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RESILIENCE AND SUSTAINABILITY OF HYDRAULIC STRUCTURES: THE ROLE OF NUMERICAL SIMULATION AS AN EARLY WARNING TOOL FOR STRUCTURAL INTEGRITY ASSESSMENT

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Hydraulic structures such as dams play a major role in the sustainable storage of clean water for daily use, irrigation, flood defence systems and the sustainable supply of electricity generation. Therefore, these structures should be preserved from external and internal impacts, e.g. natural hazards (earthquakes and floods), mechanical vibrations (pumps and turbines), sedimentation due to high velocities and fluid structures (flow-induced vibrations) (Ahmad Mazlan et al., 2020; Al-Obaidi, 2020; Alcocer-Yamanaka et al., 2020; Antoine et al., 2020). The tall and huge dam, which is also ageing and located in an earthquake-prone area with obvious structural deficiencies, is the most affected and prone to catastrophic structural failure (Adamo et al., 2020; Zhuang et al., 2019). Several dam failure events, such as the failure of the Oroville and Toddbrook spillways due to high-velocity water during prolonged rainfall and flooding, flow-induced vibrations due to earthquakes and material fatigue, have highlighted the urgent need for predictive and adaptive approaches to assess dam safety (Balmforth, 2020; France et al., 2018; Goodling et al., 2018; Heidarzadeh & Feizi, 2022; Hollins et al., 2018; Hughes, 2020; Koskinas et al., 2019; Stelloh et al., 2017; Vahedifard et al., 2017; White et al., 2019). Therefore, a well-equipped monitoring system, especially for seismic and structural damage, is crucial as an early warning system and as a basis for the selection of appropriate non-structural or structural measures to extend design and operational life. An example of a well-equipped seismic and structural condition monitoring system is the Cabril Dam in Portugal, which is capable of detecting dynamic vibrations (seismic behaviour during earthquake event) (Oliveira & Alegre, 2020).

The International Committee on Large Dams (ICOLD) has pointed out that high-risk dams must be regularly inspected for structural integrity to ensure the best structural condition and safety. This is supported by the member countries, including Malaysia, through the National Committee on Large Dams (MYCOLD). The management and evaluation of the condition of dams in Malaysia was carried out using the specific checklist of the Malaysia Dam Safety Guidelines (MyDAMS). MyDAMS was prepared by MYCOLD members who are representatives of dam owners, operators, government agencies involved in dam management/issues and dam practitioners in Malaysia. Several dams were inspected and assessed in the Malaysian landscape, including the Muda and Ahning Dams (Kedah), the Jor and Mahang Dams (Perak), the Sultan Abu Bakar Dam (Pahang), the Babagon Dam (Sabah), the Bakun Dam (Sarawak) and the Kenyir Dam (Terengganu). Problems investigated included structural integrity (e.g. concrete cracking and deterioration), soil erosion, landslides and severe collapse potential (BERNAMA, 2023).

Physical assessment on site has traditionally been carried out either manually or automatically using the appropriate system deployed from space (satellite), from the air or the ground (manually or with an advanced system such as a sensor) for static and dynamic monitoring of variables (e.g. water level, temperature, soil settlement, displacement, stress). During the on-site physical assessment, there were limitations to the measurements due to site accessibility, especially in downstream areas such as flooded stilling basins with built-in baffle blocks and outlets for water discharge. In addition, the need for expertise led to an increase in costs and was limited to several inspection periods, which limited the results and analysis and delayed the decision-making process. In addition, several results contain anomalies due to equipment malfunctions and insufficient maintenance work. Due to these limitations, numerical simulation plays an important role in the early prediction of dam failure incidents. Numerical simulation encompasses a range of modelling techniques used to understand and predict the physical behaviour of dam systems under various loading conditions.

The robustness of this tool, which is a powerful complement to physical monitoring systems, allows engineers to simulate failure scenarios that are scarce, or costly to replicate in the field to solve the problem and avoid delays in engineering decisions. Even though the advanced numerical tools are more expensive due to the computational package and simulation time, the robustness can outweigh the cost and provide comprehensive data processing, analysis and visualisation that can improve the decision-making process. Examples of commercial numerical simulation packages are ANSYS, Flow-3D, etc., which provide a robust solution for structural and fluid analysis under either hydrostatic or hydrodynamic conditions with the effect of a single variable or the integration effect between variables (Zaid, 2023; Zhang et al., 2013). Computational fluid dynamics (CFD) is used in flow analysis to simulate complex flow conditions around spillways, spillway gates and stilling basins for erosion and pressure distribution patterns, while finite element analysis (FEA) is used to evaluate structural deformations and stresses. Advanced modelling for coupling analysis, i.e. fluid-structure interaction (FSI), considers the combination between fluid and structural domain using (CFD-FEA) under various conditions (static structure or harmonic motion for dynamic conditions) and is essential for the coupled interaction between hydraulic characteristics of flow (water) and dam structural behaviour, which is important for flow-induced vibration (FIV) and dynamic loading scenarios. The variables selected for dynamic structural analysis are usually natural frequency, operating frequency, damping ratio and stiffness, while dynamic flow analysis includes turbulence intensity, turbulence kinetic energy, hydrodynamic force, hydrodynamic pressure, Froude number, Reynolds number and flow regime.

The numerical simulation results can first be validated with the on-site inspection data (e.g. velocity and water level) or with experimental simulations on a specially constructed physical model based on the actual size of the dam structure (e.g. 1:25, 1:50). The validated data should be within 10%, which shows that the numerical model is good. This satisfactory result of the validation shows that the numerical tools are suitable for future predictions and optimisations (Badoe et al., 2022; Khanjanpour & Javadi, 2020; Zhang et al., 2007). Once the first phase of data validation has been completed, the prediction work can be carried out based on the developed and validated model. This is to ensure that the numerically simulated data and results are reliable and accurate. The simulation time depends on the size of the developed model (e.g. 2D or 3D), the variables (single or multiple effects) and the type of meshing (e.g. tetrahedral, hexahedral) as well as the size of the elements (coarse, medium and fine). In this case, the grid-independent study is performed to determine the most appropriate element type and element sizes for the intended simulation work. The predicted data can be used as informative management to improve the decision-making process regarding the modification of rules and regulations and the appropriate selection of maintenance and rehabilitation works. In addition, the current and future state of structural integrity can be predicted earlier. Subsequent incidents can thus be avoided and minimised.

Simulation-driven approaches support resilience, sustainability and risk mitigation by, firstly, increasing structural reliability by enabling timely reinforcement and retrofitting based on failure predictions. Secondly, by optimising maintenance schedules based on predictive insights, dependency on reactive interventions is reduced. Third, improving the safety aspect relies on early detection of defects or inadequate design and allows conservative but cost-effective design improvements. Fourth, the integration of simulated data with sensor networks that provide real-time simulation enables live modelling via digital twin frameworks. Last but not least, the reduction of socio-economic impact enables early warning that minimises the human and economic consequences of failures.

In conclusion, numerical simulation modelling is of utmost importance for the early prediction of the state of structural integrity both in the present and future state. Moreover, based on the simulation results, structural modifications can be made to accommodate the current situation and updated guidelines. In this way, catastrophic incidents can be avoided and remediation costs minimised. In addition, the whole technical aspect can be taken into account to ensure the resilience and sustainable operation of dams. The integration of numerical simulations into early warning systems is a decisive step forward in the management of dam-related incidents. These tools support the resilience and sustainability of critical hydraulic infrastructures by simulating complex physical interactions and predicting structural responses to evolving risk conditions. As recent unpredicted natural hazards intensify in the face of climate change impacts and many existing dams approach the end of their service life, the use of simulation-based early warning systems will be essential. Future work should prioritise the development of real-time, data-driven models supported by specific entities (government, private subsidiaries and higher education institutions) in monitoring networks and capacity building.

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