-seismic, and post-seismic periods. According to the dam safety criteria adopted by the Royal Irrigation Department, these values remain below the warning threshold, indicating that the internal deformation induced by the earthquake was limited and did not suggest structural instability of the embankment.

The hydraulic response of the dam was evaluated using electric piezometers, open-end standpipe piezometers, and reservoir water level records. The piezometer data exhibited temporal variations that generally followed fluctuations in reservoir water level throughout the observation period. No abrupt increase or anomalous pore-water pressure was detected during or immediately after the earthquake (Figures 12 - 23). Although a gap in the monitoring records occurred between 28 January and 7 March 2025 due to lightning damage to the monitoring system, the available measurements before and after this period showed consistent hydraulic behaviour without evidence of abnormal pressure build-up associated with the earthquake.

Comparison between the piezometer records and the DInSAR observations indicates that, although DInSAR detected the largest cumulative surface displacement during the co-seismic period, the pore-water pressure remained consistent with the long-term hydraulic behaviour of the dam. The absence of abnormal pore-pressure variation suggests that the observed surface deformation was not accompanied by significant changes in seepage conditions or internal hydraulic loading. Consequently, the field monitoring results support the interpretation that the earthquake produced a temporary deformation response while the embankment maintained stable hydraulic performance.

Overall, the field monitoring observations consistently demonstrate that the earthquake generated measurable but limited deformation within Lam Chae Earth Dam. The inclinometer data revealed only small internal displacement, shear strain remained below the engineering warning threshold, and the piezometer measurements showed no abnormal pore-water pressure response. These independent observations collectively indicate that the embankment maintained its structural and hydraulic stability throughout the monitoring period, providing an essential basis for validating the deformation detected by the DInSAR analysis.

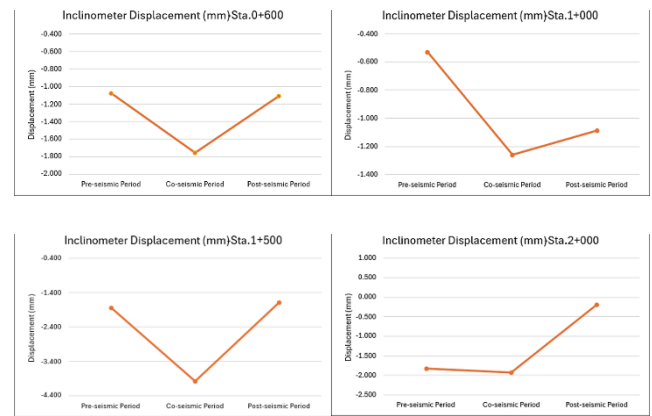


Figure 10 Inclinometer-measured internal displacement at Lam Chae Earth Dam during the pre-seismic, co-seismic, and post-seismic periods: (a) Sta. 0+600, (b) Sta. 1+000, (c) Sta. 1+500, and (d) Sta. 2+000.

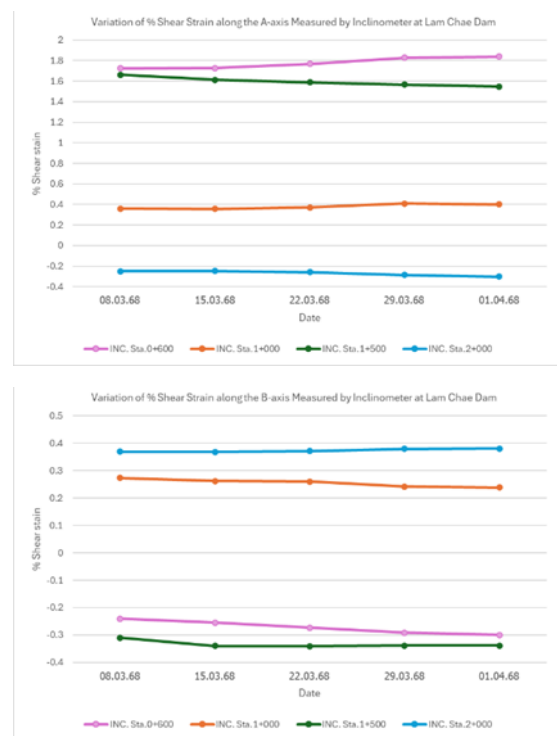


Figure 11 The changes in shear strain (%) along the A axis and B axis.

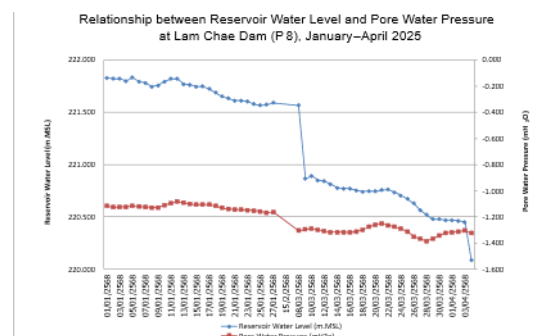


Figure 12 The relationship between the reservoir water level and the pore water pressure at Lam Chae Dam (embedded-type piezometer) during January–April 2025.

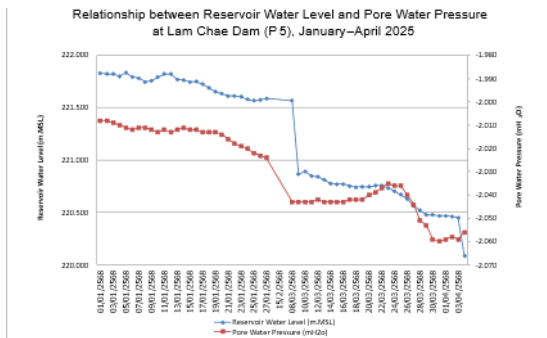


Figure 13 The relationship between the reservoir water level and the pore water pressure at Lam Chae Dam (embedded-type piezometer) during January–April 2025.

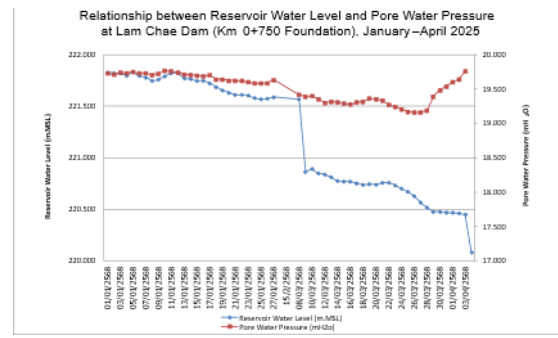


Figure 17 The relationship between the reservoir water level and the pore water pressure at Lam Chae Dam (open end standpipe piezometer) during January–April 2025.

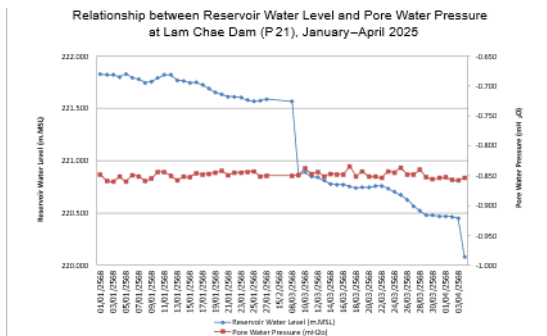


Figure 14 The relationship between the reservoir water level and the pore water pressure at Lam Chae Dam (embedded-type piezometer) during January–April 2025.

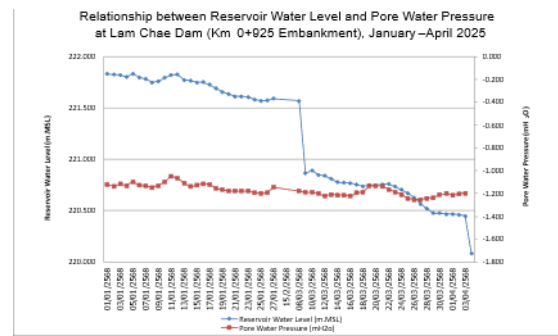


Figure 18 The relationship between the reservoir water level and the pore water pressure at Lam Chae Dam (open end standpipe piezometer) during January–April 2025.

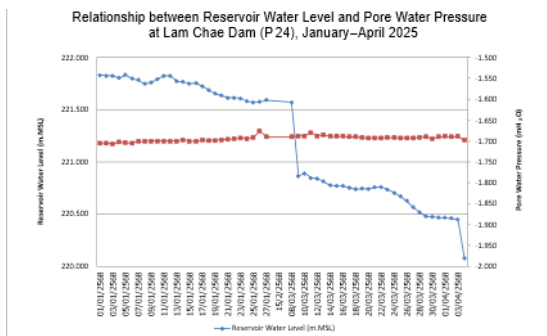


Figure 15 The relationship between the reservoir water level and the pore water pressure at Lam Chae Dam (embedded-type piezometer) during January–April 2025.

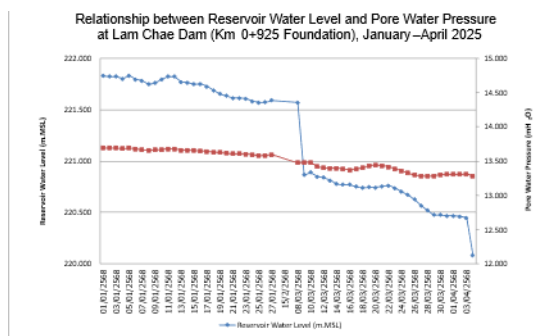


Figure 19 The relationship between the reservoir water level and the pore water pressure at Lam Chae Dam (open end standpipe piezometer) during January–April 2025.

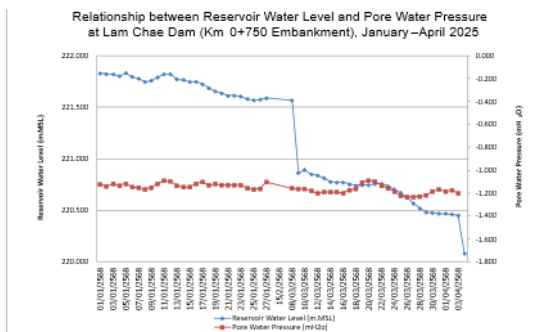


Figure 16 The relationship between the reservoir water level and the pore water pressure at Lam Chae Dam (open end standpipe piezometer) during January–April 2025.

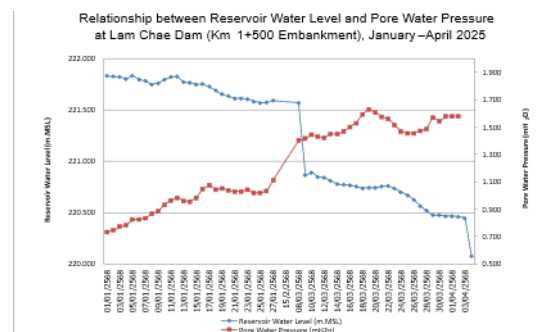


Figure 20 The relationship between the reservoir water level and the pore water pressure at Lam Chae Dam (open end standpipe piezometer) during January–April 2025.

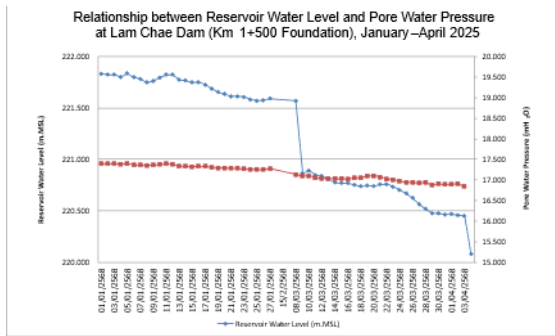


Figure 21 The relationship between the reservoir water level and the pore water pressure at Lam Chae Dam (open end standpipe piezometer) during January-April 2025.

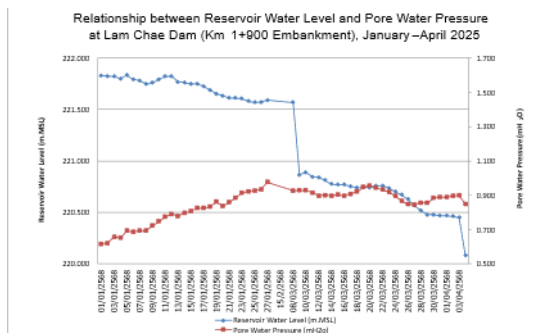


Figure 22 The relationship between the reservoir water level and the pore water pressure at Lam Chae Dam (open end standpipe piezometer) during January-April 2025.

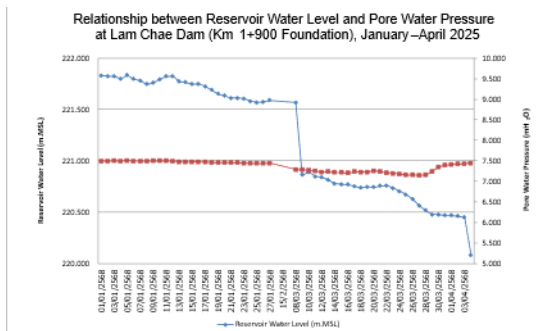


Figure 23 The relationship between the reservoir water level and the pore water pressure at Lam Chae Dam (open end standpipe piezometer) during January-April 2025.

3. To comprehensively evaluate the seismic response of Lam Chae Earth Dam, the DInSAR-derived surface displacement was integrated with field monitoring observations, including inclinometer measurements, shear strain, piezometer records, and reservoir water levels. Since DInSAR and inclinometers measure deformation using different observation principles and units, the displacement data were first normalized using the Min–Max normalization method to facilitate comparison of their temporal deformation patterns. The normalized displacement profiles for each monitoring location are presented in Figure 24–27, while the corresponding displacement values are summarized in Table 2.

The comparison demonstrates that both DInSAR and inclinometer measurements exhibit a consistent temporal trend. In all monitoring sections, the largest displacement occurred during the co-seismic period, followed by a reduction during the post-seismic period. Although the displacement magnitude measured by DInSAR (approximately -27 to -30 mm) was considerably larger than that measured by the inclinometers (approximately -1.258 to -3.980 mm), this difference is expected because the two techniques monitor different components of dam behaviour. DInSAR measures cumulative surface deformation along the satellite Line-of-Sight (LOS), whereas inclinometers directly measure internal displacement within the embankment. Consequently, the difference in displacement magnitude reflects the measurement characteristics of each technique rather than inconsistency between the datasets.

To quantitatively evaluate the agreement between the two monitoring techniques, Pearson's correlation coefficient (r) was calculated using the normalized displacement values. High positive correlations were obtained at Sta. 0+600 ($r = 0.917$) and Sta. 2+000 ($r = 0.909$), while Sta. 1+500 ($r = 0.799$) exhibited a moderately strong positive relationship. In contrast, Sta. 1+000 ($r = 0.175$) showed a relatively weak correlation. The lower correlation at this location may be attributed to radar-specific uncertainties, including vegetation-induced decorrelation, atmospheric delay, geometric differences between the radar measurement point and the inclinometer location, and local surface conditions affecting interferometric coherence. Furthermore, only three observation periods (pre-, co-, and post-seismic) were available for statistical analysis, which limits the interpretation of statistical significance. Therefore, the correlation analysis should be regarded as supporting evidence of temporal consistency rather than conclusive statistical validation.

The integrated interpretation of the field monitoring data further supports the DInSAR observations. Although both DInSAR and inclinometers detected increased deformation during the co-seismic period, the measured shear strain remained below the 2% warning threshold established by the Royal Irrigation Department, and no abnormal increase in pore-water pressure was observed in either the electric or open-end standpipe piezometers. In addition, pore-water pressure variations continued to follow the reservoir water level without abrupt hydraulic responses associated with the earthquake. These observations indicate that the earthquake produced measurable surface and internal deformation but did not trigger progressive internal deformation or abnormal hydraulic behaviour within the embankment.

Overall, the combined use of satellite-based DInSAR and conventional field monitoring provides a more comprehensive assessment of dam behaviour than either technique alone. DInSAR offers spatially continuous measurements of surface deformation over the entire dam crest, whereas field instruments

provide direct information on internal deformation and hydraulic conditions. The agreement between these independent datasets increases confidence in the interpretation that Lam Chae Earth Dam experienced a transient response to earthquake loading, while maintaining overall structural and hydraulic stability throughout the monitoring period. These findings demonstrate that integrating remote sensing observations with conventional geotechnical monitoring represents a reliable and practical approach for post-earthquake dam safety assessment.

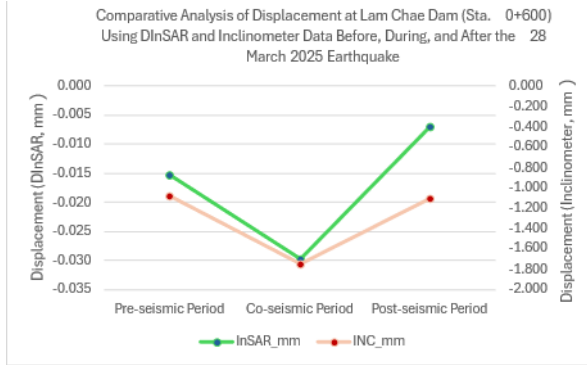


Figure 24 Comparative analysis of displacement values at Lam Chae Dam using data from the DInSAR technique and Inclinator before, during, and after the earthquake event on March 28, 2025.

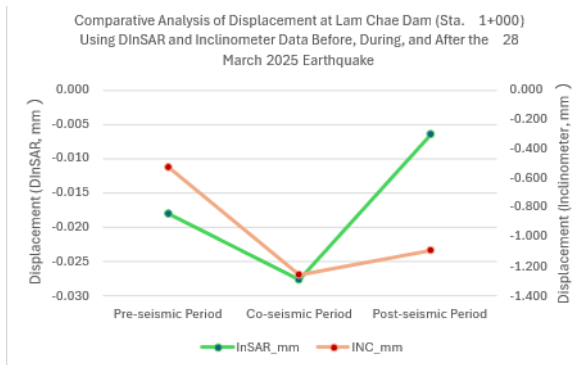


Figure 25 Comparative analysis of displacement values at Lam Chae Dam using data from the DInSAR technique and Inclinator before, during, and after the earthquake event on March 28, 2025.

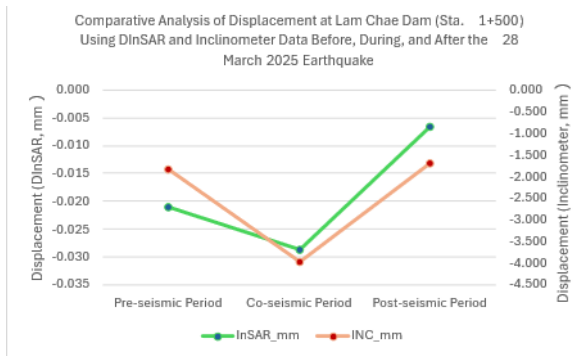


Figure 26 Comparative analysis of displacement values at Lam Chae Dam using data from the DInSAR technique and Inclinator before, during, and after the earthquake event on March 28, 2025.

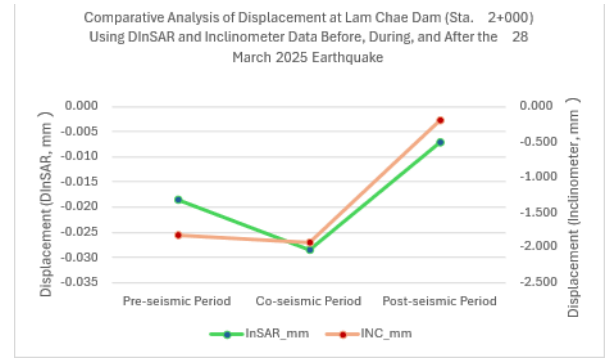


Figure 27 Comparative analysis of displacement values at Lam Chae Dam using data from the DInSAR technique and Inclinator before, during, and after the earthquake event on March 28, 2025.

Table 2 Comparison of displacement values obtained from DInSAR and inclinometers.

No.	Sta.	Period	DInSAR (mm.)	Inclinometer (mm.)
1.	0+600	Pre-seismic	-15.38	-1.07
		Co-seismic	-29.70	-1.75
		Post-seismic	-7.00	-1.10
2.	1+000	Pre-seismic	-17.98	-0.52
		Co-seismic	-27.68	-1.25
		Post-seismic	-6.51	-1.08
3.	1+500	Pre-seismic	-21.08	-1.83
		Co-seismic	-28.69	-3.98
		Post-seismic	-6.54	-1.68
4.	2+000	Pre-seismic	-18.60	-1.82
		Co-seismic	-28.61	-1.92
		Post-seismic	-7.15	-0.18

4. Conclusion

This study evaluated the post-earthquake behaviour of Lam Chae Earth Dam following the 28 March 2025 Mw 7.7 Myanmar earthquake by integrating Sentinel-1 Differential Interferometric Synthetic Aperture Radar (DInSAR) observations with conventional field monitoring data, including inclinometer measurements, shear strain, piezometer records, and reservoir water levels. Unlike previous studies that primarily relied on either satellite observations or field instrumentation alone, this study demonstrates the value of combining both datasets to provide a more comprehensive assessment of dam performance after a seismic event.

The DInSAR analysis detected measurable surface deformation, with the largest cumulative Line-of-Sight (LOS)

displacement occurring during the co-seismic period (approximately - 27 to - 30 mm), followed by a reduction in displacement magnitude during the post-seismic period. Although the displacement measured by DInSAR was substantially larger than that recorded by the inclinometers, both monitoring techniques exhibited consistent temporal deformation patterns, with the greatest deformation occurring during the earthquake and decreasing afterwards. This agreement indicates that the observed differences primarily reflect the different measurement principles of the two techniques rather than inconsistencies in the monitoring results.

The integrated interpretation of the field monitoring data further supports the DInSAR observations. Inclinometer measurements indicated only limited internal deformation, while the calculated shear strain remained below the 2% warning threshold established by the Royal Irrigation Department. In addition, both electric and open-end standpipe piezometers showed no abnormal increase in pore-water pressure associated with the earthquake, and pore-water pressure variations continued to follow fluctuations in reservoir water level. These independent observations consistently indicate that, although the earthquake produced measurable deformation, no evidence of progressive internal deformation or abnormal hydraulic behaviour was identified, and the dam maintained overall structural and hydraulic stability throughout the monitoring period.

A retrospective DInSAR analysis of Mae Kuang Udom Thara Dam following the 20 October 2022 earthquake revealed a deformation pattern comparable to that observed at Lam Chae Earth Dam, with the largest displacement occurring during the co-seismic period followed by a gradual reduction during the post-seismic period. The consistency between the two case studies suggests that the transient deformation response identified in this study may represent a common behaviour of earth-fill dams subjected to earthquake loading, although further investigations involving additional dams are required to confirm this observation.

Despite its effectiveness, DInSAR remains subject to several limitations, including atmospheric phase delay, temporal and spatial decorrelation caused by vegetation and surface conditions, the temporal resolution of Sentinel-1 acquisitions, and the fact that displacement is measured only along the satellite Line-of-Sight (LOS). Consequently, DInSAR should not be used as a standalone tool for dam safety assessment. Instead, satellite observations should be interpreted together with conventional field monitoring data to improve the reliability of deformation assessment and reduce uncertainties associated with each individual technique.

Overall, this study demonstrates that integrating Sentinel-1 DInSAR with conventional geotechnical monitoring provides a reliable and practical framework for post-earthquake dam safety assessment. The proposed approach enables simultaneous

evaluation of spatial surface deformation and internal embankment behaviour, thereby improving confidence in engineering interpretation and supporting long-term structural health monitoring and dam safety management of earth-fill dams in seismic regions.

5. Acknowledgments

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