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Seismic fragility analysis of concrete dams: A state-of-the-art review

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ABSTRACT

Given the recent impetus for probabilistic based analyses of dams, and the limited previous attempts to address this timely question, there is a need for a comprehensive assessment of the disparate previous work. Hence, this paper provides a comprehensive and comparative review of major (over twenty) publications addressing seismic fragility analyses of concrete dams.

First, fundamental concepts are reviewed and clarified to facilitate comprehension of the later part. Then, papers are individually scrutinized, key figures redrawn to provide a uniform basis for comparison. When deemed necessary, additional clarifications and cross referencing with equations in the first part are provided.

Next, tables summarizing the various methods are presented, on the basis of which the authors provide a set of minimum requirements for seismic fragility curve/surface development. It is noted that the vast majority of the papers still relied on linear analyses with simplified limit states. On the other hands few papers pursued a nonlinear approach and addressed the collapse mechanism and/or hybrid limit state definitions.

Finally, the contextual framework within which fragility curves are used is presented within the scope of a performance based earthquake engineering analysis of a concrete dam.

1. Introduction

Dams, a most critical component of our energy generating infrastructure are aging and their deterioration levels are reaching critical values. Indeed the American Society of Civil Engineers (ASCE) 2013 report card for America's infrastructure [1] categorized the US dam hazards as (1) high (potentially causing loss of life), (2) significant (economic losses), (3) low, and (4) undetermined. About 14,700, 12,400, 59,000, and 1300 dams fall in each one of those four categories. The geographical distribution of the hazardous dams is shown in Fig. 1 and the number of high-hazard dam is reported to have increased by nearly 40% over the past decade [2]. The Association of State Dam Safety Officials (ASDSO) reports that by 2020, 70% of the US dams will be over 50 years old [3] and most of them are unlikely to safely withstand current design guidelines for potential maximum floods (PMF) and maximum credible earthquakes (MCE). Although few damages/failures have been reported for the concrete dams, Appendix A, this remains nevertheless a critical societal concern.

Furthermore, due to environmental constraints, few new dams are built, and older ones are expected to have a longer life

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Abbreviations: 2D, two-dimensional; 3D, three-dimensional; AD, Anderson-Darling test; AIC, Akaike information criterion; ASCE, American Society of Civil Engineers; ASDSO, Association of State Dam Safety Officials; ASI, acceleration spectral intensity; CDF, cumulative distribution function; CIA, cumulative inelastic area; CID, cumulative inelastic duration; CLA, cloud analysis; COV, coefficient of variation; CP, collapse prevention; CS, conditional spectrum; DBL, design base level; DC, damage control; DCR, demand capacity ratio; DI, damage index; DPM, damage probability matrix; DS, damage state; DSA, double stripe analysis; DSDR, damage spatial distribution ratio; EDP, engineering demand parameter; EIDA, extended incremental dynamic analysis; EPA, effective peak acceleration; ETA, endurance time analysis; ETAF, endurance time acceleration function; FEMA, Federal Emergency Management Agency; FFT, fast Fourier transform; FSI, fluid-structure interaction; FSS, factor of safety against sliding; GSI, geological strength index; H, horizontal; IDA, incremental dynamic analysis; IM, intensity measure; Lg, very large data; LHS, Latin hypercube sampling; LS, limit state; MCE, maximum credible earthquakes; MCS, Monte Carlo simulation; MDL, maximum design level; MLE, maximum likelihood estimation; MM, material/modeling uncertainty; MMI, modified Mercalli intensity; MOM, method of moments; MSA, multiple stripe analysis; NLg, no very large data; PBEE, performance based earthquake engineering; PBEE-2, second generation performance based earthquake engineering; PDF, probability density function; PFMA, potential failure mode analysis; PGA, peak ground acceleration; PGA^H, Horizontal peak ground acceleration; PGV, peak ground velocity; PMF, potential maximum floods; PSA, pseudo-spectral acceleration; PSDA, probabilistic seismic demand analysis; PSHA, probabilistic seismic hazard analysis; RV, random variable; S, serviceability; SED, specific energy density; SIL, seismic intensity level; SSA, single stripe analysis; SSE, sum of squared error; UHS, uniform hazard spectrum; V, vertical.

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Nomenclature

$\mathbf{a}$	vector of autocorrelated RVs with zero mean
a	linear regression constant in CLA
$a(\mathbf{x}_{conc})$	fluctuations around M_0
A_{acc}	Gaussian RV of the amplitude $X_{acc}(t)$
$A_{OS}^{\%}$	percentage of the overstressed area
A_C	cracked area on dam face
A_T	total area of dam face
b	linear regression constant in CLA
c	constant parameter in scattering of artificial ground motion
C	collapse
C_{LS}	capacity parameter associated with the given LS
d	correlation length for spatially random material
$\mathrm{d}\lambda_{\mathrm{IM}}(im)$	slope of the hazard curve
D	demand parameter
$\mathrm{DI}^{\mathrm{opening}}$	joint opening damage index
$\mathrm{DI}^{\mathrm{sliding}}$	joint sliding damage index
$\mathrm{DI}^{\mathrm{cracking}}$	crack-based damage index
edp	a specific (known) value of EDP
E_c	elasticity modulus in concrete
E_f	elasticity modulus in rock
E_K	absolute kinetic energy
E_D	viscous damping energy
E_R	nonlinear resorting work
E_P	work per seismic applied forces
E_Q	absolute seismic input energy
E_H	work done by hydrodynamic pressure
f_t	concrete tensile strength
f_c	concrete compressive strength
F_i^{-1}	inverse of the cumulative distribution function of the ith RV
$g_i(\mathbf{x},\mathbf{y})$	LS function for the ith component
$h(t)$	time-dependent deterministic (envelope) function
H_d	dam height
im	a specific (known) value of IM
I_A	arias intensity
$I(\mathbf{w}_j)$	indicator of safety or failure based on MCS
I_{C_j}	index set for the modes belonging to the jth cut-set
$\mathbf{L}$	lower triangular matrix obtained by Cholesky's decomposition of the covariance matrix
L_C	cracked length at the dam base
L_T	total length at the dam base
m_{DS}	downstream face slope of the dam
M_0	mean value of M_{conc}
M_{conc}	random concrete properties
(M_{bin}, R_{bin})	magnitude and distance associate with a bin
NT	arbitrary data points of artificial ground motion
N_{ele}	number of elements in the finite element mesh
N_{obs}	number of observations for curve fitting
N_{∞}	very large number for MCS
N_{sim}	total number of simulations
N_{fail}	total number of failed models
N_{RV}	number of (basic) random variables
N_{GM}	number of (scaled) ground motions
N_{WL}	number of pool elevations
N_{BSRV}	number of basic structural random parameters
N_C	number of cut-sets in failure evaluation
P_f	probability of failure
P_E	probability of occurrence of at least one earthquake during the life time
$P[A\vert B]$	conditional probability that A is true given that B is true
P_{LS}	limit state probability
R_{ck}	characteristics strength
$Resp$	response of the system
S_0	distance between each two points of spatially random material

$S_a(T)$	spectral acceleration at period T
$S_v(T)$	spectral velocity at period T
$S_d(T)$	spectral displacement at period T
$S_a(T,t)$	spectral acceleration at period T and time t of ETAF
$S_d(T,t)$	spectral displacement at period T and time t of ETAF
S_a^{1-to-N}	combined acceleration response spectra including the effective mass
t	time
t_{trg}	target time
t_{tot}	total duration of signal (ground motion)
trg	target value of the considered quantity
T_R	return period
$V_{M_{conc}}$	coefficient of variation of material property
$\mathbf{w}_j$	jth vector of the RVs
$\mathbf{x}$	structural uncertainty
$\mathbf{x}_{conc}$	position vector of M_{conc}
$\mathbf{x}_{conc\,i}$	coordinates of the element's center for the spatially random material
X	an uncertain random variable
$X_{acc}(t)$	artificially generated seismic excitation using a non-stationary stochastic process
$\mathbf{y}$	randomness of the external actions
$\mathbf{Z}$	a vector containing N_{ele} uncorrelated Gaussian RV
β	logarithmic standard deviation (dispersion)
$\hat{\beta}$	estimated standard deviation value
β_{com}	logarithmic standard deviation due to combined uncertainties
β_{RTR}	logarithmic standard deviation due to only ground motion record-to-record variability
β_{MM}	logarithmic standard deviation due to material/modeling uncertainty
$\delta^{\mathrm{opening}}$	joint opening displacement
$\delta^{\mathrm{sliding}}$	joint sliding displacement
ε_{δ}	error term in drift capacity model
ε_f	error term in capacity model for interface joint tensile strength
ε_C	errors associate with capacity model
η	median of the fragility function
$\hat{\eta}$	estimated median value
η_{RTR}	median of the fragility function due to only ground motion record-to-record variability
η_{com}	median of the fragility function due to combined uncertainties
θ_{SF}	generic safety factor
κ	shape parameter of Weibull distribution
λ	scale parameter of Weibull distribution
λ_0	scale factor of artificial ground motion
λ_{IM}	annual rate of ground motion exceedance
λ_{LS}	mean annual frequency of exceeding a specific limit state
$\pi_i(N_{sim})$	random permutation of N_{sim}
$\sigma_{t,D}$	tensile normal stress demand
$\sigma_{t,C}$	tensile normal stress capacity
τ_D	tangential stress demand
τ_C	tangential stress capacity
ϕ_n	phase angles in the interval $[0,2\pi]$
Φ	standard normal CDF
ω_n	equally spaced frequencies at the interval $[0,\omega_u]$
ω_u	maximum excitation frequency of artificial ground motion
$\vert$	condition event symbol (given)
$\bigcap$	intersect symbol
$\bigcup$	union symbol
$\in$	membership symbol