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Seismic fragility of arch dams based on damage analysis

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ABSTRACT

Seismic fragility provides a measure for evaluating the safety margin of structures above specific hazard levels. This study investigates the seismic fragility of arch dams using the dynamic damage analysis model of dam–reservoir–foundation systems, in which the radiation damping of semi-unbounded foundation rock, opening of contraction joints, and damage cracking of dam concrete are taken into account. The 210 m-high Dagangshan Dam in Southwest China is analyzed as a case study. Five hundred nonlinear damage analyses are performed using the Monte Carlo simulation technique considering both epistemic and aleatory uncertainties, which are characterized by random material parameters and ground motions, respectively. Three limit states, i.e., slight damage, moderate damage, and severe damage, are proposed according to the calculated damage distribution and joint opening, and seismic fragility curves are subsequently generated using the incremental dynamic analysis approach. Analysis results show that the Dagangshan Dam may be severely damaged by strong earthquakes when uncertainties in material parameters and ground motions are considered.

1. Introduction

Seismic safety is a key issue in the design and safety evaluation of dams in seismically active regions. Epistemic (analysis modeling and material parameters) and aleatory (earthquake ground motion) uncertainties exist in seismic safety evaluation of dams [1]. Considering the possibly significant effect of these uncertainties on the seismic response of dams, predicting the seismic damage to dams using probabilistic methods, such as fragility analysis, is preferable. Fragility analysis has become a useful tool for the seismic safety evaluation of dams to manage uncertainties, and meanwhile plays an important part in the framework of risk-based decision-making.

Several researchers have investigated the seismic fragility of concrete gravity dams by considering the uncertainties arising from earthquake ground motion and material parameters. In 2016, Hariri-Ardebili and Saouma [2] comprehensively reviewed the state-of-the-art of the seismic fragility analyses of concrete dams. Herein, we introduce some researches that are closely related to the topic of this paper. Please refer to [2] for other extensive literature on the seismic fragility of concrete dams.

Tekie and Ellingwood [1] proposed a methodology for developing seismic fragilities of concrete gravity dams. They defined four-level limit states according to dam cracking, sliding in the dam–foundation interface, and deformation of dam crest, and they took into account the uncertainty in material parameters, which are determined by Latin hypercube sampling (LHS), to characterize the performance of the dam–foundation system. Lupoi and Callari [3] developed the fragility curves of gravity dam–reservoir–foundation systems using a standard Monte Carlo simulation procedure. Ghanaat et al. [4] identified sliding at the dam base and lift joints as two prominent failure modes of gravity dams, and they developed seismic fragilities for both failure modes. Bernier et al. [5] considered the influence of spatial variation of friction angle on seismic fragility. For the seismic fragility analysis of concrete dams, Hariri-Ardebili and his co-workers performed an uncertainty quantification for the parameters in the cohesive crack model [6], analyzed the possible failure modes of concrete dams [7], discussed the relationship between intensity measure (IM) and engineering demand parameter [8], and developed the seismic collapse fragility curves of gravity dams with beside joint nonlinearity and concrete nonlinearity [9].

On the contrary, the seismic fragility modeling of arch dams remains at an early stage of development, and available examples of their analysis are few in literature. Yao et al. [10] analyzed the seismic fragility of a 305 m-high arch dam in Southwest China, which only three contraction joints were modeled using nonlinear contact model. Kadkhodayan et al. [11] analyzed the seismic response of a 203 m-high arch dam with nonlinear contraction and peripheral joints in Iran and calculated its seismic fragility curves using the incremental dynamic analysis approach. In these studies, the analysis model of dam–water–foundation systems was oversimplified: (1) the semi-unbounded foundation was assumed massless; (2) the dam concrete was assumed linear elastic; and (3) only the aleatory uncertainty of earthquake

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ground motion was taken into account. The actual seismic response characteristics of arch dams may not be revealed with these simplified models, and thus the limit states cannot be appropriately defined.

This study investigates the seismic fragility of arch dams based on the comprehensive model of dam–reservoir–foundation system [12–15], which models the radiation damping of foundation, opening of contraction joints, and damage cracking of dam concrete. The 210 m-high Dagangshan Dam is used as case study. The epistemic uncertainty in material parameters and aleatory uncertainty in earthquake ground motions are taken into account using the Monte Carlo simulation technique. Four material parameters, i.e., elastic modulus of concrete, tensile strength of concrete, elastic modulus of foundation rock, and damping ratio of system, are assumed uncertain, and five parameters samples are obtained by LHS. To consider the uncertainty in ground motions, ten sets of three-component ground motions are selected from the PEER strong ground motion database [16] and scaled to 10 intensity levels. Each ground motion is paired with all five parameter samples, and thus nonlinear damage analysis is performed for 50 trials at each intensity level. Five hundred nonlinear analyses are implemented to generate seismic fragility curves. According to the calculated damage distribution and joint opening, three limit states of seismic damage (i.e., slight damage, moderate damage, and severe damage) are suggested, and, correspondingly, the seismic fragility curves are calculated using the incremental dynamic analysis.

2. Procedures to generate seismic fragility curves

Seismic fragility curves express the probability of structural damage when structures are subjected to given seismic IM. They may be developed by many methods [2,17], such as the multiple stripe analysis, cloud analysis, and incremental dynamic analysis. In this study, the incremental dynamic analysis is used for estimating the seismic fragility curves of arch dams. The nonlinear damage analyses are carried out at a set of ground motion levels, and the probabilities associated with the different damage states are evaluated using the Monte Carlo simulation technique considering both epistemic and aleatory uncertainties. The fragility curves are obtained by the following procedures.

(1) The probability of dam reaching or exceeding a limit state under a certain intensity level is estimated by the fraction

$$F(LS|IM) = \frac{j}{M \times N}, \tag{1}$$

where $F(LS|IM)$ is the conditional probability of dam reaching or exceeding limit state LS under seismic intensity IM; M is the number of parameter samplings; N is the number of selected seismic ground motion records; and j is the number that dam reaches or exceeds limit state LS among all trials ($M \times N$) at each intensity level.

(2) The fragility curves are fitted by two ways based on Eq. (1) at all intensity levels. One way is the fragility curves are directly fitted by spline functions. The other way is the fragility curves are assumed in the form of two-parameter lognormal distribution function [1,18,19]:

$$P_{LS}(y) = \Phi\left[\frac{\text{In}(y/m)}{\beta}\right], \tag{2}$$

where $P_{LS}(y)$ is the probability that a ground motion intensity y will result in the limit state LS. Φ is standard normal distribution; and m and β is the mean and logarithmic standard deviation of y, respectively. m and β are determined by the least square method.

This investigation presents the seismic fragility analysis of the Dagangshan Dam, a 210 m-high double curvature arch dam in Southwest China. Fig. 1 summarizes the analysis steps, which includes modeling of dam–water–foundation system, selection of uncertain model parameters and ground motion records, nonlinear seismic analyses, classification of limit states, and construction of fragility curves. The analysis steps are presented in detail in the next sections.

It should be noted that the seismic fragility curves may be defined by peak ground acceleration (PGA) [1,5] and acceleration response spectrum [3,4], respectively. In this investigation, PGA is selected as the independent variable of the seismic fragility curves.

3. Nonlinear modeling of dam–reservoir–foundation system

3.1. Analysis procedure

The analyzed system is composed of concrete dam, flexible foundation rock, and reservoir. The nonlinear behavior, which resulted from contraction joint opening and concrete damage, is considered and identified as index for classifying limit states. The radiation damping of semi-unbounded foundation rock is also recognized in the investigation. Theoretically, the compressibility of the impounded water should also be taken into account. However, as commonly did in current design and research [19,20], the impounded water is assumed incompressible, and the dam–water interaction effects are represented using the generalized added mass technique [21] for saving computing efforts and being consistent with the engineering practice.

The nonlinear dynamic response of dam–reservoir–foundation system is analyzed using the analysis procedure developed in [12–15] and performed using the commercial finite element software ABAQUS [22]. The radiation damping of infinite foundation is simulated by a 3D viscous-spring artificial boundary [23]. The contraction joint is described using a contact boundary model [24]. The plastic damage model, developed by Lee and Fenves [25], is adopted to simulate the damage cracking of concrete materials during strong earthquakes. Fig. 2 illustrates the nonlinear strain–softening constitutive relation, where σ and ε denote concrete stress and strain, respectively; E_0 is the initial (undamaged) elastic modulus; d_t is the tensile damage factor that varies from 0 (undamaged material with elastic behavior) to 1 (fully damaged material); G_f is the fracture energy; f_t is the tensile strength; ε_f is the maximum elastic and limiting tensile strains, respectively; and l_c is the characteristic length of concrete (commonly defined as thrice the maximum aggregate size). See Reference [12–15] for details on the analysis procedure.

3.2. Finite element model

The Dagangshan Dam was completed in 2015 (Fig. 3). The base and crest of the dam are at El. 925 m and El. 1135 m above sea level, respectively. The dam consists of 29 blocks, with a total crest length of 533 m. The thickness of the crown cantilever varies from 52 m at the base to 10 m at the crest.

Fig. 4 shows the finite element model of the Dagangshan Dam foundation system and 28 contraction joints [26]. The dam–foundation model is composed of 37,120 solid elements and 53,817 nodes. To simulate concrete damage, the dam is finely discretized into 26,235 elements and 41,862 nodes, and the mesh size is approximately 2 m in the vertical direction. The global coordinates x, y, and z are in the cross-stream, stream, and vertical directions, respectively. The positive directions are the left bank to the right bank, from the upper stream to the down stream, and from the base to the crest, respectively.

3.3. Material parameters

The material properties of the concrete and foundation rock used in this study are selected mainly based on the design data. For the dam concrete, the material properties are mass density = 2400 kg/m^3 and Poisson's ratio = 0.17. The limiting tensile strain ε_f is set at 400 μm/m, and the characteristic length l_c is 0.45 m [27]. The fracture energy G_f is proportional to the tensile strength f_t. For example, G_f is 280 N/m given