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# COUPLING FEM MODELLING AND MT-INSAR MONITORING FOR DAM SAFETY: THE CASE OF VADOMOJÓN DAM (SPAIN)

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## Abstract

*Recent advances in remote sensing allow an almost continuous and reliable monitoring of embankment dams, that is complementary to traditional monitoring and essential to ensure their safety and proper operation. Multi-temporal Interferometric Synthetic Aperture Radar (MT-InSAR) techniques provide long-term deformation time series for stable scatterers in dams and associated infrastructures. This information is particularly valuable in cases where conventional monitoring systems are limited or compromised, as it facilitates a continuous assessment of the dam's settlement and deformation patterns.*

*However, the delay between spatial data acquisition and the update of the time-series of deformations, hinder the applicability of these techniques to real-time monitoring and alert systems. To overcome this issue, cutting-edge research is focused on the integration of MT-InSAR, traditional auscultation and reduced-order models of dam behavior.*

*This study presents the integration of MT-InSAR monitoring, conventional monitoring and FEM modelling, applied to Vadomojón Dam, a 75 m high earthfill structure located on the Guadajoz River in southern Spain. The deformations detected by MT-InSAR are compared with those obtained from conventional instrumentation and a physics-based numerical model of the dam. Special attention is given to the temporal variability of crest settlement measurements, using the reservoir level record as the primary input for the model.*

*A detailed analysis of the patterns of deformation obtained by MT-InSAR is presented, distinguishing between dam consolidation deformation and second and third order deformation "noises". A modeling strategy using the Finite Element Method (FEM) is proposed, consider-*

*ing the underlying physical processes, and validated with MT-InSAR deformation patterns. The proposed methodology may prove useful for developing coupled MT-InSAR-FEM models in cases where information on the actual behavior of the embankment dam is more limited. This research leads the path to the development of models of reduced complexity calibrated with MT-InSAR data, allowing the almost real-time simulation of critical conditions, as floods, dam failure and seismic scenarios.*

**Keywords:** remote sensing, FEM modelling, embankment dams, integrated monitoring systems, alert systems.

# 1 INTRODUCTION

Embankment dams play a crucial role in water resource management, flood control, and hydroelectric power generation. Due to their large-scale nature and susceptibility to settlement and deformation, effective monitoring systems are essential to ensure their long-term performance and structural integrity. Traditional instrumentation, such as inclinometers, extensometers, and geodetic surveys, provides direct displacement measurements but often lacks extensive spatial coverage and requires significant maintenance efforts. In contrast, remote sensing technologies such as MT-InSAR enable the acquisition of deformation data over large areas with high spatial resolution and minimal maintenance costs. The development of satellite-based monitoring solutions offers a promising alternative for the assessment of embankment dams, particularly in cases where access to ground-based instruments is limited or the monitoring infrastructure is compromised.

This study evaluates the effectiveness of MT-InSAR for monitoring embankment dam settlements by analyzing its application to Vadomojón Dam (Figure 1). By comparing MT-InSAR-derived deformation data with conventional instrumentation and a numerical model based on physical principles, we aim to provide insights into the accuracy and reliability of MT-InSAR techniques for dam safety assessments.
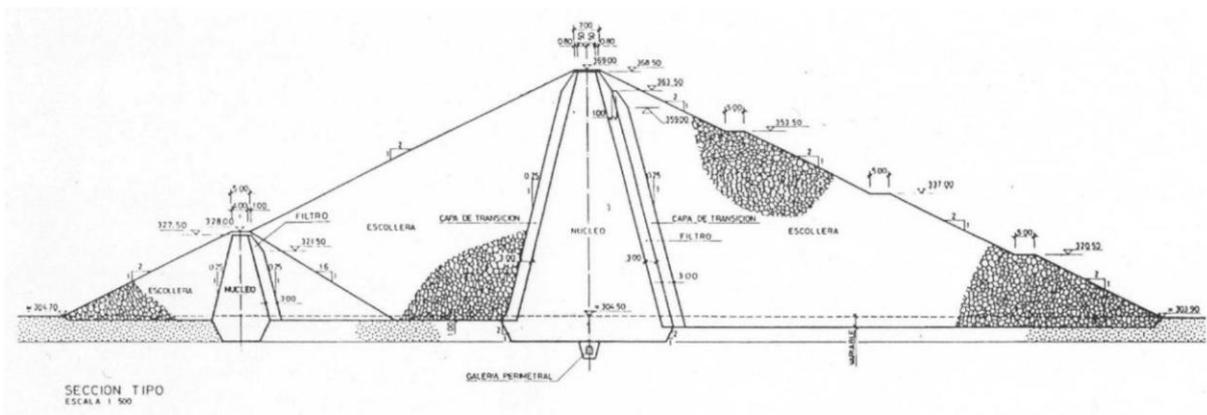


Figure 1: Profile of Vadomojón Dam

# 2 METHODOLOGY

## 2.1 InSAR Data Acquisition and Processing

MT-InSAR relies on the processing of radar signals acquired by satellite sensors to detect ground displacement over time. The technique involves measuring the phase differences between multiple radar images captured at different time intervals, allowing for the identification of surface deformations with millimeter-scale precision. For this study, Sentinel-1 satellite data were utilized due to their consistent acquisition schedule and free accessibility. The data were processed using Persistent Scatterer Interferometry (PSI) and Small Baseline Subset (SBAS) techniques to enhance measurement accuracy and minimize noise caused by atmospheric disturbances. Advanced filtering methods were applied to reduce decorrelation effects and improve signal coherence over the dam structure.

## 2.2 Ground-Based Monitoring and Validation

To validate the MT-InSAR results, conventional monitoring data, including geodetic measurements and piezometric readings, were collected from an established network of monitoring stations on the dam structure. A total of 19 control points were available along the dam crest and berms to measure vertical displacements over time (Figure 2).
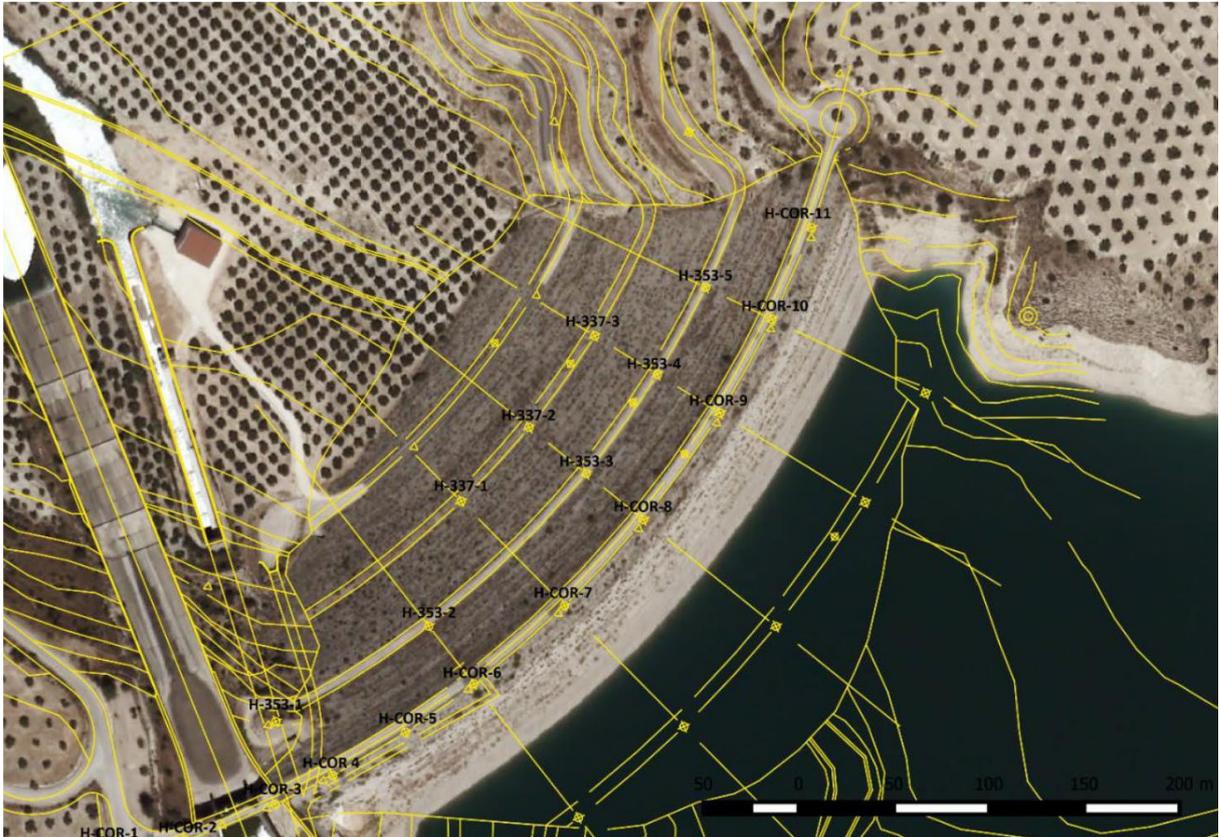


Figure 2: Location of conventional leveling points in Vadomojón Dam

These observations were compared with the InSAR-derived deformation patterns to assess the consistency and reliability of satellite-based monitoring. Additional environmental data, including precipitation records, temperature fluctuations, and reservoir water levels, were incorporated into the analysis to contextualize observed deformation trends. These auxiliary datasets helped to interpret the seasonal variability of dam settlement and assess potential correlations with hydro-meteorological factors. Conventional and MT-InSAR monitoring results were integrated in a common database accessible by web, EyeRADAR Dam.

## 2.3 Numerical Modeling Using FEM

A numerical model was developed using the Finite Element Method (FEM) to simulate the mechanical response of Vadomojón Dam under different operational conditions. The model incorporated material properties, reservoir level fluctuations, and external environmental factors to predict expected deformation patterns. By comparing the numerical simulation results

with both InSAR and ground-based measurements, the study aimed to establish a comprehensive understanding of the dam's behavior. The computational model was calibrated using historical settlement data, ensuring an accurate representation of the dam's structural response to changing hydrostatic conditions. Sensitivity analyses were also conducted to evaluate the impact of varying material stiffness, hydraulic conductivity, and loading conditions on deformation patterns.

A two-dimensional Finite Element Method (FEM) model has been developed to analyze the highest section of the Vadomojón Dam. The numerical simulations were carried out using the MIDAS GTS-NX software, implementing a fully coupled hydro-mechanical analysis. The hydraulic behavior was simulated under transient conditions for a substantial portion of the control period, with reservoir levels varying over time according to actual recorded data.

The constitutive model adopted for the dam's core was the Hardening Soil Model, which extends the hyperbolic Duncan-Chang formulation by incorporating a cap-yielding surface to account for isotropic compression stress paths. This model effectively captures the nonlinear stress-strain response of the material under deviatoric loading conditions. The model parameters were calibrated based on laboratory tests conducted during the dam's construction phase. Conversely, the foundation and rockfill shoulders were represented using linear elastic models with a Mohr-Coulomb failure criterion to account for material strength characteristics.

It is important to note that none of these models incorporate time-dependent parameters or mechanisms capable of simulating secondary consolidation effects. However, this limitation does not compromise the objectives of the study, as the focus is not on replicating the absolute magnitude of settlements but rather on analyzing their temporal variations relative to the mean trend. These fluctuations are primarily driven by changes in effective stress resulting from transient seepage conditions. Furthermore, the influence of suction on effective stress in partially saturated zones was not considered in this analysis.

## 3   RESULTS AND DISCUSSION

### 3.1 Settlement Patterns and Deformation Trends

The MT-InSAR analysis (Figures 3 and 4) revealed a consistent pattern of settlement along the crest of Vadomojón Dam, with measured vertical displacements exhibiting a strong correlation with reservoir level variations. The observed settlement rates agreed with historical records from geodetic surveys, confirming the reliability of InSAR measurements. The temporal analysis indicated that settlement rates were more pronounced during rapid reservoir drawdowns, highlighting the influence of hydrostatic pressure variations on embankment behavior. These findings align with theoretical expectations that embankment dams experience increased consolidation during reservoir drawdown due to changes in effective stress distribution.
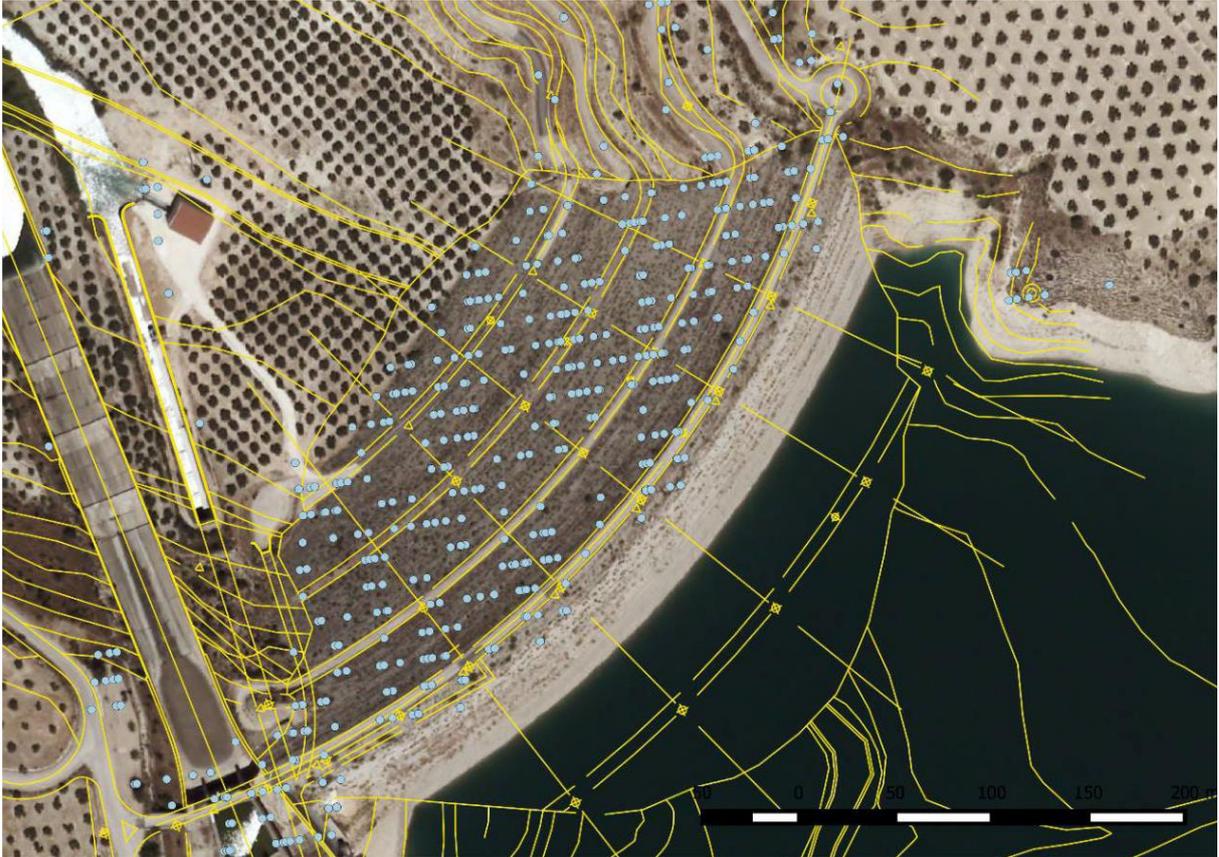
Figure 3: Location of MT-InSAR measuring persistent scatterers in Vadomojón Dam
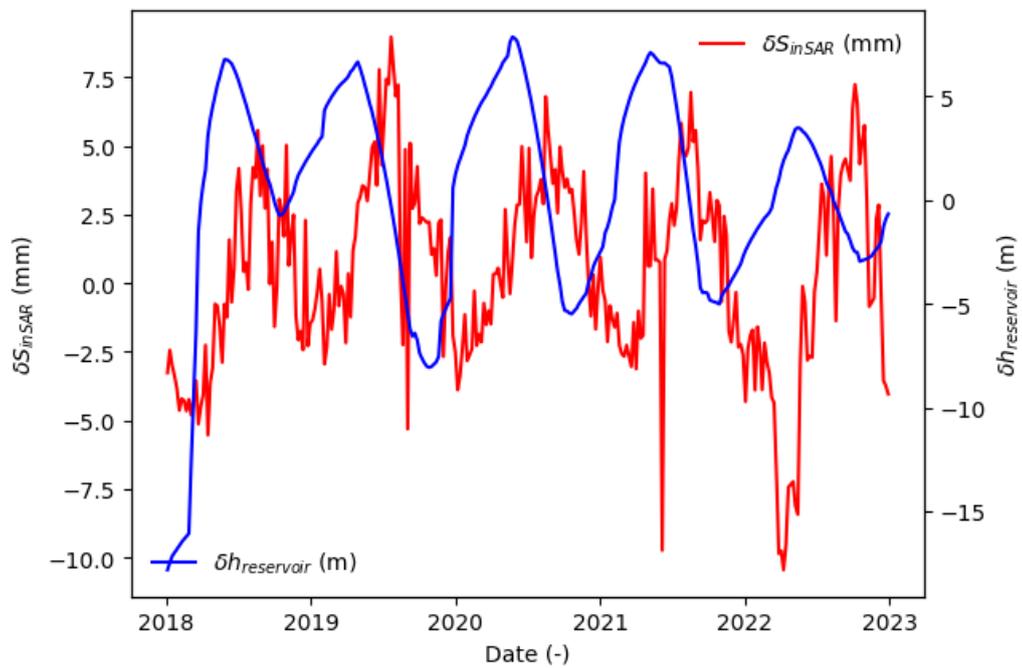


Figure 4: Comparison of water level evolution (blue line, in meters above sea level) and MT-InSAR measured deformation in the crest of Vadomojón Dam (red line, in mm) in the period 2018-2023. Dam consolidation trend was removed.

### 3.2 Comparison with Ground-Based traditional monitoring

The validation process demonstrated a high degree of agreement between MT-InSAR-derived displacements and conventional monitoring data (Figure 5). Minor discrepancies were observed, particularly in areas with dense vegetation or complex terrain, where signal decorrelation may have affected measurement accuracy. Despite these limitations, InSAR provided a valuable complementary dataset to enhance the spatial coverage of traditional monitoring techniques. The integration of MT-InSAR with ground-based observations allowed for a more robust assessment of dam stability, providing early indications of potential structural issues. Furthermore, long-term analysis of InSAR-derived settlement rates provided valuable insights into progressive deformation trends that may not be fully captured through periodic ground-based surveys.
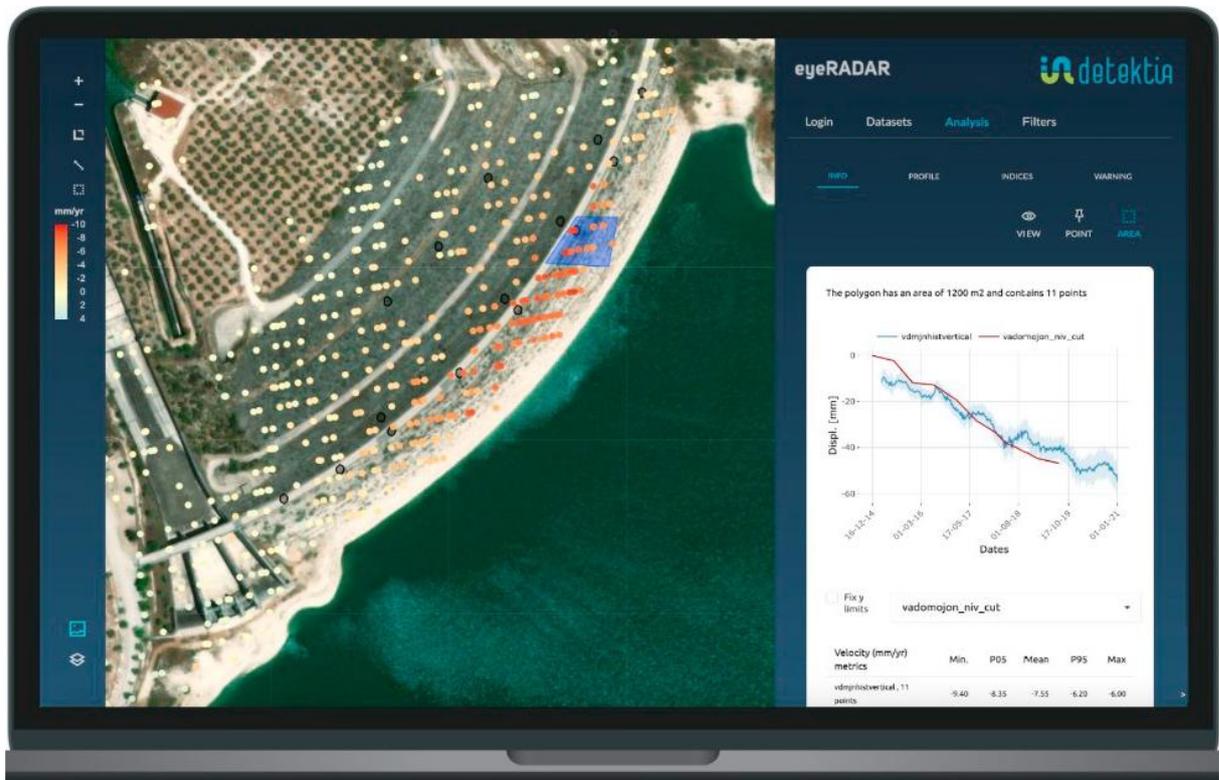


Figure 5: Comparison of deformation in the crest measured with traditional levelling (red) and MT-InSAR (blue) in the period (2014-2019).

### 3.3 FEM Model Validation and Interpretation

The FEM simulation results aligned closely with the observed deformation patterns, reinforcing the physical plausibility of InSAR measurements. By incorporating reservoir level fluctuations and material behavior into the numerical model, the study successfully captured the temporal evolution of settlement trends (Figure 6).
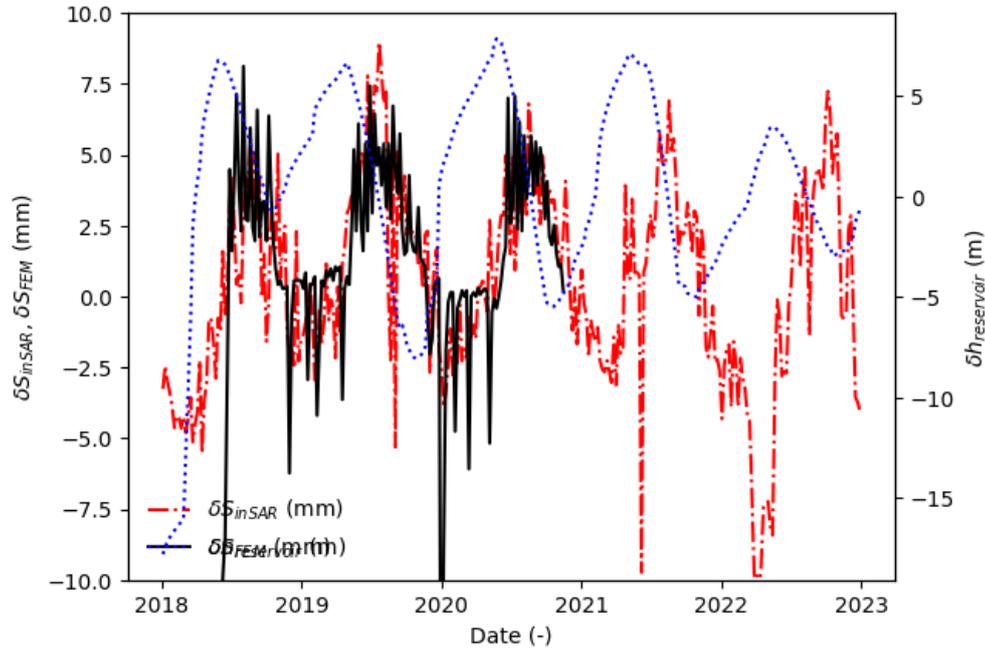
Figure 6: Plot showing modelled deformation (black, in mm) and MT-InSAR measured deformation (red, in mm) for the crest of Vadomojón dam with respect to water level evolution (blue, in meters above see level) in the period 2018-2023. Dam consolidation trend was removed.

This integration highlights the potential of combining InSAR observations with numerical modeling to improve predictive capabilities and enhance early warning systems for embankment dams. The model's predictive performance was further validated through sensitivity analyses, demonstrating its ability to simulate various operational scenarios and assess potential future risks.

## 4 CONCLUSIONS

This study demonstrates the effectiveness of MT-InSAR for monitoring embankment dam deformations, using Vadomojón Dam as a case study. The findings highlight the strong agreement between MT-InSAR measurements, conventional monitoring data, and FEM simulations, validating the feasibility of satellite-based deformation monitoring for dam safety assessments. The integration of MT-InSAR with numerical modeling enhances the interpretability of displacement patterns and provides a valuable tool for decision-making in dam management.

Future research should focus on the integration of MT-InSAR, traditional auscultation and reduced-order models of dam behavior. This research leads the path to the development of models of reduced complexity calibrated with MT-InSAR data, allowing the almost real-time simulation of critical conditions, as floods, dam failure and seismic scenarios.

EU and b) the Industrial Doctorate Program of the Community of Madrid (IND2020/TIC-17528; IND2023/TIC-28743).

## REFERENCES

[1] International Commission on Large Dams (ICOLD). General Synthesis.

[2] Caldeira, L. (2019). Internal erosion in dams: studies and rehabilitation. International Journal of Civil Engineering, 17, 457-471.

[3] Slimani, N., Boukhemacha, M. A., & Marouf, N. (2023). Surface and Internal Erosion in Embankment Dams: A Comparative Review. Selected Studies in Geotechnics, Geoinformatics and Remote Sensing.

[4] Milillo, P., Perissin, D., Lundgren, P., & Lanari, R. (2016). Monitoring dam structural health with InSAR and GPS: A case study of Mosul Dam, Iraq. Journal of Geophysical Research: Solid Earth, 121(6), 4765-4780. https://doi.org/10.1002/2016JB013071 .

[5] Zhang, L., Ding, X., Lu, Z., & Jung, H. S. (2014). Application of InSAR technology for monitoring the deformation of the Three Gorges Dam. Remote Sensing of Environment, 152, 26-38. https://doi.org/10.1016/j.rse.2014.05.015 .

[6] Hu, J., Li, Z., Ding, X., Zhu, J., & Sun, Q. (2013). InSAR monitoring of the Xiaolangdi Dam on the Yellow River. IEEE Transactions on Geoscience and Remote Sensing, 51(1), 225-232. https://doi.org/10.1109/TGRS.2012.2194158.

[7] Marchamalo Sacristán, M., Ruiz Armenteros, A. M., Lamas Fernández, F., González Rodrigo, B., Martínez Marín, R., Delgado Blasco, J. M., Bakon, M., Lazecky, M., Perissin, D., Papco, J., & Sousa, J. J. (2023). MT-InSAR and Dam Modeling for the Comprehensive Monitoring of an Earth-Fill Dam: The Case of the Benínar Dam(Almería, Spain). Remote Sensing, 15(11), 2802. https://doi.org/10.3390/rs15112802.

[8] Zhou, W., Li, S., Zhou, Z., & Chang, X. (2016). InSAR Observation and Numerical Modeling of the Earth-Dam Displacement of Shuibuya Dam (China). Remote Sensing, 8(10), 877. https://doi.org/10.3390/rs8100877

[9] Fetel, R.H. Comparison of Finite Element Methods and Satellite InSAR for Monitoring Deformations of a Large Tailings Dam. PhD Thesis

[10] Smith, J. A., & Brown, L. M. (2023). Digital Twin for Dam Safety: Integrating Real-Time Monitoring and Numerical Modeling. Water Resources Research, 59(4),e2023WR032456. https://doi.org/10.1029/2023WR032456.

[11] Johnson, P. R., & Lee, H. K. (2024). A Digital Twin Framework for Earthfill Dams: Enhancing Predictive Maintenance and Risk Management. Journal of HydraulicEngineering, 150(2), 04023045. https://doi.org/10.1061/(ASCE)HY.1943-7900.0002001HY.1943-7900.0002001).

[12] Wang, X., & Zhang, Y. (2023). Application of Digital Twin Technology in the Monitoring and Management of Earthfill Dams. Computers and Geotechnics, 151, 104923. https://doi.org/10.1016/j.compgeo.2023.104923

[13] Huerta, A. (2022). Hybridized methods for compressible and incompressible flows within computational engineering-based digital twins strategies. CIMNE.

[14] Noureddine, M. A., De Martin, F., ElMeouche, R., Sammuneh, M. A., Ababsa, F., &Beaufils, M. (2024). Seismic Digital Twin of the Dumanoir Earth Dam. Innovations in Smart Cities Applications Volume 7.

[15] Bekele,B. M., Song, C. R., Eun, J., &Kim, S. (2022). Fast Detection of Anomalies in A Model Earth Dam  Based on ADistributed Temperature Sensing Data Integrated withArtificialIntelligence.ACEM22 Proceedings. http://www.i-asem.org/publication_conf/acem22/2.%20GE/1.GE217/3.%20GE2177_7305A.pdf.

[16] Duncan,J.M.,Chang,C. Y.(1970).Nonlinear analysisof stress and strain in soils. JSoil-Mech Found Div 96(5), 1629–1653. https://ascelibrary.org/doi/abs/10.1061/JSFEAQ.0001458

[17] Marchamalo-Sacristán, M., A. Fernández-Landa, C. Sancho, A. Hernández-Cabezudo, V. Krishnakumar, C. García-Lanchares, J. Sánchez, Martínez-Marín Rubén, J.G. Rejas-Ayuga, I. González-Tejada, L. Jordá, A.M. Ruiz-Armenteros, F. Lamas-Fernández (2024) EyeRADAR-Dam: Integration of MT-InSAR with monitoring technologies in a pilot monitoring system for embankment dams. Procedia Computer Science, https://doi.org/10.1016/j.procs.2024.06.420.