*Symposium "Dams for People, Water and Environment and Development" - 92nd ICOLD Annual Meeting – New Delhi , India 29 Sept. - 03 Oct. 2024*

# Methodology for simulating crack propagation in concrete dams

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# 1 ABSTRACT

This paper presents an extensive methodology that integrates insights from several referenced studies and is currently used to simulate crack propagation in concrete dams. It emphasizes the fusion of advanced computational techniques with empirical data to precisely model crack behavior. Notably, the Extended Finite Element Method (XFEM) is highlighted for its efficacy in simulating crack growth, particularly under dynamic loads like seismic events. The methodology encompasses meticulous geometric modeling, determination of material properties, and consideration of boundary conditions and loads. Calibration against experimental data ensures the fidelity of the simulations, while sensitivity analyses probe the impact of crucial parameters on crack propagation. This comprehensive approach enhances comprehension of concrete dam behavior and facilitates the formulation of effective maintenance and safety strategies.

Keywords: Crack propagation, concrete dams, Extended Finite Element Method (XFEM), computational modeling, empirical data integration, seismic events, geometric modeling, material properties, boundary conditions, sensitivity analysis, maintenance strategies.

# 2 INTRODUCTION

Crack propagation in concrete dams is a critical aspect influencing their structural integrity and longevity (Abdulrazeg et al., 2014; Campos et al., 2016; Habib et al., 2021). These dams, designed to withstand hydrostatic pressures, environmental variations, and seismic events, may develop cracks over time, posing threats to their safety and functionality (Abdulrazeg et al., 2014; Campos et al., 2016; Habib et al., 2021). Understanding crack development mechanisms is imperative for maintenance and safety assessments. This paper explores methodologies for simulating crack propagation in concrete dams, utilizing advanced computational techniques and empirical data to analyze structural behaviors under diverse stress conditions.

Concrete, despite its durability, is susceptible to cracking under tensile stress induced by factors such as water pressure, temperature changes, and geological shifts (Abdulrazeg et al., 2014; Campos et al., 2016; Habib et al., 2021). Early detection and management of cracks are crucial for preserving dam integrity. Various computational methods, notably the Extended Finite Element Method (XFEM), facilitate accurate modeling of crack propagation (Abdulrazeg et al., 2014; Campos et al., 2016; Habib et al., 2021). XFEM's ability to incorporate discontinuities within elements without altering the mesh structure enables precise depiction of crack behavior, especially during dynamic events like seismic activities.

Simulation commences with creating a precise geometric model of the dam, reflecting actual conditions and existing flaws. Material properties, including elasticity and fracture energy, are defined based on empirical data (Abdulrazeg et al., 2014; Campos et al., 2016; Habib et al., 2021). XFEM employs special functions to model cracks, crucial for studying events like seismic activities where cracks may propagate unpredictably. Boundary conditions define the dam's interactions with its environment, including hydrostatic pressures, thermal loads, and seismic forces, ensuring accurate representation in simulations.

Reliability hinges on calibration and validation, comparing simulation results with experimental data or real-world observations (Abdulrazeg et al., 2014; Campos et al., 2016; Habib et al., 2021). Sensitivity analysis identifies how variations in inputs affect outputs, crucial for understanding uncertainties in material properties or environmental conditions. Integrating these computational tools with empirical data provides a comprehensive framework for predicting failure points in concrete dams, enhancing safety, and optimizing maintenance practices.

# 3 STEPS IN THE SIMULATION PROCESS

## 3.1 *Selection of Simulation Technique*

Technique: The Extended Finite Element Method (XFEM) is a powerful computational technique employed for modeling crack propagation in concrete dams. Unlike traditional finite element methods, XFEM does not require remeshing as cracks propagate, making it particularly efficient for simulating crack growth. This method utilizes special enrichment functions to represent the discontinuities caused by cracks within the finite element framework. By incorporating these enrichment functions, XFEM can accurately capture the complex behavior of cracks under dynamic loads, such as seismic events or hydraulic pressure fluctuations. This capability allows engineers to analyze crack propagation patterns and their impact on the structural integrity of concrete dams with high precision and computational efficiency (Abdulrazeg et al., 2014).

In the study conducted by Campos et al. (2016), XFEM was employed to simulate crack propagation in concrete dams under seismic loading scenarios. The XFEM methodology enabled the researchers to incorporate dynamic loading conditions representative of earthquake events into their simulations. By utilizing XFEM, the study was able to accurately model the propagation of cracks within the concrete dams during seismic events. This allowed for a detailed analysis of how cracks evolve and propagate under the influence of seismic forces, providing valuable insights into the structural response of concrete dams to earthquake-induced loading. XFEM's capability to simulate crack propagation under dynamic loading scenarios enhances the understanding of the behavior of concrete dams during seismic events, aiding in the development of more robust seismic design and retrofitting strategies.

## 3.2 *Geometric Modeling*

Detailed Representation: Construct a detailed 3D model of the dam, incorporating geometrical specifics such as dimensions and known weaknesses like existing cracks or defects (Habib et al., 2021).

Geometric modeling is paramount in accurately representing concrete dams within computational simulations. This process entails capturing precise dimensions, crack locations, surface features, and defects. Historical inspection data provides vital insights into existing cracks, integrated into the model for precise simulation of their structural impact. Surface roughness and irregularities are meticulously considered to faithfully replicate real-world conditions. Mesh generation further enhances the model, discretizing the structure into elements or nodes for efficient analysis. This detailed geometric model serves as the cornerstone for simulations, enabling researchers to investigate the dam's response to various loading conditions and evaluate its structural integrity under different scenarios.

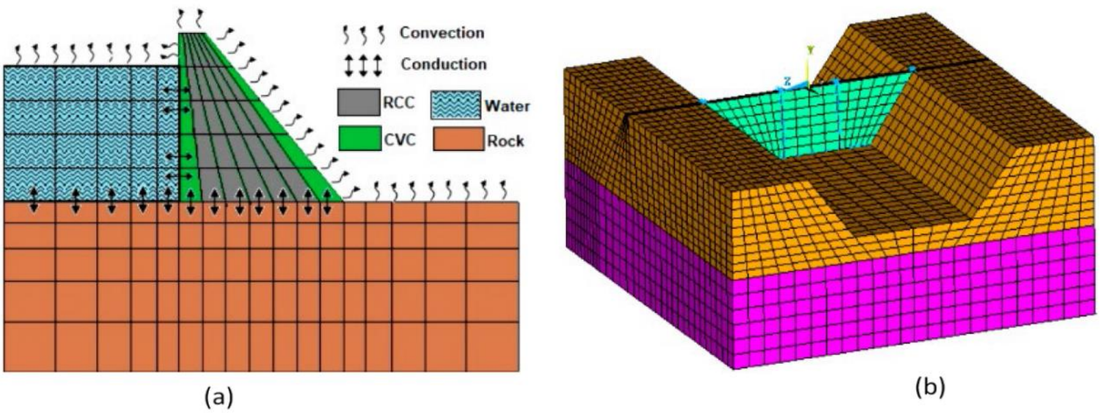


Figure 1.(a) 2D (Bayagoob & Bamaga, 2019), (b) 3D (Kartal, 2012) simulation of RCC dam and its foundation

### 3.3 *Material Properties*

Empirical Data: Source data on concrete's mechanical properties from experimental setups or from industry-standard databases, considering variations due to the dam's age or specific environmental exposure (Abdulrazeg et al., 2014).

Elasticity modulus and fracture energy for dam concrete were adopted from previously published empirical research and adjusted based on the dam’s exposure conditions.

### 3.4 *Crack Modeling*

In the study by Campos et al. (2016), the evolution of cracking in the joints of concrete dams was comprehensively addressed through the implementation of enrichment functions within XFEM. This sophisticated approach allowed for a detailed exploration of how cracks develop and propagate over time, shedding light on the dynamic nature of crack evolution.

Through XFEM, researchers were able to capture the intricate details of crack behavior, including the stress singularity at the crack tip and the displacement across the crack faces. By integrating enrichment functions into the finite element model, the simulation accurately depicted the evolution of cracking in the joints, offering valuable insights into the underlying mechanisms driving crack growth.

This evolutionary perspective provided a deeper understanding of how cracks initiate, propagate, and interact with their surrounding environment. By capturing the dynamic evolution of cracking in the joints, the study contributed to enhanced predictive capabilities for assessing the long-term structural integrity of concrete dams.

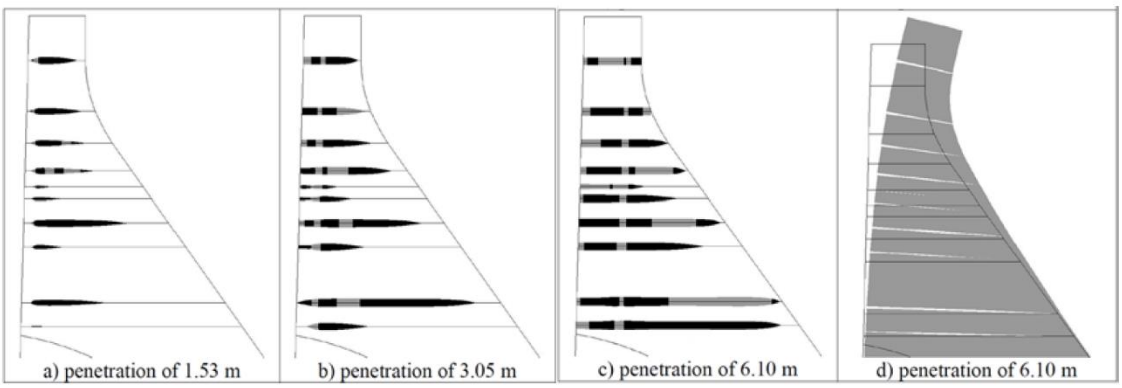


Figure 2.Evolution of the cracking in the joints. Campos et al. (2016)

### 3.5 *Boundary Conditions*

In the study by Habib et al. (2021), the definition of boundary conditions encompassed the complex interactions between the concrete dam, the water in the reservoir, and the underlying foundation. Specifically, the researchers considered the dam as a structural entity subjected to various loads and constraints, including hydrostatic pressures from the reservoir and foundation support.

The boundary conditions were carefully defined to reflect the behavior of the water in the reservoir, which was assumed to be incompressible and inviscid. This assumption allowed for the accurate modeling of hydrostatic pressures exerted on the dam structure due to the weight of the water column. Additionally, the underlying foundation was treated as an elastic body, providing support to the dam while accounting for its deformations under load.

By incorporating these system interactions into the finite element model, the study aimed to simulate the realistic response of the concrete dam under different loading conditions. This comprehensive approach to defining boundary conditions enabled researchers to assess the structural integrity and stability of the dam more accurately, considering the complex interactions between the dam, reservoir water, and foundation.

The boundary conditions for a gravity dam included the hydrostatic pressure from the reservoir, modelled to reflect seasonal water level variations and their effect on stress distribution.

### 3.6 *Loads and Forces*

In the context of the simulation conducted by Campos et al. (2016), the application of seismic forces, particularly those generated by the 1967 Koyna earthquake, led to the generation of dynamic tensile stresses within the concrete dam. These tensile stresses result from the dynamic loading imposed on the dam structure during seismic events, causing fluctuations in forces and deformations that induce tensile forces along certain regions of the dam.

Dynamic amplification factors were incorporated into the simulation to accurately model the increased tensile stresses experienced by the dam during seismic events. These factors account for the dynamic response of the dam to seismic loading, considering factors such as the dam's natural frequency, stiffness, and damping characteristics.

Understanding the distribution and magnitude of tensile stresses is crucial for assessing the structural integrity of concrete dams during seismic events. Excessive tensile stresses can lead to the initiation and propagation of cracks, which may compromise the overall stability and safety of the dam. By simulating the response of the dam to seismic forces and analyzing the resulting tensile stresses, researchers can gain valuable insights into the behavior of concrete dams under earthquake loading conditions and develop strategies to mitigate potential risks.

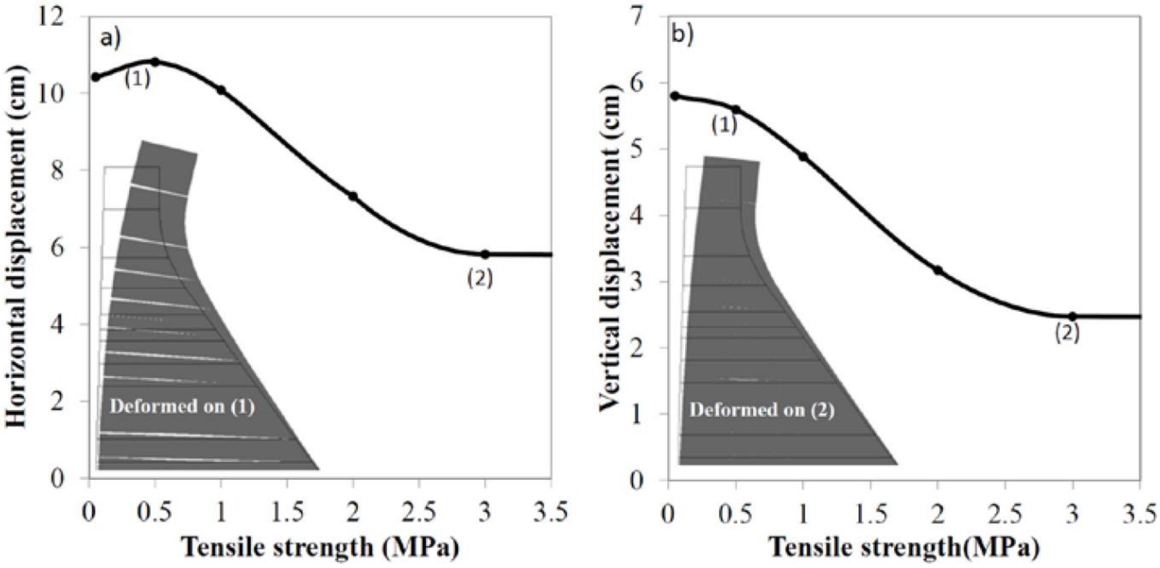


Figure 3.Influence of the tensile strength of the joints on: a) horizontal displacement and b) vertical displacements at the crest. Campos et al. (2016)

### 3.7 *Initial Conditions*

In the study by Abdulrazeg et al. (2014), static analyses of gravity and hydrostatic loads served as the starting point for dynamic simulations of concrete dams. These static analyses provided baseline conditions to establish the pre-stressed state of the dam under normal operational conditions.

The initial conditions for the dynamic simulations were derived from the static load of water at maximum reservoir capacity. This represented the worst-case scenario in terms of hydrostatic pressure acting on the dam. By using the maximum reservoir capacity as the initial condition, researchers ensured that the dynamic analysis captured the most severe loading conditions that the dam would experience during its operational lifespan.

Furthermore, these initial conditions served as the basis for further dynamic analysis, allowing researchers to assess the dam's response to dynamic loading scenarios such as seismic events. By establishing the pre-stressed state of the dam through static analyses and incorporating realistic initial conditions into the dynamic simulations, the study provided a comprehensive understanding of the structural behavior of concrete dams under various loading conditions.

### 3.8 *Thermal Effects*

In the research conducted by Habib et al. (2021), the modeling of thermal effects due to hydration played a significant role in understanding the aging process of roller-compacted concrete (RCC) used in dams. This involved considering the heat generation during the hydration process, which is the chemical reaction between water and cement, leading to the hardening of concrete. The heat generated during hydration contributes to temperature variations within the concrete, affecting its mechanical properties over time.

The simulation included the modeling of thermal cycles to assess the impact of seasonal temperature changes on the aging process of RCC. Specifically, the researchers focused on evaluating the creep behavior of RCC under varying thermal conditions. Creep refers to the gradual deformation of concrete over time under sustained loading, which is influenced by factors such as temperature variations and moisture content.

By incorporating thermal effects due to hydration and aging into the simulation, the study aimed to provide insights into how seasonal temperature changes affect the long-term mechanical behavior of RCC in dams. This detailed analysis of creep behavior under different thermal conditions contributes to a better understanding of the performance and durability of RCC structures over their operational lifespan.

### 3.9 *Calibration and Validation*

In the study by Campos et al. (2016), experimental data played a crucial role in validating simulation outcomes and enhancing the accuracy of the model. Validation involved comparing the results obtained from the simulation with real-world measurements and experimental data gathered from past inspections of concrete dams.

One aspect of calibration included comparing the simulated crack paths with those observed during past inspections of concrete dams. By aligning the simulated crack paths with observed data, researchers were able to assess the accuracy of the simulation in predicting crack propagation. Any discrepancies between the simulated and observed crack paths were used to refine and adjust the material model parameters, ensuring that the simulation accurately reflected real-world conditions.

Additionally, adjustments to the material model parameters were made based on feedback obtained from the comparison between simulated outcomes and experimental data. This iterative process of calibration and adjustment aimed to enhance the predictive capabilities of the simulation model, making it more reliable for assessing the behavior of concrete dams under various loading conditions.

By validating the simulation outcomes against experimental data and adjusting the model parameters accordingly, the study ensured that the simulation accurately represented the complex behavior of concrete dams. This approach enhanced the confidence in the simulation results and provided valuable insights for improving the understanding of crack propagation and structural behavior in concrete dams.

### 3.10 *Calibration and Validation*

In the study by Habib et al. (2021), sensitivity analyses were conducted to assess the influence of parameter variability on simulation results. This involved systematically altering material properties, crack geometry, and loading conditions to explore their effects on the behavior of concrete dams.

For instance, a series of simulations were performed by varying the concrete tensile strength to understand its impact on crack initiation and propagation under different loading scenarios. By systematically adjusting the tensile strength within the simulation model, researchers were able to observe how changes in this material property affected the likelihood and extent of crack formation within the concrete dam.

Additionally, sensitivity analyses were conducted to explore the effects of variations in crack geometry and loading conditions on simulation outcomes. This involved altering parameters such as crack length, depth, and orientation, as well as adjusting the magnitude and distribution of applied loads.

Through these sensitivity analyses, researchers gained valuable insights into the sensitivity of the simulation results to changes in key parameters. By systematically exploring parameter variability, the study enhanced the understanding of the factors influencing crack initiation and propagation in concrete dams under different loading conditions. This information is crucial for improving the accuracy and reliability of simulation models used in the assessment and design of concrete dam structures.

## 4 CONCLUSION

In conclusion, this paper presents a comprehensive methodology for simulating crack propagation in concrete dams, integrating insights from various referenced studies to enhance our understanding of structural behavior under diverse stress conditions. By leveraging advanced computational techniques like the Extended Finite Element Method (XFEM) and empirical data, the methodology offers a robust framework for precise modeling of crack behavior. XFEM proves particularly effective in capturing crack growth dynamics, especially under dynamic loads such as seismic events. The methodology encompasses meticulous geometric modeling, determination of material properties, and consideration of boundary conditions and loads, ensuring a holistic approach to simulation.

Validation against experimental data and sensitivity analyses further validate the accuracy and reliability of the simulations, enhancing our confidence in the predictive capabilities of the model. The detailed representation of concrete dams, including considerations for aging effects and thermal variations, provides valuable insights into long-term structural performance.

Overall, this methodology facilitates a deeper understanding of crack propagation mechanisms and aids in the formulation of effective maintenance and safety strategies for concrete dams. By combining advanced computational tools with empirical data, this approach contributes to the optimization of maintenance practices and the enhancement of dam safety, ultimately safeguarding critical infrastructure and the communities that depend on it.

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