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Seismic fragility for high CFRDs based on deformation and damage index through incremental dynamic analysis

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ABSTRACT

In this paper, a seismic fragility analysis method based on incremental dynamic analysis (IDA) is extended to evaluate the seismic performance of high concrete face rockfill dams (CFRDs). Permanent deformation and face-slab damage index using a modified generalized plasticity model for rockfills and a plastic-damage model for face-slabs are considered to be dam damage measures (DMs) after defining a new face-slab damage index. The verification to damage index through the Zipingpu CFRD and previous research indicates that the grading standards are reasonable. Fragility curves and the probabilities are determined for each DM under different earthquake intensities. The results of fragility analysis demonstrate that this method can provide a strong scientific basis for predicting the earthquake destruction and loss of high CFRDs.

1. Introduction

In China, many high concrete face rockfill dams (CFRDs) have been built or designed. These dams are commonly distributed in areas experiencing strong ground motions, therefore, seismic performance assessments must be performed for these dams. Seismic fragility analysis is one of the most effective methods to evaluate seismic performance. This method can predict when these structures will reach or exceed a certain limit state's probabilities under different strengths of seismic action and employs fragility curves or matrices to describe the probability distributions of all limit states. IDA is a parametric analysis method based on nonlinear dynamic time history analysis and has been widely used in structural fragility analysis [1]. However, due to the complexity of high CFRDs, there have been few related reports on their fragility analysis based on IDA applied in this engineering field. In this paper, a seismic performance assessment for high CFRDs is performed based on a fragility analysis using IDA.

Deformation and face-slab damage are the two major forms of destruction of CFRDs; CFRDs that have exhibited such destruction as the Zipingpu CFRD in 2008 (156 m) [2]. Considering the nonlinear characteristics of concrete, Lee and Fenves [3] proposed a plastic damage model to independently determine the damage in pull and pressure modes and the stiffness recovery phenomenon in the reverse loading of concrete, and this model has been successfully applied to concrete face-slabs [4]. Thus, it is reasonable and feasible to regard the relative settlement of dam crests and damage index as evaluation indices of seismic performance.

2. Fragility analysis method based on IDA

IDA method**:** Several scholars have attempted to introduce IDA into the preliminary safety assessment of dams. For example, Kong and Pang et al. [5] first introduced IDA to seismic safety assessment of high CFRDs based on three aspects permanent deformation, stability of dam slope, safety of face-slabs for the first time using an equivalent linear constitutive model, and gained the fragility curves and probabilities. Hariri-Ardebili and Saouma [6] applied IDA to obtain the collapse fragility curves of concrete dams. Mohammad Alembagheri and Mohsen Ghaemian [7] performed a damage assessment of a typical arch dam through IDA subjected to a set of 12 earthquakes, and damage propagation was investigated and various IDA curves were created. These studies achieved a preliminary assessment of dam safety and demonstrated that the IDA method is suitable for large water and hydropower engineering.

Fragility analysis method: The seismic fragility curves provide the conditional probabilities of the structural response reaching or exceeding certain limit states corresponding to the seismic capacity under different earthquake intensities. After calculating the response of the structures under different ground motion intensities with the IDA, the relationships between the limit states and DMs are quantified by combination with the definition of the limit states, and then, the seismic fragility is determined. According to the previous research [8], in general, the seismic fragility is assumed to follow a lognormal cumulative distribution function of double parameters, defined as follows:

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$$P_R(C|IM = X) = \Phi\left[\frac{\ln(X/\theta)}{\sigma}\right] \tag{1}$$

3. Seismic records and performance parameters

3.1. Selection of seismic records

In this paper, the ground motion inputs adopt actual and artificial seismic records respectively. The response spectra based on the site conditions of a high earth-rockfill dam in the southwest of China are chosen to be the target response spectra, as described in Formula (2), β(T) is the magnification response spectrum of ground motion acceleration, and $T_1 = 0.12$ s, $T_2 = 0.34$ s, $\beta_{max} = 2.5$, and $\gamma = 1.0$. According to the proposal of Vamvatsikos et al. [9], 10–20 earthquake records meet the requirements of IDA analysis. First, 10 actual seismic records which are well agreeable with the target response spectra based on site conditions are selected in PEER [10]. Then one seismic wave is artificially generated based on the target response spectrum and is used for a comparison purpose. The acceleration response spectra of 11 earthquake waves are shown in Fig. 1.

$$\beta(T) = \begin{cases} 1 & T \le 0.04s \\ 1 + (\beta_{max} - 1)\frac{T - 0.04}{T_1 - 0.04} & 0.04s < T \le T_1 \\ \beta_{max} & T_1 < T \le T_2 \\ \beta_{max}(\frac{T_2}{T})^{\gamma} & T_2 < T \le 6s \end{cases} \tag{2}$$

3.2. Proposal of dam failure grades

Relative settlement ratio of the dam crest: Kong and Pang et al. [5] considered relative settlement ratios of 0.4%, 0.7%, and 1% of the dam crest (crest settlement values/height of the dam) as the assessment limitation and analyzed the fragility when this dam exhibited minor, moderate and severe failure. Swaisgood et al. [11] surveyed 69 dams, regarded the relative settlement ratio of the dam crest as an index, and divided the degree of earthquake damage into four failure grades: healthy (< 0.1%), minor (0.012–0.5%), moderate (0.1–1.0%) and severe (> 0.5%). In this paper, we refer to the related safety assessment and grading standards described above and consider that the simulated maximum post-earthquake deformation results based on the generalized plastic model are smaller than measured values [12], e.g., the maximum settlement deformation simulated with a generalized plasticity model is about 0.77 m, whereas the actual measured value was 1 m for the Zipingpu CFRD. Finally, we establish three limit failure states with relative settlement ratios of 0.2%, 0.4%, and 0.6% of the dam crest corresponding to three failure grades (minor, moderate and severe).

Damage index of face-slabs: In the earthquake damage prediction and post-earthquake evaluation of concrete structures, many scholars use the damage index to quantitatively describe the degree of failure.

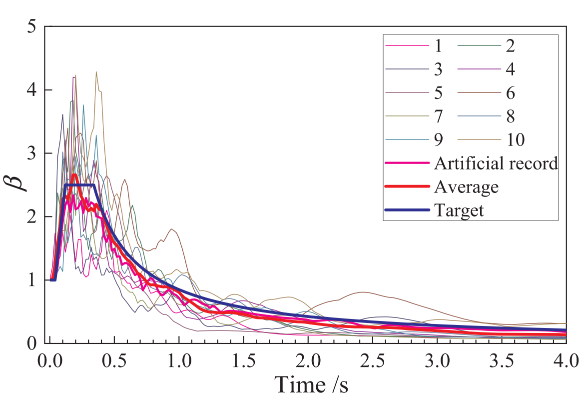

Fig. 1. The curves of earthquake acceleration response spectra.

For concrete dams, for example, Wang and Zhang et al. [13] considered the influence of the damage location on the overall structures of gravity dams and proposed the following dividing values: a damage index of 0.05 for intact and minor failure, a damage index of 0.15 for minor and moderate failure, and a damage index of 0.45 for moderate and severe failure; the upper limit of severe failure was 0.75. Mohammad Alembagheri and Mohsen Ghaemian [7] carried out damage assessment for a typical arch dam through nonlinear IDA. In this paper, referring to the structural damage index described above and considering the importance of the location of the damage on the CFRDs, we believe that the higher the damage location is, however the smaller the impact will be on the structure; finally, we define the damage index. In accordance with the research results of Xu et al. [14], the face-slab damage mainly occurs in the range of 0.4H-0.9 H (H: dam height) under the action of an earthquake. The damage index of face slabs is proposed as:

$$\mathrm{DI} = \alpha\cdot\frac{\sum_{i=1}^{n}\left(d_i\cdot S_i\cdot\frac{0.9H - h_i}{0.25H}\right)}{\sum_{i=1}^{n}\left(S_i\cdot\frac{0.9H - h_i}{0.25H}\right)} \tag{3}$$

where d_i is the damage factor of the ith element of the face slab, n is the number of face slab elements in 0.4–0.9 H, S_i is the area of the ith element of the face slab, h_i is the center height to the face-slab bottom of the ith element of the face slab, DI is the damage index of the face slabs; and α is the influence coefficient, which is generally 2.0. As shown in Fig. 2. In this paper, referring to the related literatures of the failure grading of gravity dam, we regard DI = 0.03, 0.15, and 0.45 as the dividing values of minor, moderate and severe failure, respectively.

4. Finite element analysis

In this paper, the distribution characteristics and change rules of every DM under different seismic records with different earthquake intensities are analyzed in detail by performing two-dimensional (2-D) nonlinear finite element numerical calculations for a typical CFRD with a height of 250 m (Fig. 2) based on GEODYNA [15]. The static and dynamic calculations of the rockfill, transition and cushion are all simulated by the modified generalized plasticity constitutive model [16], and the model parameters are shown in Table 1. The contact between the face slab and cushion is simulated by the generalized plasticity interface model [17], whose parameters are based on the literature [18]. The plastic-damage behavior of concrete face-slabs simulated with the plastic-damage model [4,14], and the parameters are obtained from the literature [4]. Ground motion inputs are added in the form of a viscoelastic boundary combined with an equivalent load at the boundary of the finite element model to simulate the interaction of finite fields with infinite domains [19].

5. Results of IDA and fragility analysis

5.1. IDA results

This study selects the PGA of the earthquake as the earthquake IM and modulates the amplitude at equal intervals (the range is 0.1 g) until the failure of different DMs to severity. The IDA curves corresponding to different ground motion records of the PGA-relative settlement ratio of the dam crest and PGA-damage index are obtained after a large number of nonlinear finite element calculations, as shown in Fig. 3. It may be seen from Fig. 3(a) that with the increase of the IM value, the changes of the relative settlement ratio of the dam crest become slower, which indicates that the rockfills are denser under a stronger earthquake. However, Fig. 3(b) shows that the damage index changes slowly under a weak earthquake and quickly under a strong earthquake, which demonstrates that the face-slab safety is high under a weak earthquake, but the risk will increase under a strong earthquake.