Review

A Short Review Note on Finite Element Method for Hydraulic Structural Engineering

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ABSTRACT

Dams play a critical role in water resources engineering, providing irrigation and drinking water through the creation of reservoirs. However, geotechnical and hydraulic engineers face challenges such as the possibility of piping events and collapse due to water leaking under the dam body, as well as variation in bearing capacity, void ratio, and water content in different regions of the ground where the dam body consolidates. The paper also highlights the advances in hydraulic structural engineering through the Finite Element Method (FEM) and other numerical modelling techniques, which have enabled more accurate design and analysis of hydraulic structures such as dams, spillways, weirs, and sluice gates. The maintenance and rehabilitation of these structures are also discussed, with a focus on developing non-destructive testing methods and innovative repair and retrofitting techniques to improve their structural integrity and hydraulic efficiency. The challenges and opportunities in hydraulic structural engineering research are explored, including the impact of climate change, sustainable design, and integration of new technologies like artificial intelligence and the Internet of Things. As hydraulic structures become more resilient and adaptive to withstand extreme events and support sustainable development, there will be an increased need for continued research and innovation in FEM and other advanced numerical modelling techniques to support hydraulic structural engineering advancements.

Keywords: Finite Element Method; Hydraulic Structures; Numerical Modeling; Sustainability

1. Introduction

Hydraulic structures are crucial infrastructure components for water resources management, providing various functions such as storage, conveyance, diversion, and regulation [1]. Hydraulic structural engineering is a multidisciplinary field that deals with the design, construction, maintenance, and management of these structures [2],[3]. The hydraulic structures include dams, weirs, barrages, spillways, channels, culverts, and other components that form an integral part of water supply systems [4].

Hydraulic structures often experience complex interactions with flowing water [5]. FEM allows the simulation of fluid-structure interaction problems where the movement of the water affects the structural response [6]. For instance, in the design of spillways or overflow structures, engineers must consider the impact of water forces on the structure, which FEM can model by coupling fluid dynamics with structural analysis. This is particularly critical in assessing [7] the performance of structures under extreme storm events or seismic activity [8]. In scenarios where hydraulic structures are built on or near soil, understanding the soil-structure interaction is vital. FEM can model the interaction between the structure and surrounding soil, accounting for factors such as soil consolidation, water table fluctuations, and pore pressure effects [9],[10]. This is important for structures like levees and embankments, where the stability and deformation of the soil can significantly influence structural performance. Utilizing FEM, engineers can perform sensitivity analysis and optimization of hydraulic structures [11]. By modelling different design variables such as material properties, geometric configurations, and reinforcement strategies, FEM enables engineers to identify the most efficient configurations that meet safety and performance requirements without extensive physical prototypes [12],[13]. Research progress in hydraulic structural engineering has been driven by the need for efficient, safe, and sustainable water resource management [14],[15]. The advances in this field are aimed at improving the performance and resilience of hydraulic structures, reducing their environmental impact, and ensuring their

long-term sustainability [16],[17]. This research progress has been achieved through a combination of experimental, numerical, and analytical techniques that have advanced our understanding of hydraulic behaviour, materials science, and structural mechanics[18],[19].

This review paper aims to provide a summary of the recent research progress in hydraulic structural engineering. The following are the objectives of this summary manuscript;

1   The paper will review the advances in the construction, maintenance, and management of hydraulic structures.
2   It will also highlight the challenges and opportunities in this field and suggest future research directions.
3   The paper will draw upon the latest research articles, technical reports, and conference proceedings to provide a comprehensive understanding of the research progress in hydraulic structural engineering.

2. Advancement in Hydraulic Engineering

Advances in the design of hydraulic structures have been made in recent years, the new technologies and improved understanding of the behaviour of these structures. Here are some of the key advances in hydraulic structure design:

The use of advanced materials, such as fibre-reinforced composites and high-performance concrete, has enabled engineers to design hydraulic structures that are more durable, resistant to corrosion, and have a longer service life [20]. Computational modelling, such as Finite Element Method (FEM) and Computational Fluid Dynamics (CFD), has made it possible for engineers to optimize the design of hydraulic structures by simulating their behaviour under different loading conditions [21]. 3D printing has enabled engineers to quickly and cost-effectively produce prototypes of hydraulic structures, allowing them to test and refine their designs before committing to large-scale production [22]. Innovative design approaches, such as biomimicry, have inspired engineers to design hydraulic structures that mimic the behaviour of natural systems, such as the flow of water in a river or the structure of a coral reef [23].

The use of sensors and other technologies to create smart structures has enabled engineers to design hydraulic structures that can monitor their health and detect potential failures before they occur [19],[24]. Overall, advances in the design of hydraulic structures have enabled engineers to create structures that are more durable, cost-effective, and sustainable, while also improving the safety and functionality of these critical infrastructure assets.

3. Numerical Analysis in Hydraulic Engineering

One of the techniques used in hydraulic structural engineering research is numerical modelling. Numerical modelling is a computational approach that allows engineers to simulate and predict the behaviour of hydraulic structures under different loading conditions [25],[26]. This technique involves the use of mathematical models and computer programs to solve complex equations and simulate the behaviour of hydraulic structures in a virtual environment [21],[27],[28].

Numerical modelling techniques have become increasingly sophisticated and powerful over the years, allowing for more accurate and reliable predictions of the behaviour of hydraulic structures [29]. Some of the commonly used numerical modelling techniques in hydraulic structural engineering research are:

FEM is a numerical technique that divides a complex structure into smaller elements and solves the equations governing the behaviour of each element. FEM is widely used for analyzing the stress, strain, and deformation of hydraulic structures under different loading conditions [30]. CFD is a numerical technique

that simulates the flow of fluids in a hydraulic structure. CFD can be used to predict the velocity, pressure, and turbulence of fluid flow in a hydraulic structure, which is essential for designing and optimizing hydraulic structures [31]. DEM is a numerical technique that simulates the behaviour of granular materials, such as sediment and soil, in a hydraulic structure. DEM can be used to predict the movement and settling of sediment in a reservoir or river, which is important for managing sedimentation in hydraulic structures[32]. BEM is a numerical technique that solves equations at the boundary of a hydraulic structure. BEM is commonly used for simulating the behaviour of wave propagation and erosion in hydraulic structures [33].

Numerical modelling techniques have several advantages over traditional experimental methods in hydraulic structural engineering research. They are cost-effective, time-efficient, and allow for a more detailed analysis of complex hydraulic structures [34]. Numerical modelling techniques also provide a safe and controlled environment for testing and optimizing hydraulic structures, without the risk of physical damage or failure [35]. However, numerical modelling techniques also have limitations and challenges. The accuracy of numerical models depends on the quality and reliability of the input data, and uncertainties in the behaviour of hydraulic structures can affect the accuracy of the simulation results [36]. Therefore, numerical modelling techniques should be used in conjunction with experimental methods and field observations to ensure a comprehensive and reliable analysis of hydraulic structures.

3.1. Computational Fluid Dynamics (CFD)

Computational Fluid Dynamics (CFD) is a numerical modelling technique used to simulate the behaviour of fluids, such as water, in hydraulic structures. The technique involves solving a set of mathematical equations that describe the behaviour of fluid flow, such as velocity, pressure, and turbulence. To use CFD, engineers first create a digital model of the hydraulic structure and the surrounding environment. The model is divided into small, interconnected cells or volumes, forming a mesh or network. The equations governing the behaviour of fluid flow are solved numerically for each cell or volume in the mesh, taking into account the properties of the fluid, the geometry of the structure, and the surrounding environment. CFD can be used to analyze the behaviour of hydraulic structures under different flow conditions, such as water flow in a channel or river, or the behaviour of water in a reservoir or dam. The technique can also be used for optimizing the design of hydraulic structures and predicting their performance over time. Overall, numerical modelling techniques such as FEM and CFD provide a powerful tool for analyzing the behaviour of hydraulic structures under different loading conditions and for optimizing their design and performance. However, these techniques should be used in conjunction with experimental methods and field observations to ensure accurate and reliable analysis.

3.2. Integration of Finite Element Method

Integration is a critical component of the Finite Element Method (FEM) modelling process. It involves the numerical integration of the equations governing the behaviour of each element in the structure. The first step in the integration process is to subdivide the element into smaller segments. Each segment is defined by a set of nodes and a corresponding set of shape functions. The shape functions describe the behaviour of the element within the segment. Once the element is subdivided, the equations governing the behaviour of each segment are integrated numerically. This is typically done using quadrature integration, which involves approximating the integral using a finite number of

sample points. The sample points are chosen based on the order of the shape functions used to describe the behaviour of the element. The higher the order of the shape functions, the more sample points are required to achieve an accurate approximation. After the sample points are selected, the integrals are evaluated numerically using the sample points and corresponding weights. This involves multiplying the values of the shape functions and the integrand at each sample point by the corresponding weight and summing the results.

The numerical integration process is repeated for each segment of the element, and the results are combined to obtain the overall behaviour of the element. This process is repeated for each element in the structure, and the results are combined to obtain the overall behaviour of the entire structure.

Finite Element Method (FEM) is a powerful numerical modelling technique used to analyze and optimize the design of hydraulic structures. FEM can be used to analyze the stresses within hydraulic structures under different loading conditions. This can help engineers identify potential failure points and optimize the design of the structure to minimize stress concentrations. FEM can also be used to analyze the deformation of hydraulic structures under different loading conditions. This can help engineers optimize the design of the structure to minimize deformations and ensure that it remains stable and functional. FEM can be used to analyze the fatigue life of hydraulic structures, which is important for ensuring that the structure remains safe and functional over its expected service life. FEM can be used to analyze the dynamic behaviour of hydraulic structures under different loading conditions, such as earthquakes or high winds. This can help engineers optimize the design of the structure to ensure that it can withstand these types of extreme events. Fluid-structure interaction analysis: FEM can also be used to analyze the interaction between hydraulic structures and the fluid flowing through them. This can help engineers optimize the design of the structure to minimize turbulence and ensure that it operates efficiently.

4. Data Collection for Finite Element methods

Data collection is a critical aspect of Finite Element Method (FEM) modelling, as accurate and reliable input data is essential for obtaining accurate and reliable results.

The material properties of the components that make up the hydraulic structure, such as the modulus of elasticity and Poisson's ratio, are essential for accurately modelling the behaviour of the structure under different loading conditions. The geometric properties of the hydraulic structure, such as its length, width, and thickness, are also essential for accurately modelling its behaviour. The boundary conditions of the hydraulic structure, such as the type and magnitude of the loads applied, are critical for accurately modelling the behaviour of the structure. The density of the mesh used in the FEM model is also important for obtaining accurate results. A finer mesh can provide more accurate results, but it also increases the computational complexity of the model. Environmental factors, such as temperature and humidity, can also affect the behaviour of hydraulic structures and should be taken into account during data collection. Overall, accurate and reliable data collection is essential for obtaining accurate and reliable FEM results. Engineers should use a combination of experimental data, field observations, and numerical simulations to collect the necessary data and validate the accuracy of the FEM model.

5. Discussion

This article is a review note of already existing selective literature, no practical or experimental assessments were done to complete this study; hence this is the limitation of the current study.

FEM is instrumental in performing failure analysis of hydraulic structures. By simulating extreme loading scenarios, such as flash floods, overtopping, or breach conditions, engineers can predict how and when a failure might occur. This analysis aids in the development of risk assessments and mitigation strategies to enhance the safety and reliability of hydraulic installations. Fluid-structure interaction problems often involve nonlinear behaviour due to large displacements, material yielding, or turbulence in fluid flow. Accurately capturing these nonlinear effects requires sophisticated modelling techniques and computational resources, which can complicate the analysis. Hydraulic structures are frequently subjected to dynamic loads resulting from waves, seismic activity, or water surges [37]. Capturing the interaction between these dynamic forces and the structural response necessitates advanced dynamic analysis techniques within the FEM framework. The quality of the mesh can significantly impact the accuracy of FEM results. For complex geometries and fluid dynamics, generating a high-quality mesh that accurately captures all features while maintaining computational efficiency poses a challenge. High-fidelity FEM simulations involving fluid-structure interaction can be computationally intensive, requiring extensive resources. As model complexity increases, the need for parallel computing or high-performance computing (HPC) systems becomes essential to manage simulation times [38]. Recent advancements in computational techniques are enhancing the application of FEM in hydraulic structural engineering i.e. developments in coupled computational fluid dynamics (CFD) and FEM.

6. Conclusion

Hydraulic structural engineering is a rapidly evolving field, driven by the demand for resilient, sustainable infrastructure. Advances in numerical modelling techniques, particularly the Finite Element Method (FEM), have enabled engineers to optimize the design of hydraulic structures and ensure their safety and performance under different loading conditions. FEM can provide valuable insights into the stresses, deformations, fatigue life, dynamic behaviour, and fluid-structure interactions of hydraulic structures, allowing engineers to optimize their design and enhance their efficiency. Furthermore, recent research has focused on developing non-destructive testing methods, innovative repair and retrofitting techniques, and sustainable design strategies to improve the maintenance and rehabilitation of hydraulic structures. The advancements in FEM and hydraulic structural engineering have contributed significantly to the development of safer, more efficient, and sustainable infrastructure. Future research efforts should focus on developing more resilient and adaptive hydraulic structures that can withstand extreme events, integrating new technologies, and promoting sustainable design practices. By addressing these challenges and opportunities, we can ensure the longevity and performance of hydraulic structures and support sustainable development for generations to come.

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