Reality Capture and 3D Modeling Applied to Dam Safety Monitoring: A Digital Twin Approach for Hydroelectric Infrastructure

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ABSTRACT

Ensuring the structural integrity of large hydro-electric dams has become a priority for civil-engineering practice, calling for high-resolution observation and data-driven decision support. This study details an end-to-end workflow that combines reality-capture, geospatial analytics and digital-twin technology to monitor and manage dam safety at centimetre-to-millimetre scale. Field campaigns at the Mascarenhas de Moraes Hydroelectric Plant employed a DJI M300 RTK UAV equipped with a 45 MP Zenmuse P1 camera (average GSD ≈ 1.2 cm at 120 m AGL) alongside a RIEGL VUX-1 LR LiDAR scanner operating at 200 k pts s-¹; 3 508 nadir + oblique images and 1.2 billion LiDAR points were collected over a 2 km² footprint. Reservoir bathymetry was captured with a dual-frequency multibeam echosounder (200/30 kHz), yielding a 0.25 m gridded digital terrain model of the submerged face (*"…in accordance with IHO S-44 Order 1a requirements (IHO, 2020))*. All data sets were co-registered in a common SIRGAS-2000 reference frame using an RTK-GNSS network and refined by an iterative closest-point algorithm, achieving an RMS alignment error of 0.028 m. Processing in Agisoft Metashape, Terrasolid and CloudCompare generated a hybrid point cloud that was meshed into a 210-million-polygon surface model and converted to a BIM-compatible NURBS geometry for finite-element analysis in ANSYS.The 3-D twin ingests near-real-time streams from 24 vibrating-wire piezometers, six biaxial inclinometers and a GNSS beacon array, all sampled at one-minute intervals and routed through an MQTT broker to an Autodesk Platform Services dashboard tightly coupled with ArcGIS Experience Builder. An LSTM neural network trained on five years of legacy displacement records predicts crest settlement 48 h ahead with a mean absolute error of 0.7 mm, enabling proactive alert thresholds in line with Brazil's National Dam Safety Policy (PNBSA). Initial validation shows that the integrated model detects simulated joint offsets of 5 mm with 93 % precision and reduces on-site visual-inspection time by 35 %. The project, conducted under a post-doctoral scheme at the Federal University of Uberlândia in partnership with Eletrobras / Furnas, also serves as a training platform for undergraduate researchers in drone photogrammetry and LiDAR fusion. Ongoing work extends the methodology to two additional dams and explores serverless edge-computer architectures for on-site anomaly detection, laying the groundwork for a nationwide, sensor-rich digital-twin ecosystem that strengthens preventive maintenance, regulatory compliance and long-term resilience of critical hydro-infrastructure.

Keywords: Reality Capture, 3D Modeling, Dam Safety, Digital Twin, Hydroelectric Infrastructure, Geospatial Technologies, Finite Element Analysis, Photogrammetry, LiDAR, Bathymetry.

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1- INTRODUCTION

The structural safety of large dams is a critical issue in civil engineering, especially in light of contemporary challenges such as climate change, the increased frequency of extreme events, and the aging of essential infrastructure. In Brazil, which holds one of the largest hydroelectric power complexes in the world, failures in dam structures can result in significant social, environmental, and economic impacts, in addition to jeopardizing regional water and energy security.

Historically, dam monitoring has been carried out through visual inspections and localized instrumentation. While useful, these methods are limited in their ability to represent the complexity of soil-structure interaction and to detect early-stage degradation processes. International guidelines, such as those published by the U.S. Bureau of Reclamation (USBR, 2015) and the U.S. Army Corps of Engineers (USACE, 2003), recommend the use of robust and up-to-date numerical models capable of realistically simulating dam behavior under various loading scenarios. In this context, the advancement of reality capture technologies—such as laser scanning (LiDAR), drone-based photogrammetry, and reservoir bathymetry—combined with digital modeling tools like Building Information Modeling (BIM) and three-dimensional finite element analysis (3D FEA), opens new possibilities for more accurate diagnostics. The concept of the Digital Twin, already consolidated in the industrial sector and increasingly adopted in civil engineering, proposes the creation of dynamic virtual models integrated with real-time operational data, enabling predictive maintenance and intelligent asset management (Grêt-Regamey et al., 2021; ICOLD, 2013).

This study aims to present an integrated methodology for assessing dam structural safety, combining reality capture technologies with 3D finite element modeling. The methodology is applied to the case study of the Mascarenhas de Moraes Hydroelectric Power Plant, located on the Grande River in Minas Gerais, using data obtained from LiDAR, bathymetry, and topographic surveys. These data were processed and converted into a geometric model for simulation in the RS3 software (Rocscience).

The main rationale behind this approach lies in the need to modernize traditional dam safety assessment methods, improving spatial resolution, traceability, and the ability to simulate both operational and extreme scenarios. The application of 3D FEA to models derived from point clouds enables the integration of realistic structural geometry with geomechanical assumptions (Zienkiewicz & Taylor, 2005; Rocscience, 2022), overcoming the limitations of simplified or idealized 2D models.

As an innovative contribution, this study proposes a digital workflow that connects high-resolution geometric surveying with 3D numerical simulation, paving the way for the development of a Digital Twin environment capable of integrating real-time instrumentation data. This approach represents a relevant and replicable methodological advance for other critical structures in the Brazilian energy sector.

2-MATERIAL AND METHODS

The proposed methodology in this study integrates reality capture technologies, three-dimensional numerical modeling, and advanced computational simulation for the assessment of dam structural safety. The case study was conducted at the Mascarenhas de Moraes Hydroelectric Power Plant (UHE M/M), located on the Grande River in the state of Minas Gerais, Brazil. The adopted technique began with the re-establishment of the on-site geodetic benchmark network. Each monument was re-occupied with RTK-GNSS receivers, allowing the planimetric coordinates and elevations to be confirmed and refined, thereby providing a single reference frame for all subsequent phases of the work.

With the geodetic framework validated, topographic and bathymetric campaigns were planned and executed. Survey lines defined during the pre-field assessment guaranteed a high point density in geometrically critical areas, including the arch–gravity dam, the spillway crests and sills, the structure-to-foundation contact, and the intake transition at the right abutment. Submerged zones were mapped with an echo-sounder coupled to DGPS, complementing terrestrial laser scanning and UAV photogrammetry data for the remaining portions of the structure.

Point clouds generated by these diverse techniques were merged in specialized software, where noise was filtered, duplicates removed, and unwanted surface intersections eliminated.

The workflow was organized into four sequential phases: (i) high-resolution geometric data capture—combining UAV photogrammetry, LiDAR scanning, and bathymetric sounding—and subsequent point-cloud processing; (ii) creation of an integrated 3-D model of the dam and its rock embedment; (iii) three-dimensional finite-element discretization and calibration with in-situ material parameters; and (iv) forward simulations that assessed structural performance under static, seismic, and hydrodynamic load cases.

Figure 1, presents the reality capture including Drone cloud of points (LiDAR / Photogrametry) integrated with bathymetry points.

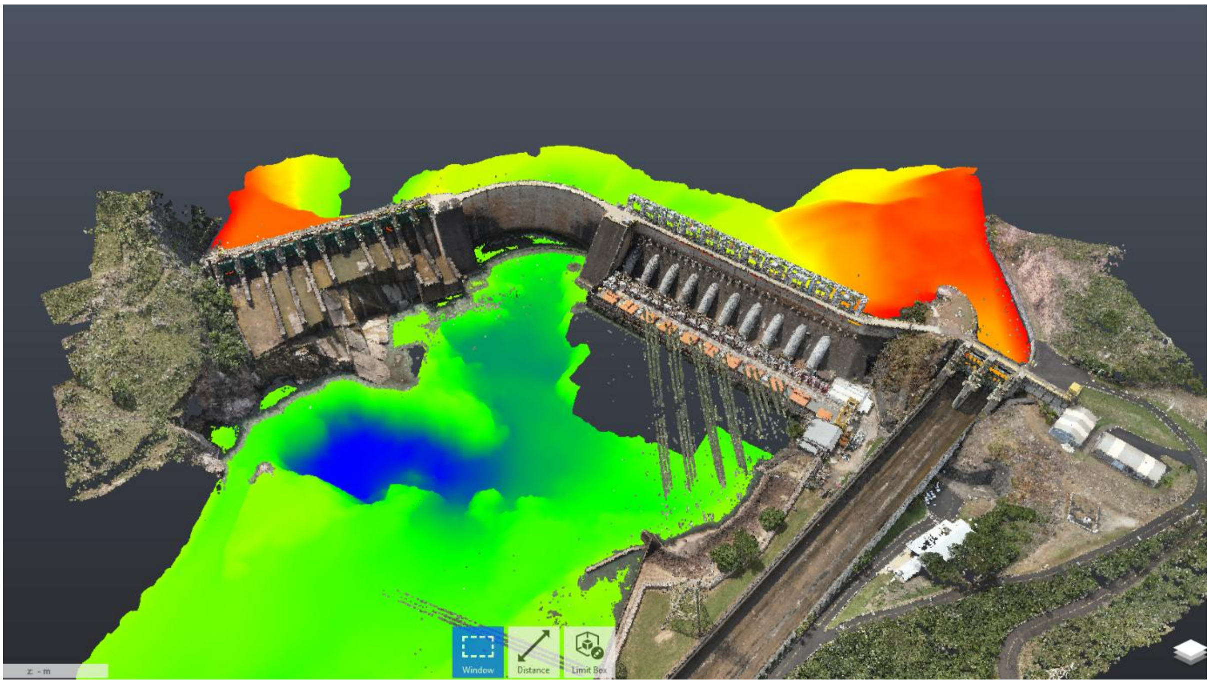

Figure 1 – Lidar and Bathymetry (hybrid cloud) of points (Mascarenhas de Moraes – DAM)

The entire survey was managed with dedicated bathymetry software installed on an on-board computer, which received, organized, and stored the data streamed from the GNSS receiver. The layout of the sounding lines (cross-sections) was established during the project's pre-field diagnosis and planning phase. The echo-sounder was fitted with DGPS receivers that delivered planimetric accuracy of ±8 mm ± 1 ppm × RTK baseline length and altimetric accuracy of ±15 mm ± 1 ppm × RTK baseline length for the vessel's position. In addition, the echo-sounder was calibrated at the beginning and end of each survey day. The colour scale depicts water depth, clearly illustrating how deeply the concrete is embedded in the underlying rock mass.

3- DATA PROCESSING

A consistent hybrid cloud, already aligned to the local geodetic system, from which a detailed three-dimensional model was built in Autodesk Revit, presented at Figure 2a. Each structural element was created as an independent block, Figure 2b, facilitating individual selection and extraction of geometric properties such as volume, center of gravity, and surface area—while the foundation line was represented as a shell surface to maintain coherence between the structure and its base.

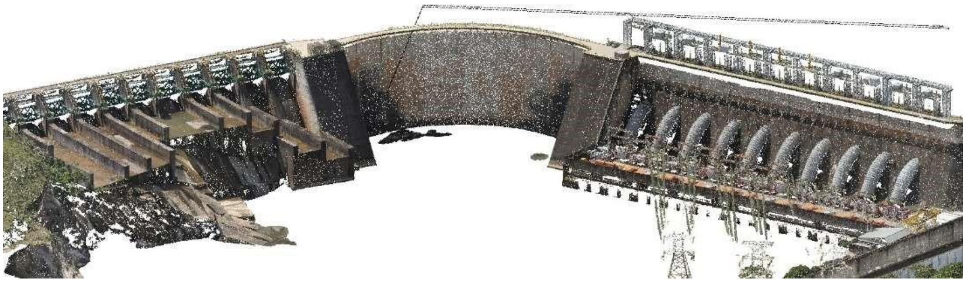

Figure 2a – Cloud of Points – Autodesk Recap

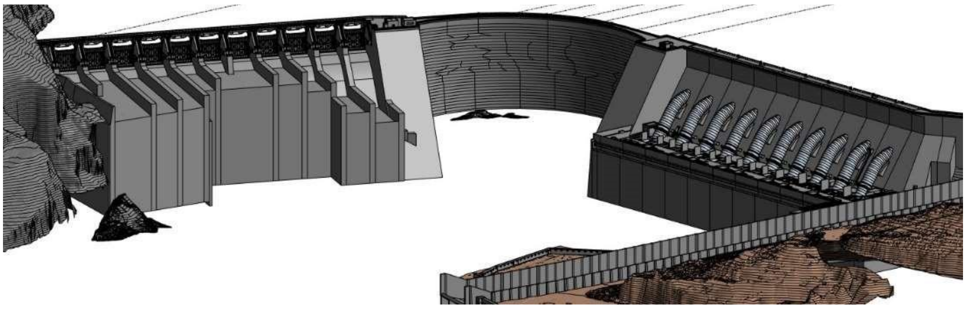

Figure 2b – Geometric Model (BIM) – Autodesk Revit

Figure 3 provides a view of the spillway from the North Abutment Block, juxtaposing the point-cloud-derived mesh with the corresponding Revit geometric model.

Figure 3(a) – Cloud of points Recap

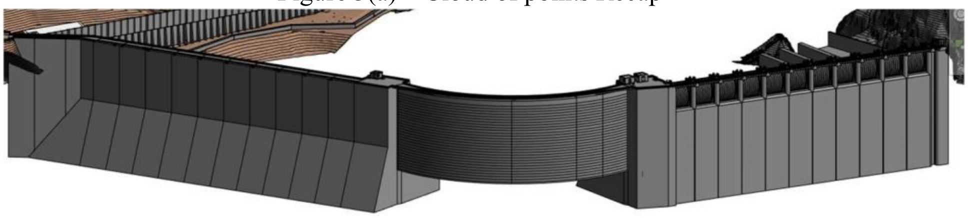

Figure 3(b) BIM Model - Revit

The final model, free of duplicate lines or overlapping surfaces, was exported in Autodesk Revit (.rvt) and InfraWorks (.iwx) formats, retaining topographic metadata, material attributes, and element hierarchy required for volume calculations and subsequent structural analyses. In parallel, cadastral measurements of notable levels, slopes of the upstream and downstream faces, and geometries needed to determine construction material volumes were linked to the BIM elements, ensuring traceability between field data and digital quantifications.The geometric base for numerical modeling was constructed by integrating different data sources: conventional topographic surveys, reservoir bathymetry, and laser scanning (LiDAR). The consolidation of these techniques resulted in a hybrid high-density point cloud capable of representing with high fidelity the geometry of the dam, the underlying rock mass, and the surrounding terrain.

The point cloud was processed using specialized software to remove noise, align coordinates, and convert the data into surface models compatible with BIM environments and geotechnical simulation platforms. From this geometric model, a three-dimensional volume was generated and imported into RS3 (Rocscience), the software used for numerical modeling and analysis.

4-Three-Dimensional Finite Element Modeling

The three-dimensional modeling was performed using RS3, a platform based on the Finite Element Method (FEM) designed for 3D geotechnical analyses. The dam and its foundation rock mass were discretized into 156,151 four-node tetrahedral elements, with an average edge length of 13 meters. The mesh was developed to balance geometric resolution, numerical stability, and computational efficiency.

The material properties were defined based on values found in the technical literature, adopting the Mohr-Coulomb failure criterion, which is suitable for brittle materials with linear elastic-plastic behavior. Table 1 summarizes the parameters used for the structural concrete and the intact basaltic rock.

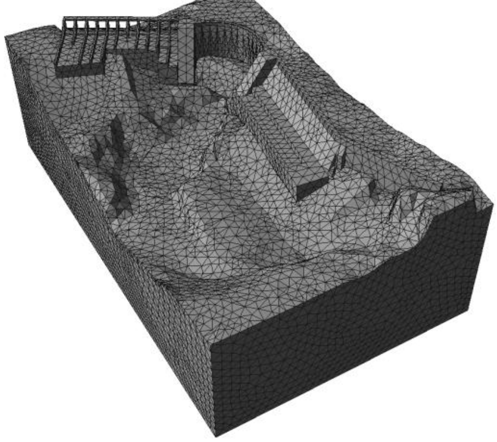

Figure 5 – Three-dimensional view of the finite element mesh (front view).

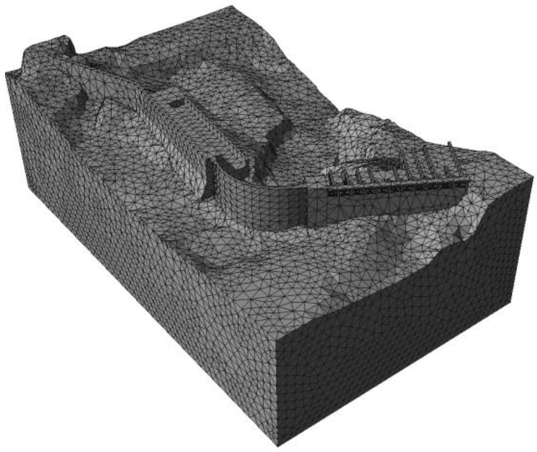

Figure 6 – Three-dimensional view of the finite element mesh (rear view).

The material properties were defined based on values found in the technical literature, adopting the Mohr-Coulomb failure criterion, which is suitable for brittle materials with linear elastic-plastic behavior. Table 1 summarizes the parameters used for the structural concrete and the intact basaltic rock.

Table 1 – Material parameters used in the numerical model

Material	f_{ck} [MPa]	γ [kN/m³]	c [kPa]	ϕ [º]	E [GPa]	ν [-]
Rock	-	22	300	30	20	0,30
Concrete	25	25	513	35	28	0,20

Legend: f_{ck} – characteristic compressive strength of concrete; γ – unit weight; c – cohesion; ϕ – internal friction angle; E – Young's modulus; ν – Poisson's ratio.

Boundary conditions were applied through displacement constraints on the contact surfaces between the structure and the rock mass, simulating lateral and bottom confinement. Loading was applied in two phases: (i) the structure's self-weight and (ii) hydrostatic pressure corresponding to the reservoir's Maximum Maximorum Level

(MML). The solver was configured with a tolerance of 0.001 and a maximum of 500 iterations, ensuring computational stability and result convergence.

5-Results and Discussion

The simulations performed using the three-dimensional model made it possible to evaluate the structural behavior of the Mascarenhas de Moraes Hydroelectric Power Plant dam under two loading conditions: (i) self-weight only, and (ii) the combination of self-weight and hydrostatic pressure corresponding to the reservoir's maximum operating level. The results include distributions of vertical stresses, displacements, and principal strains, enabling an integrated analysis of the interaction between the concrete structure and the underlying rock mass.

5.1 Behavior under Self-Weight

In the first stage of the simulation, only the self-weight of the dam was considered. Vertical stresses increased progressively with depth, as expected, due to the accumulation of load throughout the structure. The highest stress concentrations occurred at the base and in the contact zones with the rock foundation.

The displacements observed were predominantly vertical, with maximum values below 4 mm, attributed to the elastic deformation of the constituent materials. Horizontal displacements were negligible (< 1 mm), indicating good stiffness and global structural stability under gravitational actions.
The distribution of effective stresses and shear strains revealed a cohesive and stable structural behavior, with no indication of localized instability. The high-quality mesh and well-defined boundary conditions contributed to producing stress fields consistent with the expected physical behavior.

5.2 Behavior under Hydrostatic Loading

In the second stage of the analysis, hydrostatic pressure was applied to the upstream face of the dam, considering the reservoir's Maximum Maximorum Level (MML). The introduction of this load resulted in a significant increase in both stress and displacement, particularly in the central curved region of the dam structure. The maximum horizontal displacement in the "y" direction was approximately 9.8 mm, while in the "x" direction it was 4.4 mm. Vertical displacement remained below 1.9 mm. These values indicate that, even under extreme loading conditions, the dam continued to operate predominantly within the elastic range.

Principal strains increased in magnitude but remained within safe limits expected for conventional concrete structures. The simulation also highlighted how the curved geometry of the dam contributes to stress redistribution, emphasizing the importance of three-dimensional analysis for such structures.

5.3 Technical Discussion

The results demonstrate that, even with the adoption of literature-based parameters, the methodology was effective in representing the overall structural behavior. The 3D FEM simulation enabled the observation of spatial effects, such as out-of-plane displacements and stress concentrations in specific regions, which would not be adequately captured by simplified 2D models.

Moreover, the numerical model shows potential to serve as the core of a Digital Twin system, integrating real-time data from instrumentation, periodic inspections, and monitoring sensors. Such integration supports the implementation of predictive maintenance and risk management strategies, in line with international dam safety guidelines (USBR, 2015; ICOLD, 2013).

6. Final Considerations

This study presented an integrated methodology for assessing the structural safety of dams, combining reality capture technologies with three-dimensional finite element modeling (3D FEM). The proposed approach was applied to the case of the Mascarenhas de Moraes Hydroelectric Power Plant through the development of a detailed geometric model based on LiDAR data, bathymetry, and topographic surveys, subsequently imported and analyzed using the RS3 software (Rocscience).

The simulation results indicated that the dam structure behaves in a stable manner under both self-weight and hydrostatic loading conditions corresponding to the reservoir's maximum operating level. The distributions of stress, strain, and displacement remained within safety thresholds, consistent with the mechanical properties of conventional concrete and intact rock foundations. The 3D modeling approach enabled the identification of critical stress concentration zones and the capture of out-of-plane effects, demonstrating clear advantages over simplified two-dimensional analyses.The proposed methodology proved to be effective, replicable, and scalable, offering technical support for predictive safety evaluations, maintenance planning, and structural intervention strategies.

By incorporating technologies such as BIM (ISO 19650-1-2018), point cloud data, 3D FEM, and GIS tools, the approach paves the way for the establishment of a Digital Twin system applied to dams—aligned with the best practices recommended by institutions such as the Bureau of Reclamation (2015), USACE (2003), and ICOLD (2013). As a future development, it is recommended that specific field campaigns be conducted to obtain physical and mechanical parameters of the concrete and rock mass at the Mascarenhas de Moraes plant. This would allow for the calibration of numerical models with in situ data, improving the reliability of structural simulations. Furthermore, integrating real-time structural health monitoring systems represents a key next step toward the full implementation of a functional Digital Twin for dam safety management.

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REFERENCES

BUREAU OF RECLAMATION. *Best Practices in Dam and Levee Safety Risk Analysis*. Denver, CO: U.S. Department of the Interior, 2015. Disponível em: https://www.usbr.gov/ssle/damsafety/risk/methodology.html. Acesso em: 7 jun. 2025.

UNITED STATES ARMY CORPS OF ENGINEERS (USACE). *Engineering and Design – Slope Stability*. EM 1110-2-1902. Washington, D.C., 2003.

INTERNATIONAL COMMISSION ON LARGE DAMS (ICOLD). *Guidelines for Use of Numerical Models in Dam Engineering*. Bulletin 154. Paris: ICOLD, 2013.

GRÊT-REGAMEY, A. et al. Digital twin technologies for infrastructure: A review of applications in civil and environmental engineering. *Automation in Construction*, v. 132, p. 103967, 2021.

ZIENKIEWICZ, O. C.; TAYLOR, R. L. *The Finite Element Method for Solid and Structural Mechanics*. 7. ed. Oxford: Elsevier, 2013.

ROCSCIENCE INC. *RS3 – 3D Finite Element Analysis for Geotechnical Engineering: User Guide*. Toronto, 2022.

INTERNATIONAL HYDROGRAPHIC ORGANIZATION (IHO). *Standards for Hydrographic Surveys – S-44, 6th ed.* Monaco: IHO, 2020.

ISO 19650-1. *Organization and digitization of information about buildings and civil-engineering works, including building information modelling (BIM) — Information management using BIM — Part 1: Concepts and principles.* Geneva: International Organization for Standardization, 2018.

HEIJMANS, S.; FRANGOPOL, D.M.; ESHELBY**, S.** Digital twins for civil-infrastructure asset management: a critical review and implementation framework. *Structural Safety*, **110**, 102613, 2024.