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Review paper

Comprehensive review of critical infrastructure monitoring approaches and prospective routes to dam sustainability in the face of climate change instability

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Abstract: Huge infrastructure such as the dam was categorised as critical infrastructure and should be maintained for continuous operation during its intended lifetime. Over the years, instability due to climate change has become a serious threat to dams and therefore requires regular monitoring of structural integrity. This article provides a comprehensive review of dam safety and structural health monitoring under numerous environmental conditions (e.g. normal conditions, flood and earthquake). Interestingly, this study analyses the impact of climate change on the partial failure and collapse of dams based on historical data. A comparison between monitoring approaches, such as the monitoring method, the type of instrumentation and the method of data analysis, was further discussed to understand the complementarity of each approach. Several future directions were outlined to highlight high-risk scenarios and interesting research areas for dam safety and monitoring to support dam sustainability. This will help to develop effective tools and techniques for accurate maintenance based on the issues at hand. A deeper understanding of the relationship between environmental factors (hydraulic impacts) and structural behavioural changes will greatly benefit the various studies on basic fluid-structure interactions, comprehensive emergency plans under the influence of climate change, reliable methods

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for dam maintenance and retrofitting, and holistic dam safety monitoring plans (surveillance approaches and disaster preparedness). In short, early detection of dam risks, analysis of expected failure and thorough interventions based on regular monitoring are essential for the sustainability and resilience of dam infrastructure.

Keywords: climate change, dam monitoring, dam safety, dam sustainability, dynamic monitoring, environmental variables

1. Introduction

A dam functionally provides a service for the entire water cycle, from storage and distribution to the conversion of hydropower into green energy and flood protection. For the past decade, the safety and sustainability of dams have been of paramount importance for the continued operation of dams. The uncertainties of the global climate, which influence the intensity and frequency of hydrometeorological parameters and hazards, raise concerns about the structural integrity of dams, especially large, high and ageing types [1–9]. Some of the recorded huge dams worldwide were Jinping I (305 m), Xiaowan (294.5 m), Baihetan (289 m), Xiluodu (285.5 m), and Inguri (271.5 m) [4]. The protection of this huge dam is crucial to ensure its sustainable operation. However, several reported dam incidents such as the historic Malpasset in 1959, Niedów in 2016, Oroville in 2017 and Toddbrook in 2019 emphasize the necessity of dam safety, especially dam monitoring and the development of early warning systems [10–17]. Moreover, this approach is paramount to minimize the catastrophic failure of these structures, which can have huge socio-economic and environmental impacts. The total failure of the Malpasset concrete dam has highlighted a weakness in the exploration of the site, particularly in geological and geotechnical aspects [12, 18]. In addition, the failure of the Oroville concrete spillway was due to the lack of an early warning system caused by an internal structural failure (the formation of a hole due to the weak foundation caused by the strong infiltration of the underdrain flow) [13, 14, 16]. In other cases, the Toddbrok Concrete Spillway experienced a cascading failure that highlighted the inconsistencies in maintenance and emphasized the need for advanced monitoring [17].

Conventionally, structural health monitoring was conducted to evaluate the structural integrity condition during periodical inspection through abnormality of the result and provide corrective measures if needed. The inspection was carried out based on the formalized guidelines of the International Committee on Large Dams [19]. However, the specific regulations and guidelines were the responsibility of the dam owner or operator and were prepared by each of the member countries such as the Department of Irrigation of Drainage Malaysia in collaboration with the Malaysian National Committee on Large Dams (MyCOLD) and the Australian National Committee on Large Dams (ANCOLD) to adapt to the local dam conditions and parameters [20, 21]. Typically, safety inspection was conducted based on the physical on-site inspection. However, this approach has some flaws such as the requirement of an experienced engineer, limited on-site access and lack of technical information at the limited access areas such as underwater foundations [22]. Therefore, a comprehensive on-site assessment through the robust development of advanced monitoring tools to detect static and dynamic characteristics of dam behaviour is required to provide a comprehensive and accurate data collection method for reliable analysis, particularly under changing climatic conditions [23]. Static monitoring involves recording periodic data (daily, monthly and annually) of dam displacement at a reference point in different directions and environmental variables such as normal water level and temperature [24, 25]. Dynamic monitoring focuses on the vibration aspect in terms of dynamic structural response, such as operating frequency and mode shapes during rare or extreme events, such as water waves due to flooding or seismic activity due to earthquakes [23, 26–32]. Figure 1 shows the effect of environmental variables on the changes in dam behaviour under climate change uncertainties.

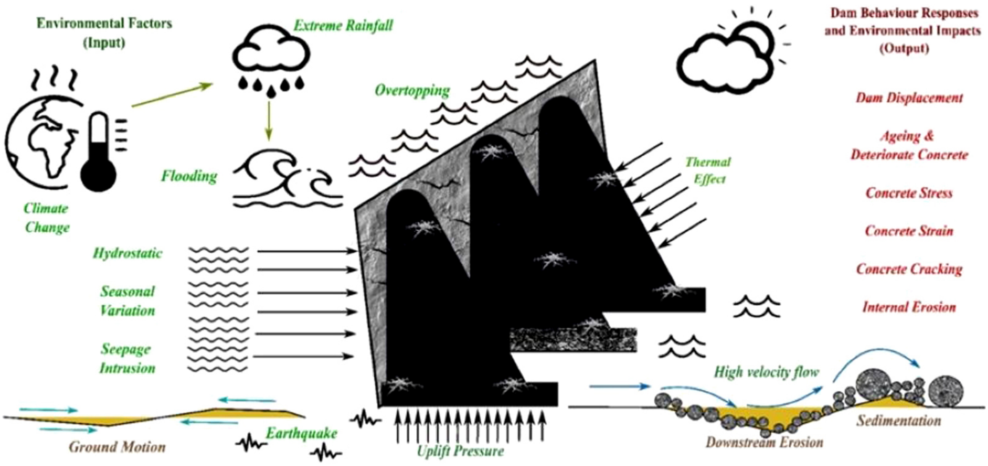

Fig. 1. The effect of environmental variables on the changes in dam behaviour under climate change uncertainties

The structural health monitoring effort to support dam safety and sustainability of dam, especially in times of climate change uncertainty is essential and in line with the United Nations Sustainable Development Goals (SDGs) No. 6 (clean water through sustainable water resources management and conservation of critical water infrastructure), No. 9 (sustainable development through resilient infrastructure and promotion of innovative monitoring and technology) and No. 13 (mitigating climate change by strengthening climate resilience and climate adaptation strategy for critical infrastructure) [33]. In addition, the robust integration and evolution of monitoring systems are essential for maintaining the structural integrity and operational safety of dams in the face of climate change-related risks. Structural health monitoring in [34] cludes the monitoring of environmental variables and behavioural changes in the dam under static and dynamic monitoring aspects.

Tremendous efforts have been made to address the importance of dam safety monitoring and the development of monitoring tools under normal conditions as described in previous literature. However, most of this fails to reconcile the purpose of dam safety and the monitoring approach developed with the sustainability of dams under the uncertainties of climate change. In recent years, monitoring of the structural condition of critical infrastructure has been increasingly reported, emphasizing the importance of this issue for dam safety and sustainability [22, 35–38].

Despite the review of the progress of these monitoring tools and the dynamic parameters identified, the literature is insufficient for concrete dams and the extraction of the technical data in extreme events and the ageing of concrete dams. The problem with these ageing dams is that they were built more than 50 years ago and are not equipped with modern structural monitoring tools, which exposes them to the risk of total failure, especially in vulnerable areas [39]. There is also a lack of real-time monitoring technologies and limited integration of static and dynamic monitoring data for the development of robust monitoring models for future predictions. Furthermore, the potential application of advanced approaches (artificial intelligence and numerical simulation) in processing monitoring data to improve the safety and sustainability of dams in the face of climate change has only been explored to a limited extent. The novelty of this study is that it provides a holistic overview of the static and dynamic monitoring approaches for concrete dams based on a comparative analysis of space-based, airborne and ground-based monitoring tools. In addition, the monitoring parameters based on the appropriate selection of monitoring instruments are presented. This work thus fills gaps in the existing research by highlighting the monitoring parameters and challenges and provides an outlook on the sustainability of dams by applying advanced technologies to support dam safety and sustainability.

This article aims to shed light on the concept of sustainability in dam engineering, especially the safety and monitoring of dams, by proposing innovative and advanced monitoring tools. The relationship between the root factor (climate change), dam sustainability, SDGs and dam safety (dam monitoring) has been highlighted before looking closer at the monitoring tools and parameters to recognize the importance of monitoring the structural condition of dams for dam sustainability. The specific objective of this study is to provide the reader with a broad overview of the types of monitoring tools and the challenges that a concrete dam faces under the effects of climate change (summary of monitoring parameters). Review of existing and new monitoring approaches for concrete dams, focussing on static and dynamic systems for both normal operation and extreme conditions. The specific objective of the study is to compare the monitoring tools and advancement in data analysis of monitoring parameters, analyse the challenges and limitations of current monitoring and data analysis management practises for dams (specific tools and climate change), identify the impact of climate change on partial or total dam failure based on the selected dam failure incidents and provide a future perspective for sustainable monitoring of dams to improve resilience and safety.

2. The structural health monitoring (SHM) system

2.1. The global overview of the SHM system for the concrete dam

The comprehensive structural health monitoring (SHM) System for monitoring the static and dynamic properties of concrete dams comprised of the hardware components; physical instruments, sensors [40, 41], software components; prediction models in damage modelling, and detection algorithms [42, 43] as shown in Figure 2.

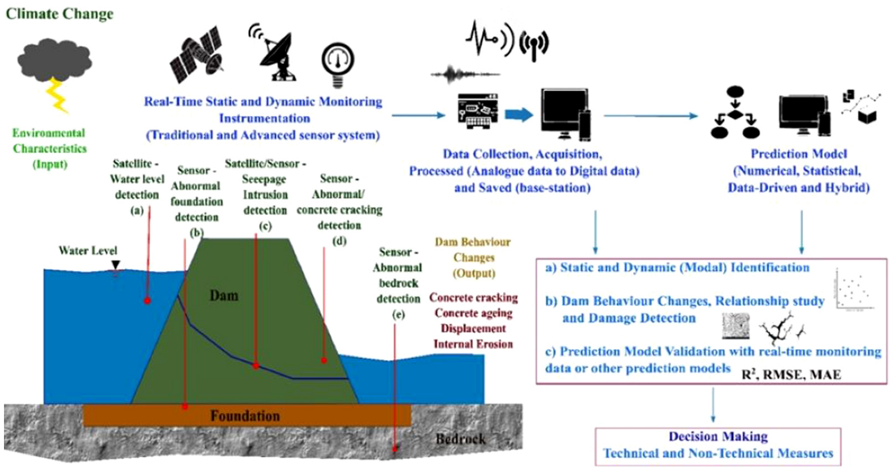

Fig. 2. The comprehensive Structural Health Monitoring (SHM) System for monitoring the static and dynamic properties of concrete dams

The predictive model includes numerical, hybrid and data-driven models. Software components in dam engineering are rarely carried out due to the significant computational cost of predictive models [31]. Moreover, the predictive model should be updated frequently with the latest changes to avoid static model simulation and prediction, compromising dam safety [36]. However, the combination of hardware and software models is essential for accurate real-time monitoring effects (estimation of dam behaviour) [36, 44–46]. The advancement of technology opens the development of more sophisticated monitoring tools as an alternative to physical site limitations for static and dynamic monitoring [36, 40, 47–56].

2.2. Real-time monitoring tools for static and dynamic properties detection

Monitoring tools ranging from conventional to high-end types have been widely used or installed and used to monitor the impact of environmental factors on the behaviour of dams based on static and dynamic monitoring. Traditional visual inspections and ground-based instruments consist of either manual or automatic types such as inverse plumb line in Jinping I dam (ultra-high arch) for detection of dam deformation [57], inverted pendulum monitoring instrument (stainless steel wire) for horizontal deformation detection in Jinping I dam [58], crack gauge detection and strain gauge [59, 60], piezometer, Casagrande piezometer [61], vibrating wire piezometer [61], pressure cell (flat cell filled with oil) [61] and, conventional terrestrial (total station, electronic theodolite, and distomat) [62], non-polarizable electrodes [63] and ground-based radar (GB-SAR) [64]. However, the conventional ground-based type requires a longer physical set-up time, bulky and mobile instruments for on-site inspection and is based on spot monitoring. The limited accessibility of the site posed the problem of instrumentation in particular. The total robotic station installed in the concrete dam is essential for monitoring dam deformation, namely for horizontal and vertical displacement data in the Zhentouba I (gravity concrete dam) and Dagangshan (double curved concrete arch) dams in China [65]. The advantage of this system is the high precision due to the integration of corrections for atmospheric refraction and the reduction of errors in real-time monitoring. However, this system is sensitive to atmospheric conditions that require correction for refraction and curvature. Other advanced real-time ground-based monitoring tools consider hybrid seismic and structural monitoring approaches to detect dynamic parameters, particularly seismic activity during earthquakes in the 132 m high Cabril Dam (double curvature arch dam) in Portugal [23]. This monitoring is essential to adapt to the effects of climate change and hazard uncertainties. The use of multi-sensing monitoring approaches such as acoustic emission, micro-seismic, cross-hole acoustic wave detection, crack gauge and strain gauge techniques was adopted in the crack detection of concrete dams in China [59]. The advantages of this advanced and multi-sensing it provides comprehensive crack detection across micro and macro levels; and real-time monitoring of crack propagation and structural stress. Figure 3 shows an example of the ground-based monitoring tools.

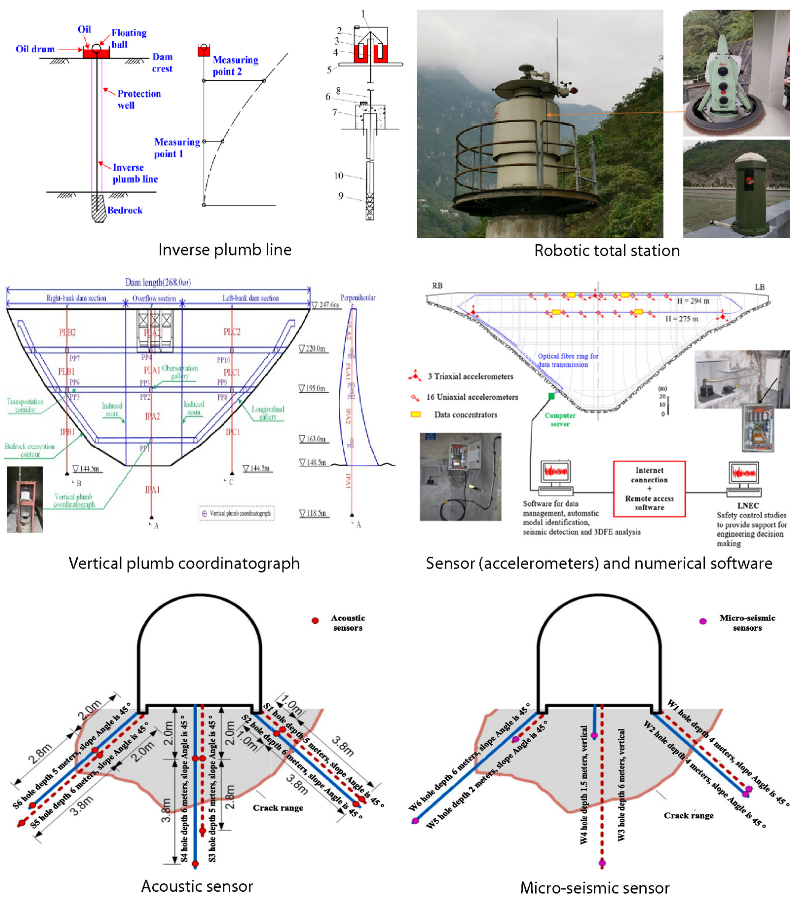

Fig. 3. Example of the ground-based monitoring tools [23, 57–59, 65]

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The space-based monitoring approach was Global Navigation Satellite System (GNSS), Landsat, Sentinel-1 and Sentinel-2 sensors [40, 62] as depicted in Figure 4. The GNSS was used to record the horizontal and vertical displacements of the Atatürk Dam in Turkey (concrete gravity dam). In addition, this instrument provides high accuracy in monitoring large deformations and is effective for long-term monitoring. Hybrid artificial intelligence and multiple satellite sensors (Landsat, Sentinel-1 and 2) with different bandwidths and indexes were used for the reservoir (environmental variable) in Latyan Dam, Iran [40]. The application of this approach is recommended as it improves the prediction by the hybrid tools. However, this approach is limited by the high resolution of the image and the sensitivity of the sensor to the environment, which reduces the accuracy.

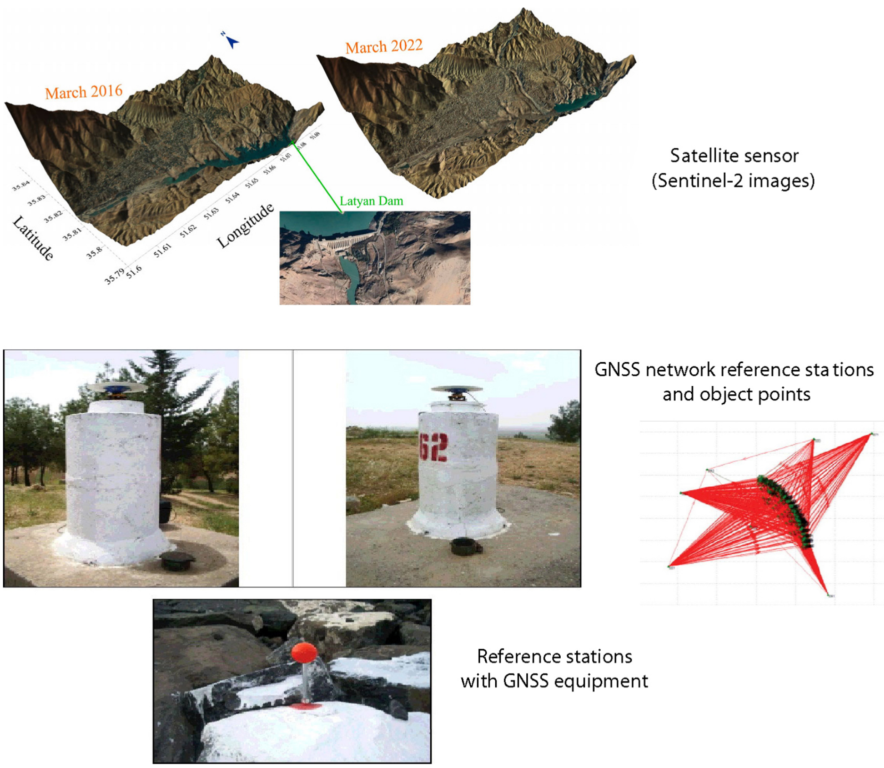

Fig. 4. Example of the space-based monitoring tools [40, 62]

Drone-based monitoring was promoted to close the gaps between space-based and ground-based instruments for the estimation of water levels. Spatial and temporal data were collected with this instrument at the 103.5-meter Ridracoli dam (double-curvature arch-gravity) in Italy [66]. Furthermore, this type provides a truthful source for developing a three-dimensional (3D) model based on the collected images during observations from different angles [67].

2.3. Static and dynamic monitoring data analysis and monitoring model: Physical model and prediction model (numerical, statistical, data-driven and hybrid)

Monitoring of static and dynamic properties (particularly historical data such as annual water level and dam deformation) is usually collected during the physical inspection on site, either manually or with the help of other instruments, as mentioned in the previous section. This monitoring is essential to detect and correct abnormal changes in the structure of the dam. In addition, monitoring of current data can be done on-site when the device is installed in a specific dam such as the Cabril Dam. Alternatively, the construction of a physical model is essential to replicate the behaviour of the real dam (based on the similarity law and Froude number) using historical data and actual dam characteristics. In addition, the required research can be carried out to some extent by developing a numerical model using the 3D design drawing that is similar to the real dam. Similar to physical modelling, the numerical model will replicate the actual characteristics of the dam and the model will be validated with historical data from on-site monitoring or monitoring of the physical model. However, the monitoring data collected usually contains missing and above-normal threshold (anomaly or error) data. Current advances in data collection, analysis, outlier detection and manipulation are significantly improving monitoring data and making it more accurate and reliable for the decision-making process. This is especially true for dams that are exposed to extreme weather conditions that cause frequent flooding and are prone to earthquakes, as well as ageing concrete dams.

The monitoring data collected should be error-free to serve as input for the future predictive model. The predictive model should be able to predict actual conditions near the input and output to minimize costs, especially for future mitigation and control measures. Comparison with historical monitoring data is rather possible for the identification of changes in dam behaviour. Typically, numerical or deterministic, data-driven (statistical) and hybrid models are used to analyse the collected monitoring data. Once the processing and analysis of the predictive data are completed, the validation phase with other monitoring data from the real site and other predictive models is essential for verifying performance and accuracy.

The model consists of data-driven, with statistical and computational tools as a methodology. Relationship between the deformation of representative monitoring points and variation of reservoir water level [57]. This approach was conducted due to the limitation of traditional variational analysis for deformation analysis (combination effect of the ultra-high dam and the complex water level conditions). This approach used a panel data clustering model, optimized through the CRITIC (CRiteria Importance Through Inter-criteria Correlation) method and the Constraint Satisfaction Problem (CSP) index. This approach integrates temporal and spatial data from dam monitoring to analyze deformation patterns. This model can solve the deformation analysis based on representative measuring points and key monitoring parts instead of a lot of measuring points and improve the reliability of arch dam deformation analysis [57].

Other research focuses on the integration of numerical simulation (FEM) with statistical analysis for the analysis of time and spatial data [58]. In addition, data-driven techniques are used to interpret the chaotic influences on deformation monitoring in concrete arch dams (under environmental and operational factors). Experimental data monitoring is carried out using the developed hydraulic physical model and focuses on analysing the influence of contraction joints on the vibration characteristics using a scanning laser vibrometer. The collected data from the conducted research significantly improves the structural safety assessments for large concrete arch dams [68].

The other vibration data collection and analysis used a combination of approaches, namely forced vibration testing (on-site monitoring data collection) and numerical modelling (FEM) of the Daniel–Johnson multi-arch dam [69]. On-site data collection and combination with the prediction model are crucial for predicting abnormal structural behaviour in ageing dams. In addition, anomalies can be detected early and corrective measures can be proposed to avoid the worst effects, such as catastrophic failure. In addition, the forecast data serves as input for the planning of new dams (with similar characteristics, locations and conditions). In monitoring other vibration aspect (seismic activity), historical data of the selected dams (Karaj, Dez, Karun-I, Karun III, Morrow Point, Luzzone) and a numerical model for the dynamic properties are used [70]. This hybrid model represents a significant advance in the analysis of old arch dams, as it takes into account the complex interactions between material heterogeneity and dynamic state. The developed model is of great use for predicting the current and future behaviour of dams under dynamic conditions, especially ageing dams. Fig. 5 shows the comparison between the physical model and the prediction model (numerical, statistical, data-driven and hybrid).

Table 1. Example of comparison between the physical model and prediction model (numerical, statistical, data-driven and hybrid)

Type of model (name)	**Parameters**	**Limitation**	**Advantages**	**Type of dam and country**	**Researcher**
Data-Driven: Panel Data Clustering (PDC) Model	Displacement (absolute quantity, growth, fluctuation) and spatiotemporal deformation characteristic	Sensitive to database variations, requires optimization of cluster numbers for consistency and data interpretation	Effectively captures spatial-temporal deformation trends and reduces the monitoring workload (clustering representative points)	Ultra-high arch dam, Jinping I, China (concrete double curvature arch dam) (Height – 305 m)	[57]
Statistical model: PCCM (Panel Data-CRITIC-CSP Model)	Water levels (rapid rise, fall, normal operation), deformation zones, temporal-spatial correlation, and deformation fluctuation	Requires accurate zoning rules and data integration, (High computational cost) for large datasets.	Integration of multi-weighted factors for dynamic deformation analysis, provides a specific zone of dam deformation and improves the reliability of monitoring results.		

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Type of model (name)	**Parameters**	**Limitation**	**Advantages**	**Type of dam and country**	**Researcher**
Numerical model: Finite Element Method (FEM)	Deformation data, hydraulic components, time and spatial coordinates of monitoring points, chaotic residual series.	Requires accurate preprocessing of spatiotemporal data and handling of large datasets.	Accurate deformation prediction (both time and space) and highlight the chaotic effects in residual data.	Ultra-high arch dam, Jinping I, China (concrete double curvature arch dam) (Height – 305 m)	[58]
Statistical models and data-driven model: Spa-tiotemporal Hybrid Model	Hydraulic components of deformation (from FEM), spatial coordinates, and time-based monitoring data from sensors.	Limited consideration of the complex correlations between monitoring points over time.	Integration of hydraulic and spatiotemporal factors (accurate real-time monitoring)		
Physical model: Arch dam model with base-excitation system (1:1500 scale model)	Dynamic properties (Natural frequencies, vibration amplitudes, mode shapes, effects of contraction joints, dynamic deflections)	Limited to scale model experiments and limited coverage to the real-world dynamics	Deeper insights into the relationship between joints of contraction effect on the vibrational behaviour, and the use of advanced tools such as scanning laser vibrometry for high-precision data	High arch dams, Xiaowan Arch Dam, China (Height – 292 m)	[68]
Hybrid model: On-site Forced-Vibration test and Numerical Model (Finite Element Method)	Dynamic properties (Natural frequencies, mode shapes, damping ratios, vibration amplitudes, dynamic displacement response)	Limited to forced-vibration frequencies (1.0–8.3 Hz), cannot fully account for non-linear effects or long-term behaviour under environmental changes	Provides precise identification of modal frequencies, damping characteristics and mode shapes and improves dam safety assessment based on the hybrid approach	Daniel–Johnson Dam (Manic-5 Dam), Canada (Multiple-arch) (Height – 214 m)	[69]
Hybrid model: Numerical Model (Finite Element Method) and statistical model (Random field theory and polynomial chaos expansion)	Material characteristic and dynamic properties (Material heterogeneity, natural frequencies, damping ratios, vibrational modes, correlation length)	Requires high computational power for solving large-scale eigenvalue problems; limited by the complexity of heterogeneous material assumptions	Accurately captures the effects of material heterogeneity on vibration characteristics and improves sensitivity analysis for risk assessment	Old arch high dams (Karaj, Dez, Karun-I, Karun III, Morrow Point, Luzzone) (Height -between 140 and 224 m in height)	[70]

2.4. Static and dynamic parameters detection using the monitoring tools

Several cases of total and partial dam failures were recorded worldwide and discussed in this section following the analysis of the monitoring data and the monitoring modelling approaches. Turbulence-induced seismic signals were observed as surface waves generated by the spillway flow [8]. The 180-year-old Toddbrok (at the time of the incident) experienced a failure of the concrete spillway due to the persistent torrential rainfall (Over 190 mm in 24 hours) and flooding, which caused a high velocity of 15 m/s and washed away the concrete slab (due to water injection into the cracked concrete, uplift pressure and slab displacement) [17, 71]. Figure 5 shows the failure event recorded during the physical on-site assessment by the dam experts.

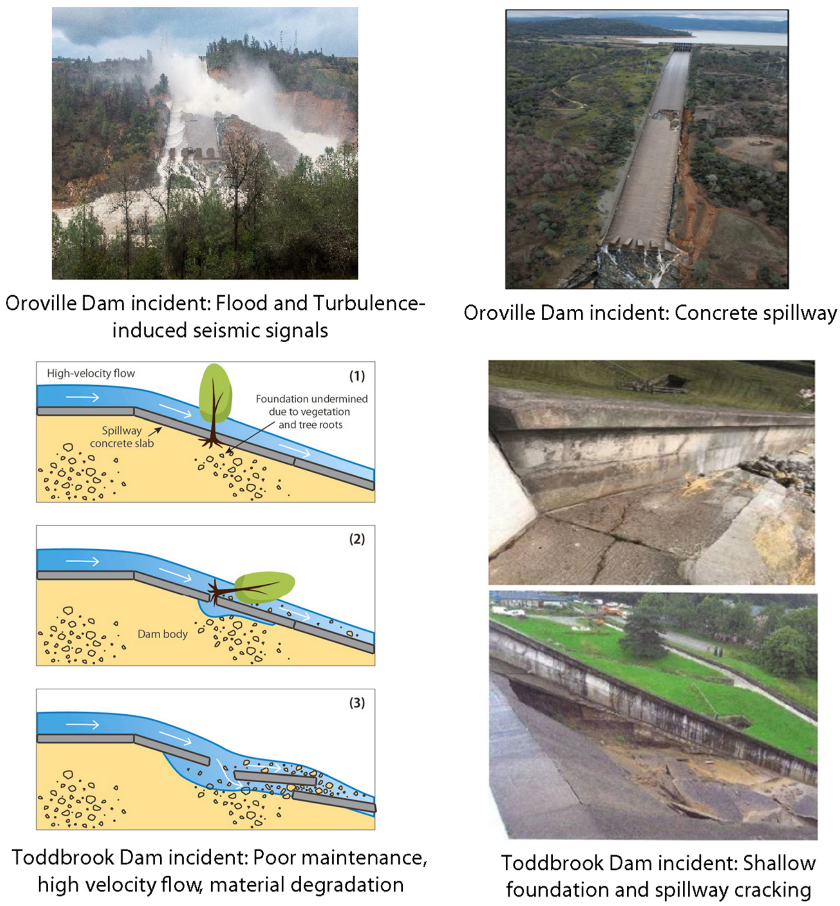

Fig. 5. Monitoring parameters during the dam incidents (environmental factor and structure damage) [17, 71–73]

3. Prospective routes to dam sustainability based on reviewed monitoring tools, monitoring parameters and analysis of monitoring data

Numerous prospective routes to support dam sustainability were directed from the listed limitations and advantages from critical review and discussion. The following section provides the listed fascinating areas of research to ensure the resilience and safety of the dam.

3.1. Developing a robust framework based on the successful implementation of case studies on the sustainable monitoring system

A robust framework for monitoring the structural condition of dams to support sustainability is essential to capture both the static and dynamic characteristics of the dam. Therefore, it is recommended that dam owners or operators develop comprehensive monitoring tools, such as those implemented in the Cabril Dam (Seismic and Structural Health Monitoring System), especially for dams located in vulnerable areas [23]. In this way, the risk to the concrete dam, especially the ageing dam, can be minimised. This approach can improve the decision-making process for corrective actions such as maintenance and retrofitting works. Therefore, the dam can be operated continuously without jeopardising the structural integrity of the dam.

3.2. Sustainability through technological advances: integration between the monitoring data from advanced tools with the prediction model under climate change uncertainty

Climatic instability has a massive impact on current and future weather uncertainties. Therefore, advanced monitoring tools such as space-based and ground-based (sensor-based) instruments are crucial, especially related to dynamic parameters (water level fluctuations, velocity data during extreme flood events and seismic activity during earthquakes) as an alternative to traditional physical inspections [40, 65]. In addition, AI-based analyses are essential for predicting failures and detecting anomalies to accurately capture the impact of environmental stresses on the behaviour of the dam. In addition, comprehensive tools such as the Internet of Things (IoT)-supported real-time data acquisition and processing ensure robust integration of the required data.

3.3. Dam behaviour behaviour study by the consideration of physical model experiment (PME) and Computational Structural Dynamics (CSD)

The investigation of the dynamic effects on the dam behaviour changes via a full-scale physical model experiment based on the actual dam is essential as a preparation for a future sudden event such as earthquake-induced ground motion [69]. Therefore, linear and non-linear dynamic analysis based on frequency and time is required to capture the effects. In addition, the dedicated seismic system equipped with an accelerometer can record the seismic activity. The data is processed by the dedicated system and used as input to the CSD system for modelling and simulation purposes.

4. Conclusions

Critical infrastructure, namely dams, especially concrete dams, are increasingly exposed to climate-related stresses, such as extreme rainfall events leading to flash floods and frequent flooding, frequent seismic activity during earthquakes and self-endangerment due to dam ageing. These factors jeopardise the structural integrity of dams and make them vulnerable to catastrophic failure.

This comprehensive review emphasizes and supports the shift from traditional to advanced techniques (technological innovation approach), whether in terms of hardware (physical instruments such as ground-based sensors, drones and space-based satellites) or software (advanced predictive models using numerical approaches or artificial intelligence). Real-time data monitoring is therefore essential to support the sustainability of dams. Furthermore, the integration of hardware and software approaches is recommended to ensure the resilience and adaptability of dams under climatic uncertainties. Furthermore, integrated static and dynamic monitoring for safety and sustainability should be emphasised to capture both short- and long-term structural changes during the threatened event. In this way, abnormal changes in the behaviour of the dams are detected at an early stage and appropriate and reliable measures can be taken to improve the condition of the dams. This effort aligns with the United Nations SDGs No. 6, 9 and 13.

The comprehensive review indicates an unexplored, limited and fascinating area of research to be explored, such as the incorporation of artificial intelligence as a tool for early prediction. This can be achieved by integrating machine learning techniques to detect data anomalies and predict the truth. In this way, the decision-making process can be accelerated and reliable maintenance or retrofitting work can be carried out at an early stage. Furthermore, the integration of multi-monitoring approaches is recommended to compensate for the weaknesses of individual monitoring tools and enable accurate data detection. In addition, international standards for data monitoring approaches (the type of monitoring system and standard parameters) should be defined. This is important to learn from the follow-up implementation of the structural health monitoring system at Cabril Dam.

In a nutshell, the safety and sustainability of dam infrastructure should shift from traditional to robust and sophisticated approaches such as integrated, innovative and sustainable monitoring tools. This comprehensive review provides a future perspective on sustainable dam monitoring by advancing technology as part of the monitoring approach, data management and future forecasting to support dam sustainability.

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References

[1] L.B. Sidek, et al., "Social and Economic Impact Due to Ageing and Climate Change in Sultan Abu Bakar Dam, Cameron Highlands Hydropower Scheme", in *Proceedings of the 2nd International Conference on Dam Safety Management and Engineering*, L. Mohd Sidek, G.H.A. Salih, A.N. Ahmed, I. Escuder-Bueno, and H. Basri, Eds. Springer Nature, 2023, pp. 813–826.

[2] N. Adamo, N. Al-Ansari, V. Sissakian, J. Laue, and S. Knutsson, "Dam Safety: Technical Problems of Ageing Concrete Dams", *Journal of Earth Sciences and Geotechnical Engineering*, vol. 10, no. 6, pp. 241–279, 2020.

[3] J. Fluixá-Sanmartín, A. Morales-Torres, I. Escuder-Bueno, and J. Paredes-Arquiola, "Quantification of climate change impact on dam failure risk under hydrological scenarios: a case study from a Spanish dam", *Natural Hazards and Earth System Sciences*, vol. 19, no. 10, pp. 2117–2139, 2019, doi: 10.5194/nhess-19-2117-2019.

[4] Z. Li, C. Yin, R. Chen, Z. Wu, J. Chen, and X. Lu, "A novel deformation monitoring model for high arch dams using impulse response-based equivalent temperature and machine learning-aided separate modeling", *Expert Systems with Applications*, vol. 238, art. no. 122328, 2024, doi: 10.1016/j.eswa.2023.122328.

[5] J.-H. Choi, C. Jun, P. Liu, J.-S. Kim, and Y.-I. Moon, "Resolving Emerging Issues with Aging Dams under Climate Change Projections", *Journal of Water Resources Planning and Management*, vol. 146, no. 5, art. no. 04020025, 2020, doi: 10.1061/(asce)wr.1943-5452.0001204.

[6] X. Chen and F. Hossain, "Understanding Future Safety of Dams in a Changing Climate", *Bulletin of the American Meteorological Society,* vol. 100, no. 8, pp. 1395–1404, 2019, doi: 10.1175/bams-d-17-0150.1.

[7] J.-M. Zhang, Z. Yang, X. Gao, and J. Zhang, "Geotechnical aspects and seismic damage of the 156-m-high Zipingpu concrete-faced rockfill dam following the Ms 8.0 Wenchuan earthquake", *Soil Dynamics and Earthquake Engineering*, vol. 76, pp. 145–156, 2015, doi: https://doi.org/10.1016/j.soildyn.2015.03.014.

[8] P.J. Goodling, V. Lekic, and K. Prestegaard, "Seismic signature of turbulence during the 2017 Oroville Dam spillway erosion crisis", *Earth Surface Dynamics*, vol. 6, no. 2, pp. 351–367, 2018, doi: 10.5194/esurf-6-351-2018.

[9] M. Heidarzadeh, H. Miyazaki, T. Ishibe, H. Takagi, and R. Sabeti, "Field surveys of September 2018 landslide-generated waves in the Apporo dam reservoir, Japan: Combined hazard from the concurrent occurrences of a typhoon and an earthquake", *Landslides*, vol. 20, pp. 143–156, 2022, doi: 10.1007/s10346-022-01959-8.

[10] S. Kostecki and W. Rędowicz, "The Washout Mechanism of the Niedów Dam and its Impact on the Parameters of the Flood Wave", *Procedia Engineering*, vol. 91, pp. 292–297, 2014, doi: 10.1016/j.proeng.2014.12.062.

[11] S. Kostecki and R. Banasiak, "The Catastrophe of the Niedów Dam – The Causes of the Dam's Breach, Its Development, and Consequences", *Water*, vol. 13, no. 22, art. no. 3254, 2021, doi: 10.3390/w13223254.

[12] P. Londe, "The Malpasset Dam failure", *Engineering Geology*, vol. 24, no. 1-4, pp. 295–329, 1987, doi: 10.1016/0013-7952(87)90069-X.

[13] A. Koskinas, et al., "Insights into the Oroville Dam 2017 Spillway Incident", *Geosciences*, vol. 9, no. 1, art. no. 37, 2019, doi: 10.3390/geosciences9010037.

[14] L. Hollins, D. Eisenberg, and T. Seager, "Risk and Resilience at the Oroville Dam", *Infrastructures*, vol. 3, no. 4, art. no. 49, 2018, doi: 10.3390/infrastructures3040049.

[15] A.B. White, B.J. Moore, D.J. Gottas, and P.J. Neiman, "Winter Storm Conditions Leading to Excessive Runoff above California's Oroville Dam during January and February 2017", *Bulletin of the American Meteorological Society*, vol. 100, no. 1, pp. 55–70, 2019, doi: 10.1175/bams-d-18-0091.1.

[16] F. Vahedifard, A. AghaKouchak, E. Ragno, S. Shahrokhabadi, and I. Mallakpour, "Lessons from the Oroville dam", *Science*, vol. 355, no. 6330, pp. 1139–1140, 2017, doi: 10.1126/science.aan0171.

[17] M. Heidarzadeh and S. Feizi, "A cascading risk model for the failure of the concrete spillway of the Toddbrook dam, England during the August 2019 flooding", *International Journal of Disaster Risk Reduction*, vol. 80, art. no. 103214, 2022, doi: 10.1016/j.ijdrr.2022.103214.

[18] P. Duffaut, "The traps behind the failure of Malpasset arch dam, France, in 1959", *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 5, no. 5, pp. 335–341, 2013, doi: 10.1016/j.jrmge.2013.07.004.

[19] *Dam safety guidelines (ICOLD Bulletin 59)*. International Commission on Large Dams, 1987.

[20] ANCOLD, *Guidelines on Risk Assessment*. Sydney, Australia: Australian National Committee on Large Dams, 1994.

[21] *Malaysia Dam Safety Management Guidelines (MyDAMS)*. 2017.

[22] P. Bukenya, P. Moyo, H. Beushausen, and C. Oosthuizen, "Health monitoring of concrete dams: a literature review", *Journal of Civil Structural Health Monitoring*, vol. 4, no. 4, pp. 235–244, 2014, doi: 10.1007/s13349-014-0079-2.

[23] S. Oliveira and A. Alegre, "Seismic and structural health monitoring of Cabril dam. Software development for informed management", *Journal of Civil Structural Health Monitoring*, vol. 10, no. 5, pp. 913–925, 2020, doi: 10.1007/s13349-020-00425-0.

[24] G. Sevieri, M. Andreini, A. De Falco, and H.G. Matthies, "Concrete gravity dams model parameters updating using static measurements", *Engineering Structures*, vol. 196, art. no. 109231, 2019, doi: 10.1016/j.engstruct.2019.05.072.

[25] Y.Y. Huang, L. Xiao, and T.F. Bao, "Transformation from Measured Strains to Viscoelastic Stresses considering Temperature History for Concrete Dams", *KSCE Journal of Civil Engineering*, vol. 23, no. 4, pp. 1725–1732, 2019, doi: 10.1007/s12205-019-1220-x.

[26] D.V. Ruiz, C.S.C. de Bragança, B.L. Poncetti, T.N. Bittencourt, and M.M. Futai, "Vibration-based structural damage detection strategy using FRFs and machine learning classifiers", *Structures*, vol. 59, art. no. 105753, 2024, doi: 10.1016/j.istruc.2023.105753.

[27] H. Li, B. Liu, W. Huang, H. Liu, and G. Wang, "Vibration load identification in the time-domain of high arch dam under discharge excitation based on hybrid LSQR algorithm", *Mechanical Systems and Signal Processing*, vol. 177, art. no. 109193, 2022, doi: 10.1016/j.ymssp.2022.109193.

[28] Y. Wang, G. Xu, and F. Liu, "Holding Force and Vertical Vibration of Emergency Gate in the Closing Process: Physical and Numerical Modelling", *Applied Sciences*, vol. 11, no. 18, art. no. 8440, 2021, doi: 10.3390/app11188440.

[29] S. Pereira, F. Magalhães, J.P. Gomes, Á. Cunha, and J.V. Lemos, "Vibration-based damage detection of a concrete arch dam", *Engineering Structures*, vol. 235, art. no. 112032, 2021, doi: 10.1016/j.engstruct.2021.112032.

[30] S. Pereira, F. Magalhães, Á. Cunha, C. Moutinho, and J. Pacheco, "Modal identification of concrete dams under natural excitation", *Journal of Civil Structural Health Monitoring*, vol. 11, no. 2, pp. 465–484, 2021, doi: 10.1007/s13349-020-00462-9.

[31] G. Sevieri and A. De Falco, "Dynamic structural health monitoring for concrete gravity dams based on the Bayesian inference", *Journal of Civil Structural Health Monitoring*, vol. 10, no. 2, pp. 235–250, 2020, doi: 10.1007/s13349-020-00380-w.

[32] S. Guo, et al., "Seismic damage investigation of arch dams under different water levels based on massively parallel computation", *Soil Dynamics and Earthquake Engineering*, vol. 129, art. no. 105917, 2020, doi: 10.1016/j.soildyn.2019.105917.

[33] S. Felder, S. Erpicum, S. Mulligan, D. Valero, D. Zhu, and B. Crookston, "Hydraulic Structures at a Crossroads Towards the SDGs", *IAHR White Papers*, no. 2, 2021.

[34] G.R. Darbre and J. Proulx, "Continuous ambient-vibration monitoring of the arch dam of Mauvoisin", *Earthquake Engineering & Structural Dynamics*, vol. 31, no. 2, pp. 475–480, 2002, doi: 10.1002/eqe.118.

[35] A. Sivasuriyan, D.S. Vijayan, R. Munusami, and P. Devarajan, "Health assessment of dams under various environmental conditions using structural health monitoring techniques: a state-of-art review", *Environmental Science and Pollution Research*, vol. 29, no. 57, pp. 86180–86191, 2021, doi: 10.1007/s11356-021-16749-3.

[36] G. Prakash, R. Dugalam, M. Barbosh, and A. Sadhu, "Recent advancement of concrete dam health monitoring technology: A systematic literature review", *Structures*, vol. 44, pp. 766–784, 2022, doi: 10.1016/j.istruc.2022.08.021.

[37] G. Bolzon, A. Frigerio, M. Hajjar, C. Nogara, and E. Zappa, "Structural health assessment of existing dams based on non-destructive testing, physics-based models and machine learning tools", *NDT & E International*, vol. 150, art. no. 103271, 2025, doi: 10.1016/j.ndteint.2024.103271.

[38] O. Avci, O. Abdeljaber, S. Kiranyaz, M. Hussein, M. Gabbouj, and D.J. Inman, "A review of vibration-based damage detection in civil structures: From traditional methods to Machine Learning and Deep Learning applications", *Mechanical systems and signal processing*, vol. 147, art. no. 107077, 2021, doi: 10.1016/j.ymssp.2020.107077.

[39] B.K. Patra, A. Bagchi, and P. Narayan, "Assessment of seismic resilience of aging concrete gravity dams", presented at the Symposium "Dams for People, Water and Environment and Development", 29 Sept.–03 Oct. 2024, New Delhi, India, 2024.

[40] O.M. Sorkhabi, B. Shadmanfar, and E. Kiani, "Monitoring of dam reservoir storage with multiple satellite sensors and artificial intelligence", *Results in Engineering*, vol. 16, art. no. 100542, 2022, doi: 10.1016/j.rineng.2022.100542.

[41] J.R. Vazquez-Ontiveros, C.A. Martinez-Felix, G.E. Vazquez-Becerra, J.R. Gaxiola-Camacho, A. Melgarejo-Morales, and J. Padilla-Velazco, "Monitoring of local deformations and reservoir water level for a gravity type dam based on GPS observations", *Advances in Space Research*, vol. 69, no. 1, pp. 319–330, 2022, doi: 10.1016/j.asr.2021.09.018.

[42] D. Rakić, M. Stojković, D. Ivetić, M. Živković, and N. Milivojević, "Failure Assessment of Embankment Dam Elements: Case Study of the Pirot Reservoir System", *Applied Sciences*, vol. 12, no. 2, art. no. 558, 2022, doi: 10.3390/app12020558.

[43] S. Wang, B. Yang, H. Chen, W. Fang, and T. Yu, "LSTM-Based Deformation Prediction Model of the Embankment Dam of the Danjiangkou Hydropower Station", *Water*, vol. 14, no. 16, art. no. 2464, 2022, doi: 10.3390/w14162464.

[44] T.F. Bao, Z.R. Wu, C.S. Gu, and D.J. Zheng, "A Model for Dam Health Monitoring", in *Earth & Space 2008: Engineering, Science, Construction, and Operations in Challenging Environments*. ASCE, 2008, pp. 1–8, doi: 10.1061/40988(323)29.

[45] T. Singh, S. Sehgal, C. Prakash, and S. Dixit, "Real-Time Structural Health Monitoring and Damage Identification Using Frequency Response Functions along with Finite Element Model Updating Technique", *Sensors*, vol. 22, no. 12, art. no. 4546, 2022, doi: 10.3390/s22124546.

[46] J. Song, Y. Chen, and J. Yang, "A Novel Outlier Detection Method of Long-Term Dam Monitoring Data Based on SSA-NAR", *Wireless Communications and Mobile Computing*, vol. 2022, art. no. 6569367, 2022, doi: 10.1155/2022/6569367.

[47] T. Oommen, E.H. Bouali, K.S. Sajinkumar, M.K. Corcoran, and J.B. Dunbar, "Using Radar Remote Sensing from Space to Monitor Dams", in *Geo-Extreme 2021*. ASCE, 2021, pp. 311–317, doi: 10.1061/9780784483688.031.

[48] Y. Mao, J. Zhang, H. Qi, and L. Wang, "DNN-MVL: DNN-Multi-View-Learning-Based Recover Block Missing Data in a Dam Safety Monitoring System", *Sensors*, vol. 19, no. 13, art. no. 2895, 2019, doi: 10.3390/s19132895.

[49] C. Liao, D. Cai, H. Chen, W. Luo, and M. Li, "Development and In Situ Application of Deformation Monitoring System for Concrete-Face Rockfill Dam Using Fiber Optic Gyroscope", *Sensors*, vol. 20, no. 1, art. no. 108, 2020, doi: 10.3390/s20010108.

[50] M. Klun, D. Zupan, J. Lopatič, and A. Kryžanowski, "On the Application of Laser Vibrometry to Perform Structural Health Monitoring in Non-Stationary Conditions of a Hydropower Dam", *Sensors*, vol. 19, no. 17, art. no. 3811, 2019, doi: 10.3390/s19173811.

[51] H. Xu, H. Li, X. Yang, S. Qi, and J. Zhou, "Integration of Terrestrial Laser Scanning and NURBS Modeling for the Deformation Monitoring of an Earth-Rock Dam", *Sensors*, vol. 19, no. 1, art. no. 22, 2019, doi: 10.3390/s19010022.

[52] R. Xi, X. Zhou, W. Jiang, and Q. Chen, "Simultaneous estimation of dam displacements and reservoir level variation from GPS measurements", *Measurement*, vol. 122, pp. 247–256, 2018, doi: 10.1016/j.measurement.2018.03.036.

[53] M. Scaioni, M. Marsella, M. Crosetto, V. Tornatore, and J. Wang, "Geodetic and Remote-Sensing Sensors for Dam Deformation Monitoring", *Sensors*, vol. 18, no. 11, art. no. 3682, 2018, doi: 10.3390/s18113682.

[54] S. Pereira, F. Magalhăes, J.P. Gomes, Á. Cunha, and J.V. Lemos, "Dynamic monitoring of a concrete arch dam during the first filling of the reservoir", *Engineering Structures*, vol. 174, pp. 548–560, 2018, doi: 10.1016/j.engstruct.2018.07.076.

[55] L.E. Acosta, et al., "Displacements Study of an Earth Fill Dam Based on High Precision Geodetic Monitoring and Numerical Modeling", *Sensors*, vol. 18, no. 5, art. no. 1369, 2018, doi: 10.3390/s18051369.

[56] P. Milillo, et al., "Space geodetic monitoring of engineered structures: The ongoing destabilization of the Mosul dam, Iraq", *Scientific Reports*, vol. 6, art. no. 37408, 2016, doi: 10.1038/srep37408.

[57] Y. Liu, et al., "Deformation Analysis of an Ultra-High Arch Dam under Different Water Level Conditions Based on Optimized Dynamic Panel Clustering", *Applied Sciences*, vol. 12, no. 1, art. no. 481, 2022, doi: 10.3390/app12010481.

[58] B.W. Wei, B. Liu, D.Y. Yuan, Y. Mao, and S.Y. Yao, "Spatiotemporal hybrid model for concrete arch dam deformation monitoring considering chaotic effect of residual series", *Engineering Structures*, vol. 228, art. no. 111488, 2021, doi: 10.1016/j.engstruct.2020.111488.

[59] Z. Zhao, B. Chen, Z.R. Wu, and S. Zhang, "Multi-sensing investigation of crack problems for concrete dams based on detection and monitoring data: A case study", *Measurement*, vol. 175, art. no. 109137, 2021, doi: 10.1016/j.measurement.2021.109137.

[60] M. Wang, J. Chen, H. Wei, B. Song, and W. Xiao, "Investigation on Seismic Damage Model Test of a High Concrete Gravity Dam Based on Application of FBG Strain Sensor", *Complexity*, vol. 2019, art. no. 7837836, 2019, doi: 10.1155/2019/7837836.

[61] S.M. Seyed-Kolbadi, M.A. Hariri-Ardebili, M. Mirtaheri, and F. Pourkamali-Anaraki, "Instrumented Health Monitoring of an Earth Dam", *Infrastructures*, vol. 5, no. 3, art. no. 26, 2020, doi: 10.3390/infrastructures5030026.

[62] H.H. Yavaşoğlu, et al., "Monitoring the deformation and strain analysis on the Ataturk Dam, Turkey", *Geomatics, Natural Hazards and Risk*, vol. 9, no. 1, pp. 94–107, 2018, doi: 10.1080/19475705.2017.1411400.

[63] A. Soueid Ahmed, et al., "Determination of the permeability of seepage flow paths in dams from self-potential measurements", *Engineering Geology*, vol. 268, art. no. 105514, 2020, doi: 10.1016/j.enggeo.2020.105514.

[64] P. Wang, C. Xing, and X. Pan, "Reservoir Dam Surface Deformation Monitoring by Differential GB-InSAR Based on Image Subsets", *Sensors*, vol. 20, no. 2, art. no. 396, 2020, doi: 10.3390/s20020396.

[65] J. Zhou, B. Shi, G. Liu, and S. Ju, "Accuracy analysis of dam deformation monitoring and correction of refraction with robotic total station", *PLoS One*, vol. 16, no. 5, art. no. e0251281, 2021, doi: 10.1371/journal.pone.0251281.

[66] E. Ridolfi and P. Manciola, "Water Level Measurements from Drones: A Pilot Case Study at a Dam Site", *Water*, vol. 10, no. 3, art. no. 297, 2018, doi: 10.3390/w10030297.

[67] S. Zhao, F. Kang, J. Li, and C. Ma, "Structural health monitoring and inspection of dams based on UAV photogrammetry with image 3D reconstruction", *Automation in Construction*, vol. 130, art. no. 103832, 2021, doi: 10.1016/j.autcon.2021.103832.

[68] S. Wang, Y. Zhang, M. Cao, and W. Xu, "Effects of Contraction Joints on Vibrational Characteristics of Arch Dams: Experimental Study", *Shock and Vibration*, vol. 2015, art. no. 327362, 2015, doi: 10.1155/2015/327362.

[69] O. Gauron et al., "Forced-Vibration Tests and Numerical Modeling of the Daniel–Johnson Multiple-Arch Dam", *Journal of Performance of Constructed Facilities*, vol. 32, no. 2, art. no. 04017137, 2018, doi: 10.1061/(asce)cf.1943-5509.0001137.

[70] M.A. Hariri-Ardebili, S. Mahdi Seyed-Kolbadi, V.E. Saouma, J.W. Salamon, and L.K. Nuss, "Anatomy of the vibration characteristics in old arch dams by random field theory", *Engineering Structures*, vol. 179, pp. 460–475, 2019, doi: 10.1016/j.engstruct.2018.10.082.

[71] A. Hughes, "Report on the Nature and Root Cause of the Toddbrook Reservoir Auxiliary Spillway Failure on 1st August 2019", Dams & Reservoirs Ltd, 2020. [Online]. Available: https://damsafety.org/reference/report-nature-and-root-cause-toddbrook-reservoir-auxiliary-spillway-failure-1st-august.

[72] J.W. France, P.A. Dickson, H.T. Falvey, S.J. Rigbey, and J. Trojanowski, "Independent Forensic Team Report Oroville Dam Spillway Incident", 5 January 2018. [Online]. Available: https://damsafety.org/sites/default/files/files/Independent%20Forensic%20Team%20Report%20Final%2001-05-18.pdf. [Accessed: 23 Nov. 2023].

[73] CDWR, "Oroville Dam", FL_Oroville-4657_02_18_2017.jpg. California: California Department of Water Resources, 2017.

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