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An incrementation-adaptive multi-transmitting boundary for seismic fracture analysis of concrete gravity dams

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ABSTRACT

This study presents a numerical framework and methodology that features a nonlinear extended finite element formulation for earthquake fracture analysis of dam-reservoir-sediment-foundation coupled systems and an adaptive time incrementation multi-transmitting boundary for modeling seismic wave propagation in both infinite reservoir and foundation domains. To improve the convergence rate during the iterative solution of the highly nonlinear dynamic equilibrium equation, the original Multi-Transmitting Formula (MTF) is modified and coupled to the automatic incrementation time-stepping scheme through the introduction of a fictitious time scale in conjunction with an interpolation scheme that links the fictitious time scale to the real time scale. Meanwhile, the dynamic crack initiation and propagation in the body of the dam is represented by the extended finite element method including the effects of branching and intersecting cracks. As an application of the proposed formulation, the seismic cracking behavior of a representative concrete gravity dam system is analyzed.

1. Introduction

Concrete gravity dams play a vital part in generating electric power, supplying water for agriculture, industries and households, controlling flooding, and assisting river navigation. Their stability and safety during strong earthquake shaking has been a subject of public concern and research attention. As such, in the past few decades, considerable research efforts have been directed towards the numerical modeling and response evaluation of these critical infrastructures. However, despite the significant progress made thus far, the computational modeling of concrete gravity dams subjected to earthquake ground motions still poses a challenging task for the civil engineering profession as it requires solving a complex multi-physics problem that involves the consideration of a number of essential issues pertaining to the dam, the impounding reservoir, the sediment at the reservoir bottom, and the foundation supporting the dam, such as (i) complex interaction between the dam, the reservoir, the sediment and the foundation (e.g., [1]); (ii) infinite extent of the reservoir and foundation domains (e.g., [2]); (iii) inelastic material behavior of the concrete in the dam, the water in the reservoir, and the rock in the foundation (e.g., [3]).

In particular, under severe seismic excitations, cracks may develop in the unreinforced concrete masses in the body of the dam as a result of the concrete's low tensile strength. Accurate representation of the nonlinear material behavior of concrete is critical in the seismic response evaluation of concrete gravity dams, which has continued to attract significant research interest and new developments are still being reported. At the macroscopic level, these modeling techniques and procedures can be broadly classified into two categories, i.e., the continuum-damage-mechanics-based approach (e.g., [4–8]) and the fracture-mechanics-based approach (e.g., [9–12]). However, it should be noted that for the time being, accurate finite element modeling of dynamic crack propagation in the context of fracture mechanics is still challenging because the polynomial shape functions that are conventionally utilized in the standard Finite Element Method (FEM) cannot capture the stress singularities at the crack tip. This problem has been recently alleviated by procedures such as the Extended Finite Element Method (XFEM) (e.g., [13–16]), which ensures the aforesaid singularities by means of special enriched functions in combination with additional degrees of freedom.

In addition to the complicated nonlinear constitutive behavior of the dam concrete, another significant consideration in the modeling of the dam-reservoir-sediment-foundation system is the unbounded reservoir and foundation domains. For these two unbounded domains, the radiation condition requires that the waves traveling in the direction away from the structure towards infinity should be out-going, which will not be reflected back to the structural domain. Over the past few decades, a plethora of numerical schemes have been developed for modeling infinite domains. A rigorous approach is to couple the FEM for modeling the dam domain with the Boundary Element Method (BEM) for modeling the infinite reservoir and foundation domains (e.g., [17–20]). However, it is noted that the coupling of the FEM and the BEM does not appear to be that straightforward. Furthermore, modeling

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the nonlinear constitutive behaviors of the water in the reservoir and the rock in the foundation by the BEM also seems to be a challenging task. As pointed out by Hatzigeorgiou and Beskos [21], nonlinear time-domain boundary element formulation accounting for dynamic fracturing behaviors of both the dam and the foundation in the finite strain regime still requires further development. Apart from the combined FEM-BEM approach, a rational and logical scheme for the simulation of unbounded media is to represent the region of interest using standard finite elements and the far-field region using infinite elements (e.g., [22,23]). Generally, the Infinite Element Method (IEM) performs well in the frequency domain analyses of dynamic problems. However, it has been questioned for its effectiveness on the application to transient problems [24,25]. Alternatively, infinite domains can be treated by first truncating the infinite domain into a finite computational model and then applying an Artificial Boundary Condition (ABC) on the edge of the truncated boundary of the finite model. The ABCs in the literature can be generally grouped into two categories, i.e., nonlocal ABCs (such as the BEM) and local ABCs (see, e.g., [2], for a thorough review). For instance, a commonly utilized local ABC is the Lysmer and Kuhlemeyer's viscous boundary [26], the essential notion of which is to place viscous dashpots along the truncated boundary to absorb the radiated energy. Owing to its simplicity and applicability for nonlinear transient problems, this technique has underlain much research in the simulation of unbounded domains (e.g., among others, [27,28]). However, it is worthy of note that the performance of this ABC is dependent on the wave incident angle. The energy absorption is perfect for waves propagating to the boundary at normal angles of incidence. For waves that impinge the boundary at oblique angles of incidence, it is only approximate, not perfect. Aside from the Lysmer and Kuhlemeyer's viscous boundary [26], other notable local ABCs include, but not limited to, [27–30]. It is, however, worth mentioning that for these local ABCs, some of them were formulated in the frequency domain (e.g., [29]), while others were intended for analysis in the time domain (e.g., [30]). On a further note, some of the ABCs only apply to the cases of acoustic wave propagation in fluids (e.g., [29,30]), while some of them only work for elastic wave propagation in solids (e.g., [27,28]). A unified ABC that works for both fluid and solid media of infinite extent and can be easily implemented in nonlinear finite element codes is warranted. In addition to the aforementioned local ABCs, more sophisticated local ABCs also exist (e.g., [31,32]). However, although such ABCs generally exhibit a better performance than the classical Lysmer and Kuhlemeyer's ABC, the applications of these ABCs to practical problems are hindered by two inherent weaknesses. First, the solution accuracy of such ABCs are dependent on the order of the ABC. As a result, the implementation of the high-order ABCs, particularly the high-order derivatives, in standard finite element codes could be cumbersome. Additionally, high-order ABCs may suffer from stability issues [33].

Clearly, significant challenges still remain in the modeling of seismic wave propagation in the unbounded reservoir and foundation domains as well as dynamic crack propagation in the dam domain. Motivated by the aforementioned challenges, the objective of this research is to extend the Multi-Transmitting Formula (MTF) proposed by Liao et al. [34,35] to develop an improved time-increment-adaptive multi-transmitting boundary for XFEM-based seismic fracture analysis of concrete gravity dam systems including unbounded reservoir and foundation domains. Accordingly, the paper is organized into seven sections. Specifically, Section 2 describes the numerical modeling and the automatic time incrementation solution procedure for nonlinear seismic response analysis of dam-reservoir-sediment-foundation coupled systems. Next, Section 3 presents the extended finite element formulation including the effects of branching and intersecting cracks for the modeling of dynamic crack initiation and propagation in the solid domain. Then, Section 4 proposes an adaptive time incrementation multi-transmitting boundary for the simulation of unbounded reservoir and foundation domains, which allows for use in nonlinear seismic fracture analysis of dam-reservoir-sediment-foundation coupled systems. Immediately following Section 4, in Section 5, a series of numerical experiments are conducted to assess the performance of the proposed transmitting boundary for the modeling of transient wave propagation in 1D and 2D unbounded fluid and solid domains. After the verification of the proposed boundary, Section 6 applies the numerical framework and methodology developed in Sections 2–4 to simulate the earthquake behavior of dam under seismic excitations, in which the earthquake behavior of a representative concrete gravity dam system as well as the formation and evolution of cracks in the body of the dam is analyzed and compared with those predicted by existing numerical and experimental studies. Finally, Section 7 summarizes the major conclusions and recommendations obtained from this research work.

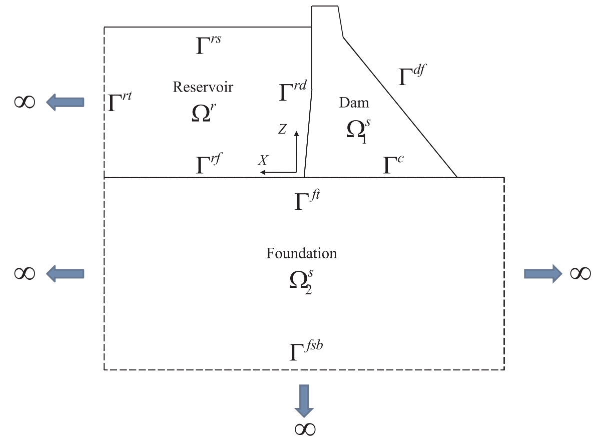

Fig. 1. Schematic illustration of a dam-reservoir-sediment-foundation coupled system.

2. Numerical formulation and adaptive time incrementation solution procedure

This section covers the numerical formulation for the dam-reservoir-sediment-foundation coupled system. As illustrated in Fig. 1, the system to be analyzed is a concrete gravity dam impounding a reservoir extending to infinity in the upstream direction and resting on a semi-unbounded foundation. It is also assumed that sediments are present at the bottom of the reservoir. As manifested in Fig. 1, the reservoir constitutes a spacial fluid domain Ω^r, in which the superscript r of the form $(\cdot)^r$ denotes the water in the reservoir that is assumed to be a linear compressible inviscid fluid. The boundary for the fluid domain is defined as $\partial\Omega^r = \Gamma^{rs} \cup \Gamma^{rt} \cup \Gamma^{rf} \cup \Gamma^{rd}$, in which Γ^{rs}, Γ^{rt}, Γ^{rf}, and Γ^{rd} denote the reservoir's surface, the reservoir's truncated boundary, the reservoir-foundation interface, and the reservoir-dam interface, respectively. On the other hand, the dam and the foundation form a spacial solid domain Ω^s, in which the superscript s of the form $(\cdot)^s$ denotes solid. The solid domain can be divided into the dam sub-domain Ω_1^s and the foundation sub-domain Ω_2^s, in which the subscript i of the form $(\cdot)_i^s (i = 1, 2)$ is utilized to indicate either the dam or the foundation. The boundaries for the dam and foundation domains are $\partial\Omega_1^s = \Gamma^{rd} \cup \Gamma^c \cup \Gamma^{df}$ and $\partial\Omega_2^s = \Gamma^{ft} \cup \Gamma^{fsb}$, respectively, in which Γ^{rd}, Γ^c, Γ^{df}, Γ^{ft}, and Γ^{fsb} denote the dam-reservoir interface, the dam-foundation interface, the dam's free traction surface, the foundation's top boundary, and the foundation's side-and-bottom boundary, respectively. For the sake of brevity, only the basic description of the dam-reservoir-foundation coupled system is given here. Further elaboration on the governing equations and boundary conditions for the fluid and solid domains as well as the coupling of the fluid and solid domains is referred to [36].

Upon integrating the governing equations by parts over domains Ω^r, Ω_1^s, and Ω_2^s, introducing the boundary conditions defined on the boundaries $\partial\Omega^r$, $\partial\Omega_1^s$, and $\partial\Omega_2^s$ to the domain integrals, and performing