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A digital twin method for real-time analysis of structural deformation and failure for high arch dams

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ABSTRACT

Digital twin technology provides an innovative solution for structural health monitoring and failure risk assessment of high arch dams. However, current digital twin models for dam safety monitoring remain in the exploratory stage and lack integration with real-time sensor data, which limits their effectiveness, accuracy, and responsiveness in assessing structural health and failure risk. In this study, a novel digital twin model that combines deep transfer learning with the finite element method (FEM) is proposed, enhancing prediction accuracy and enabling real-time structural state characterization. The proposed model outperforms traditional parameter inversion-based numerical models, improving the prediction accuracy by 47 %. By introducing a spatial variability loss function and a skip connection strategy, both of which are validated through ablation experiments, the model optimizes the deformation distribution and improves the predictive performance. Furthermore, integrating an approximate Bayesian neural network with the FEM allows for real-time stress prediction and uncertainty-based failure risk assessment, providing a comprehensive framework for dam safety management. Extensive validation confirms the robustness and reliability of the model, making it a promising tool for high arch dam monitoring. These findings lay a solid foundation for advancing high-fidelity digital twin applications in dam engineering. Future research will focus on further optimizing neural network architectures and extending digital twin applications to high-fidelity simulations, ensuring more accurate and reliable structural safety assessments.

1. Introduction

Concrete arch dams, renowned for their superior load-bearing capacity, high overload capacity, lightweight and flexible nature, and outstanding seismic performance, have been applied widely in global water resource management and utilization projects [1,2]. In particular, with the advancement of China's Western Development Strategy, as shown in Fig. 1, a series of ultrahigh arch dams, such as the Jinping I Arch Dam (305 m), Xiaowan Arch Dam (292 m), Baihetan Arch Dam (279 m), and Wudongde Arch Dam (270 m), have been constructed and put into operation [3]. Given their large dam bodies, substantial reservoir capacities, and high stress levels, safety monitoring and real-time assessment are crucial for high arch dam safety [4,5]. Deformation, a critical indicator of the stress distribution and stability of arch dams, can reveal potential failure risks through abnormal changes, allowing for early detection and intervention. Therefore, comprehensively monitoring deformation and quantifying the structural risks of arch dams are key challenges in ensuring their safety and stability.

Structural health monitoring (SHM) methods are used in the safety assessment and monitoring of arch dams and are categorized into data-driven and mechanism-driven models [6]. Data-driven models include statistical models based on hydrostatic–seasonal–time (HST) theory and machine learning techniques, whereas mechanism-driven models rely on finite element methods and engineering reliability theory to assess the failure risk [7,8]. The HST model decomposes dam deformation into three components: hydrostatic pressure, temperature, and ageing [9]. The hydrostatic pressure component represents reversible deformation under hydrostatic pressure and self-weight [10]; the temperature

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