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Seismic cracking of concrete gravity dams by plastic–damage model using different damping mechanisms

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ABSTRACT

Utilizing two different damping mechanisms, seismic cracking response of concrete gravity dams is examined by a plastic–damage model implemented in three-dimensional space. The material constitutive law employed herein is based on the one proposed by Lee and Fenves for the 2-D plane stress case. This plastic–damage model basically intended for cyclic or dynamic loading was founded on the combination of non-associated multi-hardening plasticity and isotropic damage theory to simulate the irreversible damages occurring in fracturing process of concrete. In this study, considering the HHT scheme as an implicit operator, the time integration procedure to iteratively solve the governing nonlinear equations is presented. Further, seismic fracture responses of gravity dams due to constant and damage-dependent damping mechanisms are compared. In order to assess the validity of the proposed model, several simple examples are solved and their results are presented first. Subsequently, Koyna gravity dam, which is a benchmark problem for the seismic fracture researches, is analyzed. It is concluded that employing the damage-dependent damping mechanism leads to more extensive damages and also predicts more reliable crack patterns in comparison with the constant damping mechanism in seismic analysis of concrete dams. Furthermore, including dam–water interaction intensifies the existing differences between the results of the two damping mechanisms.

1. Introduction

Although there are numerous high concrete dams throughout the world, their fracture responses under strong ground excitations have been monitored and reported only in a few cases. Koyna gravity dam in India experienced a destructive earthquake in 1967. The Koyna earthquake with a maximum acceleration of around 0.5*g* caused major structural damage to the dam including horizontal cracks on the upstream and downstream in a number of its non-overflow monoliths [1].

In order to assess the seismic safety of concrete dams, nonlinear models simulating crack propagation within the dam body need to be employed. There have been many attempts to numerically capture damage and failure in concrete structures. The cracking process in concrete is distinct from cracking of other materials, such as metal and glass, in which it is not a sudden onset of new free surfaces, but continuous forming and connecting micro-cracks. Furthermore, cracking reduces the stiffness of concrete structural components. Various constitutive models have been proposed for concrete on the basis of damage mechanics and/or plasticity. In order to accurately simulate the degradation in the mechanical properties of concrete, the use of continuum damage mechanics is necessary. However, the concrete material also experiences some irreversible deformations during unloading such that the continuum damage theories alone cannot be used successfully. Therefore, the nonlinear material behavior of concrete can be realistically simulated by two separate material mechanical processes: damage and plasticity.

Plasticity theory has been widely used to describe the concrete behavior [2–4]. The main characteristic of these models is a yield surface that includes pressure sensitivity, path sensitivity, non-associative flow rule, and work or strain hardening. However, these investigations fail to address the degradation of the material stiffness due to micro-cracking. On the other hand, the continuum damage theory has also been employed to model the material nonlinear behavior such that the mechanical effect of the progressive micro-cracking and strain softening are represented by a set of internal variables (i.e. decrease of the stiffness) at the macroscopic level [5–13]. The use of coupling between damage and plasticity has been found to be necessary for capturing the observed experimental-based behavior of concrete [14–25].

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However, only a limited number of studies have been performed to investigate the dynamic behavior of concrete dams with concrete modeling based on a plastic–damage constitutive law [26–28]. The plastic–damage model, which was originally proposed by Lubliner et al. in 1989 and later on modified by Lee and Fenves in 1998, is employed herein to investigate the nonlinear dynamic behavior of concrete dams in two different damping mechanisms. It should be emphasized that the available implementation of the model is limited to 2-D plane stress state [26]. The present study utilizes the model in three-dimensional formulation implemented in a special finite element program, SNACS [29] for the seismic application to a typical gravity dam in 3-D modeling of cracking and damage. In this respect, the present study can be considered to be the first for this class of plastic–damage models which can be applied to study the nonlinear seismic response of concrete dams.

The paper is organized as follows. Section 2 highlights the framework of the plastic–damage model. In Section 3, the incremental–iterative procedure implemented for the time integration scheme to solve the dynamic equilibrium equations of dams in a nonlinear context is derived. In Section 4, simple applications including several single-element uniaxial tests and one structural simulation of an L-shaped concrete panel are presented to validate the implementation of the plastic–damage model. In Section 5 seismic fracture response of Koyna dam in damage-dependent damping mechanism is compared with the results for the constant damping mechanism.

2. Plastic–damage constitutive law

The constitutive relations of the plastic–damage model are fully described by Lee and Fenves in [18,30]. Although both 3-D and 2-D plane stress formulations of the model have been presented in the mentioned references, their implementation was limited to 2-D applications [26]. In the 3-D implementation of the model, the apex's singularity of the linear potential function proposed and used by Lee and Fenves needs to be avoided. Moreover, singularities of the yield surface must be taken into account. These would enforce certain modifications in 3-D formulation.

Computational aspects of the treated model in 3-D space along with the stress update algorithm are thoroughly discussed in [31]. However for the sake of clarity and completeness of this paper, a brief description is presented herein.

2.1. Framework of plastic–damage model

In order to describe full states of damage on the elastic stiffness in a three-dimensional stress state, a 4th-rank tensor needs to be used [24]. However, scalar degradation damage models are useful for practical applications due to simplicity [22,32,33]. Furthermore, a scalar representation for damage on the stiffness can be significantly enhanced to predict various states of damage when it is combined with plasticity theory. Based on the infinitesimal strain theory, the fundamental relations of a rate-independent plastic–damage model as the backbone model of its corresponding rate-dependent model can be expressed as follows.

2.1.1. Stress–strain relationship

The strain tensor, $\boldsymbol{\varepsilon}$, is decomposed into the elastic part, $\boldsymbol{\varepsilon}^{e}$, and the plastic part, $\boldsymbol{\varepsilon}^{p}$ (i.e., $\boldsymbol{\varepsilon}=\boldsymbol{\varepsilon}^{e}+\boldsymbol{\varepsilon}^{p}$). The elastic part is defined as the recoverable portion in the total strain. The stress, $\boldsymbol{\sigma}$, and the effective stress, $\bar{\boldsymbol{\sigma}}$, are defined by:

$$\boldsymbol{\sigma}=(1-D)\bar{\boldsymbol{\sigma}} \tag{1}$$

$$\bar{\boldsymbol{\sigma}}=\mathbf{E}_0:(\boldsymbol{\varepsilon}-\boldsymbol{\varepsilon}^{p}) \tag{2}$$

where $\mathbf{E}_0$ is a rank-four elastic stiffness tensor. The degradation damage variable, D, is used to represent a scalar form of damage in the elastic stiffness.

To determine the required effective stress tensor, the evolution law for the plastic strain tensor needs to be established. The plastic strain rate is evaluated by a flow rule, which is assumed to be related to a scalar potential function Φ. For a plastic potential defined in the effective stress space, the plastic strain rate is given by:

$$\dot{\boldsymbol{\varepsilon}}^{p}=\dot{\lambda}\nabla_{\bar{\boldsymbol{\sigma}}}\Phi \tag{3}$$

where $\nabla_{\bar{\boldsymbol{\sigma}}}\Phi=\partial\Phi/\partial\bar{\boldsymbol{\sigma}}$ and λ is a nonnegative function referred to as the plastic consistency parameter. The evolution law of the plastic–damage variables in tension and compression (i.e., $\kappa_{\aleph}$, $\aleph\in\{t,c\}$) playing the role of hardening variables, in addition to the plastic strains, is necessary to be specified. It is expressed as:

$$\dot{\boldsymbol{\kappa}}=\dot{\lambda}\mathbf{H}(\bar{\boldsymbol{\sigma}},\boldsymbol{\kappa});\quad \boldsymbol{\kappa}=\begin{pmatrix}\kappa_t\\ \kappa_c\end{pmatrix} \tag{4}$$

The function $\mathbf{H}$, which actually represents hardening components, is derived considering plastic dissipation which includes the specific fracture energy defined as the fracture energy, $G_{\aleph}$, normalized by the characteristic length, $l_{\aleph}$ (i.e., $g_{\aleph}=G_{\aleph}/l_{\aleph}$) [18,31]. In a finite element analysis, this is used to keep results mesh-objective. Furthermore, the damage variables in tension and compression, which are denoted by D_t and D_c respectively, are explicit functions of the plastic–damage variables in tension and compression introduced above. Since the model is accurately capable of capturing the two major damage phenomena, the uniaxial tensile and compressive ones, multi-dimensional degradation behavior can be possibly evaluated by interpolating between these two main damage variables as:

$$D=1-(1-D_c(\kappa_c))(1-sD_t(\kappa_t)) \tag{5}$$

in which s is called the stiffness recovery parameter such that $0\le s\le 1$ and used to include the elastic stiffness recovery during elastic unloading process from tension to compression:

$$s(\hat{\bar{\boldsymbol{\sigma}}})=s_0+(1-s_0)r(\hat{\bar{\boldsymbol{\sigma}}}) \tag{6}$$

in which, s_0 is a minimum value for s usually set to zero and the scalar quantity r is a weight factor which ranges from zero when all principal stresses are negative to one when they are all positive. Symbolizing $\langle x\rangle$ as the ramp function (i.e., $\langle x\rangle=(x+|x|)/2$), $r(\hat{\bar{\boldsymbol{\sigma}}})$ is defined as:

$$r(\hat{\bar{\boldsymbol{\sigma}}})=\left(\sum_{i=1}^{3}\langle\hat{\bar{\sigma}}_i\rangle\right)\Bigg/\left(\sum_{i=1}^{3}|\hat{\bar{\sigma}}_i|\right) \tag{7}$$

2.1.2. Non-associated flow rule

Since the Drucker–Prager linear function in the original formulation of Lee and Fenves [18,26] has a singular point at its apex which needs to be avoided in a 3-D implementation, the Drucker–Prager hyperbolic function is employed here as the plastic potential function:

$$\Phi=\sqrt{\beta_H^2+2\bar{J}_2}+\alpha_p\bar{I}_1;\quad \beta_H=\varepsilon_0\alpha_p f_{t0} \tag{8}$$

where $\bar{I}_1$ and $\bar{J}_2$ are the first and second invariants of the effective stress tensor; the parameter α_p should be calibrated to give proper dilatancy; f_{t0} is the maximum uniaxial tensile strength of concrete. Moreover, ε_0, which is called the eccentricity parameter,