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AI tools for the structural health assessment of concrete dams: merits and limits

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Abstract

Assessing the structural conditions of large concrete dams involves collecting and processing a large amount of data on the response (e.g., in terms of displacements) to seasonal variations in external actions (typically, changes in temperature and water level). Measurements are usually provided by the instruments traditionally installed on the facility, while emerging vision-based technologies can provide supplementary information as needed. Artificial intelligence methodologies (mainly, machine and deep learning) trained on monitoring data can improve the quality of the gathered information, predict the expected structural response, and detect anomalies. However, locating and identifying the type and severity of potential damage remains a challenging task. This paper discusses the related difficulties with specific reference to the peculiarities of concrete dams, where the sensitivity of measurable quantities to degradation scenarios can be critical.

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1. Introduction

Artificial intelligence (AI) permeates various areas of our lives, including humanities and arts (Caruso and Spadaro 2024; Rawas 2024; Ezhilmurugan, P., Yashavini 2024). One particularly relevant application field is image processing, which is used in security (e.g., facial recognition), virtual reality and video games (El Fadel, 2025; Lampropoulos,

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2025; Yannakakis and Togelius, 2025). The ability to perform accurate image-based analyses is a powerful diagnostic tool in healthcare (Hernström et al., 2025; Mascaldi et al., 2025) and, potentially, structural mechanics. In this context, AI tools greatly improve the quality of the information that can be acquired even using moving instruments mounted on drones, eliminating (or, at least, reducing) noise and blurring from snapshots (Archana and Jeevaraj, 2024; Dede et al., 2025; Trigka and Dritsas, 2025; Hajjar et al., 2025). AI technologies have attracted the interest of the dam community in several aspects (Hariri-Ardebili et al., 2023; Cai et al., 2025). In this paper, we review the application of AI in the field of structural integrity, highlighting the advantages and challenges brought to the dam engineering sector.

2. AI assisted monitoring of concrete dams

One major damaging source of quasi-brittle (concrete, masonry) structure is fracture. The appearance and evolution of surface cracks can be detected automatically in high resolution images by exploiting the feature extraction capabilities of deep learning and machine learning algorithms (Bhowmick et al., 2020; Hamishebahar et al., 2022; Parente et al., 2022; Iraniparast et al., 2023; Reis et al. 2025). Pattern-matching algorithms combined with digital image correlation techniques allow relative movements to be assessed with high accuracy (Hassam, 2019; Belloni et al.; 2023). The stereoscopic arrangement of cameras permits to determine the distribution of opening and sliding displacements that develop (in-plane and out-of-plane) at discontinuity surfaces (Malowany et al., 2017; Dizaji et al., 2021) such as the natural (cracks) and artificial (construction) joints, which are the main non-linearity source in dams (Bolzon et al., 2025). This type of experimental information collected on-site can be used to local diagnostic purposes, to determine the joint characteristics and their evolution (Maier et al., 2006; Puntel et al., 2006).

Global surveillance systems are also placed in dams. These include sensor networks that acquire information on external actions that vary seasonally, and on the resulting changes in structural configuration. The large amount of measurements returned by these instruments can be used to train data-driven prediction models of the mechanical response of the facility under examination. Thus, it is possible to evidence any possible deviation between the actual and expected trends (Chen et al., 2021; Li et al., 2025).

Safety assessment requires identifying the source of any anomaly, which could be attributed to causes of varying severity such as: the malfunctioning of some instruments; a combination of external actions that have never occurred before; a degradation process. Finally, the damage type, position and severity should also be identified from the earliest stages (Fig. 1).

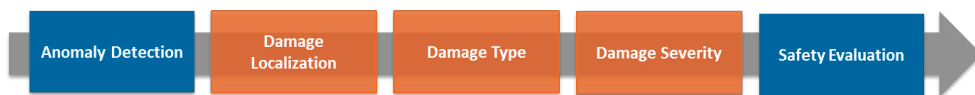


Fig. 1. Safety assessment process.

In the case of dams, the whole evaluation process is difficult to complete based on monitoring data alone. In fact, dams are resilient structures, with only a few reported failures, and the available information is hardly transferable from one situation to another as each installment is almost unique, with different geometries and ambient conditions. In all cases, imperfect and incomplete information compromises the accuracy and reliability of data-driven warning systems (Lever et al., 2025).

These limitations can be addressed by hybrid methods that integrate available measurements with the results of physics-based simulations of the system response under the most critical conditions (Bolzon et al., 2025; Zhai et al. 2025). In these approaches, monitoring data are also used to calibrate the parameters entering into numerical models, often developed in the finite element framework. Uncertainties, for example related to the characteristics of the foundation rock, can be controlled by implementing reduction and sub-structuring techniques (Li et al., 2024; Sengupta, and Chakraborty, 2025). Simulation models can be continuously updated, taking into account the evolution of structural characteristics over time, in order to build realistic digital twins of the structure under consideration.

However, the effectiveness of this approach is not guaranteed in the case of dams, both because the sources and locations of damage can be numerous and would require combinatorial calculations, and because the sensitivity of the

structural response to degradation processes can be low (Li, 2021). Thus, variations in the system response due to initial damage can be confused with experimental errors.

4. Discussion and conclusion

Artificial intelligence methods can effectively support the safety assessment of existing dams from different perspectives, processing large amounts of monitoring data and improving the quality of measurements obtained from both conventional instruments and more recently developed vision-based techniques. Despite continuous advances in algorithmic performance, comparative studies in the dam sector have shown that no single self-learning approach consistently outperforms the others under all conditions (Salazar et al., 2015).

The main challenges, however, are not purely algorithmic but physical: the measurable quantities in dams often exhibit low sensitivity to early degradation processes, which hinders the development of fully reliable automatic diagnostic tools capable of detecting damage at an incipient stage and assessing its implications for structural safety. Even when anomalies can be detected and the most affected variables identified, understanding the type and severity of the underlying process requires comparison with physics-based simulations, typically carried out within the non-linear finite element framework. Such analyses are computationally demanding and need to be systematically performed for each specific structure in order to establish a sufficiently comprehensive knowledge base for interpretation.

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