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Seismic cracking analysis of concrete gravity dams with initial cracks using the extended finite element method

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ABSTRACT

The seismic crack propagation of concrete gravity dams with initial cracks at the upstream and downstream faces has rarely been studied during strong earthquakes. In this paper, a numerical scheme based on the extended finite element method (XFEM), which has been widely used for the analysis of crack growth, is presented to deal with the numerical prediction of crack propagation in concrete gravity dams. The validity of the algorithm is discussed by comparing results obtained from the proposed XFEM with those reported in the literature. For this purpose, the cracking process and final crack profile of Koyna dam during the 1967 Koyna earthquake are simulated numerically by employing the XFEM. The computed distribution of cracking damage is consistent with the actual condition and the results of model test and available methods in literature, which verifies the validity of the calculation model. Subsequently, the Koyna dam with single and multiple initial cracks is also analyzed using the proposed approach, which is investigated to evaluate the seismic crack propagation of the concrete gravity dam with initial cracks. The effects of initial cracks on the crack propagation and seismic response of the concrete gravity dam are discussed.

1. Introduction

Concrete gravity dams are distinguished from other concrete structures because of their size and their interactions with the reservoir and foundation. In practical service, concrete gravity dams normally might have well cracked at their base or at the upstream and downstream faces caused by internal and external temperature variations, shrinkage of the concrete, differential foundation settlement, previous earthquakes or other reasons [1,2]. These cracks with limited depth will possibly develop in the dam body or, through the monoliths under static or dynamic conditions. As a result, these existing cracks weaken the seismic capacity of concrete gravity dams mainly due to the nonlinear behavior, during strong ground motions. Hence, the real analytical challenge for the crack analysis of concrete gravity dams is to predict their propagation paths under seismic loading conditions. Then, countermeasures can be taken at an early stage to stem their further growth.

Cracking plays an important role for the concrete structural behavior, and the modeling of crack growth is a problem of great importance in the simulation of failure. Many models have been developed to investigate the nonlinear seismic analysis of a cracked concrete gravity dam. There are traditionally based either on the discrete crack approach [3–5] or the smeared crack approach [6–8]. In the discrete crack model, the discontinuous displacement field at a crack is accounted for by introducing a discontinuity interface into the solid and describing its behavior by a discrete traction-separation law [9]. In a finite element mesh, discontinuity interfaces are placed at element boundaries. Hence, they need remeshing algorithms to accommodate crack propagation [10]. In the smeared crack model, cracking is modeled by modifying the strength and stiffness of concrete and by distributing or "smearing" the dissipated energy along the finite width of the localization band [11,12].

The extended finite element method (XFEM) [13–16], which is based on the cohesive segments method [17] in conjunction with the phantom node technique [18,19], can be used to simulate crack initiation and propagation along an arbitrary path, since the crack propagation is not tied to the element boundaries in a mesh. With this approach, it is not necessary to define the crack tip position, but it is possible to simply define a reference region in which the crack will propagate. The near-tip asymptotic singularity is not needed, and only the displacement jump across a cracked element is considered. Hence, the crack has to propagate across an entire element at a time to avoid the need to model the stress singularity. The phantom node method describes discontinuity by superposing the phantom elements instead of introducing additional degrees of freedom, and it is easy to incorporate into conventional finite ele-

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ment codes. The XFEM is applied to 2D [14,18,20], 3D problems [21–24], and dynamic problems [19,25–27].

Nonlinear response of cracked concrete gravity dams has been of great interest in engineering. Many studies [3–8] focused mainly on the propagation of cracks in the dam, which is accompanied by opening and closing of the cracks, including shake table experiments [28–30]. However, little efforts have been done for the case in which cracks are expected to appear at the upstream and downstream faces in non-overflow monoliths of the dam. In this case, the seismic response becomes more complex.

In comparison with numerous works concerning crack occurrence and propagation in concrete gravity dams, there are limited researches on the seismic response of concrete gravity dams with initial cracks. The crack propagation analysis of the concrete gravity dam with initial notch in the upstream wall was first studied by Carpinteri et al. [31], in which two scaled-down 1:40 models of a gravity dam were subjected to equivalent hydraulic loads, and crack mouth opening control is performed and the load vs. CMOD diagram is plotted. Assuming multiple initial notches of different sizes at different locations along the upstream face of the model dams, Shi et al. [32] used the well-quoted scale model and extended fictitious crack model to study the cracking behaviors in concrete dams, various kinds of cracking behaviors were obtained and discussed, focusing on the crack interactions. By use of the cohesive crack model, Barpi and Valente [33] investigated the behavior of a 96-m-high gravity (the prototype) with a preexisting crack in the upstream face, and the structural response and crack trajectories were reproduced. Their results showed that the initial notch in the upstream face served as the starting point of a crack that propagated toward the foundation during the loading process. Bolzon [34] used Linear Elastic Fracture Mechanics (LEFM) and cohesive crack approach to evaluation of safety against ultimate failure of large concrete gravity dams with an initial notch at the base. Pekau and Yuzhu [35] used the distinct element method (DEM) to study the seismic behavior of the fractured Koyna dam during earthquakes. Their results showed that the safety of the dam was ensured if the crack shape was horizontal or upstream-sloped, and it was very dangerous if the crack slopes downstream. Javanmardi [36] combined the discrete crack model with a theoretical model for uplift pressure variations along a cracked dam to study the seismic stability of concrete gravity dams. Wang et al. [37] studied the stability of a gravity dam on jointed rock foundation and the seismic stability of the fractured Konya gravity dam using 3D-discontinuous deformation analysis (3D-DDA). Pekau and Zhu [38,39] proposed a rigid model and a flexible FE model to study the seismic behavior of cracked concrete gravity dams. Mirzayee et al. [40] proposed a hybrid distinct element–boundary element (DE–BE) approach for modeling the nonlinear seismic behavior of fractured concrete gravity dams considering dam–reservoir interaction effects.

In this paper, the XFEM made in ABAQUS program is used to study the crack propagation and nonlinear fracture behavior of concrete gravity dams with initial cracks under earthquake conditions. The seismic crack propagation process of Koyna dam during the 1967 Koyna earthquake is simulated numerically for verification. Subsequently, the Koyna dam with single and multiple initial cracks is investigated to evaluate the seismic crack propagation of concrete gravity dams with initial cracks. The effects of initial cracks on the crack propagation and seismic response of the concrete gravity dam are studied.

2. Extended finite element method for dynamic crack analysis

The extended finite element method was first introduced by Belytschko and Black [13]. The method provides significant benefits in the numerical modeling of crack propagation, without requiring the finite element mesh to conform to the existence cracks and the remeshing for crack growth due to the approximation for a displacement vector function added to model the presence of a crack. In the XFEM, a crack is modeled by enriching the classical displacement-based finite element approximation with the framework of the partition of unity method (PUM), previously proposed by Melenk and Babuška [41], which allows local enrichment functions to be easily incorporated into a finite element approximation. This enrichment functions typically consist of the near-tip asymptotic functions that capture the singularity around the crack tip and a discontinuous function that represents the jump in displacement across the crack surfaces. By implementing the generalized Heaviside function [14], the method was further enhanced, avoiding taking into account the complicated mapping for arbitrary curved cracks. The XFEM technique used to model crack initiation and propagation in concrete gravity dams is currently implemented in ABAQUS CAE for brittle or ductile materials such as the concrete gravity dams modeled in this work [42] and is described in the following section.

2.1. The XFEM approximation

The XFEM enriches a standard displacement based finite element approximation with discontinuous functions. The approximation for a displacement vector function u with the partition of unity enrichment (Fig. 1) in the XFEM takes the form [14,42]:

$$\mathbf{u}_{\text{xfem}}(\mathbf{x}) = \sum_{i\in I}\mathbf{u}_i N_i(\mathbf{x}) + \underbrace{\sum\nolimits_{j\in J}\mathbf{b}_j N_j(\mathbf{x}) H(\mathbf{x})}_{\text{only Heaviside nodes}} + \underbrace{\sum\nolimits_{k\in K_1} N_k(\mathbf{x})\left(\sum\nolimits_{l=1}^{4}\mathbf{c}_k^{l1}F_{l1}(\mathbf{x})\right) + \sum\nolimits_{k\in K_2} N_k(\mathbf{x})\left(\sum\nolimits_{l=1}^{4}\mathbf{c}_k^{l2}F_{l2}(\mathbf{x})\right)}_{\text{only crack-tip nodes}} \quad (1)$$

where $\mathbf{x} = \{x,y\}$ is the two-dimensional coordinate system, I is the set of all nodes in the mesh, $N_i(\mathbf{x})$ is the shape function associated with node i, $\mathbf{u}_i$ are the classical degrees of freedom for node i. $J \subset I$ is the set of nodes whose shape function support is cut by a crack, $\mathbf{b}_j$ is the vector of corresponding additional degrees of freedom for modeling crack faces (not crack-tips). If the crack is aligned with the mesh, $\mathbf{b}_j$ represent the opening of the crack, $H(\mathbf{x})$ is the Heaviside function. $K_1 \subset I$ and $K_2 \subset I$ are the set of nodes whose shape function support contains the first and second crack tips in their influence domain, respectively. $\mathbf{c}_k^{l1}$ and $\mathbf{c}_k^{l2}$ are the vector of corresponding additional degrees of freedom which are related to the modeling of crack-tips, as the near-tip regions are enriched with four different crack functions. $F_{l1}(\mathbf{x})$ and $F_{l2}(\mathbf{x})$ are crack-tip enrichment function. If there is no enrichment, then the above equation reduces to the classical finite element approximation $\mathbf{u}_{\text{fem}}(\mathbf{x}) = \sum_i \mathbf{u}_i N_i(\mathbf{x})$.

The first term on the right-hand side of the above equation (Eq. (1)) is applied to all the nodes while the second term is valid for nodes whose shape function support is cut by the crack interior, and the third (fourth) term is used only for nodes in which shape function support is cut by the crack tip.

2.2. Enrichment functions

To model the discontinuity in displacement field, the enrichment function $H(\mathbf{x})$ which we refer to as a generalized Heaviside enrichment function is implemented in simulation of powder-die contact surface, in which the function $H(\mathbf{x})$ takes on the value of +1 above the crack, and -1 below the crack. The function $H(\mathbf{x})$ is given by

$$H(\mathbf{x}) = \begin{cases} 1 & \text{if } (\mathbf{x}-\mathbf{x}^*).n \geqslant 0 \\ -1 & \text{otherwise} \end{cases} \quad (2)$$