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Seismic Fragility Analysis of a High Arch Dam-Foundation System based on Seismic Instability Failure Mode

Hui Liang(1), (2), Jin Tu(1),(2), Shengshan Guo(1), (2), Jianxin Liao(3), Deyu Li(1), (2), Shiqi Peng(3)

(1) *Earthquake Engineering Research Centre, China Institute of Water Resources and Hydropower Research, Beijing, China;*

(2) *State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, Beijing, 100048 China;*

(3) *China Three Gorges Projects Development Co., Ltd, Beijing, 100038, China*

Abstract

In this paper, a high concrete arch dam is selected as a case study for the analytical fragility analysis based on the seismic instability failure mode. The arch dam and dam abutment are analyzed together as a coupled system. A comprehensive approach considering the opening and closing of contraction joint, the boundary of probable sliding rock mass of dam abutments, the interface between the dam and foundation as well as the effect of foundation radiation damping is presented. The random and uncertainty parameters containing the friction coefficients and cohesions are generated with Latin hypercube sampling method (LHS). The approximate IDA is performed, and the slippage and the sliding area ratio are chosen as the engineer demand parameters (EDP) respectively. Different damage levels are firstly identified by the slippage-based rules and sliding area ratio-based rule respectively based on their corresponding overall mean IDA curves. Seismic fragility curves are developed for defined damage levels based on seismic instability failure mode. Moreover, a comparative analysis of the effect of residual cohesion on the seismic fragility analysis of the arch dam is performed considering two different models i.e. model I (without residual cohesions) and model II (with residual cohesions). The results reveal that sliding area ratio-based rule can better reveal the whole process of sliding development of the arch dam abutment and the influence of residual cohesions. The existence of residual cohesion delays the sliding development and enhances the seismic stability of arch dam-foundation systems.

Keywords: high arch dam-foundation system; seismic instability failure mode; dynamic contact model; Latin hypercube sampling; seismic fragility analysis

1 Introduction

Seismic safety of high dams is an inevitable problem during the construction of momentous water conservancy projects. Existing practical examples of high dams subjected to strong earthquakes show that dam abutment is the weak part. The overall instability of the dam-foundation system caused by its damage is one of the most important concerns in the seismic design and safety assessment of high dams, which faces with complicated geological conditions and various loads.

Moreover, there are various uncertainties, such as epistemic (modeling and material parameters) and aleatory (earthquake ground motion, flood etc.) uncertainty during the design, construction and operation of dams [1, 2, 3], which significantly affect the seismic performance of concrete dams. Fragility analysis, which plays an essential role in seismic probabilistic risk assessment within the framework of performance-based seismic design, is gradually applied to water conservancy and hydropower projects, such as gravity dams and arch dams. Hariri-Ardebili M A et al. [4] provide a comprehensive state-of-the-art review of existing application on fragility analysis of concrete dams. The detailed procedures and different methods are summarized and a comparative review of major researches and publications is presented. A consistent procedure is particularly presented to perform fragility analysis for the sliding failure mode of concrete gravity dams in order to identify and track natural and epistemic uncertainty separately [5].

However, among those described researches, few attempts have been partly made on the effect of various uncertainties on seismic performance of concrete arch dams. In view that the quantitative study of progressive failure of concrete dams is an important part of risk analysis, Hariri-Ardebili, Furgani and Meghella [6] compare and analyze more than 20 indexes using Endurance Time Analysis method (ETA) based on the concept of damage index and performance index, which provides an effective method for the selection of engineering demand parameters in seismic performance evaluation of dams. The seismic fragility analysis of a high arch dam including dam concrete cracking and contraction joint opening and closing is performed considering both epistemic and aleatory uncertainties, and seismic fragility curves under different damage levels are drawn [7].

In general, seismic fragility analysis of high arch dams is still in its infancy. Thus, this paper focuses on the seismic fragility analysis of a high concrete arch dam-foundation system based on the seismic instability failure mode. Both two models i.e. model I without residual cohesions and model II with residual cohesions (30% of the corresponding peak cohesions) are considered for a comparative analysis of the effect of residual cohesion on the seismic fragility of the arch dam. Different damage levels are defined through slippage-based rules and sliding area ratio-based rules. Furthermore, the corresponding fragility curves are extracted for the seismic stability evaluation of concrete arch dams.

2 Computational Methodology

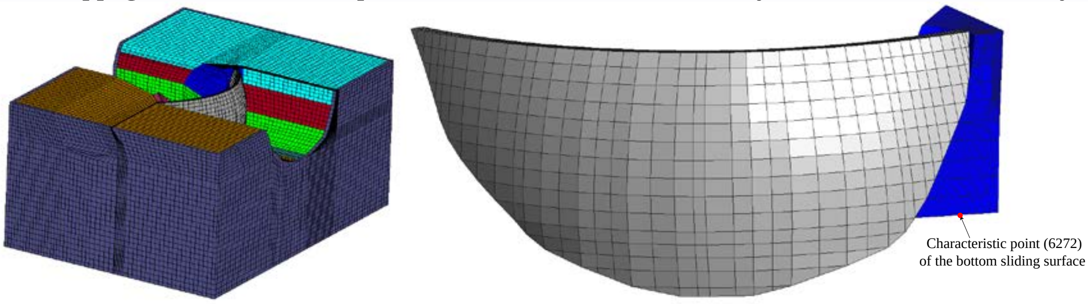
2.1 Generation of seismic fragility curve

Fragility is expressed as the probability of engineering structure reaching a certain limit state or performance level under different earthquake intensity levels in seismic engineering [8, 9]. A large amount of data is needed in order to obtain fragility curves of structures with reasonable and accurate consideration of the effects of uncertainties on structural performance. In this paper, analytical fragility analysis is adopted, of which the data base is obtained from the structural dynamic response under a series of earthquakes with increasing seismic intensity levels. IDA method is used to develop seismic fragility curves of the concrete arch dam-foundation system. A series nonlinear dynamic analyses are performed considering epistemic uncertainty.

3 Nonlinear modeling of a high arch dam-foundation system

3.1 Finite element model

A double-curvature arch dam is selected as a case study, located in strong earthquake area in Southwest China. The height of the dam is 289 m, and the crest is at El. 834 m. The thickness of the dam crest is 14.0m, and the maximum thickness of dam bottom is 83.91m. The three-dimensional finite element mesh of arch dam-foundation system is established, shown in Fig. 1. The whole model contains about 130,000 nodes and 120,000 solid elements. Fig. 1(b) shows the location of the selected observation point (node number 6272), of which the slippage can be used to represent the overall seismic stability of the dam-foundation system.



(a) Dam-reservoir-foundation system (b) Selected observation point (number 6272)

Fig. 1 Finite element mesh of the arch dam-foundation system[12]

3.2 Material parameters

The material parameters of dam concrete are as follows: mass density = 2400.0 kg/m^3 and Poisson's ratio = 0.167. The static elastic modulus is 24.0 GPa and dynamic elastic modulus is 1.5 times of the static elastic modulus. The normal and lognormal distribution are considered for friction coefficients and cohesions respectively [10]. The parameters used in the dynamic contact model are defined using the properties listed in Table 1. The widely used Latin hypercube sampling method (LHS) [11] is adopted to handle the current impact of parameter uncertainties in view of its accuracy and efficiency for the probabilistic analysis.

Table 1 The material properties and probability distributions for the random parameters

Material parameters	Mean/Base-case model	COV	Minimum	Maximum	type
Friction coefficient μ_{bottom}	0.432	0.200	0.2592	0.6048	Normal
Cohesion c_{bottom} (MPa)	0.193	0.400	0.08293	0.3872	Log-normal
Friction coefficient μ_{crack}	1.100	0.200	0.6600	1.5400	Normal
Cohesion c_{crack} (MPa)	1.200	0.400	0.5156	2.4076	Log-normal
Friction coefficient μ_{side}	0.420	0.200	0.2520	0.5880	Normal
Cohesion c_{side} (MPa)	0.090	0.400	0.03867	0.1806	Log-normal

3.3 Static and dynamic loads

The static loads include self-gravity of the dam body, water pressure in the upstream and downstream under the normal water level, upstream sediment pressure and temperature load. The representative value of horizontal design seismic acceleration of the arch dam is 0.406 g, which is equivalent to 2% of the exceeding probability in 100 years, and the vertical value is 2/3 of the horizontal value, which is 0.271 g.

4 Probabilistic analysis

In order to study the effect of residual cohesions on the seismic stability of arch dam-foundation systems, two models, i.e. model I without residual cohesions and model II with residual cohesions (30% of the corresponding peak cohesions is selected as a case study), are considered for the probabilistic analysis with the advanced dynamic contact model. Herein, the sample size N is taken as 50 for probabilistic analysis.

PGA is selected as IM, scaled to multiple levels from zero to 1.0g with steps of 0.1g in the IDA of arch dams. The shear strength parameters on each potential sliding surface are considered as random variables. The residual slippage of the characteristic point at the bottom sliding surface is selected as one of the indexes to quantitatively evaluate the seismic sliding stability of the arch dam abutment. Moreover, the sliding area ratio (ratio of the sliding area to the bottom sliding surface) is chosen as another damage index for evaluating seismic stability of the arch dam-foundation. Thus, the total number 10×N=500 of nonlinear dynamic analyses are performed for both model I and II, and IDA curves are generated from discrete points with the spline interpolation.

5 Results and discussion

5.1 Limit state definition

In this paper, IDA curves are used to define the limit states of the arch dam-foundation. The overall mean slippage-based and sliding area ratio-based IDA curves with their 50% fractile are obtained from probabilistic analysis. The different limit states of seismic stability of the arch dam-foundation system under earthquakes are defined for the seismic fragility analysis.

5.1.1 Slippage-based rule

Fig. 2 describes different slippage-based limit states defined for the concrete arch dam-foundation system through the overall mean IDA curve and 50% fractile IDA curve. It shows that the curve is divided into three stages by two turning points. Therefore, according to the appearance of turning points in each stage, the two limit states and the corresponding residual slippage threshold of arch dam foundation system based on sliding instability failure mode can be defined as: (1) Local sliding damage, corresponding to the residual slippage of 0.0 m of the characteristic point at the first turning point, i.e. the initial sliding of the characteristic point; (2) Overall sliding failure, corresponding to the residual slippage of 0.04 m (40.0 mm) at the second turning point.

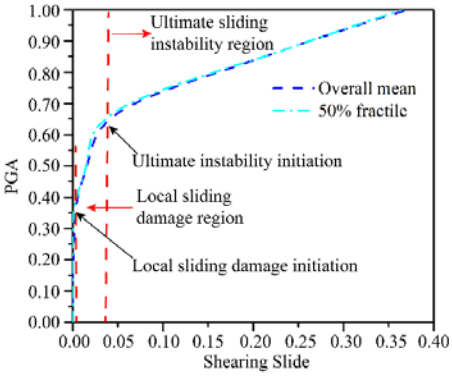


Fig. 2 Slippage-based limit states definition[12]

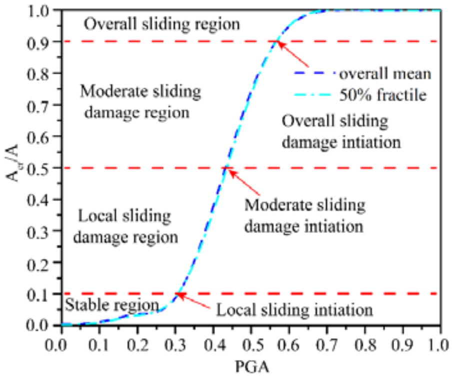


Fig. 3 Sliding area ratio-based limit states definition[12]

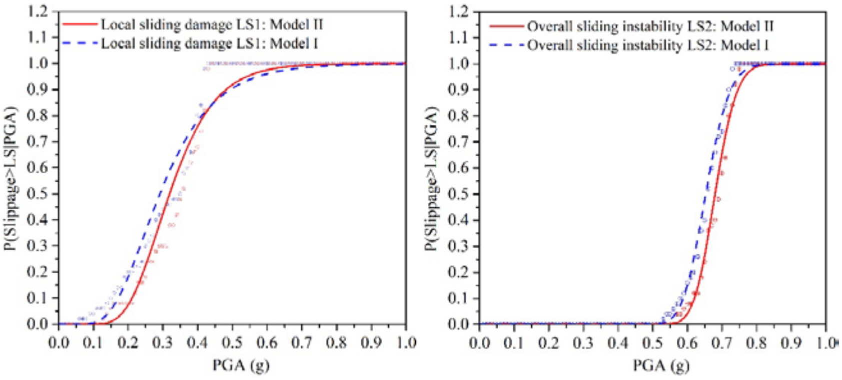
5.1.2 Sliding area-based rule

Fig. 3 depicts the sliding area ratio-based limit states of the concrete arch dam-foundation system. Different regions are divided by the red dotted line for each limit state, detailly shown in Fig. 6. According to Fig. 6, based on the sliding area ratio versus PGA curve, the process of seismic sliding stability of arch dam foundation system can be divided into four stages, and the limit states of the arch dam foundation system can be divided into: (1) Local/Slight sliding damage, corresponding to the sliding area ratio of 10%; (2) Moderate sliding damage, corresponding to the sliding area ratio of 50%; (3) Overall sliding failure, corresponding to the sliding area ratio of 90%.

5.2 Seismic fragility curves

5.2.1 Slippage-based rule

Fig. 4 (a) and (b) presents the comparison of fragility curves of model I and II for different limit states. Clearly, as shown in Fig. 4 (a) and (b), for model I, the probability of occurrence of local sliding damage is about 80%, and it is zero for overall sliding failure under maximum design earthquake (MDE, 2% probability of exceedance in 100 years, PGA = 0.406 g). Even if PGA reaches maximum check earthquake (MCE, 1% probability of exceedance in 100 years, PGA = 0.481 g), the probability of occurrence of overall sliding failure of the arch dam-foundation system is still zero. As for model II, the probability of occurrence local sliding of the arch dam-foundation system decreases slightly, which is similarly approximate 80% under MDE i.e. PGA of 0.406 g. The probability of occurrence of local sliding of arch dam foundation system is about 90%, and the probability of overall sliding failure is still zero when PGA reaches 0.481 g. It can be considered that the arch dam can maintain stability under maximum check earthquake.



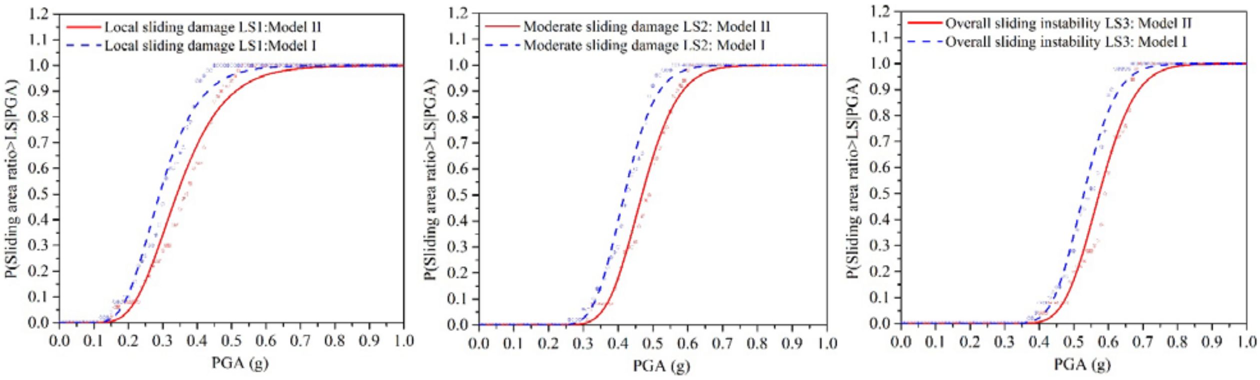
(a) Local sliding damage (b) Overall sliding instability

Fig. 4 Comparison of fragility curves of model I and II for different limit states[12]

5.2.2 Sliding area ratio-based rule

Fig. 5 (a), (b) and (c) presents the comparison of fragility curves of model I and II for different limit states based on the sliding area ration. According to Fig. 5 (a) and (b), for model I, when PGA reaches 0.406 g, the probability of occurrence of slight sliding damage is about 90%, and that of moderate sliding damage is less than 55%. The probability of occurrence of overall sliding failure is about 0.5%. When PGA reaches 0.481 g, the probability of overall sliding failure of the arch dam foundation system is about 20%. As for model II under design earthquake, the corresponding probability of occurrence of slight sliding damage is about 70% and it's less than 30% for moderate sliding damage. Meanwhile, the probability of occurrence of overall sliding failure is about zero. There is a 5% decrease for the probability of occurrence of overall sliding failure under check earthquake with respect to model I.

Moreover, compared with slippage-based fragility curves, sliding area ratio-based curves can reflect the difference between model I and model II more obviously, and it can better reveal the whole process of sliding development of the arch dam abutment and the influence of residual cohesions.



(a) Local/Slight sliding damage (b) Moderate sliding damage (c) Overall sliding instability

Fig. 5 Comparison of fragility curves of model I and II for different limit states[12]

6 Conclusions

This paper presents the development of seismic fragility curves of a high concrete arch dam based on seismic instability failure mode. Damage levels are defined first according to slippage-based rule. Two damage levels are defined from the corresponding slippage of the two turning points based on the overall mean slippage-based IDA curves. Afterwards, three damage levels are identified based on the sliding area ratio-based rule from the overall mean sliding area ratio-based IDA curves. Moreover, seismic fragility curves are extracted for the seismic stability of concrete arch dams under earthquake hazards for both two models, i.e. model I without residual cohesions and model II with residual cohesions (30% of the corresponding peak cohesion). It can be said that the arch dam is able to maintain good stability under MCE. Sliding area ratio-based curves can reflect the difference between model I and model II more obviously. It can better reveal the whole process of sliding development of the arch dam abutment and the influence of residual cohesion. The probability of occurrence of overall sliding failure of the dam-foundation system given by sliding area ratio-based rule is higher than that given by slippage-based rule under check earthquake. It is safer to use sliding area ratio-based rule to evaluate the seismic stability of dam-foundation system.

7 Acknowledgements

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8 Copyrights

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