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REVIEW PAPER

A Milestone Vision on The Applied Methodologies for Concrete Dam Health Monitoring

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Abstract

This research reviews the applied various methodologies for concrete dams' health monitoring and assessment. The main type of dams focused on this review is the embankment fill dams that serves as an important function in water supply, irrigation, and hydroelectric power. The emphasis is devoted on the integration and assessment of static and dynamic methods for dams monitoring in order to improve safety and increase the life span of dams. Static methods are usually monitor changes that are prolonged over time and are critical for the assessment of the enduring structural health. Whereas, dynamic methods are considered as real-time data crucial to address immediate changes in the environment and operation. Mathematical models and structural health monitoring techniques were surveyed that improves the encompass of hydraulic, thermal, crack, and time (HTCT) model for extreme conditions. In addition, the use of artificial intelligence (AI) was explored and particularly for internal erosion monitoring. Comparison of such analyses reveals that static monitoring is efficient in its approach to assessment over the long term, while dynamic monitoring performs better in coping with instant changes. Based on the review findings, therefore, it could be concluded that an integrated approach with the use of static and dynamic methods, supported by advanced computational models, would enhance the effectiveness of monitoring systems. The future work shall focus on the development of such integrated systems to increase the resilience of dam infrastructures, while the monitoring technologies have to be adapted continuously to the environmental challenges and the complexity of dam systems.

Keywords: Structural health monitoring dam; Static Monitoring dam; Dam dynamic monitoring; Safety enhancement; Dam lifespan.

1. Introduction

1.1 Background

Concrete dams are backbone infrastructure, and they perform several vital functions, such as conveying water to households, supporting the irrigation process, producing electricity by utilizing hydropower, and supporting a structure for flood control. Since the failure of the structure can expose the situation to very serious risks, this is an extremely critical category of dams with a technically careful assessment in their construction and maintenance. It is through comprehensive inspection that ensures safety and effective performance of these diverse functions [1]. The high quality, durability, and high resistance against the forces of nature are conformed to using RCC for the dam structure. RCC has high resilience to temperature variations throughout a day and at the time of seismic shocks. It is the most preferred material considering strength and resilience toward the long term in a safe, durable construction [2].

In order to automatically assess the health and safety of civil engineering structures, identify potential structural damages before they reach failure and collapse modes, locate damaged or vulnerable areas, and quantify the degree of damage severity, structural health monitoring, or SHM, has emerged as a useful and emerging technology. Senses play an important and necessary role in SHM. Contact and non-contact sensors in conjunction with wired, wireless, and Internet-of-Things (IoT) systems are primarily considered to record a variety of structural responses and influential environmental and/or operational data, dependent on the primary goal of a SHM project, the type and size of civil structures, their geographical locations and accessibility, weather conditions and economic justification [3].

Even though dams have been built for thousands of years, dam engineers are always working to create innovative technologies that will increase both the safety and the financial viability of building new dams. Particularly in recent decades, the methodical development of diverse dam construction technologies has created a solid basis for comprehending the behavior of dams, permitting the construction of larger dams and leading to noticeably higher levels of dam safety. Due to its advantages in terms of efficiency and safety, gravity dam and arch dam configurations are being used in a growing number of projects as a result of the successful development of roller-compacted concrete dams and traditionally vibrated concrete dams. However, there is still a clear problem with concrete dams temperature spikes [4].

Roller Compacted Concrete (RCC) concreting technology development is among others that have brought a revolutionary change in the construction of dams. In comparison to traditional processes, this technology will be proved to be a far quicker and more cost-effective process in speeding up construction and ultimately bringing prices down. This development has really increased the rate at which the construction of dams is done and slashed the resources that could be expended, hence saving us a lot of time and money [5]. Modern innovations in this field, such as Rock-Filled Concrete (RFC) and low-cement concrete, have therefore completely changed the paradigm for the design and construction of dams. The improvements, in the meantime, also have the potential to reduce the waste of resources through problems that have persisted in the sector, such as temperature-related cracking. These developments are great progress in obtaining green methods of construction that go a long way toward environmental protection while building up critically important infrastructure [2], [6].

Our aging and deteriorating concrete dams need rehabilitation and refurbishment in order to extend their service life and ensure safety. In this operation, key works would have to involve underwater activities and shotcrete, but also the full panoply of techniques, from mortar recovery to cementitious concrete. Techniques like these have been honed through a suite of international projects in such a manner that they have been proven efficient in their role of ensuring and advancing the safety of their respective structures for many years to come [7]. Issues such as alkali-aggregate reactions are very important to be addressed in the process of maintaining buildings and other structures in order to ensure durability and strength. These are a series of active chemical reactions in concrete that gradually result in the loss of both strength and, in turn, a reduction in stability and safety throughout the life of a building [8].

The goal of recent research has been to investigate ways to protect concrete buildings against the damaging effects of severe weather. Researchers are advocating for the use of innovative construction and maintenance strategies that boost the resilience and longevity of dams [9]. Building on this, the strategic construction, like the phased building of gravity dams on mountain rivers, highlights ongoing improvements in construction methods aimed at reducing lead times and costs [10]. Concrete dams are crucial to global infrastructure, so ongoing research and technological development focus on improving their construction, maintenance, and performance under various environmental and operating conditions.

The literature on the health monitoring of concrete dams reveals gaps, particularly in the exploration of specific methodologies. While some studies have introduced new models and techniques, comprehensive reviews and comparative analyses of these methodologies are extremely scarce. For example, the development of a mathematical monitoring model that integrates the aging and temperature components for concrete dams is a significant advancement, yet the comparative effectiveness of this model against other models has not been discussed in detail [11]. However, the introduction of a denoising contractive sparse deep autoencoder model to handle incomplete dynamic data in dam monitoring represents a novel approach that has not been broadly evaluated within the context of existing literature [12].

The proposal of a dam displacement health monitoring model that considers extreme climate conditions and employs multi-output least-square support vector regression for efficiency improvement is another example of methodological innovation. However, the literature does not extensively compare this model's performance across different climatic conditions or dam types [13]. Moreover, while systematic literature reviews on structural health monitoring systems for bridges have been conducted, a similar comprehensive review focusing on concrete dam health monitoring methodologies, especially comparing machine learning algorithms and feature extraction techniques, is missing [14]. The challenge of imputing missing deformation data in dam monitoring has been addressed through a new method, yet the integration of this method with other monitoring techniques and its comparative analysis remains underexplored [15]. Furthermore, the identification and elimination of gross errors in deformation monitoring data through a combined method highlights the need for more robust error handling techniques, but literature on the comparative effectiveness of these techniques is limited [16].

The application of Generative Adversarial Networks in structural health monitoring is a recent development, indicating a gap in the review of such applications specifically for concrete dams [17]. Additionally, the identification of structural modal parameters using seismic monitoring data provides valuable insights, yet the literature lacks a comprehensive analysis of different modal identification methods and their applicability to concrete dams [18]. The methodology for monitoring internal erosion in earth and rockfill dams using artificial intelligence techniques represents a novel approach, but the literature does not extensively cover the integration of these techniques with traditional monitoring methods [19].

The development of a model for dam multiple-point displacement monitoring based on the support vector regression algorithm introduces a new perspective on handling spatiotemporal correlations, yet the literature does not thoroughly compare this model with existing single-point monitoring models [20]. In summary, while individual studies have contributed valuable methodologies for concrete dam health monitoring, the literature reveals a significant gap in the comprehensive review and comparative analysis of these methodologies, highlighting the need for further research in this area.

Health monitoring systems are classically associated with static data: this is the case for dams, which are classically equipped with systems capable of measuring displacements, stresses, relative movements between joints or temperatures, aiming at the study of the structural static behavior. In any case, vibration-based health monitoring systems have already been successfully implemented in many different large civil structures such as bridges, wind turbines, stadia roofs, and bell towers [21].

The "Baixo Sabor" hydroelectric powerhouse consists of two dams, 12.6 km distant from each other, on the Sabor river, a tributary of the Douro river in "Torre de Moncorvo", northeast of Portugal. This work focuses on the upstream dam, a concrete double-curvature arch dam, embedded in a narrow valley zone, 123 m in height, whose crest is 505 m long. The arch is composed of 32 concrete vertical blocks separated by vertical contraction joints and crossed, in its full length, by six horizontal visit galleries. The spillway of the dam consists of four floodgates, each 16 m long. Figure 1 shows an aerial view of the dam and of the reservoir and a closer picture of the spillway. From this aerial photography, it can be observed that the powerhouse containing turbines for electricity production is quite close to the dam site [21].

Figure 1: *Baixo Sabor arch dam, reservoir and dam from above, and downstream spillway detail [21].*

Structural health monitoring (SHM) tasks for dams are typically carried out by calibrating a prediction model between input variables such as environmental and age-related parameters, and the monitored dam responses, as illustrated conceptually in Figure 2. Existing prediction models can be broadly classified into two categories: deterministic and statistical models. Deterministic models utilize numerical techniques such as finite element method to predict the dam responses. The advantage of deterministic models is that they can be applied during the first filling of the reservoir, which is generally considered to be the most critical period in the service life of a dam. Andonov et al used such a model to demonstrate the safety of Tsankov Kamak dam (TK dam) located in Bulgaria under earthquake-induced natural hazards. However, such models require significant modeling effort, model calibration (which is often cumbersome), and are inadequate to represent nonlinear processes such as damage and leakage. On the other hand, statistical models operate directly on measured data (i.e., they fit models to the data directly) without utilizing physics-based models as predictors [22].

This study significantly contributes to the current state of knowledge on health monitoring in concrete dams through a broad and exhaustive review of the most recent methodologies and their performances. Our research critically discussed recent innovations in mathematical modeling and AI-driven technologies compared to traditional monitoring techniques for their improved accuracy and efficiency. Moreover, by discussing real-world applications and the challenges related to integration, the research not only presents the value of these advances but also proposes novel solutions for enhancing the robustness and reliability of dam health monitoring systems. These contributions are crucial as they address major gaps in the literature and guide future research and implementation strategies in the field.

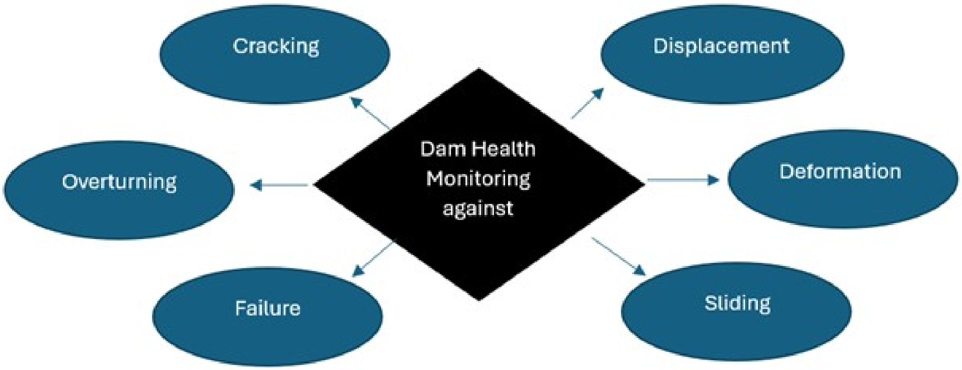

Figure 2: *Dam health monitoring.*

1.2 Significance of Research

The significance of research in concrete dam health monitoring is underscored by the critical need to ensure the safety and longevity of these structures, which are vital for water supply, irrigation, and hydroelectric power generation. Recent advancements in mathematical models and monitoring techniques have greatly enhanced the ability to diagnose and predict the structural health of concrete dams. For example, the formulation of a mathematical model for monitoring concrete dams will result in the reconstruction of the aging and temperature parts, which further results in a more realistic representation of the dam's displacement and, hence, an enhancement of the separated displacement component interpretation; this ensures higher accuracy in health diagnostics [23]. In addition, the hydraulic, thermal, crack, and time (HTCT)model considers the extreme cold environment in dam health monitoring, improving the efficiency and accuracy of the model [13].

Development of the dam safety monitoring model with the integration of gross error identification will help to address strong nonlinearity in overcoming the problems with identifying and eliminating gross errors from deformation monitoring data, which will increase the prediction accuracy significantly [24]. It also recognizes the need to utilize support vector regression algorithms in the monitoring of multi-point displacements when analyzing the global health status of a dam regarding structural health in general, considering the correlation displacements at multi-point measurements [15]. The advancement in Seismic and Structural Health Monitoring (SSHM) systems for dams, using software for the automated analysis of monitoring data and computational 3D finite element models, significantly furthers the study of the dynamic behavior of dams for SSHM [16].

Research is also being carried out to assess the influence of cracks on dam safety through change-point detection methods for timely and accurate evaluation of the structural condition [25]. The crack's elastic net monitoring model enhances the interpretability and robustness of the displacement monitoring data modeling, in a way that a much more refined insight into the displacements induced by the cracks is attained [17]. The impact of environmental changes on dam structures underlines the need for continuous structural health monitoring (SHM) to predict and mitigate possible damages[18]. The employment of artificial intelligence techniques, in particular deep neural autoencoders, has opened new prospects for monitoring internal erosion in earth and rockfill dams for the detection and analysis of damaged dam structures [26]. Finally, in sensitivity analyses involving static performance of concrete gravity dams, the understanding becomes much more complex concerning dam systems and SHM importance in the furtherance of engineering science and technology [27].

1.3 Objectives

This study is oriented towards ensuring the safety of concrete dams through the proper modeling of displacements and the challenge of extreme climatic conditions. The identification of major errors and systematic review of existing health monitoring methods is a crucial research area for improving these techniques' effectiveness in ensuring dam stability within varied environmental conditions. This includes:

- Evaluation of effectiveness of the methods of monitoring of health.
- Discussion of the pros and cons of each method.
- Identifying the challenges of using these methods and think about possible solutions.

2. Literature review

Keeping dams safe is essential, not just for the dam itself, but for the communities that rely on them. That is why it's important for those who own dams and the policymakers to develop systems and models to monitor dam health. These instruments are essential for averting catastrophic events and dam breakdowns, not merely for reducing maintenance expenses. Scholars are working hard on complex models that track the behavior of dams using data from sensors on the dam or by combining historical data with computer simulations. These monitoring programs' primary goal is to identify any early warning indicators. Early detection of these can alert us to possible threats and provide us enough time to take appropriate action [28].

For legislators and dam owners, monitoring the condition of dams and developing predictive models are essential jobs. These models are vital in averting future disasters and dam breakdowns that could affect neighboring communities, in addition to improving the effectiveness and economy of maintenance. Scientists are working very hard to create these novel models. They employ information from sensors on dams or examine past data and computer simulations to learn more about the physics of dam systems. Water pressure, temperature, the age of the concrete, and its mechanical qualities are some of the variables that can alter how a dam acts, including how it bends and the stress on its concrete and other structural features. The relationship between the loads on the dam and the structural responses as illustrated in Figure 3. The main goal of any DHM program is to identify, as early as possible, any anomaly in the dam responses, which can result in upcoming danger and allow the dam owner a sufficient time to implement a corrective measure [28].

The methodologies for health monitoring of concrete dams include techniques dealing both with static and dynamic conditions, offering guaranteed structural safety and operational security. Concerning static monitoring techniques, the focus is mainly on the evaluation of displacements and cracking to get a behavioral and general health evaluation of the dam structure; in this sense, SVR algorithms are applied in modeling multiple-point displacements to get a comprehensive insight into dam behavior, considering spatiotemporal correlations that help in increasing the accuracy and robustness of the monitoring model [11]. Similarly, the changepoint detection techniques used are those applied to identify cracks and assess their influence on both structural safety and static health monitoring approaches in times of assessment that are both timely and accurate [29].

In the dynamic monitoring technique's is that the seismic monitoring data are fundamental in the identification of the modal parameters of the dam, which are necessary for the realization of seismic response analyses of the structure, the calibration of the finite element models, and post-earthquake damage assessment [30]. The smart advances in SSHM have been developed into automatic monitoring systems coupled with data analysis together with 3D finite element computational models to further heighten the understanding of the dynamic behavior of the dam when it comes to seismic events [13]. The development of the monitoring techniques based on artificial intelligence, such as deep neural autoencoders, in the framework of acoustic data processing, opens new frontiers to monitor one of the main dynamic challenges of proper earth and rockfill dam operation internal erosion [31].

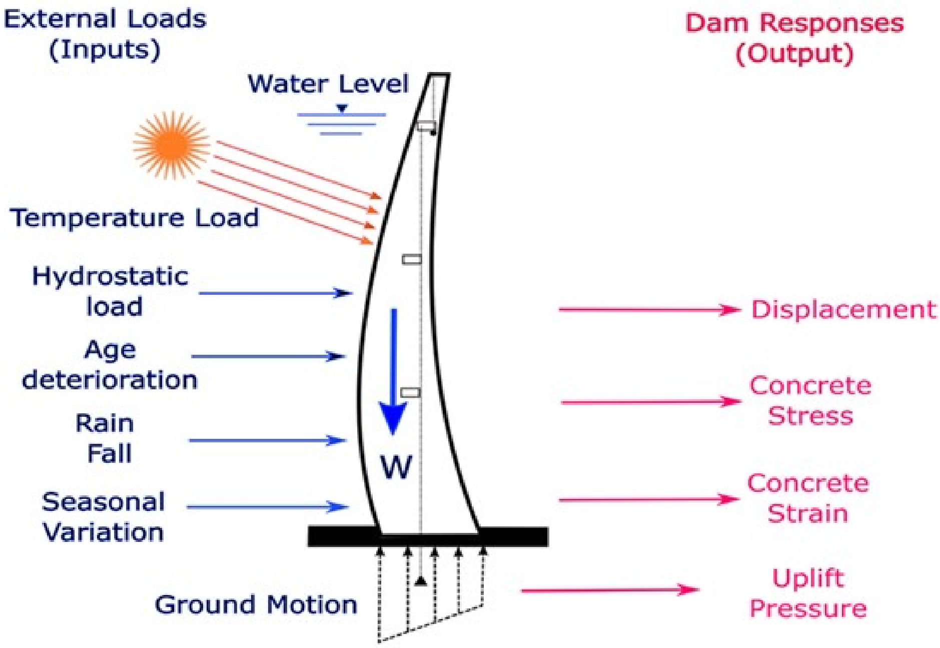

Figure 3: *Various external loads acting on a dam and the resulting dam responses.*

This approach complements traditional static monitoring by offering insights into the effects of internal erosion on dam responses to external stimuli. Moreover, the development of Bayesian frameworks to static and dynamic SHM should emphasize the necessary usage of monitoring system observations on the decrease in the uncertainties in numerical models. This improvement of the model ultimately enhances the reliability in predictive models and the estimation of the seismic fragility[16]. From these research works, it is possible to state that the full approach to dam health monitoring, uniting static assessments of displacements and cracking with dynamic evaluations of the seismic response and internal erosion, is mostly beneficial with the addition of advanced computational methods and AI techniques. This approach leverages advanced computational and AI techniques to enhance the accuracy and reliability of monitoring efforts.

Although relevant advances have been made in the development of models that combine the effects derived from diverse environmental and operational factors, as is the case for aging and temperature, with the detection of anomalies in the health of dams, there is still a large gap in the literature for comprehensive comparative evaluations of these models [11]. Examples include the denoising contractive sparse deep autoencoder model for managing incomplete dynamic data, though these models represent major advances, they are applied very little, if at all, in wider dam monitoring practices.

In this paper, the addressed gaps are covered by a systematic review of the latest methodologies on dam health monitoring and their integration with mathematical modeling and AI-driven technologies. Thus, our objective is to discuss critically some recent innovations compared to traditional techniques in view of accuracy, efficiency, and challenges of integration. This research not only helps improve understanding of these techniques but also points out the way forward in terms of their development and implementation strategies, therefore leading to more solid and reliable dam health monitoring systems.

2.1 Static monitoring dam

Static monitoring forms part of the dam health assessment and is based on systematic observation and subsequent analysis of the structural integrity of the dam through measurements of deformations of a static nature influenced by variations of a physical nature—typically comprising parameters like water level, temperature, environmental factors, and others. These are important approaches for the sustainable operation and prolonged life of a dam system, especially in regions that are at risk of seismic activities. Static features are a very interesting alternative to dynamic methods, which normally have relevance to offer only in a continuous scheme with respect to the event being analyzed, as in the case of earthquakes, and therefore provide continuous insight into the structural health of the dam from measurements of its static behavior over time [32],[33].

Static monitoring encompasses the identification of potential structural damage and the prediction of long-term deformations, facilitating informed decisions regarding dam management and safety measures. By measuring how the dam's shape changes in response to things we can measure, like water pressure and temperature changes, static monitoring helps us spot any alterations in the dam's structure, These alterations could already be the first signs of damage or even of failure [16],[25]. The approach applies state-of-the-art technologies, such as wireless sensors and advanced modeling, for the assurance of safety of the dams and gaining proper knowledge about their behavior. Improved knowledge of the health of the structures of the dams through those intelligent sensors and data systems becomes very key from varied responses of the dam to the varied types of environmental factors, either with load or unload. This is important because it is made possible to form predictive models important in assessing and preserving the safety of the dams [34].

On the other hand, static monitoring and other forms of structural health monitoring are enormously important for safeguarding the safety of the dams and bridges. Structural health monitoring helps us determine through such procedures whether structures can really support the loads intended and at the same time adapt to varying environmental conditions. This is important for their safety and serviceability in a wide range of circumstances [35],[36]. In conclusion, one of the most giant elements of the maintenance of dam safety is static monitoring. In a nutshell, it is all about continuous observation and measurement of the static changes in dams, caused by operational and environmental factors. Such a monitoring system is one of the giant aspects of structural health monitoring that assists in correctly assessing and repairing dams [27].

Static monitoring is a flexible technique that enables monitoring from national energy use down to household energy use or securing buildings and the environment. After finding out that some static energy meters were not giving correct measurements, Basten Have and his co-workers came up with a new monitoring approach. The improved methodology is very useful mainly when the energy load is close to zero in order to find and compensate for disturbances that would make the measurements be out of sequence. This smart technique acquires more accurate readings by making use of a flickering LED from meters [37]. Jerzy Jasieńko and team performed a static analysis to investigate and fortify the brick vaults and pillars in the St. James Basilica. They further demonstrated the importance of static analysis for the structural sustainability of old buildings by using composite materials for the alleviation of tensions and the repair of cracks [38].

Zhigang Li and the associates have developed a static monitor tool to bring out improvements in the safety of the environment. It contains several specially made measuring devices regarding static electricity where it may pose a hazard. The device is favorable for enhancing safety in sensitive areas. It is also ideal for real-time monitoring and control purposes Polina Ilyinichna Ragozina and V. N. Ignatyev collaborated on identifying issues of software synchronization using the static analysis method. The research explains more on how this static analysis is very useful in ensuring the security and dependability of the software systems [39]. More in a novel approach, Eric Bodden and his team resorted to static analysis for runtime monitor verification; their overall goal was to make the software correct by improvement and hardening of the monitoring code. The way to achieve that is with the aid of static analysis showing quite well how it can be worth it to find issues early in the software life cycle, which actually helps to save costs and improve reliability [40].

At the same time, Tong Xiliang designed a static level-monitoring method that is intelligent in detecting whether the constructions are floating or settling down. In consequence, the collecting of data is done automatically and is more appropriate for continuous remote monitoring work, hence an important tool that is useful for the assessment of the structural stability with time [41]. Ying Huang and Donghai Xie proposed a new method of detection for static objects in video surveillance. Their proposed method achieved the easy identification and monitoring of static objects in any kind of scenario, significantly enhancing real-time analysis with the effective handling of noise interference [42]. Further enhancing the static analysis of existing timing analysis tools, Kwan-Yu Kim and colleagues developed an effective software monitoring framework that improves dependability. The developed software resolved the problems that were accumulating from the hardware variations, thereby providing additional predictable and reliable service routines on any platform [43]. Wang Tao and Zhou Wenqian took dynamic measurements up a notch by using vibrating wire sensors. They demonstrated how methods usually reserved for static cases can be brilliantly adapted to dynamic situations too [44].

Jeffrey D. Campbell designed a static monitoring system specifically for electronic manufacturing areas to guard against electrostatic discharge. His work really shows how crucial static monitoring is for protecting delicate electronic components[45]. Considered together, these studies underscore the rich applications and methodologies under which static monitoring has found its uses: energy meter enhancement, software reliability and environmental safety, structural health monitoring. This would indicate that improvement in static monitoring of dams is being achieved

Table 1 It provides a structured understanding of various static monitoring techniques, focusing on how they are applied to different types of dams. The uniqueness of each Method has both Advantages and Limitations for various aspects of dam safety and analysis.

Table 1: *Overview of Analytical Methods in Static Monitoring of Dams: Highlighting principles, advantages, limitations, and real-world applications.*

Method of Analysis	Principle	Advantages	Limitations	Name (Type) of Dam	Citations
Regression Analysis	Uses statistical techniques to model the relationship between dam deformation and influencing factors like water level, temperature, and seismic activity.	Provides a clear quantitative relationship Can predict future deformations based on past data.	May oversimplify complex interactions. Dependent on quality and quantity of historical data.	Hoover Dam (Arch-gravity)	[46]
Neural Networks	It uses multiple layers of artificial neurons for learning patterns in the data and for making predictions of dam conditions based on inputs of pressure, temperature, and structural response.	Capable of handling nonlinear relationships Can improve accuracy with more data.	Requires large datasets for training Complex to set up and interpret.	Oroville Dam (Embankment)	[33], [16]
Deep Learning Algorithms	Utilizes advanced forms of machine learning to analyze and predict dam behavior by processing vast amounts of data, including images and sensor readings.	Highly accurate in pattern recognition Can handle multifaceted data inputs simultaneously.	Computationally intensive Needs substantial computational resources and expertise.	Three Gorges Dam (Hydroelectric gravity dam)	[25], [18]
Ambient Vibration Measurement	Measures natural frequencies of dam structures to assess their condition. Uses sensors to record vibrations without external force application.	Non-invasive and continuous monitoring Useful for detecting changes in structural properties over time.	Sensitive to environmental noise May require frequent recalibration of sensors.	Fei-Tsui Dam (Arch)	[47], [48]
Seismic Response Analysis	Analyzes how dams respond to seismic activities by measuring the resulting vibrations and strains.	Essential for assessing dam safety in earthquake-prone areas Helps in understanding dynamic properties of the dam.	Requires specific instrumentation Data analysis can be complex due to the chaotic nature of earthquakes.	Kurobe Dam (Arch)	[49], [50]

2.2 Dynamic monitoring of dam health

One of the critical issues pertaining to the safety and sustainability of critical dam infrastructures is the dynamic monitoring of their health. From the basic techniques of dynamic monitoring, advanced techniques must include the latest methodologies in the form of SSHM: Seismic and Structural Health Monitoring systems, currently designed for real-time assessment of dam conditions by analysis of vibrations due to seismic events and operational activities [51]. These techniques are important because of the varying environmental and operational factors that may act upon dam structures over time: climate change, changes in weather, and pollution. This really makes continuous monitoring an absolute must for the prediction and safeguarding against structural damage [46].

The introduced innovative methodologies in monitoring are artificial intelligence techniques, where deep neural autoencoders are used in the analysis of acoustic data to assist in the detection of the internal erosion process, a major cause of failure in earth and rockfill dams [52]. In the same way, the employment of Bayesian frameworks in dynamic structural health monitoring of concrete gravity dams is promisingly reducing the uncertainties that are involved in the response of the monitoring systems and enhancing the reliability of the system [53]. As it can be also further indicated, automatic measurement, acquisition, and transmission data technologies in the SSHM system have contributed much to the further improvement of management and safety control for large dams [54].

Numerical modeling is one of the major exercises in assessing the behavior of the dam under different conditions, such as first impounding, seismic loading, and possible insights for safe operational practices, as well as future displacements [16]. Automatic identification of a modal and detection of seismic vibration is another ability the software supports in continuous vibration monitoring to help in achieving full understanding of the dam's dynamic behavior [25]. Vibration-based monitoring also takes into account environmental effects, such as water depth and air temperature, so as to enable the right assessment of the dam's health [55].

Emerging techniques, such as Digital Image Correlation, make it possible to measure displacements and to evaluate cracks, giving new forms of understanding the behavior of a dam under different environmental situations [56]. Moreover, they embody a significant advance, integrating modal identification and analysis algorithms into blind source separation (BSS)-based health monitoring methods, which allow the changes of a structure's integrity in a dam to be detected [57]. These dynamic monitoring techniques are very important in providing proactive management of dam safety in such a way that potential issues can be tackled and alleviated on time to avoid catastrophic failures.

The dynamic monitoring of the health of dams shows great progress in the integration of several methodologies and emphasizes SSHM (seismic and structural health monitoring) issues, detection of internal erosion, displacement monitoring, and applications of methods for artificial intelligence and machine learning techniques. As seen in the study by Jin-Soo Kim, the importance of using integrated software for automatic monitoring data analysis and 3DFE models for simulating the dam's dynamic behavior has been highlighted for this purpose. The method is found to be crucial in discriminating seismic events from operational vibrations for an accurate assessment of dam health [58].

Applying deep neural autoencoders for the processing of acoustic data to detect internal erosion in earth and rockfill dams is an innovative approach to understanding the effects of such an occurrence on the dam response to different external stimuli [13]. Therefore, the development of the HTCT model by Chongshi Gu et al. pertains to accurately monitoring the dam displacement health, especially under severely cold conditions, which consider the effects of extreme climate and engineering measures [46]. Arvindan Sivasuriyan et al. discuss the critical role of continuous monitoring in predicting structural damages caused by environmental changes, emphasizing the impact of soil erosion and scouring on dam structures [52].

Table 2: *Overview of Dynamic Monitoring Methods for Dams: Analyzing techniques, applications, and limitations.*

Method of Analysis	Principle	Advantages	Limitations	Name (Type) of Dam	Citations
Seismic and Structural Health Monitoring (SSHM)	Utilizes sensors to measure dynamic responses from seismic events and ambient conditions.	Provides real-time data on dam behavior Allows for immediate response to potential structural issues.	Sensor maintenance and calibration can be challenging Dependent on continuous power and data transmission.	Cabril Dam (Arch dam)	[58], [53]
Artificial Intelligence Techniques	Employs machine learning, like deep neural autoencoders, to analyze sensor data for anomaly detection.	Enhances detection of subtle patterns and anomalies Reduces false positives in data interpretation.	Requires extensive training data High complexity in model development and interpretation.	Cahora Bassa Dam (Arch dam)	[25]
Numerical Modeling	Uses 3D finite element models to simulate dam behavior under various operational and environmental conditions.	Allows for scenario testing without real-world risks Helps in planning for extreme conditions.	High computational costs Accuracy depends on the quality of input data and model assumptions.	Hoover Dam (Concrete arch-gravity dam)	[26], [62]
Advanced Data Processing Algorithms	Implements techniques like the light gradient boosting tree with Bayesian optimization to analyze deformations.	Improves prediction accuracy of dam deformation Efficient in handling large datasets.	Complex setup and tuning required. Potential overfitting with complex models.	Oroville Dam (Earth fill dam)	[63], [64]

M. M. Zheleznov and Haydar Al'-Dami's work contributes to the development of technical recommendations for conducting accurate studies of structural deformation in dams [53]. Muhammad Amer Jamil and Sabah Mahdi Rumayd's research on the Fei-Tsui arch dam in Taiwan showcases the use of wireless sensing systems for seismic response data and ambient vibration measurement, highlighting the importance of system natural frequencies in safety assessment [59]. Sérgio Oliveira and André Alegre's experience with the SSHM system of Cabril dam underlines the significance of software for automatic modal identification and the comparison between experimental data and computed results [15].

Advances in laboratory instrumentation for dam breach studies, as discussed in Context, emphasize the need for non-intrusive monitoring techniques to capture the complexity of eroding dam flows [60]. Qiubing Ren et al. suggested a support vector regression-based model for multi-point displacement monitoring of dams, taking into consideration the spatiotemporal correlation among the measuring points [61]. Finally, Xiang Zhi-Qian et al. apply their study to an arch dam in China, presenting an enhanced method of reducing the environmental effects on a vibration-based structural health monitoring approach by using a random forest model to adjust for non-structural factors [17]. All these developments collectively enhance the effective working of dynamic monitoring methodologies for dam health, which provide a holistic approach to the safety and operational integrity of dam structures worldwide. A structured view of the different dynamic monitoring techniques and their application to specific types of dams is presented in Table 2. All these methods have uniqueness in offering benefits in the dam safety understanding and management domain, but with challenges.

3. Assessment of evaluation

Comparative analysis of static and dynamic monitoring techniques shows distinct advantages, applications, and limitations in each approach, as found across research studies in various domains. Static monitoring techniques, as defined within the context of chip design, use process monitors to provide information about global and local process variations within a chip, thereby finding a very useful application in controlling power management for battery-operated mobile devices [65]. Static methods, on the other hand, have been utilized in the case of SHM, for monitoring the trends of the development of main crack displacements in the damaged masonry macro-elements over time, giving an insight into the state of the structural integrity and the effectiveness of the safety interventions [66].

These techniques are not time-dependent in nature and are therefore very vital for detecting states that are fixed over a large period of time. Dynamic monitoring techniques, however, are interested in capturing and analyzing changes that occur over a period of time and therefore specifically help in detecting conditions in a dynamic nature. For instance, dynamic state estimation in power systems, now enhanced with the new phasor measurement units, has had models added for capturing slow dynamics [67]. Dynamic methods are crucial for the structural engineering analysis of reinforced concrete buildings with seismic analysis, more so high-rise structures, which are more prone to earthquake forces, as the methods consider forces of inertia [68]. Moreover, dynamic frequency excitation and measurement based on vibrating wire sensors have shown effectively that measurements of strain can be gained continuously and the method be applicable to dynamic measurements [69].

While static monitoring techniques can provide dependable and simplicity monitoring for conditions that do not change over time, dynamic techniques are able to offer the flexibility and accuracy needed to be aware and respond to those changes. The choice between static and dynamic monitoring is thus essentially an issue of the requirements of a particular application, which include the kind of phenomena to be observed, the degree of accuracy of the observation, and the environmental conditions under which monitoring is taken [70],[71].

Static dam health monitoring can best be applied in the monitoring of long-term structural health in dams located within highly active seismic zones. Perhaps the most effective capability of static deformation measurements is the ability to measure long-term structural health without the need for constant vibration monitoring, which may be significant only during an earthquake [33], [72], [73], [74]. There have been developed a few techniques for coupling linear and nonlinear modeling processes to attain optimal residual error between identified models and measured static deformation, further enabling a higher level of accuracy with the prediction concerning long-term deformation and structural health [49]. Besides, the application of artificial intelligence, particularly deep neural autoencoders, to treat the geophones' acoustic data from inside the dams, will be a milestone for monitoring the most important failure mechanism in earth and rockfill dams internal erosion [35]. Such a methodology couples analysis of acoustic data with the Cumulative Sum Algorithms and Fuzzy Logic in showing high potential for early detection of internal erosion, the consequence of assuring the safe operation of these structures [75].

Obvious are the limitations of static dam health monitoring. Implementation of a permanent monitoring system on a vast dam is costly. Many dams may not be accessible for study because of national security concerns [36]. Moreover, most of the existing models are concerned with a single measurement point, which might be ineffective in assessing the overall status of the dam, especially in extremely cold regions, which might affect the model accuracy due to very harsh climate conditions [27]. Furthermore, the important data derived from both static and dynamic tests points out the limitations at present in the methodologies, on the other hand, with the complexities of the dam systems that call for sensitivity analysis of the performance of dam structures under static conditions [76]. In brief, while static monitoring approaches provide effective tools for the prediction and appraisal of the structural health of dams, their limitations point only toward the need for continuous innovation and adaptation of monitoring techniques to meet challenges posed by environmental conditions, accessibility issues, and inbuilt complexity in dam systems.

Consequently, when assessing dam health, the dynamic monitoring could be highly effective by providing real-time data on structural integrity, hence advancing the betterment of safety and operational efficiency for such a critical infrastructure. The application of the Bayesian framework to model updating in SHM of concrete gravity dams has shown a significant decrease in computational cost and uncertainties that help to improve the reliability of SHM systems [15]. Similarly, the best development of models sensitive to extreme climate conditions, such as HTCT, is coupling multi-output least-square support vector regression with grey wolf optimization for dam displacement monitoring to enhance accuracy and efficiency, especially in regions where the conditions are extremely cold [25].

The use of ambient vibration signals measured close to dams, as demonstrated with the Sayano-Shushenskaya Dam, offers a feasible method for continuous SHM without direct access to the dam, using autoencoders to account for environmental effects [57]. Moreover, advancements in software for automatic data management and analysis, as seen in the SSHM system of Cabril dam, facilitate the automatic identification of seismic vibrations and comparison with numerical models, aiding in informed decision-making [26]. The adaptation of vibration-based SHM to account for environmental and seismic excitations, as applied to an arch dam in China, further illustrates the capability of dynamic monitoring to distinguish between structural and non-structural changes [64].

The limitations of dynamic monitoring are also evident. The behavior of dams is very complex under different environmental and operational conditions, and thus, the monitoring technologies and methodologies are to be innovated continuously to deal with such a challenge. The permanent monitoring systems are considered to be very expensive; besides, some national security concerns resulted in the limitation of the access to the dams and difficulties in continuous monitoring of large dams Moreover, even though methods such as Digital Image Correlation are promising for displacement monitoring and cracking assessment, the fact that it would be deployed in outdoor environments makes it necessary to further validate and adapt to the different conditions [77].

The relevance of this work is derived from the contribution it will make to the technology of sustainable concrete. In this framework, the study of the incorporation of ceramic wastes into cementitious systems lends added value to critical environmental concerns associated with their disposal, offering a new approach towards sustainability in construction materials. Ceramic waste will not only replace raw materials at their source; it will also reduce carbon emissions at the production stage in cement manufacturing and provide resistance to degradation of concrete, which is essential for enhancing durability in infrastructural constructions. In this regard, results obtained herein indicated that the previous study agreed with this investigation, where ceramic waste was considered as a potential SCM due to its capability of enhancing the mechanical properties of concrete.

The present work probes deeper into durability aspects to indicate greater resistance to environmental degradation due to ceramic waste. It also identifies that high ceramic content could adversely affect workability, our results show that an optimized proportion will achieve a balance without compromising workability between mechanical strength and durability. This nuanced understanding provides a practical guideline for industry adoption of ceramic waste in sustainable concrete production.

In conclusion, therefore, dynamic monitoring of dam health through structural health monitoring systems, advanced computational models, and innovative methodologies has been made effective for the enhancement of dam safety and management but is limited with costs, access, and adaptability of technologies to complex environmental and operational conditions [78],[76].

4. Conclusion

This review provides a new, systematic survey of monitoring techniques for assessing the state of concrete dams, which are considered critical for infrastructure safety on a global scale. The distinctiveness of this current review paper lies in the comprehensive analysis that distinctly differentiates the advantages and challenges posed by each method of monitoring. Here, we show that dynamic monitoring indeed creates the necessary real-time data to tackle the environmental issues at stake while static monitoring provides fundamental long-term health data to observe gradual changes. Most importantly, this work proposes an unprecedented approach to integrate these monitoring techniques using advanced computational models and artificial intelligence. This integration is expected to totally reform dam monitoring systems in a more holistic and effective way. This improvement affords greater resilience of the dam infrastructure against the possibility of failure and therefore, fills a very important gap in infrastructure monitoring and sets the ground for future innovation in the many other improvements needed in preparedness strategies.

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