BETON AĞIRLIK BARAJLARININ DOĞRUSAL OLMAYAN SİSMİK ANALİZLERİNDE KULLANILAN YER HAREKETİ SEÇME VE ÖLÇEKLEME TEKNİKLERİNİN İNCELENMESİ

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ÖZET:

Beton ağırlık barajları için güvenlik tahkiki sırasında güvenliği belirleyen en önemli etmenler yer hareketi seçimi ve ölçeklemesi olmaktadır. Binaların doğrusal olmayan zaman aşımı analizleri için kullanılan ASCE/SEI-7-10 yöntemi gibi prosedürler barajlar için de takip edilmektedir. Bina türü yapılar için bu yöntemler detaylı bir şekilde incelenmiş olsa da, yöntemlerin etkinliği ve doğruluğu baraj tipi yapılar için incelenmemiştir. Bu çalışmada beton ağırlık barajlarındaki sismik istem değerlerinin etkin bulunması amacı ile barajların zaman aşımlı doğrusal olmayan analizlerinde kullanılan seçme ve ölçeklendirme yöntemleri incelenmiştir. Çok kullanılan bir geometriye sahip bir baraj monoliti için ölçekleme yöntemleri yerel koşullara uygun olarak seçilmiş 15 yer hareketi kullanılarak karşılaştırılmıştır. Malzemenin doğrusal olmayan özellikleri, baraj-rezervuar etkileşimi ve yer hareketlerinin dikey bileşenleri analizlere dahil edilmiştir. Sismik istemleri belirlemek için maksimum kret deplasmanı, maksimum kret ivmesi ve bu tip sistemler için hasar indikatörü olarak sıklıkla kullanılan çatlama miktarı mühendislik istem parametreleri olarak kullanılmıştır. Sıklıkla kullanılan dokuz değişik ölçekleme yöntemi incelenmiş, bu yöntemlerin ortalama istem değerlerini öngörmedeki etkinliği ve buna bağlı olarak gösterdikleri yayılım karşılaştırılmıştır. Efektif analiz için kullanılması gereken yer hareketi serisi sayısı belirlenmiştir.

ANAHTAR KELİMELER: Yer hareketi seçimi, yer hareketi ölçeklemesi, doğrusal olmayan analiz, beton ağırlık barajı, hasar seviyesi

EVALUATION OF MOTION SELECTION AND SCALING FOR THE NONLINEAR SEISMIC ANALYSIS OF CONCRETE GRAVITY DAMS

ABSTRACT:

The selection and scaling of the ground motions is usually the most effective factor determining the results of the safety assessment for concrete gravity dams. The guidelines for the nonlinear transient analyses of buildings, such as the one presented in ASCE/SEI-7-10, are generally applied to these structures. While these procedures are well-studied for the moment frames, their effectiveness and consistency has not been studied for gravity dam structures. 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 a focus on the efficient prediction of the seismic demands on these structures. For a gravity dam monolith, 15 ground motions were used to evaluate the scaling procedures selected considering the local site conditions. The material nonlinearity, dam-reservoir interaction and vertical component of ground motions were considered in the analyses. The engineering demand parameters to quantify the seismic demands were selected as the crest displacement, the maximum crest acceleration and the crack extent, a direct indicator of the damage on the monoliths. In total, nine different commonly applied 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.

KEYWORDS: Ground motion selection, ground motion scaling, nonlinear analysis, concrete gravity dam, damage level

1. INTRODUCTION

The selection and scaling of ground motions is one of the most important issues in earthquake engineering as the ground motion records are widely being used in the design and evaluation of structures by engineers. The choice and the possible combinations of the accelerograms add a significant layer of uncertainty on the prediction of the response of a structural system. Therefore, 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 since the failure comprises a great risk to the society both in terms of life safety and economic consequences. 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 (Soysal et al., 2016). The propagation of the cracking on the unreinforced concrete is dependent ın the specific nature of the loading (Tinawi et al., 2000). Therefore, the ground motion section is very important for the design and evaluation of these systems for seismic hazards. In this study, the performance of different ground motion scaling procedures for the nonlinear time history analyses of concrete gravity dams is investigated. For a specific dam site, seismic hazard analysis was conducted and 15 ground motions that naturally fit the target level was treated as the benchmark set so as to determine the target engineering demand parameter (EDP) levels. The performance of the scaling procedures was evaluated with respect to the mean values and variances of EDPs, using ground motions different than the benchmark set.

2. SITE-SPECIFIC HAZARD ANALYSIS, SELECTION AND SCALING OF THE GROUND MOTION RECORDS

USACE (2003) recommends that for the design or evaluation of a structural system for seismic hazards, the earthquake records should be selected from the events whose magnitude, distance and type of faulting comply with the maximum earthquake considered at the site. Similarly, USBR (2013) suggests the use of time histories that physically represents the ground motion scenarios. Therefore, to determine the suite of ground motions to be used in the transient analyses, cooperation with seismologists is recommended to use site-specific hazard analyses.

The dam site, located around Erzurum was selected and probabilistic seismic hazard analysis (PSHA) was conducted. The hazard level of 475-years return period was used and the deaggregation yielded a moment magnitude of 5.6 and a source-to-site distance of 12 km. Accordingly, the 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 Figure 1.

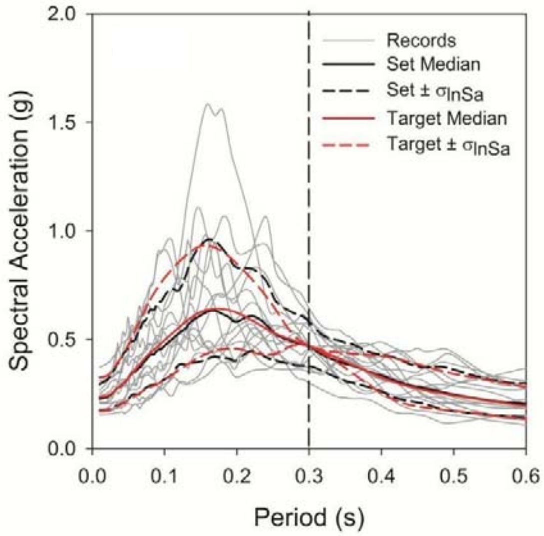


Figure 1. Acceleration spectra of the benchmark records, their mean and variance compared with the target conditional spectrum

In this study, the unscaled records were gathered from the PEER NGA-West2 (http://ngawest2.berkeley.edu) ground-motion database. The benchmark ground motion time history set that contained 15 unscaled horizontal acceleration time-series was obtained following the procedure proposed by Jayaram et al. (2011) and their vertical components were taken into account in the nonlinear analyses. 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 Figure 1.

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 Jayaram et al. (2011). 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 presented in Table 1.

In this study, nine different ground motion scaling procedures was investigated, namely 1) scaling to the acceleration value of the conditional spectrum at conditioning period (SS) 2) scaling to the acceleration spectrum intensity (ASI) 3) scaling to the effective peak acceleration (EPA) 4) scaling to the improved effective peak acceleration (EPA) 5) scaling to the peak ground acceleration value (PGA) 6) scaling to the geometric mean of maximum incremental velocity (MIV) 7) scaling to the geometric mean of a pre-defined intensity measure (IM) 8) scaling according to ASCE/SEI-7-10 specifications (ASCE, 2010) (ASCE) 9) non-stationary spectral matching (RSPM).

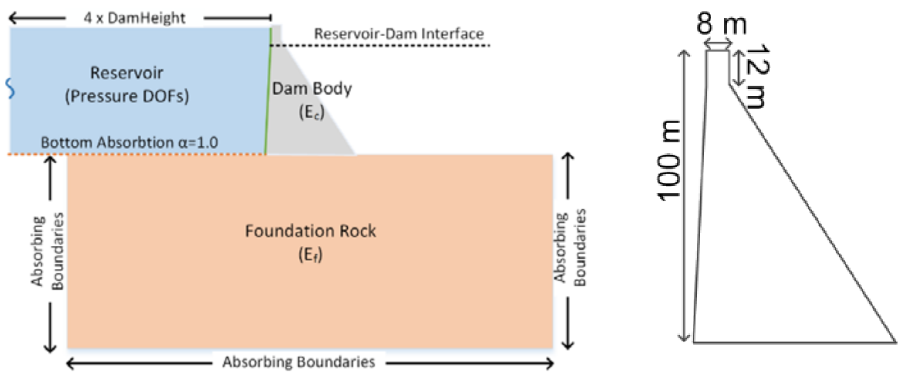
Table 1. M_W, R_{JB} and V_{S30} for the benchmark and comparison sets

Benchmark Set	M_W	R_{JB} (km)	V_{S30} (m/s)	Comparison Set	M_W	R_{JB} (km)	V_{S30} (m/s)
RSN707_H2	5.3	3.6	550	RSN45_H2	5.3	18.4	667
RSN769_H2	6.9	17.9	663	RSN414_H1	5.8	9.8	617
RSN809_H1	6.9	12.2	714	RSN501_H1	5.5	11.2	609
RSN954_H2	6.7	19.1	550	RSN1642_H1	5.6	17.8	680
RSN957_H2	6.7	15.9	582	RSN1642_H2	5.6	17.8	680
RSN1020_H1	6.7	20.8	602	RSN1649_H2	5.6	37.6	996
RSN1023_H2	6.7	24.9	671	RSN2385_H2	5.9	20.1	625
RSN1126_H1	6.4	14.1	650	RSN4278_H1	5.5	11.9	650
RSN1645_H2	5.6	2.6	680	RSN4278_H2	5.5	11.9	650
RSN2622_H1	6.2	15.0	625	RSN4312_H2	5.6	14.7	922
RSN4064_H2	6.0	4.3	657	RSN4369_H1	5.5	11.7	694
RSN4083_H1	6.0	4.7	907	RSN4509_H1	5.6	11.1	685
RSN4852_H1	6.8	30.3	606	RSN4509_H2	5.6	11.1	685
RSN4865_H1	6.8	5.0	562	RSN4513_H1	5.6	5.1	717
RSN5618_H2	6.9	16.3	826	RSN4513_H2	5.6	5.1	717

3. NONLINEAR TRANSIENT ANALYSIS OF A CONCRETE GRAVITY DAM

3.1. Analysis Model

In order to simulate the dam-reservoir-foundation system (Figure 2a) behavior, the general purpose finite element software named DIANA (DIANA, 2014) was used in this study. The analyses were conducted for a 100m tall dam monolith. The upstream and downstream slopes of which were 0.05V/1H and 1H/0.65V respectively, introducing discontinuity points at the "neck" of the structure (Figure 2b). The modulus of elasticity of the dam body and the foundation was assumed as 31 GPa and 61 GPa, respectively. A fracture energy of 140 N/m was used in accordance with the tensile strength of the concrete, which was assumed as 1.95MPa. The compressive strength of concrete was assumed as 20 MPa. The exponential and parabolic functional forms of softening were used for the tensile and compressive unloading branches, respectively.



(a) (b)

Figure 2. (a) Analytical model for the dam-reservoir-foundation system (b) Cross-section of the monolith

The crest displacement and acceleration and the cracked area ratio were chosen as the EDPs for the concrete gravity dam in this study. The cracked area ratio represents an index for the quantification of the damage level on the system (Soysal et al., 2016). The presented dam monolith, were subjected to both directions of ground motions (horizontal and vertical) and nonlinear transient time history analyses were conducted to compare the scaling methodologies.

3.2. Analysis Results

In order to assess the ground motion time history scaling procedures, 165 nonlinear time history analyses were performed. The first set of analyses were conducted with the unscaled benchmark sets followed by the comparison set analyses using nine different scaling procedures. The EDPs were obtained and the results from the sets were compared to the benchmark results using the median values ($\bar{x}$) and the dispersion measures (δ) as given below (Kalkan and Chopra, 2011). In order to simplify the interpretation, the displacements were normalized by the dam height.

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

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

Dam monoliths are not built with symmetric cross-sections, unlike moment frame structures. Furthermore, due to the hydrostatic forces one side of the cross-section is already under significant distress. Given the asymmetrical resistance of the section for loading in the downstream and the upstream direction (Soysal et al., 2016), for obtaining the benchmark results, the effect of ground motion direction on the response was considered. The unscaled motions were first applied on the dam from the upstream direction to the downstream direction. The same unscaled motions were then applied from the downstream direction to the upstream direction of the dam. The mean and standard deviation values for the chosen EDPs are shown in Table 2. Comparison of the mean ($\bar{x}$) values of the EDPs for the motions applied in opposite directions shows that the effect of ground motion direction was not very significant for the acceleration and displacement EDPs. The relative difference among two sets was limited to 2%. However, there were significant difference among the cracked area ratio for the two sets. The crack area ratio for the negative direction of the motion was around 25% larger compared to the positive direction.

Table 2. The mean and dispersion for the EDPs from benchmark set

	Max. Acc. (m/s^2)		**Norm. Max. Disp. (%)**		**Cracked Area (%)**	
	$\bar{x}$	**δ**	$\bar{x}$	**δ**	$\bar{x}$	**δ**
(+) loading	27.12	1.30	0.046	1.16	1.10	2.56
(-) loading	27.85	1.31	0.048	1.18	1.38	2.02

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 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.

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

	Mean Values ($\bar{x}$)			**Dispersion Values (δ)**		
	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 (%)**
Benchmark	0.036	16.823	1.096	1.735	1.751	2.557
% Relative Difference from Benchmark, Mean and Dispersion Measure						
SS	11.7	14.1	36.4	5.6	5.1	0.9
ASI	9.1	10.1	8.6	-1.7	-5.4	-15.1
EPA	13.6	13.9	35.1	2.5	-3.6	-11.4
IEPA	10.6	11.9	2.2	4.6	-7.2	-0.9
PGA	11.7	8.0	22.6	17.5	-5.4	49.2
MIV	3.4	0.2	-8.3	20.3	13.8	61.6
IM	10.0	9.6	27.4	2.6	-2.3	-3.4
ASCE	19.5	20.2	69.7	3.8	-3.7	-7.2
RSPM	9.0	3.8	-34.1	-5.0	-9.6	-30.9

The normalized crest displacement was generally predicted higher by the scaled sets compared to the unscaled benchmarks values. The results were within 3% to 20% of the benchmark displacement values. The EPA and ASCE scaling yielded the highest estimates. The only meaningful reduction in the dispersion was obtained with the spectral matching technique. The mean values of the crest acceleration EDPs from the scaled ground motions are within 1% to 20% of the benchmark results. The mean EDP was predicted higher compared to the benchmark analyses (Table 3). The results from the ASCE scaling was considerably higher than the benchmark results. On the other hand, the MIV scaling yielded close estimate for the benchmark results. The reduction in the dispersion was utmost 10% for the scaling methods obtained using the RSPM scaling. The results obtained for the total cracked area ratio 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 70% over the benchmark) compared to the other scaling techniques. The SS yielded high predictions as well. 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 RSPM scaling was as much as 34% lower than the benchmark value. The RSPM scaling reduced the dispersion by as much as 30%. Generally, the dispersion were reduced by scaling; however, for MIV scaling the dispersion was even increased by 62% compared to the benchmark set after the scaling.

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 Figure 3. The large variance in the prediction of this EDP, even after the scaling of the ground motions is clearly observed. For the dam model, ASI scaling appears to be the most effective technique.

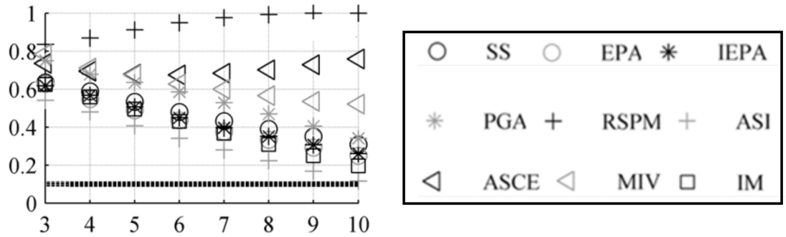


Figure 3. Probability of the mean cracked area ratio of the sample set ≤ benchmark meanx0.9 or ≥ benchmark meanx1.5

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 15% 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 RSPM 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 acceleration spectrum intensity (ASI) and maximum incremental velocity (MIV) 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. More than 10 ground motion time histories should be selected in order to obtain a close or a reasonably conservative estimate of the design goal.

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