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A dynamic reliability approach to seismic vulnerability analysis of earth dams

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Abstract. Seismic vulnerability assessment is a useful tool for rational safety analysis and planning of large and complex structural systems; it can deal with the effects of uncertainties on the performance of significant structural systems. In this study, an efficient dynamic reliability approach, probability density evolution methodology (PDEM), is proposed for seismic vulnerability analysis of earth dams. The PDEM provides the failure probability of different limit states for various levels of ground motion intensity as well as the mean value, standard deviation and probability density function of the performance metric of the earth dam. Combining the seismic reliability with three different performance levels related to the displacement of the earth dam, the seismic fragility curves are constructed without them being limited to a specific functional form. Furthermore, considering the seismic fragility analysis is a significant procedure in the seismic probabilistic risk assessment of structures, the seismic vulnerability results obtained by the dynamic reliability approach are combined with the results of probabilistic seismic hazard and seismic loss analysis to present and address the PDEM-based seismic probabilistic risk assessment framework by a simulated case study of an earth dam.

Keywords: earth dams; randomness of ground motion; seismic vulnerability; dynamic reliability; seismic risk

1. Introduction

Most old dams were designed employing out-of-date seismic analysis and design methods; therefore, most old dams are unlikely to meet current seismic design guidelines (Lupoi and Callari 2012, Hariri-Ardebili and Saouma 2016a). Therefore, reliable tools for seismic assessment of existing dams are needed to ensure effective reinforcement and retrofitting strategies (Chen *et al.* 2012, 2014, Peng *et al.* 2018). Seismic probabilistic risk assessment (SPRA) provides a useful and rational tool for seismic risk management, retrofit planning and mitigation work within a probabilistic framework (Ellingwood and Kinali, 2009). Seismic vulnerability analysis is a significant part of seismic risk assessment; it can manage various sources of uncertainty that may affect the seismic performance of dams, such as seismic activity, water levels and system properties (Hariri-Ardebili and Saouma, 2016b).

Various studies focused on seismic vulnerability analysis of dams. For instance, Yegian *et al.* (1991) and Kostov *et al.* (1998) presented a seismic risk assessment method for dams, with seismic fragility assessment conducted within the framework of Monte Carlo simulation (MCS). Tekie and Ellingwood (2003) presented an approach for assessing the seismic fragility of concrete gravity dams within the MCS probabilistic framework. They used the Latin Hypercube sampling (LHS) technique to reduce the computational burden and assumed a log-normal distribution to describe the seismic fragility. Lin and Adams (2007) presented empirical seismic fragility curves for dam systems in Canada, and these results were combined with seismic hazard results to analyze the safety of dams. Papadrakakis *et al.* (2008) proposed a Neural Networks based MCS procedure for seismic vulnerability analysis of concrete dams. Lupoi and Callari (2012) acquired seismic fragility curves of a concrete gravity dam using a standard MCS procedure based on the results of dynamic time-history analyses. Abdelhamid *et al.* (2013) performed seismic fragility assessment of a concrete gravity dam within the framework of MCS under near-fault ground motions. Bernier *et al.* (2015) studied the seismic fragility of concrete gravity dams considering the spatially variable friction angle. Bernier *et al.* (2016) also used conditional spectrum method to selected ground motion samples and to improve the fragility assessment results of dams. Ju and Jung (2015) analyzed the seismic fragility of weir structures considering the uncertainties of near field and far field ground motions. Hariri-Ardebili and Saouma (2016a) combined the results of cloud analysis to develop the seismic fragility curves of a concrete dam. Kadkhodayan *et al.* (2016) calculated the fragility curves of dams utilizing the normal distribution based on the results from incremental dynamic analyses. Wang *et al.* (2018) investigated the seismic fragility arch dams with a dynamic damage analysis model by incremental dynamic method. Regarding the seismic vulnerability analysis in other fields, Noh *et al.* (2015) developed empirical and analytical fragility functions by kernel smoothing method. Mitropoulou and Papadrakakis (2015) proposed a neural network prediction method to obtain the fragility curves.

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Wang *et al.* (2018) investigated the seismic fragility of nuclear power plant equipment with artificial neural networks.

However, most of the studies of seismic vulnerability reviewed above are based on some assumed distributions (e.g., the log-normal cumulative distribution function) using regression analysis and maximum likelihood estimation. Some deficiencies of the seismic fragility curve based on the log-normal hypothesis were pointed out by scholars; for example, specifying a functional form may not reflect the true structure of the data even though it provides a smooth fragility function (Noh *et al.* 2015). The validity of such an assumption remains questionable (Sudret *et al.* 2014). Fragility curves with log-normal hypothesis yield nonzero values even for very small input acceleration (ICHII 2002). Fragility curves have questionable accuracy compared with curves obtained by the reliability approach (Tsompanakis *et al.* 2010). Furthermore, most studies are confined to the fragility modeling of dams, and do not address the combination of the fragility models with probabilistic seismic hazard analysis and seismic loss within the whole framework of the SPRA of dams.

The main influencing uncertainties should be considered when assessing the seismic fragility of dams. A practical and rational way for dealing with these uncertainties is to conduct reliability and uncertainty analysis within the framework of a stochastic and probabilistic methodology (Yang *et al.* 2018, Zhu *et al.* 2018, Chenari and Fatahi 2019, Fei *et al.* 2019). Using the reliability method, various sources of uncertainties can be properly modeled and its effect on the seismic performance and fragility of structures can be reasonable quantified by dynamic reliability or the failure probability, and thus to obtain rigorous estimates of the fragility curves of earth dams for various predefined damage levels (Papadrakakis *et al.* 2008, Peyras *et al.* 2012). Furthermore, with reliability method, the failure probabilities can be directly used to construct fragility curves without limiting them to a specific functional form like most other studies have done. The commonly used reliability methods are approximation methods and MCS. Approximation methods are sometimes only applicable to static problems because it is difficult to acquire an explicit limit state function in seismic conditions. MCS is generally applicable to more complex problems with many sources of uncertainty in either a static or dynamic situation; however, it is based on a large number of stochastic simulations and thus very time-consuming, although some advanced sampling techniques (e.g., LHS) have been proposed.

Probability density evolution methodology (PDEM) (Li and Chen 2008, 2009, Chen and Li 2010, Huang *et al.* 2015) is an efficient dynamic reliability approach which can manage various sources of uncertainty and characterize their effect by a probability density function (PDF) at every time point. The second-order statistics, PDF, cumulative distribution function (CDF) of the desired parameters and the probability of failure can be easily obtained by this method. In addition, the accuracy and efficiency of PDEM in geotechnical problems have already been well validated (Huang *et al.* 2015, Huang and Xiong 2017).

In the present study, a PDEM-based SPRA framework is proposed for seismic risk analysis of an earth dam. First, the stochastic seismic responses and reliability of the earth dam are obtained by PDEM. The probability-of-failure results of some certain limit states for various levels of ground motion intensity are used to construct the seismic fragility curves without limiting them to a specific functional form. Then the seismic fragility results of the earth dam obtained by PDEM are combined with the results of seismic hazard and loss analysis to address the PDEM-based SPRA framework of the earth dam.

2. Seismic performance metrics and damage criteria of earth dams

One significant stage in the seismic vulnerability analysis is the determination and definition of various performance levels and the corresponding failure criteria. Dam settlement is often selected as a performance metric to quantify the damage state of earth dams and rockfill dams. For example, Gikas Sakellariou (2008) selected settlement behavior to assess the long-term performance of dams. Sica and Pagano (2009) used permanent settlement to assess the seismic performance of earth dams. Zhou *et al.* (2011) pointed out that settlement is one of most important deformation characteristic and key safety indicator of rockfill dam. In the study of Rashidi and Haeri (2017), they also used settlement to evaluate the behaviors of earth and rockfill dams during construction and the first impounding. Furthermore, some studies stated that the settlement appears to be directly related to the severity of the earthquake-related deformation and cracking (Swaisgood 2003, Wang *et al.* 2012).

Different damage criteria regarding deformation of dams have been proposed, for instance, the study of Hynes-Griffin and Franklin (1984) recommended 1 m as the rational limit of permanent settlement of an earth dam. Darbre (2004) set the allowable seismic permanent displacement of superficial sliding and deep sliding of dams as 0.20 m and 0.50 m, respectively. However, these damage criteria may be different for earth dams with different dam heights. Thus, the relative dam crest settlement (the ratio of the crest settlement to the height of the dam) may be a more suitable criterion for seismic performance assessment of earth dams. Various damage criteria with respect to the relative dam crest settlement are proposed. Swaisgood (2003) reviewed, compared and statistically analyzed nearly 70 case histories of dams that were damaged during earthquakes, and proposed four damage states regarding the relative settlement: none (0.001–0.01%); minor (0.01%–0.1%); moderate (0.1%–1%); serious (>1%). Combining the case of a dam damaged in the Wenchuan earthquake (Guan 2009) and the criteria of Swaisgood (2003), Wang *et al.*

Table 1 Seismic performance levels and corresponding damage criteria of earth dams

Performance levels	Degree of damage	Relative dam crest settlement (%)
Level 1	Minor	0.1
Level 2	Moderate	0.4
Level 3	Serious	1.0

(2012) also proposed four different damage levels of earth dams: basically undamaged (0.0–0.1%); minor (0.1%–0.4%); moderate (0.4%–1.0%); serious (>1.0%). Referring to the above safety assessment and grading standard, three critical damage states and damage criteria (Table 1) were selected in our study: minor (0.1%), moderate (0.4%) and serious (1.0%).

3. Seismic probabilistic risk assessment of earth dams based on the PDEM reliability approach

SPRA is commonly used to analyze the potential effects of an earthquake on significant structural systems. These assessments are of great significance for risk management, decision-making and emergency planning. For an earth dam, SPRA evaluates the possibility of being subjected to a certain level of earthquake motion and the consequence of such motion, which reflects the degree of earthquake damage to earth dams and the consequences to society. The SPRA of a dam consists of three parts: probabilistic seismic hazard analysis, seismic fragility and seismic loss analysis of the earth dam; it can be expressed as (Yegian *et al.* 1991, Ellingwood and Kinali 2009, Wang *et al.* 2012)

$$R=H \cdot F \cdot L \tag{1}$$

where R is the seismic risk; H is the seismic hazard that represents the probability of the occurrence of earthquakes with different intensities at a site at a given time period; F is the seismic fragility that represents the conditional probability of failure under a specific seismic intensity; L is the seismic loss of the earth dam.

The first two items, $H \cdot F$, on the right side of Eq. (1) can be expressed as following mathematical form (Yegian *et al.* 1991, Ellingwood and Kinali 2009, Wang *et al.* 2012)

$$P(Ls) = P(Ls|A = a)P(A = a) \tag{2}$$

where *Ls* represents the seismic performance levels or damage states of the earth dams, as described in Section 2; A is the earthquake intensity measure, such as peak ground acceleration (PGA); $P(Ls|A = a)$ is the seismic fragility, and is the conditional failure probability for a given seismic intensity a; $P(A = a)$ is the occurrence probability of ground motion with intensity a, which can be obtained by probabilistic seismic hazard analysis of a specific dam site; $P(Ls)$ is the total failure probability of exceeding these performance levels that can be determined by combining the fragility curves and seismic hazard curves (Zentner *et al.* 2017), and can be considered as the seismic risk probability.

The seismic fragility $P(Ls|A = a)$ is an essential part of SPRA; it can deal with the effect of uncertainties on the seismic performance and the propagation of uncertainties in the dynamic systems of earth dams (Zentner *et al.* 2017, Wang *et al.* 2018). We propose a dynamic reliability approach for seismic vulnerability analysis, and show how it can be combined in the framework of SPRA of earth dams.

In the fragility analysis of a dam, if we use **S** to denotes the desired seismic response of the dam, the seismic responses under the effect of uncertainties can be written as

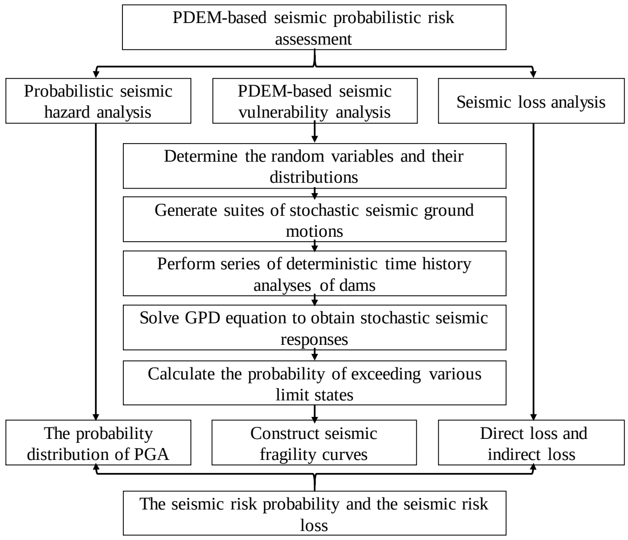


Fig. 1 PDEM-based SPRA framework of the earth dam

$$\mathbf{S}(\mathrm{t}) = \mathbf{P}_S(\boldsymbol{\theta}, \mathrm{t}) \tag{3}$$

where S is the seismic responses parameter that we want to use to assess the seismic performance of earth dams, which is a time history variable. $\mathbf{P}_S$ is a m-dimensional state vector that can be expressed as $\mathbf{P}_S = (\mathrm{p}_1, \mathrm{p}_2, \cdots \mathrm{p}_m,)^T$; $\boldsymbol{\theta}$ represent the uncertainties that may come from seismic ground motion, soil properties and so on. As the primary source of uncertainties in the seismic performance analysis of earth systems may be the randomness of ground motion (Bray and Travasarou 2007, Lopez-Caballero and Modaressi-Farahmand-Razavi 2010, Calabrese and Lai 2016), only the uncertainty of ground motion is taken into account in the present study. According to the conservation of probability principle (Li and Chen 2008), the system behaves as

$$\frac{D}{Dt}\int_{\Omega_t \times \Omega_\Theta} \rho_{S\Theta}(S, \boldsymbol{\theta}, t) dS d\theta = 0 \tag{4}$$

where $\rho_{S\Theta}(S, \boldsymbol{\theta}, t)$ is the joint probability density function of $(\mathbf{S}(t), \boldsymbol{\theta})$. Based on this, Li and Chen (2008) established the generalized probability density equation (GPD equation)

$$\frac{\partial \rho_{S\Theta}(S, \boldsymbol{\theta}, t)}{\partial t} + \sum_{j=1}^{m} \dot{S}_j(\boldsymbol{\theta}, t)\frac{\partial \rho_{S\Theta}(S, \boldsymbol{\theta}, t)}{\partial S_j} = 0 \tag{5}$$

For complicated dynamic systems such as earth dams, the equation is often solved by numerical algorithm (Li and Chen 2009) to obtain the numerical solution, as follows:

1) Partition the probability space of the random variable to select a representative point set $\boldsymbol{\theta}_q = (\theta_1, \theta_2, \ldots, \theta_{n_{\mathrm{sel}}})$.

2) For each $\theta_q (q = 1,2,3,\cdots, n_{sel})$, determine the corresponding ground motion, and obtain a suite of values for the seismic settlement of the earth dam by performing a set of deterministic seismic response analyses.

3) Substitute the set of seismic deformation results to the GPD equation, and solve the equation by a finite-difference numerical method to obtain the numerical solution of $\rho_{S\boldsymbol{\Theta}}(S, \boldsymbol{\theta}_q, t)$.

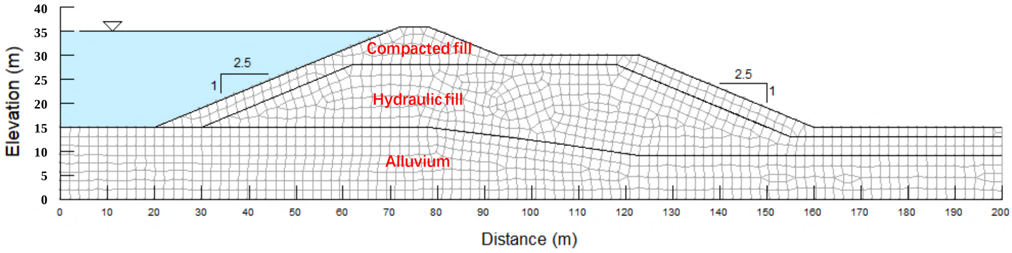


Fig. 2 The finite element model of the earth dam (unit: m)

4) Add up the $\rho_{S\Theta}(S, \boldsymbol{\theta}_q, t)$ to obtain the numerical solution of $\rho_S(S,t)$ by $\sum_{q=1}^{n_{sel}} \rho_{S\Theta}(S, \theta_q t)$.

From the numerical algorithm above, the dynamic reliability analysis in PDEM is based on a suite of deterministic seismic time-history analyses of the earth dam and the solution of the GPD equation; thus, a set of seismic ground motions is necessary. Given that historical records of ground motions in a specific site may be limited and may not have the properties of interest, a suite of synthetic stochastic ground motions are often generated to quantify the randomness of earthquake (Choi *et al.* 2004, Sudret *et al.* 2014, Ioannou *et al.* 2015, Güneyisi and Altay 2018). In the present study, a suite of acceleration time history of the ground motions is generated by a random-function-based spectral representation method, the details of which can be found in Huang and Xiong (2017) and Liu *et al.* (2016).

When the conditional failure probability of various seismic levels is obtained by PDEM, the seismic fragility curves can be constructed without using any distribution assumptions. Then, the seismic fragility results can be combined with the seismic hazard and seismic loss results using Eqs. (1) and (2) to address the whole framework of probabilistic seismic risk assessment of earth dams. To give readers a clear understanding of our methodology, the PDEM-based seismic probabilistic risk assessment framework is illustrated in Fig.1.

4. A case study of earth dam

A simple dynamic model of an earth dam in GEO-SLOPE (GEO-SLOPE International Ltd 2018) is selected for illustrative purposes (Fig. 2), and its validity and accuracy have already been verified. It is an earth dam composed of three parts: compacted fill; hydraulic fill; and alluvium. The main soil parameters are: compacted fill: unit weight γ_1 = 18 kN/m^3, effective cohesion c_1 = 5 kPa, effective friction angle φ_1 = 34°; hydraulic fill: γ_2 = 18 kN/m3, c_2 = 0 kPa, φ_2 = 34°; alluvium: γ_3 = 20 kN/m^3, c_3 = 5 kPa, φ_3 = 36°. The nonlinear model of soil is used in our study. All these soil properties are taken as deterministic values; their uncertainties have not been taken into consideration in the present study because the soil property uncertainty has a smaller effect on the seismic performance of earth structures than the uncertainty of the seismic ground motion (Lopez-Caballero and Modaressi-Farahmand-Razavi 2010, Calabrese and Lai 2016).

To quantify the uncertainties of the earthquake, a suite of synthetic stochastic ground motions composed of 254

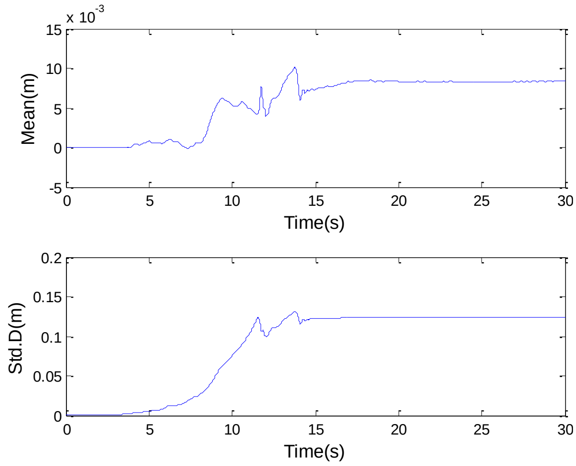


Fig. 3 Mean value and standard deviation of dam crest settlement

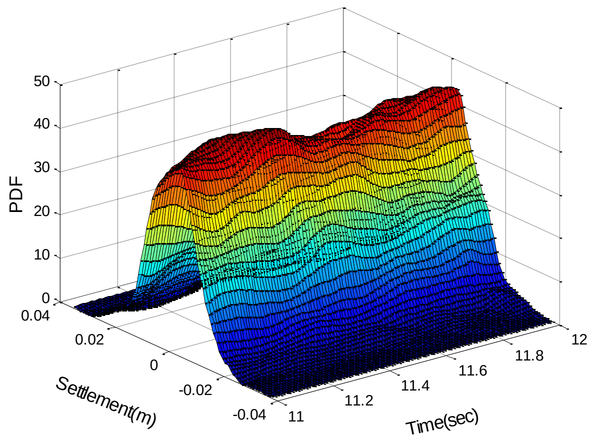
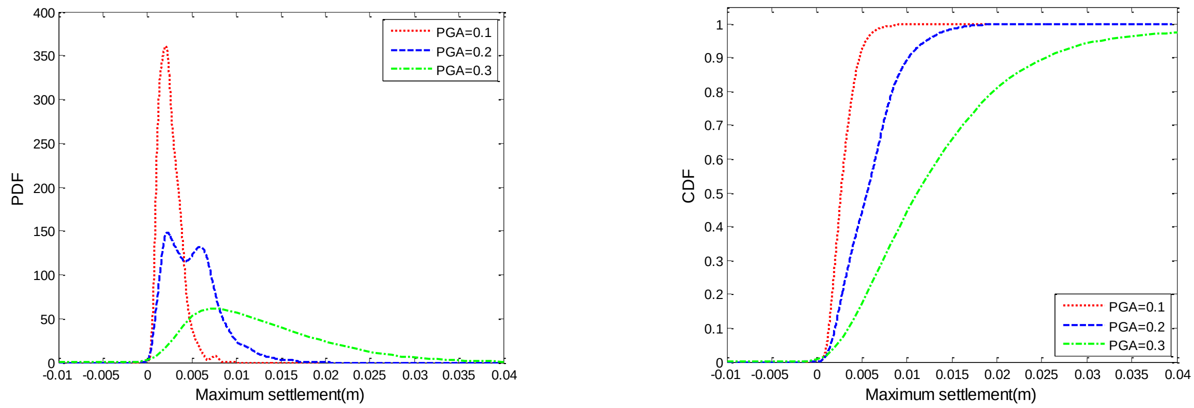


Fig. 4 Crest settlement PDF surface at the time interval of 11-12 second

acceleration time histories in a hypothetical site in China were generated by the spectral representation method (Liu *et al.* 2016, Huang and Xiong 2017). The ground motions were applied to the dynamic earth dam model to construct the stochastic analysis models of the dam for the probabilistic and fragility analysis.

4.1 Stochastic seismic responses and seismic reliability of the earth dam

The suites of time histories of dam crest settlement obtained from the dynamic finite-element analyses were substituted into the GPD equation to acquire the mean,



(a) (b)

Fig. 5 (a) PDF and (b) CDF of maximum dam crest settlement with three different seismic intensities

Table 2 Dynamic reliability of the earth dam under various seismic intensities

Dynamic Reliability		Seismic intensity level (PGA)									
		0.1 g	0.2 g	0.3 g	0.4 g	0.5 g	0.6 g	0.7 g	0.8 g	0.9 g	1.0 g
Performance levels	Level 1: 0.02 m	1	0.999	0.8671	0.6440	0.5336	0.4633	0.4036	0.3642	0.3241	0.3099
	Level 2: 0.08 m	1	1	0.9914	0.9435	0.8167	0.7154	0.6272	0.5068	0.4665	0.4469
	Level 3: 0.2 m	1	1	0.9961	0.9754	0.9027	0.8186	0.7754	0.6709	0.5912	0.5748

standard deviation, PDFs at different time points and dynamic reliability of the dam. Taking PGA = 0.3g as an example, Fig. 3 illustrates the mean value and standard deviation of the dam crest settlement, which shows great variability under the effect of earthquake randomness. The mean and deviation values rise with time because of the cumulative displacement. Fig. 4 shows 3-D crest settlement PDF surface at 11–12 s, characterized by rolling hills and high points representing high probability. To illustrate the impact of ground motion intensity on the dynamic reliability of the earth dam, the extreme value in a series of settlement time histories obtained by dynamic time-history analyses with different ground motion intensities was extracted to construct virtual random processes. These were substituted into the GPD equation to acquire the PDF and CDF of the maximum dam crest settlement, shown in Fig. 5 for three different seismic intensities (0.1g; 0.2g; 0.3g). As the PGA increases, the settlement PDF moves to the right, and becomes wider and lower. The settlement CDF also moves to the right with increasing PGA, which demonstrates that the dynamic reliability of the earth dam decreases as the ground motion intensity increases.

Using the same procedure, the suite of stochastic ground motions is scaled to multiple levels of PGA from 0.1g to 1.0g, and the dynamic reliabilities of the earth dam with different seismic performance levels under the excitation of stochastic seismic ground motions with various intensities are obtained (Table 2). It is observed that the dynamic reliability decreases with increasing intensity, and increases with the rise of performance levels.

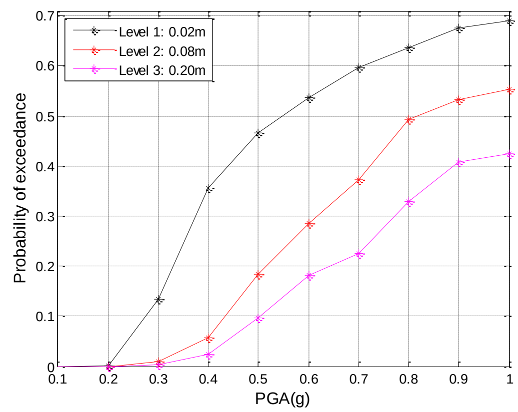


Fig. 6 Seismic fragility curves for the earth dam

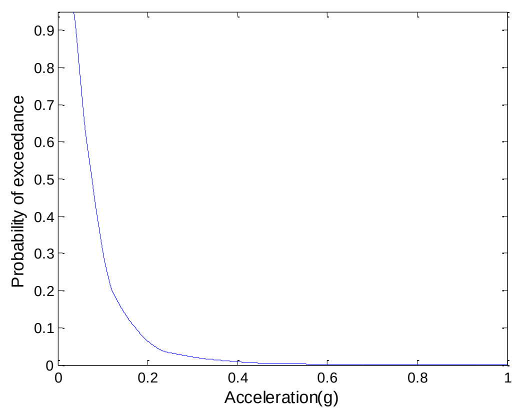


Fig. 7 Seismic hazard curve in a hypothetical site

4.2 Seismic fragility curves of the earth dam

In general, the seismic fragility of large and complex structural systems is defined as the probability of exceedance of a certain limit state for a specific level of ground motion intensity. Based on the above dynamic

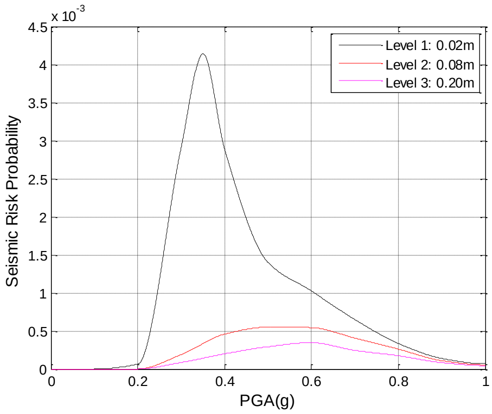


Fig. 8 Seismic risk probability of the earth dam

Table 3 Seismic probabilistic risk assessment of the earth dam with a ground motion intensity of 0.3g

Performance levels	Level 1	Level 2	Level 3
Seismic risk probability P(Ls)	0.002901	0.0001877	0.00008514
Seismic loss L(CNY)	0.4 billion	0.8 billion	1.2 billion

reliability analysis results and various predefined seismic performance levels and limit states of earth dams, the seismic fragility curves were subsequently acquired without using any distribution assumptions. Fig. 6 shows the seismic fragility curves for the earth dam, which demonstrate that the probability of failure increases with rising earthquake intensity. The uncertainty of the seismic ground motion and its impact were propagated and captured in the seismic fragility assessment and fragility curves.

For the seismic fragility curves in the present study, not all the potential uncertainties were taken into account as only ground motion uncertainties were considered. Although soil property uncertainty has a smaller effect than the uncertainty of the seismic ground motion (Lopez-Caballero and Modaressi-Farahmand-Razavi 2010, Calabrese and Lai 2016), a rigorous seismic vulnerability analysis needs to take all potential uncertainties into consideration. Kim and Sitar (2013) also pointed out that uncertainty of the soil properties have little impact on the probability results under high levels of seismic hazards (>0.1-0.2g), but it has effect under low levels of seismic hazards (<0.1-0.2g). Taking combined uncertainties of soil properties and ground motion into account can acquire more rigorous fragility results, especially in low levels of seismic hazards. In addition, the soil is strongly nonlinear material, and they show relatively different deformation characteristic under various loading conditions and stress levels. The seismic behavior and deformation of earth dam may exhibit quite different results under the coupling effect of earthquake randomness and soil nonlinearity. Due to the uncertainties of soil properties, their nonlinearity behavior is also different. On the other hand, spatial variability is an essential characteristics of soil properties due to their sedimentary environment and geological processes. A rigorous and reliable way to consider soil properties uncertainty is to model them as random field. In consequence, the uncertainty of the soil combined with the seismic ground motion uncertainty and the soil's spatial variability should be examined in future studies.

4.3 Seismic probabilistic risk of the earth dam

In the probabilistic seismic hazard analysis, the PGA was selected as an intensity measure. The probability distribution of the earthquake PGA can be assumed to be a Type II extreme value distribution (Ellingwood 2001). In China, it is often assumed to be (Shen *et al.* 2008)

$$F_A(a) = \exp(-a/a_g)^{-K} \tag{10}$$

where a is the PGA of a specific site; a_g is the PGA of the 63.2% probability of exceedance over a certain period of time; and K is the shape parameter. The parameters a_g and K can be determined from the seismic hazard analysis data of the specific site. In present study, a_g and K for typical site conditions in China are assumed to be 0.573 m/s^2 and 8.335, respectively (Shen *et al.* 2008). The seismic hazard curve for a period of 100 years is presented in Fig.7.

The seismic risk probability of the earth dam was obtained by combining the seismic fragility results of each performance level in the PDEM with the results of the probabilistic seismic hazard analysis (Fig. 8). The earth dam has different seismic risks for the three performance levels under the impact of various earthquake intensities in the 100-yr period. The highest probability of experiencing damage was at level 1 under conditions of an earthquake of about 0.35g.

The seismic loss analysis includes direct economic loss, indirect economic loss and non-economic loss. According to the Chinese standards "Post-earthquake field works – Part 4: Assessment of direct loss (GB/T 18208.4-2011)", the main forms of earthquake damage for dams are the dam damage and damage to ancillary facilities, regarded as direct economic losses, and indirect economic loss which is caused by disruption to power generation and upstream water supply utility functions. The cost of disaster relief is another form of indirect economic loss. Non-economic losses include human casualties and the psychological and mental effects of earthquakes. A comprehensive seismic loss analysis should include all these parts, but this can be very complex. In the present study, only the direct loss caused by the damage to the dam and ancillary facilities is taken into account for simplicity.

Construction costs of a hydraulic dam are very high. The cost and workload of the repair and reinforcement can also be very high, even when a small part of the dam is damaged after an earthquake. The direct economic loss resulting from the damage of a dam and ancillary facilities in China can be determined by (Shen *et al.* 2008, Wang *et al.* 2012)

$$\mathrm{L}(Ls) = \mathrm{V}\mathrm{r}_{Ls} \tag{11}$$

where L(Ls) is the direct economic loss of damage state Ls; V is the total value of the dam; and r_{Ls} is the loss ratio of the dam body when a failure state of Ls occurs, representing the ratio of the repair cost to the current cost of the dam.

In the present study, the total value of the dam V is assumed to be 4 billion CNY; r_{Ls1}, r_{Ls2} and r_{Ls3} were set as 0.1, 0.2 and 0.3, respectively (Wang *et al.*, 2012). Table 3 lists the seismic probabilistic risk assessment results of the earth dam for an earthquake of PGA = 0.3g.

The seismic risk probability and the seismic risk loss obtained in the SPRA can provide the basis for the analysis and decision-making on risk management, retrofitting, mitigation strategies and the aseismic optimization of existing old dams that may not meet the requirements of the current seismic standards, as well as to prescribe measures for seismic risk reduction.

5. Conclusions

A dynamic reliability approach is proposed for the seismic vulnerability analysis of earth dams, and a SPRA framework based on PDEM is also presented in this study. The following main conclusions were drawn.

• The crest deformation is a rational performance metric that can be used to analyze the seismic performance and damage state of earth dams. In our study we selected three performance levels related to the relative settlement of earth dams to evaluate the seismic fragility of earth dams.

• The seismic performance of the earth dam shows great variability under the effect of the uncertainty of seismic ground motion. The propagation of the randomness of the ground motion through the dynamic system of an earth dam is revealed by instantaneous PDFs in PDEM.

• The PDEM results of the failure probability are used to construct the seismic fragility curves of the earth dam without using any assumptions. The seismic fragility results of the earth dam are combined with the seismic hazard curves and seismic loss analysis to address the entire framework of the SPRA of the earth dam. The seismic risk probability and the seismic risk loss is useful for risk management analysis, retrofit and mitigation strategies and for aseismic optimization.

Acknowledgments

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