Computers and Geotechnics 65 (2015) 258–265

Contents lists available at ScienceDirect

Computers and Geotechnics

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

Research Paper

Dynamic damage evaluation on the slabs of the concrete faced rockfill dam with the plastic-damage model

Bin Xu, Degao Zou *, Xianjing Kong, Zhiqiang Hu, Yang Zhou

The State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian 116024, China
Institute of Earthquake Engineering, Dalian University of Technology, Dalian 116024, China

ARTICLE INFO

Article history:
Received 15 September 2014
Received in revised form 24 November 2014
Accepted 5 January 2015
Available online 20 January 2015

Keywords:
Plastic-damage model
Dynamic analysis
Slabs damage
Concrete faced rockfill dam
Earthquake

ABSTRACT

In this paper, a plastic-damage model for concrete was coupled with the generalized plastic model for rockfill materials and applied to the two-dimensional analysis of a concrete faced rockfill dam (CFRD). First, a plastic-damage model for concrete was programmed in the elastic–plastic dynamic analysis procedure for CFRDs. Previous test simulations were processed to demonstrate the performance and capability of the plastic-damage model and the developed procedure. Numerical simulations of the construction stage, impoundment process, and seismic excitation were conducted to investigate the tensile damage development in the concrete slab of a CFRD during an earthquake. The main tensile damage positions and areas of weakness in the slabs during an earthquake were clarified, which is important for the design of CFRDs. The procedure developed in this study could be adopted in the analysis of interactions between soil and concrete structures.

1. Introduction

Due to recent advances in soil and rock engineering, significant progress has been reported in the design and construction of rockfill dams. In China, many concrete faced rockfill dams (CFRDs) with heights over 200 m have been built or designed; for instance, the Shuibuya dam (completed in 2011) is 233 m high [1]. However, in strong seismic regions, earthquakes may cause substantial damage to CFRDs or even cause them to fail, thus endangering lives and causing vast property damage and serious environmental problems. The concrete slabs in CFRDs play the most important role as the main anti-seepage structure. Once the concrete slabs have been damaged during an earthquake, the seepage control system may become impaired or threaten the safety of the dam, i.e., the seepage failure of the Gouhou CFRD in 1993 [2] and the slab dislocation and extruding damage of the Zipingpu CFRD in 2008 [3,4]. Therefore, reliable assessment and a better understanding of the dynamic behavior and seismic response characteristics of these slabs can aid in preventing such catastrophic failures via an improved design of future dams.

Currently, the linear elastic model is widely used for the concrete slab, and CFRD construction, impoundment, and earthquake responses analyses have been performed using this approach [4–13]. The results indicated that the tensile strength of the concrete was exceeded. In fact, as a type of quasi-brittle material, concrete can be considered to exhibit linear elastic behavior only under small loads. With increasing tensile strain, cracking and damage will occur, and the concrete will display the characteristics of stiffness degradation and strain softening [14]. Furthermore, the compressive and tensile behaviors of concrete are different and should be considered in investigations of the state of the stress and the cracking behavior of concrete slabs. Considering these characteristics, the results of axial tensile stresses in slabs might greatly exceed the actual concrete tensile strength during strong seismic excitation [13].

Several elastoplastic models of concrete have been established based on damage mechanics and used to simulate the damage process and mechanism of concrete structures [14–21]. For example, the model proposed by Lee and Fenves [17] revealed the independent compressive and tensile damage pattern and the stiffness restoration under reverse loading. The earthquake damage phenomenon of the Koyna gravity dam was successfully numerically simulated with this model [18], and the elastoplastic damage model was also used to analyze the damage-cracking behavior of arch dams [22].

These damage models are primarily used in homogeneous material structures, i.e., arch dams or gravity dams. Few studies have investigated the dynamic responses of CFRDs using a damage model for concrete [23,24]. The main constraints on the use of concrete damage models in the seismic responses analysis of

* Corresponding author.
E-mail address: zoudegao@dlut.edu.cn (D. Zou).

http://dx.doi.org/10.1016/j.compgeo.2015.01.003

CFRDs are as follows: (1) the model of the rockfill materials should be matched with the concrete model. Currently, the nonlinear elastic static and dynamic models are widely used for construction, impoundment, and earthquake simulation of the CFRDs, but the plastic deformation or strain on the rockfill materials cannot be obtained with these models. Therefore, the models based on nonlinear elastic theory do not match the concrete damage model in concept. (2) A plastic interface model that can describe the complex characteristics of the interfacial element between the concrete and rockfill is required to calculate the plastic deformation of the interface.

Because of the increase in CFRD heights, the concrete damage should be considered in a seismic analysis of CFRDs, and the following problems should be resolved for damage analyses of the concrete slab of CFRDs using the advanced elastic–plastic model: (1) matching of the elastic–plastic model of rockfill materials, (2) matching of the elastic–plastic interface model and (3) integrating the computational precision, computational efficiency, and stability of the numerical procedure with different plastic models for the concrete, rockfill, and interface.

The primary purpose of this study was to investigate the dynamic damage to the concrete slabs during the earthquake period. The plastic-damage model proposed by Lee and Fevens was used to describe the behavior of the concrete. In the previous study by the authors [7,10], a developed generalized plasticity model for rockfill materials that considers the pressure dependency under monotonic and cyclic loading conditions was used to simulate the deformation of the CFRDs during step-by-step construction followed by the subsequent impoundment of the reservoir and seismic responses. An elastic-perfectly-plastic model with pressure-dependent shear stiffness was used to simulate the interfaces between the face slabs and cushion gravel [10]. An elastoplastic dynamic analysis procedure for the analysis of CFRD dynamic responses was developed with the described models. Using a 2D plane-strain model with the appropriate constitutive laws for each material of CFRDs, this study was conducted with an emphasis on the following: (1) the effect on stress distribution in the slabs with the use of different models of concrete, (2) the occurrence and development of tensile damage in the slabs during an earthquake, and (3) the seismic damage distribution and areas of weakness in the slabs.

2. Material model

This section introduces the models used in the analyses of the CFRD dynamic responses. Compressive stresses are expressed as negative values in this study, and tensile stresses are expressed as positive values.

2.1. Plastic-damage model for concrete

This paper adopts the plastic-damage model proposed by Lee and Fenves [17] to simulate the nonlinearity of concrete material during a strong earthquake. The framework of this model is briefly introduced, and details are provided in Refs. [17,19].

The stress tensor is given by:

$$\sigma = (1-d)\bar{\sigma} = (1-d)E_0(\varepsilon - \varepsilon^p) \tag{1}$$

where d is the damage variable, $\bar{\sigma}$ is the effective stress, E_0 is the initial elastic stiffness, and ε and ε^p denote the total strain and plastic strain, respectively.

During plastic deformation, the normality plastic flow rule is applied as:

$$\dot{\varepsilon}^p = \dot{\lambda}\frac{\partial\phi(\bar{\sigma})}{\partial\bar{\sigma}} \tag{2}$$

where λ is the plastic invariant, and ϕ is the plastic potential function given by:

$$\phi = \sqrt{2J_2} + \alpha_p I_1 \tag{3}$$

where $I_1 = \mathrm{tr}(\bar{\sigma})$, and $J_2 = (\mathbf{s}:\mathbf{s})/\mathbf{2}$, where $\mathbf{s}$ is the deviatoric effective stress. Furthermore, α_p is the material parameter related to the dilatancy of concrete.

The extent of damage is represented by the damage state variable κ, and its evolution is defined as:

$$\kappa = \lambda H(\bar{\sigma}, \kappa) \tag{4}$$

The yield function is defined by the effective stress and κ:

$$\bar{F}(\bar{\sigma},\kappa) = \frac{1}{1-\alpha}\left(\alpha I_1 + \sqrt{3J_2} + \beta(\kappa)\langle\bar{\sigma}_{max}\rangle\right) - c(\kappa) \tag{5}$$

where α and β are dimensionless parameters, $\bar{\sigma}_{max}$ is the maximum principle stress, c is the cohesion strength, $\langle\cdot\rangle$ is the McCauley bracket, and α and β are defined as:

$$\alpha = \frac{f_{b0} - f_{c0}}{2f_{b0} - f_{c0}} \tag{6}$$

$$\beta = \frac{f_{c0}}{f_{t0}}(\alpha - 1) - (1 + \alpha) \tag{7}$$

In the above equations, f_{c0} and f_{b0} are the initial uniaxial and biaxial compressive yield stresses, respectively, and f_{t0} is the initial uniaxial tensile yield stress, as illustrated in Fig. 1.

Two independent variables, κ_t and κ_c, are introduced to describe the damage state induced by the tensile and compressive stresses, respectively.

$$\kappa_k = \frac{1}{g_k}\int_0^{\varepsilon^p}\sigma_k d\varepsilon^p; \quad g_k = \int_0^{\infty}\sigma_k d\varepsilon^p \tag{8}$$

where $k = t$ represents the tensile state, $k = c$ represents the compressive state, g_k is the fracture energy density of concrete, and l_k is the characteristic length related to mesh size.

The degradation damage variable is expressed as:

$$d(\kappa,\bar{\sigma}) = 1 - (1 - s_t d_c(\kappa_c))(1 - s_c d_t(\kappa_t)) \tag{9}$$

$$s_t = 1 - w_t r(\hat{\bar{\sigma}}), \quad 0 \leqslant w_t \leqslant 1 \tag{10}$$

$$s_c = 1 - w_c r(\hat{\bar{\sigma}}) \quad 0 \leqslant w_c \leqslant 1 \tag{11}$$

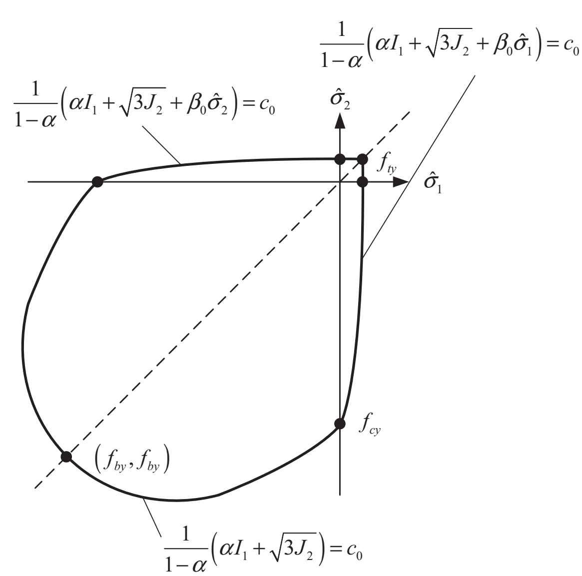

Fig. 1. Initial yield function in plane stress space of concrete.