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Seismic reliability assessment of earth-rockfill dam slopes considering strain-softening of rockfill based on generalized probability density evolution method

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ABSTRACT

This paper investigates the seismic reliability of earth-rockfill dam slopes under stochastic earthquake excitation considering strain-softening behaviour of rockfill materials. A new and efficient methodology that couples a recently developed generalized probability density evolution method (GPDEM) with a spectral representation-random function method is presented to assess the seismic reliability. To solve the GPDEM equation, the stochastic seismic responses analysis of a 242-m concrete face rockfill dam (CFRD) is translated into a series of deterministic dynamic calculations. The probability information and seismic reliability of the safety factor demonstrate that the results between the simulations considering unsoftening and softening behaviour of the rockfill materials become increasingly different as the earthquake intensifies, and strain-softening behaviour gradually appear under seismic excitation. Thus, considering the softening characteristic of rockfill materials, is of great significance to analyze the seismic safety of high earth rockfill dams. The traditional index for evaluating dam slope stability with safety factor is compared with a new index the cumulative time of the safety factor less than 1.0 ($F_s < 1.0$), suggesting that the new index is more reasonable to assess the seismic reliability of dam slopes. The results indicate that the GPDEM is an effective approach to seismic reliability assessment from the stochastic viewpoint and can directly reflect the failure probability.

1. Introduction

Landslide of dam slope is one of the main forms of earthquake damage of high CFRDs according to the results of dynamic numerical analysis [1–3] and dynamic physical model tests [4–6]. During the Wenchuan earthquake, sliding was observed on the downstream slope of the Zipingpu CFRD [7–10]; the recorded peak ground acceleration were considerably greater than those that the Zipingpu CFRD had been designed to withstand. In addition, the rockfill materials have exhibited strain-softening behaviour during sliding due to dynamic loading, especially under strong earthquakes [11]. However, few previous studies have considered the dynamic strain-softening behaviour of rockfill in a deterministic or probabilistic analysis of dam slope stability. Therefore, it is essential and worthy to perform a seismic reliability assessment for the dam slopes considering the random behaviour of earthquake ground motions and the strain-softening characteristics of rockfill.

In recent years, seismic reliability analysis and dynamic stability assessments of slopes or earth dam slopes from a stochastic perspective have a practical significance for earthquake-induced landslide disaster reduction. Peng et al. [12] proposed a new method based on artificial neural network to cope with the earth slope reliability problem under seismic loadings and illustrated the applicability of the proposed approach using two earth slope examples. Shinoda et al. [13] efficiently and accurately computed the limit states exceedance probabilities of typical embankment dams and geosynthetic-reinforced soil slopes using a low-discrepancy sequence and importance sampling with a Monte Carlo simulation (MCS) method. Al-Homoud and Tahtamoni [14–16] developed different models for evaluating the probabilistic three-dimensional stability analysis of earth slopes and embankments under earthquake loading using both the safety factor and the displacement criteria of slope failure. Tsompanakis et al. [17] developed fragility curves of embankments by MCS-based numerical approach and the commonly used lognormal empirical approach respectively. Xiao et al. [18] presented a probabilistic approach for seismic stability analysis of a slope at a given site in a specified exposure time in terms of the peak ground acceleration of the ground motion parameter. Rathje et al. [19] presented a fully probabilistic framework for assessing sliding block

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displacements by using a displacement hazard curve with scalar and vector approaches. Du and Wang [20] proposed a computationally efficient framework for fully probabilistic seismic displacement analysis of spatially distributed slope systems using spatially correlated vector intensity measures. Wang and Rathje [21] efficiently implemented a fully probabilistic approach for seismic landslide hazard mapping using ground motion hazard data and the Mean-Threshold approach on a regional scale. Hayashi and Tang [22] simultaneously considered the randomness of soil properties and seismic activity by using a MCS approach. Huang and Xiong [23] demonstrated the effectiveness and high precision of the PDEM method by comparing the dynamic reliability evaluation of slopes using a probability density evolution method (PDEM) [24,25] based on the safety factor and considering the random behaviour of earthquake ground motions, with the results of a stochastic MCS. Most of the above mentioned methods do not effectively consider the stochastic characteristics of the seismic ground motions and the seismic wave amplification. Moreover, it is worth noting that most studies have been focused on the seismic reliability of slopes that seldom considered the effect of strain-softening properties of soil which will appear under seismic excitation.

The strain-softening characteristics of soil are one of the main causes of progressive failure of slopes, which has an important influence on the stability and reliability of slopes [26]. Law and Lumb [27] proposed a limit equilibrium method of analysis, which included post-peak strength, to study long-term progressive slope stability failure. Srbulov [28] determined the stability of slopes in brittle soil using a limit equilibrium method to predict various types of progressive failures. Miao et al. [29] proposed an evolution model that considered rheologic effects to describe the progressive failure of soil slopes. Chen et al. [30] calculated the extent and degree of weakening along the potential slip surface by using a finite element analysis with strain-weakening models. Potts et al. [31,32] modelled the delayed failure phenomena and the progressive cumulative failure of a hard clay excavation slope by combining a finite element method and strain-softening model. Zhang and Zhang [33] described a new simplified method to evaluate the stability level of a strain-softening slope, and their model was established by expanding the traditional slice method and using a simplified strain compatibility equation. Conte et al. [34,35] presented a finite element approach to analyze the response of slopes and shallow foundations on soils with strain-softening behaviour. Zhang et al. [36] presented a method to analyze the progressive failure of strain-softening slopes based on the strength reduction method and strain-softening model. Liu and Ling [37] investigated the strain-softening effects of backfill soils on the deformation and reinforcement load of wrapped-face geosynthetic-reinforced soil structure walls. Wang et al. [38] simulated such failure mechanism for slopes in these soils by a proposed finite element approach considering soils with strain-softening behaviour. These studies demonstrate that strain-softening affects the stability of slopes and that ignoring this aspect may lead to inaccurate results, especially under the seismic loading. Additionally, some researches [3,6] indicated that instability of dam slopes for high earth-rockfill dams shows a shallow landslide at the top of dam where the strain-softening of rockfill occurs due to low confining pressure on the slipping surface. However, relatively few studies have focused on the seismic reliability of high rockfill dam slopes while considering the strain-softening behaviour of rockfill materials.

On the other hand, pseudo-static methods, which are usually used to evaluate the stability of dam slopes, do not accurately reflect either the characteristics of the ground motion inputs or the dynamic response of the dam [39,40]. In recent years, the finite element time-history analysis method has been increasingly used for dam slope analysis. However, the safety factor obtained from a finite element time-history analysis method cannot effectively describe dam slope stability during an earthquake, especially for high earth and rockfill dams. The cumulative time of $F_s < 1.0$ has a significant influence on the dam slope dynamic stability and it is required to be investigated during the earthquake in China Hydraulic seismic design code (NB 35047-2015) [41]. Some scholars [42–44] took into account the cumulative time of the safety factor less than 1.0 ($F_s < 1.0$) to evaluate the dynamic stability of dam slopes and provided a new way to assess slope instability; if this cumulative time exceeds 1–2 s, the dam slopes of high earth and rockfill dams might lose stability.

This paper investigates the seismic reliability of dam slopes under stochastic earthquake excitation considering strain-softening of rockfill materials. A newly developed generalized probability density evolution method (GPDEM) is adopted for the seismic reliability analysis, which can efficiently combine the stochastic dynamic analysis and deterministic finite element time history analysis methods [45]. A set of representative acceleration time histories of non-stationary earthquake ground motions with complete probability were generated by the spectral representation-random function method based on the Chinese code for seismic design of hydraulic structures of hydropower project (NB 35047-2015) [41]. According to the GPDEM, the stochastic seismic response analysis of a 242-m CFRD is translated into a series of deterministic dynamic calculations. The probability information and seismic reliability, considering the unsoftening and softening behaviour of rockfill materials, are compared based on two assessment indices safety factor and cumulative time of $F_s < 1.0$. The results can provide references for dam design to guarantee dam stability under seismic conditions.

2. GPDEM equation and seismic reliability

Correspondingly, the seismic difference equation is expressed as follows subjected to earthquake motion.

$$\overline{\mathrm{M}}\ddot{\mathrm{X}}(t) + C\dot{\mathrm{X}}(t) + \mathrm{KX}(t) = -\overline{\mathrm{M}}\ddot{\mathrm{X}}_{\mathrm{g}}(\Theta,\ \ t) \tag{1}$$

in which $\overline{\mathrm{M}}$, $\mathbf{C}$ and $\mathbf{K}$ are the mass, damping and stiffness matrices, respectively; $\ddot{\mathrm{X}}(t)$, $\dot{\mathrm{X}}(t)$, $\mathrm{X}(t)$ are the acceleration, velocity and displacement vectors, respectively; $\ddot{\mathrm{X}}_{\mathrm{g}}(\Theta,\ \ t)$ is the random earthquake ground motion excitation which will be generated by the spectral representation-random function method, and $\boldsymbol{\Theta}$ is a random vector.

The solution of Eq. (1) is continuously dependent on the random parameter **$\boldsymbol{\Theta}$,** and can be written as:

$$X(\mathrm{t}) = H(\varTheta, \mathrm{t}) \tag{2}$$

and the velocity process can be expressed as

$$\dot{X}(\mathrm{t}) = h(\varTheta, \mathrm{t}) \tag{3}$$

where $\mathbf{H} = (H_1, H_2, \ldots, H_{\mathrm{n}})^{\mathrm{T}}$, and $\mathbf{h} = (h_1, h_2, \ldots, h_{\mathrm{n}})^{\mathrm{T}}$.

More generally, any physical parameters (e.g., safety factor) can be chosen as the random variable depending on $\boldsymbol{\Theta}$ in the GPDEM equation. In this study, for the seismic reliability analysis of dam slopes, the selected physical parameters are the time series of safety factors. According to the principle of probability conservation [24], the GPDEM equation for the dam slope analysis will be expressed as

$$\frac{\partial p_{F_s\Theta}(F_s, \Theta, t)}{\partial t} + \dot{F}_s(\Theta, t)\frac{\partial p_{F_s\Theta}(F_s, \Theta, t)}{\partial F_s} = 0 \tag{4}$$

the initial condition is

$$p_{F_{\mathrm{s}}\Theta}(F_{\mathrm{s}}, \Theta, t)|_{t=t_0} = \delta(F_{\mathrm{s}} - F_{\mathrm{s}0})p_{\Theta}(\Theta) \tag{5}$$

and the joint probability density function (PDF) of $F_{\mathrm{s}}(t)$ is

$$p_{F_{\mathrm{s}}}(F_{\mathrm{s}},\ \ t) = \int_{\Omega_\Theta} p_{F_{\mathrm{s}}\Theta}(F_{\mathrm{s}}, \Theta, t)d\Theta \tag{6}$$

To solve the GPDEM equation, a set of discrete representative points $\boldsymbol{\Theta}_{\mathrm{q}}$ ($q = 1, 2, \ldots, n_{\mathrm{sel}}$) in the distribution space $\boldsymbol{\Omega}_{\boldsymbol{\Theta}}$ of basic random variable space $\boldsymbol{\Theta}$ is selected, where n_{sel} is the total number of discrete points, based on Number-Theoretical method proposed by Hua-Wang [46]. In this study, the random variable is the earthquake ground motion, and the randomness is mainly embodied in the peak ground

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