Soil Dynamics and Earthquake Engineering 31 (2011) 1594–1606

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

A comparative study of the different procedures for seismic cracking analysis of concrete dams

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ARTICLE INFO

Article history:
Received 10 March 2011
Received in revised form
18 May 2011
Accepted 25 June 2011
Available online 16 July 2011

ABSTRACT

Different procedures are compared for the three-dimensional seismic cracking analysis of gravity and arch dams during strong earthquakes. The fracture procedures include the extended finite element method with cohesive constitutive relations, crack band finite element method with plastic-damage relations, and the finite element Drucker – Prager elasto-plastic model. These procedures are used to analyze the nonlinear dynamic response of Koyna dam to the 1967 Koyna earthquake and the seismic cracking of the Dagangshan arch dam subjected to design earthquake. The cracking process and profiles of the two dams using the three different procedures are compared. The applicability and the suitability of the three procedures for seismic cracking analysis of gravity and arch dams are discussed.

1. Introduction

The seismic safety of concrete dams has received considerable attention ever since the Ms8.0 Wenchuan earthquake occurred on May 12, 2008, in the Sichuan Province of China, where many high dams are under construction or in operation. To date, linear earthquake analysis, in conjunction with maximum principal stress criterion, is commonly used in the seismic design of dams; however, it is still rather impossible to predict the cracking or failure development in dam structures, which is crucial for dam safety evaluation. In recent decades, different fracture models have been developed for seismic cracking simulation of concrete dams. Two categories of fracture models are used, namely, the discrete crack model [1] and the smeared crack [2] or crack band model [3]. In addition, elasto-plastic yielding, such as the Drucker – Prager model, is also used in some cases to analyze the failure behavior of concrete. It is significant for dam safety evaluation to examine whether the nonlinear responses obtained from different fracture procedures are comparable in terms of achieving similar conclusions. In addition, seismic cracking analyses of concrete dams subjected to strong earthquakes have been primarily carried out for two-dimensional (2D) problems [4–7]. Three-dimensional (3D) seismic analysis for dams, especially for arch type ones, is required to provide more realistic results regarding cracking profiles in dams.

The purpose of this paper is to conduct a general comparison of different fracture procedures in terms of nonlinear response and cracking development for concrete structures using 3D seismic analysis of gravity and arch dams. Three procedures are used and compared, i.e., extended finite element method [8,9] with cohesive constitutive relations (XFEM-COH), crack band finite element method with plastic-damage constitutive relation (FEPD), and the Drucker – Prager elasto-plastic model (DP). In this study, the extended finite element method (XFEM) is based on the phantom node technique [10,11], which describes discontinuity by superposing the phantom elements instead of introducing additional degrees of freedom. The phantom node method is easy to incorporate into conventional finite element codes, and it is applied to 2D [11] and 3D problems [12]. The XFEM-COH procedure is categorized under the discrete crack model but with a great improvement in avoiding element remeshing during a crack propagation process. Meanwhile, the cohesive constitutive relationship controlling the cracking behavior in concrete is assumed to obey the strain softening and corresponding stiffness deterioration. The FEPD procedure is essentially a kind of smeared crack model. A great improvement on this procedure is the modification of the strain-softening curve to ensure that the dissipated fracture energy per unit length of crack formed remains independent of the finite element mesh. This procedure is used to analyze the damage/cracking of gravity dams subjected to strong earthquakes [13]. The DP procedure with elasto-plastic theory considers yielding zones as failure criteria for structures; it is commonly used in the nonlinear analysis of concrete or rocks.

The theoretical frames of the aforementioned fracture procedures are first described, after which their corresponding constitutive relations are derived to ensure equivalent fracture energy consumed in different procedures. A benchmark example of the dynamic fracture of the single-edge notched beam is then analyzed for accuracy verification. Subsequently, the three fracture procedures

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doi:10.1016/j.soildyn.2011.06.011