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Evaluation of the Ground Motion Scaling Procedures for Concrete Gravity Dams

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Abstract

The seismic safety of dam structures is often evaluated using time history analyses conducted with a limited number of ground motions. The selection and scaling of the ground motions is usually the most effective factor determining the results of the safety assessment. The inherent variability in the ground motion as well as the difficulty of conducting the analyses for a large number of ground motions renders the selection as the most important factor in the analysis results. The guidelines for the nonlinear transient analyses of buildings, such as the one presented in ASCE/SEI-7-10, are well studied. For dams, however, it is not clear how the selection and scaling of the accelerograms should be conducted with the goals of a) consistency b) reliability and the c) practicality of the analyses. In this context, consistency implies obtaining consistent results for the same problem, reliability implies a reduction in the variability in the results while practicality implies the completion of the process with lesser effort. The selection and scaling of the ground motions for use in the nonlinear seismic analysis of the concrete gravity dams was investigated in this study with the aforementioned goals focused on the efficient prediction of the seismic demands on these structures. Three different concrete gravity dam monoliths were selected for this purpose, using 15 selected ground motions for the appropriate local site conditions. The material nonlinearity, dam-reservoir interaction and vertical component of ground motions were considered in the analyses. The engineering demand parameters were selected as the crest displacement, the maximum crest acceleration and the crack extent, a direct indicator of the damage on the monoliths. Nine different scaling methods were investigated. The effectiveness in the prediction of the mean demand and the corresponding dispersion levels were compared. The required number of motions to conduct effective analyses was determined.

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1. Introduction

The selection and scaling of accelerograms is one of the most important issues in earthquake engineering as the ground motion records are widely used in the design and evaluation of structures by engineers replacing the response spectrum based static analyses. The choice and the possible combinations of the ground motions add a significant layer of uncertainty on the prediction of the response of a structural system which can hardly be addressed by trial and error methods even using today's powerful computers. As such, well-established and documented methods are necessary for the selection and scaling of the accelerograms in order to better estimate the nonlinear structural response of a structure for an expected hazard by using real earthquake records.

Concrete gravity dams are very important structures as the failure comprises a great risk to the society both in terms of life safety and economic consequences. The design and evaluation of these systems for seismic hazards is increasingly conducted using time history analyses given the need for the accurate prediction of the performance level of the existing dam inventory as well as the new systems. The primary structural damage on these systems is in the form of tensile cracking, which initiates on the downstream and the upstream slopes of the monolith propagating towards the other side [1]. The specific nature of the loading is very important regarding the propagation of the cracking on the unreinforced concrete [2]. Thus, for both evaluation and design, the ground motion selection is a very important part of the process. The primary goal of this study, in this context, is to investigate the performance of different ground motion scaling procedures for the nonlinear time history analyses of concrete gravity monoliths with a focus on the accurate and effective prediction of the damage states on these systems. The performance of the scaling procedures were investigated by conducting seismic hazard analyses for a dam site. Sets of motions naturally matching these target levels were treated as benchmark sets in order to determine the target EDP levels. The performance of the scaling procedures, conducted using ground motion time histories (GMTH) different than the benchmark set, was quantified in terms of their proximity to the design goals in terms of the mean values of the EDPs, along with the consideration of the variances as indicators of the reliability and repeatability of the procedure.

2. The Selection and Scaling of the Ground Motion Records

2.1. Site Specific Hazard Analysis and Target Response Spectrum

For the design or evaluation of a structural system for seismic hazards, the earthquake records are recommended to be selected in a close cooperation with seismologists using site-specific hazard analyses for determining the suite of ground motions to be used in the transient analyses [3]. In this context, the probabilistic seismic hazard analysis (PSHA) of a site located near the eastern İstanbul suburban area, in Turkey, was conducted. The 975-years return period was used for this site and the deaggregation of the hazard at this site yielded a moment magnitude of 7.1 and a source-to-site distance of 35 km. Accordingly, conditional spectrum (CS) was derived by using the hazard and corresponding deaggregation information and used as the target in the selection and scaling of ground motion records. The conditional mean spectrum (red solid line) and its variance (red dotted line) is presented in Fig. 1a.

2.2. Selection of Benchmark Set, Comparison Set and Scaling Procedures

The unscaled records in this study was gathered from the PEER NGA-West2 (http://ngawest2.berkeley.edu) ground motion database [4]. The records were selected using each horizontal component individually and in the simulations the vertical component of the ground motions were taken into account [5]. The benchmark set was composed of 15 unscaled ground motions obtained by following the procedure proposed by [6]. The spectra of the selected records (gray lines), their median (black solid line) and variance (black dotted line) are compared with the target CS in Fig. 1a.

In order to identify the records to be used to compare different scaling methodologies, the records used for the benchmark analyses were excluded and a different ground motion suite of 15 records were selected according to [6]. The selected records, their moment magnitude (M_W), R_{JB} distance and V_{S30} information of the selected records in the benchmark and comparison sets are given in Table 1.

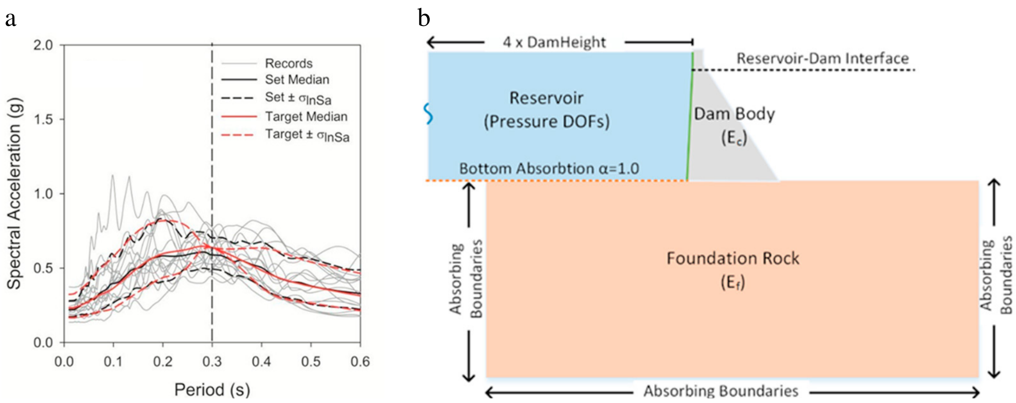


Fig. 1. (a) Acceleration spectra of the benchmark records, their mean and variance compared with the target conditional spectrum (b) Analytical model for the dam-reservoir-foundation system

Table 1. M_W, R_{JB} and V_{S30} for the benchmark and comparison sets

Benchmark Set	M_W	R_{JB} (km)	V_{S30} (m/s)	Comparison Set	M_W	R_{JB} (km)	V_{S30} (m/s)
RSN80_H2	6.6	21.5	969	RSN291_H1	6.9	27.5	575
RSN587_H1	6.6	16.1	551	RSN810_H1	6.9	12.0	714
RSN989_H1	6.7	9.9	740	RSN1613_H2	7.1	25.8	782
RSN1058_H1	6.7	36.6	528	RSN1619_H1	7.1	34.3	535
RSN1618_H1	7.1	8.0	638	RSN1795_H1	7.1	50.4	686
RSN3943_H2	6.6	9.1	617	RSN1795_H2	7.1	50.4	686
RSN3954_H2	6.6	15.6	967	RSN4846_H1	6.8	28.1	606
RSN4455_H1	7.1	23.6	585	RSN4858_H1	6.8	25.4	640
RSN4843_H1	6.8	18.2	640	RSN4872_H2	6.8	21.2	640
RSN4852_H1	6.8	30.3	606	RSN4887_H2	6.8	36.6	562
RSN4865_H2	6.8	5.0	562	RSN5779_H1	6.9	36.3	540
RSN4870_H1	6.8	29.9	562	RSN5779_H2	6.9	36.3	540
RSN5478_H2	6.9	11.7	556	RSN5804_H1	6.9	25.6	562
RSN5618_H1	6.9	16.3	826	RSN5806_H1	6.9	22.4	655
RSN5809_H2	6.9	17.3	655	RSN6949_H1	7.0	52.1	551

In this study, the effectiveness of nine different ground motion scaling procedures was investigated, namely 1) scaling to the acceleration value of the conditional spectrum at conditioning period (SS) [7] 2) scaling to the acceleration spectrum intensity (ASI) [8] 3) scaling to the effective peak acceleration (EPA) [9] 4) scaling to the improved effective peak acceleration (IEPA) [10] 5) scaling to the peak acceleration value (PGA) [11] 6) scaling to the geometric mean of maximum incremental velocity (MIV) [12] 7) scaling to the geometric mean of a pre-defined intensity measure (IM) [1] 8) scaling according to the ASCE/SEI-7-10 specifications (ASCE) [13] 9) non-stationary spectral matching (RSPM) [14].

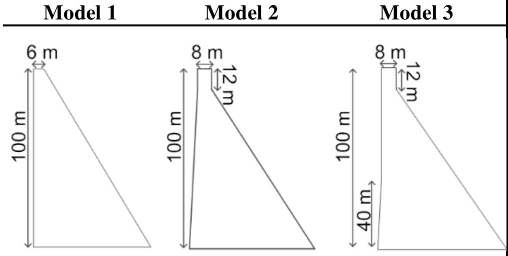
The crest displacement and acceleration and the cracked area ratio were chosen as the representative response parameters for the concrete gravity dams in this study. The last of these demand measures, the cracked area ratio, represents an index for the quantification of the damage level on the system [1]. The selected geometries, given below, were subjected to both directions of ground motions (horizontal and vertical) and nonlinear transient time history analyses were conducted to compare the scaling methodologies.

3. Nonlinear Transient Analysis of Concrete Gravity Dams

3.1. Analysis Models

The general purpose finite element software, DIANA [15] was used to simulate the dam-reservoir-foundation system behavior. The analyses were conducted for three different 100m tall monoliths with similar cross-sectional areas. The geometric and material properties of the models are presented in Table 2.

Table 2. Geometric and material properties of the models



Geometric Properties	Model 1	Model 2	Model 3
Height(m)	100	100	100
U/S Slope	Vertical	1V/0.05H	1V/0.05H
D/S Slope	1V/0.6H	1V/0.65H	1V/0.7H
T_n(sec)	0.32	0.30	0.31
Material Properties	**Structure**	**Foundation**	
Young's Modulus (GPa)	31	62	
Poisson's ratio	0.2	0.3	
Density (kg/m^3)	2400	2500	
Stiff. Prop. Damp. Coeff.	0.00125	0.008	

3.2. Analysis Results

In order to evaluate the scaling procedures, 450 nonlinear transient analyses were performed for the three different dam monoliths. Firstly, the benchmark set (unscaled) analyses were conducted followed by the comparison set analyses using the nine aforementioned scaling techniques. For each model, the engineering demand parameters, namely the maximum crest displacement and acceleration and the ratio of the cracked area to the total area of the monolith were obtained. In order to simplify the interpretation, the displacements were normalized by the dam height. The results from the sets were compared to the benchmark results using the median values ($\bar{x}$) and the dispersion measures (δ) [16]:

$$\bar{x} = exp\left(\frac{\sum_{i=1}^{n} \ln x_i}{n}\right) \qquad \delta = exp\left(\frac{\sum_{i=1}^{n} (\ln x_i - \ln \bar{x})^2}{n-1}\right)^{1/2}$$

where x_i is the value of the EDPs and n is the number of observations, which is 15 for this study.

The mean value of the results obtained from each scaled motion set should be in line with the mean value of the unscaled benchmark. One of the aims of the scaling procedure is the reduction of the dispersion of the results: it should not be forgotten that an accurate mean prediction with a large dispersion would imply that a significant number of ground motions will have to be included in a given set in order to ascertain the consistency among possible motion sets.

The mean and dispersion values of the EDPs obtained from the suites scaled with different procedures are presented in Table 3. The results are presented separately for the different monoliths. The benchmark values are reported directly in the table. The relative differences of the mean and the dispersion value from the benchmark quantity calculated as $\varepsilon_{EDP} = (x_{scaled} - x_{bm})/x_{bm}$ were calculated for directly assessing the performance of the scaling procedure. It should be noted that when the percent relative difference was a positive value, the results of the scaled sets were higher and when it was negative, the results were lower than the benchmark value.

Except for model 1, the normalized crest displacement was generally predicted higher by the scaled sets compared to the unscaled benchmarks values. The results were within -20 to 15% of the benchmark displacement values. The ASCE and IEPA scaling yielded the highest estimates. The dispersion for the scaled sets were generally similar to the benchmark set, with perhaps the only meaningful reduction obtained with the spectral matching technique.

The mean values of the crest acceleration EDPs from the scaled ground motions are within +15 to -10% of the benchmark results. In general, the mean EDP was predicted higher compared to the benchmark analyses (Table 3). The results from the ASCE and IEPA scaling were considerably higher than the benchmark results. On the other hand, the RSPM and ASI scaling yielded close estimates for the benchmark results. The reduction in the dispersion was utmost 15% for the scaling methods. The most significant reduction was obtained using the RSPM, EPA and ASI scaling. Compared to the models 2 and 3, the dispersion in the estimate was reduced more for the model 1.

The mean and dispersion values of the total cracked area on the monolith obtained from the ground motion suite scaled with the different procedures are presented in Table 3. The results obtained from the scaled suites were generally larger than their counterparts obtained from the original ground motion suite. Notably, the ASCE scaling yielded significantly higher damage area ratios (as much as 50% over the benchmark) compared to the other scaling techniques. The MIV and RSPM scaling on the other hand yielded predictions on the downside of the benchmark. The mean crack area ratio predicted from the MIV scaling was as much as 40% lower than the benchmark value. The dispersion was increased compared to the benchmark set after scaling with MIV technique. Scaling with this procedure increased the variability in the results in comparison to the unscaled, raw ground motions.

Table 3. The mean and dispersion of the EDPs for the different scaling procedures

	Mean Values ($\bar{x}$)									Dispersion Values ($\boldsymbol{\delta}$)								
	Norm. Crest Disp. (Δ_{crest}/H (%))			Crest Acceleration (m/s^2)			Total Cracked Area Ratio (%)			Norm. Crest Disp. (Δ_{crest}/H (%))			Crest Acceleration (m/s^2)			Total Cracked Area Ratio (%)		
	M1	M2	M3	M1	M2	M3	M1	M2	M3	M1	M2	M3	M1	M2	M3	M1	M2	M3
Bench.	0.031	0.034	0.034	15.115	17.105	17.479	2.216	2.548	2.876	1.670	1.684	1.695	2.011	1.757	1.741	2.130	2.140	2.040
% Relative Difference from Benchmark, Mean and Dispersion Measure																		
RSPM	-11.9	3.0	2.9	-2.3	-2.3	-3.3	-4.5	-3.8	2.4	-5.4	-4.6	-4.4	-12.7	-10.0	-12.6	-37.8	-28.5	-27.0
ASCE	-6.7	13.0	14.0	13.1	10.8	6.3	16.7	51.7	49.2	-1.0	0.9	2.5	-13.9	-5.6	-11.3	-17.7	-23.4	-24.1
MIV	-19.5	-6.5	-6.9	-3.7	-3.2	-8.1	-32.1	-32.6	-38.5	13.8	19.0	17.4	6.4	13.0	7.0	64.8	71.6	74.3
IM	-17.1	-1.8	14.0	-1.1	-2.2	6.3	-27.1	-17.9	49.2	-4.1	-2.1	2.5	-11.0	-6.1	-11.3	-30.5	-30.7	-24.1
SS	-12.4	4.8	5.9	6.2	4.8	3.3	-8.6	13.5	17.2	-0.7	0.9	2.2	-4.5	-2.7	-5.5	-22.8	-17.5	-15.5
EPA	-14.1	2.9	2.3	3.0	1.7	-2.5	-14.8	-0.3	1.4	-0.7	0.4	0.7	-12.3	-7.9	-10.6	-16.3	-18.4	-16.0
IEPA	-7.6	9.7	10.8	10.6	10.4	7.6	11.3	36.9	36.8	-2.1	3.1	4.1	-10.4	-2.1	-4.8	-21.7	-21.7	-20.2
PGA	-10.7	8.6	8.5	8.4	8.4	4.7	1.8	31.6	30.4	1.8	3.6	4.1	-12.9	-5.0	-9.7	-3.8	-13.4	-18.5
ASI	13.2	4.7	4.0	4.1	3.3	-2.1	-10.4	8.1	5.8	0.6	0.6	1.2	-12.4	-8.4	-13.3	-16.2	-15.7	-16.2

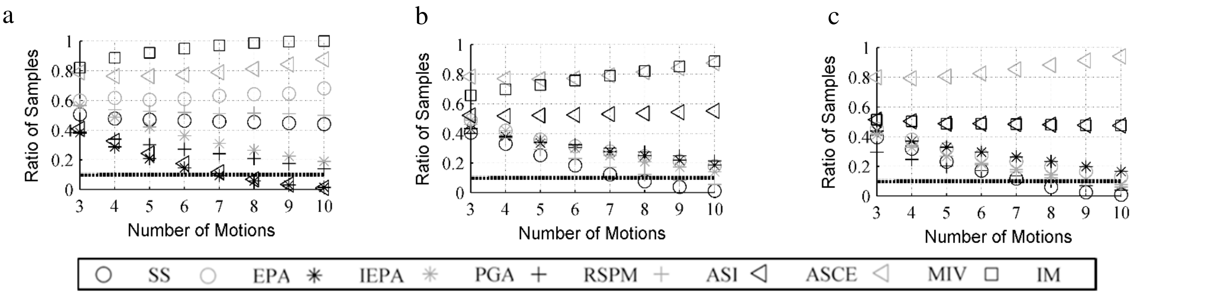


Fig. 2. Probability of the mean cracked area ratio of the sample set ≤ benchmark meanx0.9 or ≥ benchmark meanx1.5 (a) M1 (b) M2 (c) M3

The number of motions that can be used to predict the mean response reasonably well is often a very important question in a design process. Considering the sizes and the associated computational load with the nonlinear dynamic analyses, engineers would want to work with as small a ground motion set as possible. However, the reduction of the number of motions in a ground motion set is strongly dependent on the particular scaling technique's efficiency for reducing the variance in the desired EDP. In order to study this effectiveness, the ability of the chosen sets to adequately predict the benchmark mean was investigated. For the complete sample of sets that could be formed using "n" number of motions out of the 15 original, the sample statistics of the mean were compiled. "Adequate" prediction was chosen in line with the design process: i.e. the percentage of the sample results outside an acceptable bound around the mean was calculated. Prediction of a (mean) EDP lower than 90% and higher than 150% of the benchmark mean was assumed as unacceptable. Obtained henceforth, the percentage of the unacceptable ground motion sets for each scaling procedure is presented for the cracked area ratio EDP in Fig. 2. The large variance in the prediction of this EDP, even after the scaling of the ground motions is clearly observed. For the first model, ASCE, IEPA and RSPM scaling were effective. For the models 2 and 3, the stripe scaling (SS) was more effective although scaling to the ASI was almost as successful. Scaling to the IEPA can also be considered reasonably effective for these models.

4. Conclusions

In this study, the use of different ground motion scaling methods for the seismic assessment of concrete gravity dams were investigated from the perspective of accuracy and efficiency in the prediction of the performance levels of the systems. The following conclusions can be drawn based on the results of this study:

- The crest acceleration and the normalized displacement at the crest were relatively accurately predicted by the scaled set within 10% of the benchmark, almost regardless of the technique. In other words, the mean values from the scaled sets were reasonably near the mean levels for the benchmark set with the unscaled motions. However significant discrepancy between the benchmark mean and the damage level predicted using the scaled set was observed for some of the scaling techniques. The worst predictions on the lower and higher sides of the benchmark was obtained by the MIV and ASCE scaling, respectively. The deviation with respect to the benchmark mean were varying for the other scaling techniques.
- For predicting the performance of concrete gravity dam monoliths, scaling to the improved effective peak acceleration (IEPA) and the acceleration spectrum intensity (ASI) values stand out among the various choices as the most effective procedures working for the majority of the cases considered.
- The required number of ground motions for an effective prediction of the damage level resulted higher than the 7 motions commonly suggested for this goal. From 8 to 10 GMTHs should be selected in order to obtain a close or a reasonably conservative estimate of the design goal.

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