

A geotechnical approach to Digital Twin modelling of embankment dams

João Manso, Daniel Leite, Dora Roque, João Bilé Serra, João Marcelino

Geotechnical Department, National Laboratory for Civil Engineering, Lisbon, Portugal, jmanso@lnec.pt

ABSTRACT: Embankment dams are critical infrastructure systems that require reliable monitoring to guarantee safety and optimal performance. Traditional inspection methods are often resource-intensive and involve specialised equipment and training. Digital twins, which are virtual representations of physical assets, offer promising opportunities for improving infrastructure management. However, their implementation in geotechnical engineering remains in an early stage. This paper focuses on developing digital twins of embankment dams using publicly available digital elevation models and geotechnical data obtained during the early construction phases. The proposed approach combines high resolution topography data from the Copernicus programme with existing data on foundation treatment, exploratory boreholes, and preliminary structural modelling of the dam body. The study shows how accessible datasets can be used to create an initial digital twin, focusing on the geometric and geotechnical representation of subsurface interventions. While real-time data integration remains a future goal, the current model offers value in terms of design documentation, spatial analysis, and the planning of monitoring strategies. The main objective of this work is to present a methodology for creating digital twins of embankment dams, filling a gap in the literature on the design and implementation of digital twins. This work contributes to the implementation of digital twins in civil engineering, by proposing a practical, cost-effective approach to early-stage modelling. It also discusses limitations and future development opportunities.

KEYWORDS: Digital Twin, Copernicus, digital elevation models, embankment dam, construction, foundation treatment.

1 INTRODUCTION

In modern society, dams have a significant impact on water supply, irrigation, flood control, and power generation. During their operational life cycle, many dams face a range of challenges, including exposure to extreme weather conditions, aging infrastructure, and rising external loads. Dams are critical infrastructures whose failure can lead to significant human, environmental, and economic losses. Consequently, ensuring dam safety requires a continuous and adaptive risk management process. Although numerous institutions have made efforts to incorporate climate change considerations into decision-making, the practical application of such guidance to dam safety remains limited, primarily due to the lack of accessible and actionable data. At the same time, traditional dam monitoring relies on instruments such as strain gauges, tiltmeters, and piezometers. Moreover, field inspections have been conducted by maintenance and safety personnel, either visually or with the assistance of instruments. To reduce reliance on human input, automated online monitoring systems have been introduced (Mwanza et al. 2024). These systems gather data through data loggers, which is then post-processed and analysed (Liang et al. 2011). This data must then be transported back to the office for processing and transformation into a format that can be interpreted by relevant stakeholders for decision-making purposes (Clarkson & Williams 2021). While these systems are effective, they tend to be costly, require specialised maintenance, and often rely on proprietary technologies. Moreover, the data they generate is typically discrete in time and may not be available following critical events. These limitations highlight the need for more cost-effective, continuous, and reliable monitoring solutions.

Recent advancements in the integration of Artificial Intelligence and Internet of Things (AIoT) technologies have created new opportunities for the development of automated and cost-effective dam monitoring systems (Kong et al. 2024). These modern approaches use networks of wireless instruments and sensors to continuously collect data on key parameters, and transmit it in real time to cloud-based platforms for further analysis. These data are then analysed using mathematical, statistical and numerical models to enable the early detection of potential failures. In this context, Digital Twin (DT) technology has emerged as a promising concept, connecting objects and real world systems to their virtual

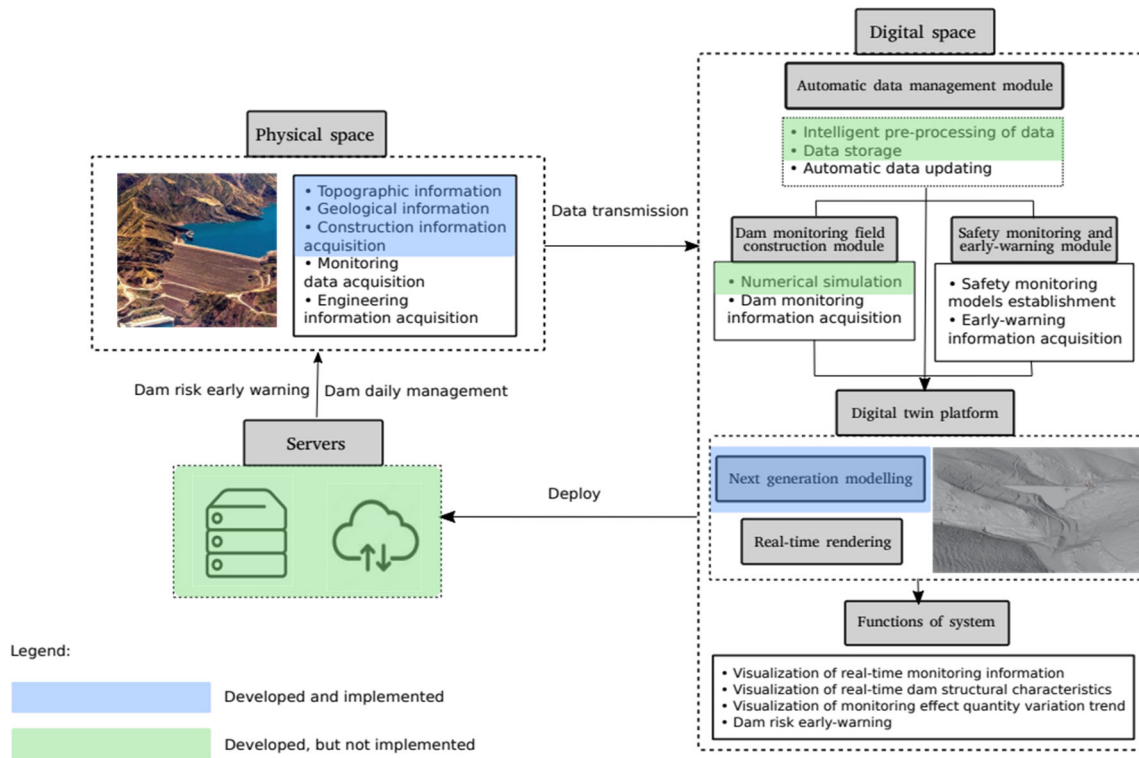
replicas via real-time data exchange. These virtual replicas can be used to monitor and analyse system performance, as well as to provide intelligent support for making cost-effective decisions (Valk et al. 2021; Singh et al. 2021). In parallel, Machine Learning (ML) applies algorithms and statistical models to large data sets, often gathered through IoT devices and stored in the cloud, to identify patterns and make data-driven predictions without the need for explicit programming.

Although ML-based approaches are increasingly being adopted in various infrastructure sectors (Mwanza et al. 2024), their integration with DT frameworks, in the context of embankment dam construction, safety management, maintenance, and cost-effectiveness, remains relatively unexplored. This highlights a clear research gap: the development of an integrated framework combining these technologies would be a significant step towards improving the safety, reliability and resilience of embankment dams. Given the opportunity to follow the construction of an embankment dam in Portugal, it was possible to develop a DT from the early stages of its construction. This involved integrating geotechnical site investigation data and executing experimental test blocks, enabling a detailed virtual representation of the physical processes involved from the beginning.

This paper proposes a methodology for developing a DT of an embankment dam by integrating multi-source spatial data. The approach involves comparing terrain modelling using the Copernicus Digital Elevation Model (DEM) with modelling using high-resolution LiDAR data. Real foundation treatment data, including injection records, and borehole logs, and injection galleries geometry, are also incorporated into the DT to improve its accuracy. The paper discusses the advantages, limitations and implications of each data source in the context of dam monitoring and virtual modelling.

The main contributions of this work are:

- A framework for terrain and structure modelling based on high resolution topography data and geotechnical investigation records.
- Integration of foundation treatment elements into a 3D digital environment to enable more detailed visualisation and analysis;
- A critical discussion of the applicability of the proposed DT, its current limitations and potential for future development and scalability.



2 METHODOLOGY

The present study proposes a framework for the development of a DT model for real-time monitoring of embankment dams for stability and early warning detection. The proposed system's overall framework, when is fully implemented, is presented in Figure 1. It includes creating a 3D model of the terrain, the dam body, and the monitoring system. This model acts as a digital environment for visualising data from different scenarios. The framework under consideration in this study follows the four steps presented in sections 2.1 through 2.5.

Figure 1. The proposed system's overall framework. The functions that are represented by blue squares have been implemented, whereas those indicated by green squares have only been developed, but not yet implemented (Adapted from Shao et al. 2025).

2.1 Topographic Data

The dam studied in this work is located in a rural, hilly area in the north of Portugal (Figure 2). At the time this paper was written, excavation and foundation treatment work was underway.



Figure 2. Area where the dam will be built.

A Digital Elevation Model (DEM) is a three-dimensional representation of elevation data, which is used to define the vertical (Z-axis) values of terrain surfaces (Li et al. 2004). In order to develop a 3D model of an embankment dam, an accurate DEM with centimetre-level precision is essential for effectively capturing and analysing surface topography (Trevisani et al. 2012). Although elevation data has

traditionally been obtained through ground-based geodetic surveys, these methods are now considered to be both time-consuming and limited in terms of spatial coverage, compared to modern remote sensing technologies (Sudra et al. 2023). However, the scales achieved through remote sensing and used in cartography do not provide the required accuracy.

One of the most well-established methods for DEM generation is digital aerial photogrammetry (DAP). This remote sensing technique enables high-density 3D geometric information to be extracted from overlapping stereoscopic images. DAP can be applied to any form of remotely sensed imagery, provided there is sufficient overlap between at least two images. Numerous Earth observation satellites launched in recent years, such as SPOT, IKONOS, QuickBird and Pléiades, have been equipped with stereo acquisition capabilities in response to this requirement (Panagiotakis et al. 2018).

Interferometric Synthetic Aperture Radar (InSAR) is another remote method for DEM generation. Synthetic aperture radar (SAR) images, acquired from different points along the platform trajectory, are used to determine the altitude of locations on the Earth surface, based on phase differences in the signal that travels from the sensor to the Earth. SAR images for DEM production can be collected from several platforms. Shuttle Radar Topography Mission (SRTM) was a global DEM achieved from images acquired from the space shuttle in 2000. Satellites are the platforms used more often. Copernicus DEM is an example of DEM achieved through this method, using data from the TanDEM-X mission collected between 2011 and 2015 (<https://doi.org/10.5270/ESA-c5d3d65>).

Another widely used technique for generating high-resolution elevation data is Light Detection and Ranging (LiDAR). This active remote sensing method operates by emitting laser pulses towards a surface and measuring the time it takes for the reflected signals to return to the sensor. One of the key advantages of LiDAR is its ability to penetrate vegetation cover, enabling highly detailed 3D models to be created that capture both surface features and the underlying topography (Gil et al. 2013). Furthermore, LiDAR systems can cover large areas with high spatial resolution and accuracy in a relatively short period, making them particularly effective for terrain analysis and mapping over extensive regions.

In the present study, the terrain of the dam construction area was modelled using elevation data from the Copernicus database. The Copernicus Data Space Ecosystem is a central hub for accessing, exploring and utilising Earth observation and environmental data (<https://documentation.dataspace.copernicus.eu/Home.html>). Two primary datasets are available: Copernicus 30 and 90. In this study, Copernicus 30 was used. The Copernicus DEM represents the Earth's surface, including buildings, infrastructure, and vegetation. It is a static collection with global coverage and is not date-dependent. It has a spatial resolution of 30 metres, supplemented by 90 metres where 30-metre tiles are unavailable. QGIS software was used to extract the necessary information for constructing the DT of the dam (Figure 3), using a cartographic reference system.

On the other hand, high-resolution LiDAR data was sourced from the official Portuguese geospatial data portal (<https://cdd.dgterritorio.gov.pt>), which provides digital elevation models (DEMs) of mainland Portugal with a spatial resolution of 50 cm. These DEMs are derived from LiDAR point clouds with an average density of 10 points per square metre, representing a raster-based elevation model of the bare earth that excludes buildings, vegetation, and other artificial surface features.

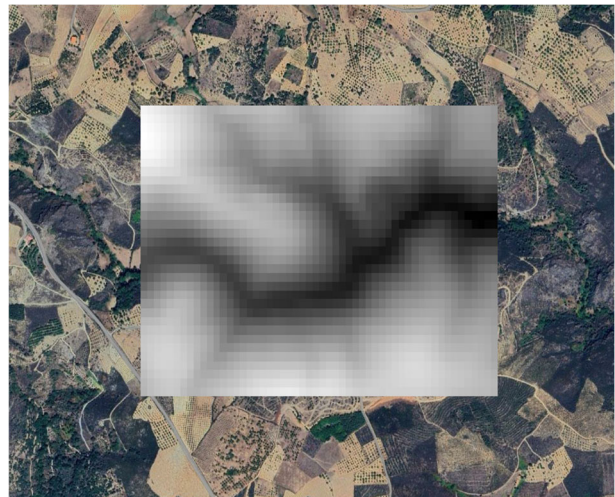


Figure 3. DEM obtained from the Copernicus database for the area around the dam.

2.2 Modelling approach

To create the Digital Twin, the chosen platform was Blender, using the Bonsai extension – an open-source, native Building Information Modeling (BIM) authoring tool based on the Industry Foundation Classes (IFC) standard. Bonsai provides a Python scripting interface that allows the execution of native Python scripts, the import of external Python modules, and the ability to interact with variables within a named scope, offering flexibility for automation and data integration.

DEM data from the Copernicus 30 database was first imported into Blender by generating a *Plane* (Mesh) entity and applying displacement modifiers based on the elevation values (Figure 4). This process resulted in a continuous terrain model with a spatial resolution of 30 metres, capturing the general topography of the area.

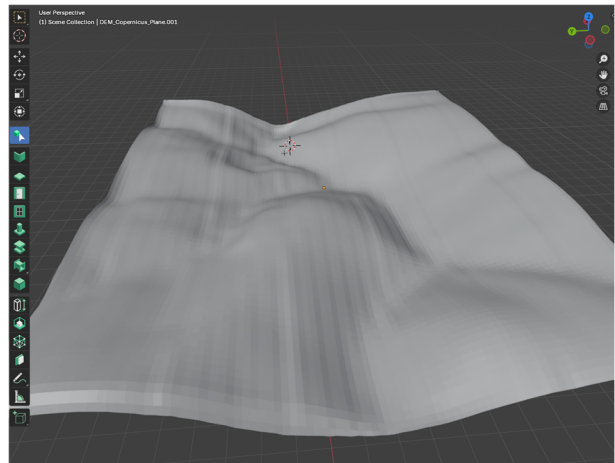


Figure 4. DEM data from the Copernicus 30 database in Blender.

In parallel, LiDAR data from the Portuguese national database (October 2024) was processed in QGIS, where the high-resolution raster file (.tif) was exported as an STL mesh. The STL was then imported directly into Blender (Figure 5). This model significantly outperforms the Copernicus-based DEM, offering centimetre-level precision and including detailed features such as the excavation areas already completed at the time of acquisition. This level of detail

enabled the accurate positioning and modelling of built elements, including the injection gallery and foundation treatment features, which were incorporated into the Digital Twin based on real project data.

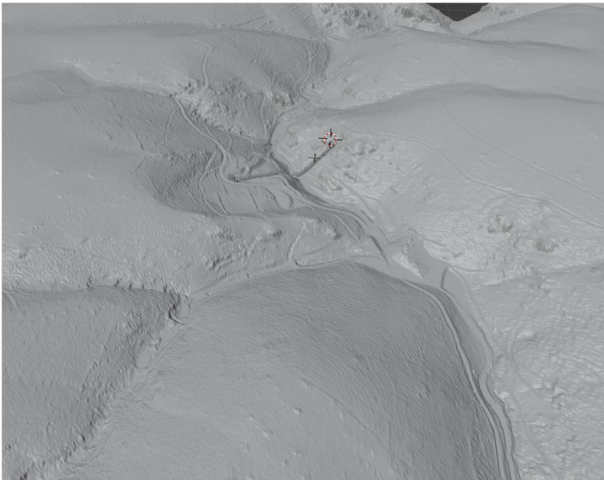


Figure 5. LiDAR data from the Portuguese national database (October 2024) in Blender.

2.3 Geotechnical data

This work followed the commonly adopted strategy of incorporating all available engineering data into the base model, including technical drawings, borehole locations obtained from construction reports or project records, and relevant geological information. As part of the preparatory investigations, three seismic profiles were created and nine boreholes, each approximately 30 metres deep, were excavated. The extracted materials were used to characterise the foundation geotechnically. After construction began, an additional six boreholes (ranging from 30 to 40 metres deep) were drilled to investigate the dam foundation further. The location of each borehole and its geotechnical data were systematically integrated into the DT model to provide a detailed and accurate representation of the subsurface conditions.

2.4 Foundation treatment records

The dam foundation is located within a deeply incised valley with steep, asymmetric slopes – the left bank is notably gentler than the right at higher elevations. The valley floor is narrow, with the watercourse confined to a strip approximately 20 metres wide.

To assess the most effective treatment methodologies for the foundation, an experimental test block was conducted on the left bank. Each borehole in this test area was modelled individually in the Digital Twin, incorporating respective injection data at each depth interval. This allows for a detailed representation of the treatment process.

2.5 Gallery of injections

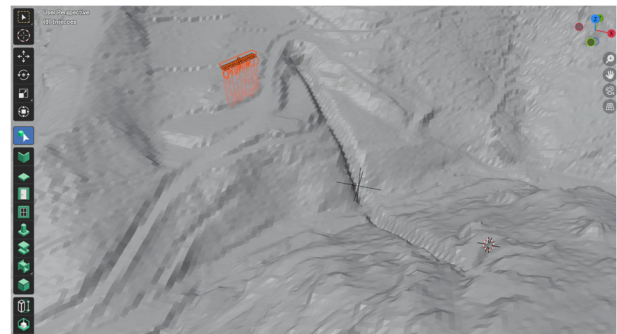
The dam design includes an injection gallery. Based on the available information from construction reports and project documentation, it was possible to model this structural element prior to its actual construction. This early modelling enabled verification of key aspects such as geometric constraints and spatial relationships with other components of the dam, ensuring consistency with design specifications and facilitating pre-construction assessments.

3 RESULTS

Considering the available terrain data, the model developed using LiDAR data outperformed the model based on Copernicus DEM data. While the DEM resolution was adequate for preliminary modelling, particularly due to its global availability, it lacked the level of detail required to accurately represent fine structural elements, in contrast to the centimetre-scale resolution provided by the LiDAR dataset.

Several aspects of the dam construction were successfully modelled, including the foundation injections (Figures 6 and 7) and the injection gallery (Figure 8). With regard to the former, it was possible to assess their spatial location relative to the dam body and identify zones of higher grout intake. One practical modelling feature was representing the injection volumes through variable cylinder radii, which enabled areas with higher grout consumption to be identified quickly. Combined with permeability test results obtained after treatment, this provided meaningful insights into the effectiveness of the foundation treatment strategy and informed potential improvements. Furthermore, the digital twin facilitated the evaluation of consistency between the planned and executed injection works, thereby improving quality control and documentation of construction activities.

Several aspects of the injection gallery were also validated through the digital model. Both the planned and as-



built structures could be analysed, enabling verification of alignment and design consistency. The integration of the gallery within the surrounding terrain was particularly evident in the LiDAR-based model, which had a higher resolution and provided a more accurate perception of topographic features and spatial relationships.

Figure 6. Relative position of the experimental test block and the dam location.

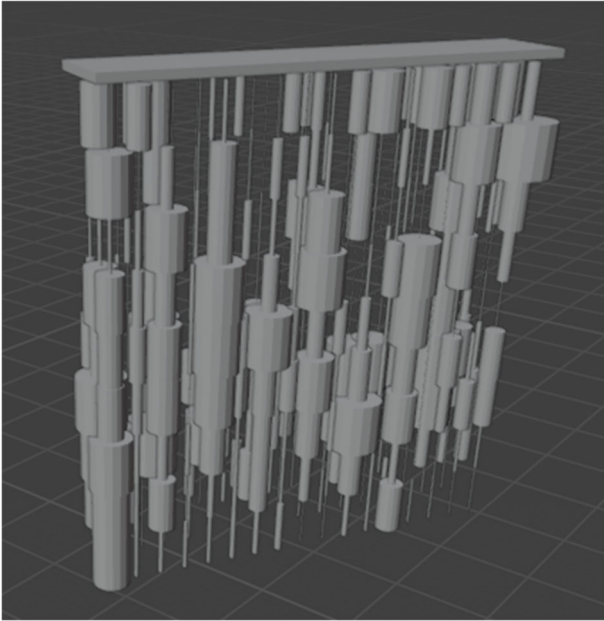


Figure 7. Experimental test block injections for foundation treatment.

4 DISCUSSION

This work successfully integrated remote sensing data, namely satellite imagery and LiDAR, to develop a comprehensive digital twin platform. Taking a real embankment dam project as an example, the digital twin platform of the system is demonstrated. Using a real embankment dam project as a case study, the methodology demonstrated the feasibility of creating a detailed digital twin before construction begins. Compared to traditional UAV-based photogrammetry, this approach offers some advantages, particularly in terms of cost, as no field campaigns were required, and applicability at an early stage. While the platform has achieved an adequate level of precision for preliminary planning and geotechnical integration, it remains static. Real-time sensor data has not yet been implemented and behavioural simulations are still pending. This highlights the potential for future development towards a fully dynamic and responsive digital twin.

5 FUTURE WORK

Future studies and developments aim to establish a comprehensive visualisation system for dam safety monitoring. This system will be based on a Digital Twin platform integrating computational programming, data processing, structural analysis and structural health diagnosis. Throughout the construction phase, geometric data obtained from UAV-based photogrammetry campaigns will be used to update the model continuously and assess construction performance. This approach builds upon the authors' previous work on UAV-based inspection and 3D image reconstruction for dam monitoring purposes (Marcelino et al. 2024; Leite et al. 2025).

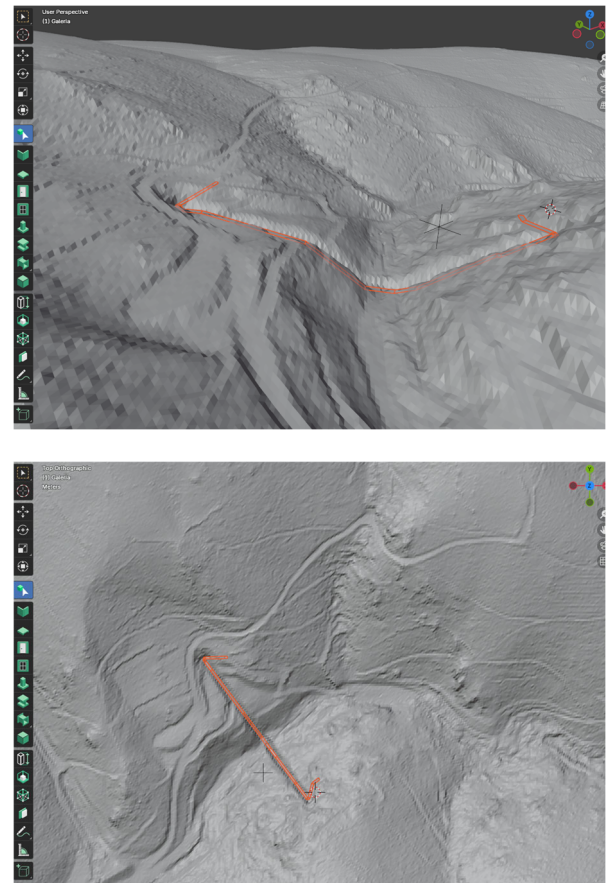


Figure 8. General view of the injection gallery in the dam.

Furthermore, integrating DTs with neural network systems and artificial intelligence (AI) significantly advances the intelligent monitoring of earth dams by enabling real-time learning and anomaly detection. Through their capacity to capture high-resolution imagery and multispectral data across extensive and otherwise inaccessible areas, UAVs can continuously supply DTs with updated information regarding geometric configurations, surface conditions, and the evolution of fissures, settlements, and seepage zones. These datasets can be used to train convolutional neural networks (CNNs) to identify patterns indicative of visual anomalies, while machine learning models can correlate such anomalies with environmental and operational conditions to predict potential failure modes. This integration allows the DT to represent the current state of the dam infrastructure and learn from historical behavioural patterns. It can also automatically identify critical areas and issue early warning alerts, contributing to predictive management strategies and enhancing the structural safety of earth dam systems (Leite et al. 2025).

In parallel, the integration of real-time sensor data, including on-site instrumentation, drone-based observations and meteorological inputs, will be explored to dynamically update the DT and enable predictive simulations, such as seepage or stability analyses, via coupling with finite element models (Cabaço et al., 2023). This draws on earlier experience in deploying multi-sensor and micro-electromechanical systems (MEMS) for geotechnical monitoring applications (Eugénio et al. 2025).

To support informed decision-making across all phases of dam safety management, the system architecture will be designed to unify various data sources in a centralised database. This will enable effective information sharing

among the stakeholders involved in the construction, monitoring and maintenance of infrastructure.

6 CONCLUSIONS

This study proposed a methodology for the initial development of a Digital Twin platform for dam safety applications. This methodology combined open-source topographic data from the Copernicus programme, LiDAR surveys and existing information relating to foundation treatment, exploratory boreholes and preliminary structural modelling. The methodology enabled the creation of a preliminary 3D environment using Blender, a highly extensible open-source 3D modelling software, which will serve as the basis for a future full-featured DT system.

The process was described in detail and the results were critically compared, in order to identify the benefits and limitations of each data source and modelling step. The findings demonstrate the potential of integrating multi-source data to create a DT framework that is low-cost, flexible and scalable.

The proposed DT platform will not only support continuous safety assessment through the integration of real-time sensors and linkage with finite element simulations, but also enhance planning, visual inspection and communication with stakeholders. Furthermore, this approach can be adapted for new embankment dam projects, from the early stages of construction, and for existing infrastructures, particularly where monitoring data is scarce or expensive to acquire.

7 ACKNOWLEDGEMENTS

This work was supported by Remote sensing for Enhanced Geo-Hazard Detection in Ground Slopes (RSEHD), with financial support from National Laboratory for Civil Engineering (LNEC).

8 REFERENCES

- Cabaço, G., Oliveira, S., Alegre, A., Marcelino, J., Manso, J. and Marques, N., 2023, September. Analysis of Dam Natural Frequencies Using a Convolutional Neural Network. In *EPIA Conference on Artificial Intelligence* (pp. 227-238). Cham: Springer Nature Switzerland.
- Clarkson, L. and Williams, D., 2021. Catalogue of real-time instrumentation and monitoring techniques for tailings dams. *Mining Technology*, 130(1), pp.52-59.
- Eugénio, D., Marcelino, J., Santos, R., Marques, N., and Manso, J. 2025. Experimental LINCOS Dam for Low-Cost Monitoring & Synthetic Data. *Proc. EPIA 2025 international conference on Artificial Intelligence*, Faro, Portugal.
- Gil, A.L., Núñez-Casillas, L., Isenburg, M., Benito, A.A., Bello, J.J.R. and Arbelo, M., 2013. A comparison between LiDAR and photogrammetry digital terrain models in a forest area on Tenerife Island. *Canadian Journal of Remote Sensing*, 39(5), pp.396-409.
- Kong, S.M., Yoo, C., Park, J., Park, J.H. and Lee, S.W., 2024. AIOT monitoring technology for optimal fill dam installation and operation. *Applied Sciences*, 14(3), p.1024.
- Leite, D., Marcelino, J., Guerra, N., Manso, J., Sardinha, R. 2025. Main failure modes in embankment dams, mappable with a drone survey. In *Fifth International Dam World Conference* (pp. 1145-1161). LNEC Press.
- Li, Z., Zhu, C. and Gold, C., 2004. Digital terrain modeling: principles and methodology. CRC press.
- Liang, L.I., Ran, L.I., Pei-shou, W.A.N.G. and Yan-lei, W.A.N.G., 2011. Applications of online monitoring technology for tailings dam on digital mine. *Transactions of Nonferrous Metals Society of China*, 21, pp.s604-s609.
- Marcelino, J., Manso, J., Leite, D., Marques, N.C. and Freire, O., 2024. Structural health monitoring and inspection of dams based on Unmanned Aerial Vehicles photogrammetry with image 3D reconstruction. In *Geotechnical Engineering Challenges to Meet Current and Emerging Needs of Society* (pp. 1807-1810). CRC Press.
- Mwanza, J., Mashumba, P. and Telukdarie, A., 2024. A framework for monitoring stability of tailings dams in realtime using digital twin simulation and machine learning. *Procedia Computer Science*, 232, pp.2279-2288.
- Panagiotakis, E., Chrysoulakis, N., Charalampopoulou, V. and Poursanidis, D., 2018. Validation of Pleiades Tri-Stereo DSM in urban areas. *ISPRS International Journal of Geo-Information*, 7(3), p.118.
- Shao, C., Zheng, S., Xu, Y., Gu, H., Qin, X. and Hu, Y., 2025. A visualization system for dam safety monitoring with application of digital twin platform. *Expert Systems with Applications*, 271, p.126740.
- Singh, S., Weeber, M. and Birke, K.P., 2021. Advancing digital twin implementation: A toolbox for modelling and simulation. *Procedia CIRP*, 99, pp.567-572.
- Sudra, P., Demarchi, L., Wierzbicki, G. and Chormański, J., 2023. A comparative assessment of multi-source generation of digital elevation models for fluvial landscapes characterization and monitoring. *Remote Sensing*, 15(7), p.1949.
- Trevisani, S., Cavalli, M. and Marchi, L., 2012. Surface texture analysis of a high-resolution DTM: Interpreting an alpine basin. *Geomorphology*, 161, pp.26-39.
- Van Der Valk, H., Haße, H., Möller, F. and Otto, B., 2022. Archetypes of digital twins. *Business & Information Systems Engineering*, 64(3), pp.375-391.