Structural Safety 59 (2016) 67–85

Contents lists available at ScienceDirect

Structural Safety

journal homepage: www.elsevier.com/locate/strusafe

Probabilistic seismic demand model and optimal intensity measure for concrete dams

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ARTICLE INFO

Article history:
Received 29 March 2015
Received in revised form 28 September 2015
Accepted 6 December 2015
Available online 2 January 2016

Keywords:
Cloud analysis
Earthquake
Fragility curve
Nonlinear finite element analysis
Uncertainty

ABSTRACT

This paper addresses the probabilistic seismic demand model (PSDM) which is the relationship between the intensity measure (IM) (such as spectral acceleration) and the engineering demand parameter (EDP) (such as displacement and crack ratio – ratio of crack length to total crack path). It expresses the probability that a system experiences a certain level of demand for a given IM level. Formulation is for a concrete gravity dam. First, IMs are categorized and the criteria for the selection of an optimal one presented. Then, cloud analysis is performed where the structure is subjected to a large set of un-scaled ground motions and the maximum responses are extracted for each one and plotted as a cloud of results.

This methodology is applied to Pine Flat gravity dam. Model is first presented followed by results and conclusions. When the results of the cloud analysis are aggregated, then one can plot the seismic fragility curve which is the probability of EDP exceedance in terms of the IM parameter.

1. Introduction

In the context of performance-based earthquake engineering (PBEE) [1] ultimately one seeks to determine the fragility curve [2] which is the conditional probability statement of the likelihood that the structural system will exceed a damage state (DS) or even a specified level of engineering demand parameter (EDP) given the intensity measure (IM) parameter. The EDP is the outcome of a nonlinear transient finite element analysis performed on the basis of an excitation governed by the IM.

Probabilistic seismic demand model (PSDM) is a conditional probability statement that expresses the probability that a system (dam-foundation coupled system in the present paper) or any of the structural components experiences a certain level of demand (D) for a given IM level, $P[\mathrm{D} \geqslant d|\mathrm{IM}]$ [3]. A PSDM is a result of probabilistic seismic demand analysis (PSDA), which is the coupling of probabilistic seismic hazard analysis (PSHA) and nonlinear structural analysis [4]. A PSDA can be summarized in the following steps:

1. Selection of a set of ground motion records based on PSHA,
2. Determination of the local and global EDPs for the structure,
3. Preparation of nonlinear finite element model,
4. Performing nonlinear transient analyses, and
5. Establishing a PSDM for the system.

The outcome of PSDA is a seismic fragility curve and selection of optimal IM parameter. PSDA and PSDM supporting theories can be found in [5–7]. Advanced IM and selection of optimal ones have been addressed by a number of researchers [8,3,9]. PSDM in turn has been applied to steel moment-resisting frame [10], reinforced-concrete frame buildings [11,12], reinforced-concrete shear wall [13], highway bridges [14,15], curved concrete bridges [16], and un-anchored steel storage tanks [17].

To the best of the authors knowledge, pioneering work in research on the probabilistic failure analysis of gravity dams was performed by [18]. This was followed by [19] where both the concrete properties and the seismic excitation were assumed to be random variables. [20,21] proposed flood and seismic fragility curves for gravity dam using nonlinear finite element method and relatively limited number of analyses (based on Latin Hypercube Sampling – LHS). [22] derived the fragility curves based on an innovative procedure where the randomness of external actions is treated separately from the structural uncertainty using linear analysis. Finally, [23,24] developed a set of fragility curves for different concrete dams accounting for both the material/modeling and seismic uncertainties. The impact of different failure modes were also considered on fragility functions.

In the present paper, a probabilistic seismic demand model is proposed for concrete dams. This approach is performed within the context of a cloud analysis (i.e. a multitude of probabilistically defined input data) [7]. From such an analysis, optimal IM (in term of efficiency, practicality, proficiency, sufficiency, and hazard

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http://dx.doi.org/10.1016/j.strusafe.2015.12.001
0167-4730/

compatibility) is selected for Pine Flat gravity dam, and the seismic fragility curves built.

2. Background theory

Given the importance of a properly defined IM, this will be critically reviewed in this section. Subsequently, the essence of cloud analysis within the context of PSDM will be addressed.

2.1. Time-dependent function IM

General formulas have been proposed to represent the intensity of a time-dependent function $f(t),\ t \subseteq [0, t_{tot}]$ where t_{tot} refers to the total duration of the function [25]. For the purpose of this study, $f(t)$ is defined to be either: (1) a time-dependent ground motion characteristics (such as acceleration, velocity and displacement), or (2) a frequency-dependent ground motion characteristics (such as acceleration, velocity and displacement response spectra).

The intensity measure relations for a raw function are given by [25]

$$\begin{aligned} f_{peak} &= max(|f(t)|) \\ f_{sum} &= \int_{t_1}^{t_2} f(t)dt \\ f_{sum}^{abs} &= \int_{t_1}^{t_2} |f(t)|dt \\ f_{avg} &= \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} f(t)dt \end{aligned} \tag{1}$$

where t_1 and t_2 refer to specific duration ($t_2 > t_1$).

For oscillatory $f(t)$ we define

$$\begin{aligned} f_{sum}^{sqr} &= \int_{t_1}^{t_2} (f(t))^2 dt \\ f_{avg}^{sqr} &= \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} (f(t))^2 dt \end{aligned} \tag{2}$$

When Eqs. (1) and (2) are integrated from t_0 to t_{tot} they yield a single scalar quantity (this is generally the case when the full ground motion record is used). On the other hand, if integration is carried between t_0 and an arbitrary t_i then a vector results. This is the case when artificial function, e.g. endurance time acceleration function (ETAF) are used [26], Fig. 1.

2.2. Ground motion based IM

The first step in PBEE consists in the definition of ground motion IMs. Since various authors have proposed a variety of IMs (mostly in the context of buildings) this section first reviews the seven most important categories, and then select those most applicable to concrete dams.

2.2.1. Category I: unscalable IMs

In this case, the IMs are independent from both the ground motion scaling methods and the characteristics of the target structure. These are: earthquake magnitude, M, epicentral distance, R_{epi}, hypocentral distance, R_{hypo}, ground motion duration, t_{tot}, and significant duration, t_{sig}. Significant duration is a measure of strong ground motion part and usually refers to a portion of ground motion which includes about 90% of the energy. The most common form for t_{sig} is:

$$t_{sig} = t_{0.95 I_A} - t_{0.05 I_A} \tag{3}$$

where I_A refers to the Arias intensity of the ground motion record. t_{sig} is also shown as D_{5-95}.

Another intensity measure that seismologists often adopt is D_{5-75}. It is similar to Eq. (3), as it is assumed that D_{5-75} is a more accurate measure for the most significant part of the ground motion.

2.2.2. Category II: ground motion dependent scalar IMs

Peak Values, The most widely used IM is the peak ground acceleration (PGA). Not only is used in hazard maps but also attenuation relations are usually available in terms of PGA. Peak ground velocity (PGV) and peak ground displacement (PGD) are other typical single-parameter scalar IMs. [27] found that PGV correlates to damage better than PGA [28].

$$\begin{aligned} \text{PGA} &= max(|\ddot{u}(t)|) \\ \text{PGV} &= max(|\dot{u}(t)|) \\ \text{PGD} &= max(|u(t)|) \end{aligned} \tag{4}$$

where $\ddot{u}(t),\ \dot{u}(t)$, and $u(t)$ refer to the acceleration, velocity and displacement time histories of the ground motion record, respectively.

Root-mean-square of acceleration, a_{RMS}, velocity, v_{RMS}, and displacement, u_{RMS}, are used as a measure of effective $F(t)$ acceleration (or velocity or displacement) of a ground motion time-history

$$\begin{aligned} a_{RMS} &= \left(\frac{1}{t_{tot}}\int_0^{t_{tot}} (\ddot{u}(t))^2 dt\right)^{1/2} \\ v_{RMS} &= \left(\frac{1}{t_{tot}}\int_0^{t_{tot}} (\dot{u}(t))^2 dt\right)^{1/2} \\ u_{RMS} &= \left(\frac{1}{t_{tot}}\int_0^{t_{tot}} (u(t))^2 dt\right)^{1/2} \end{aligned} \tag{5}$$

A set of intensity measures similar to Eq. (5), which do not account for the average values (shown in the denominator of the previous equation) and neglecting the damping ratio were also proposed [29]

$$\begin{aligned} a_{rs} &= \left(\underbrace{\int_0^{t_{tot}} (\ddot{u}(t))^2 dt}_{E_a}\right)^{1/2} \quad ; \quad v_{rs} = \left(\underbrace{\int_0^{t_{tot}} (\dot{u}(t))^2 dt}_{E_v}\right)^{1/2} \\ u_{rs} &= \left(\underbrace{\int_0^{t_{tot}} (u(t))^2 dt}_{E_d}\right)^{1/2} \end{aligned} \tag{6}$$

Arias Intensity, I_A, is a measure of dissipated energy per unit mass in an elasto-plastic system [30]

$$I_A(\xi) = \frac{\cos^{-1}\xi}{g\sqrt{1-\xi^2}}\int_0^{t_{tot}} (\ddot{u}(t))^2 dt \tag{7}$$

where ξ is the damping ratio of a structure and g the gravitational acceleration. In the standardized form, I_A with zero damping yields

$$I_A = \frac{\pi}{2g}\int_0^{t_{tot}} (\ddot{u}(t))^2 dt \tag{8}$$

Destructiveness Potential, Although the original (and standardized) I_A accounts for the ground motion peak and duration, the frequency characteristics are somehow neglected. [31] proposed a factor that measures the destructiveness potential, P_D, or capacity to induce structural damage.

$$P_D = \frac{I_A}{\upsilon_0^2} \tag{9}$$

where υ_0 is the number of zero-crossings occurrence of the ground motion record per unit time.