May 24th - May 29th

The Effect of Earthquake Record Scaling Technique on Embankment Dam Response

Hamid Karimian
BGC Engineering Inc., Canada

Somasundaram Sriskandakumar
BGC Engineering Inc., Canada

Adrian Wightman
BGC Engineering Inc., Canada

Li Yan
BC Hydro, Canada

Fifth International Conference on
Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics
and Symposium in Honor of Professor I.M. Idriss
May 24-29, 2010 • San Diego, California

THE EFFECT OF EARTHQUAKE RECORD SCALING TECHNIQUE ON EMBANKMENT DAM RESPONSE

Hamid Karimian
BGC Engineering Inc.
Vancouver, BC, CANADA

Somasundaram Sriskandakumar
BGC Engineering Inc.
Vancouver, BC, CANADA

Adrian Wightman
BGC Engineering Inc.
Vancouver, BC, CANADA

Li Yan
BC Hydro
Burnaby, BC, CANADA

ABSTRACT

The state of the practice in dynamic analysis of structures includes the selection of earthquake records based on the mean (or modal) magnitude and distance of the design earthquake, and linearly scaling of the selected records to the target spectral acceleration at the period of significance, or matching the selected records to the uniform hazard response spectrum (UHRS).

A method is presented by Baker and Cornell (2005, 2006a, and 2006b) to develop the conditional mean response spectrum of a ground motion given a target value of the spectral acceleration at the period (or period range) of significance. The shape of the spectrum is dependent on the epsilon value, where epsilon is the number of standard deviations needed for a ground motion prediction equation to return the target value of spectral acceleration. The result is referred to as the conditional mean spectrum considering epsilon (CMS-ε). The developed response spectrum falls below the UHRS at periods other than the period of significance, and is a more appropriate target for earthquake record selection and scaling. This method also provides a means for multi-component ground motion scaling (Baker and Cornell, 2006a and Abrahamson, 2006).

This method was implemented to develop period-specific scenario target spectra for use in the safety assessment of one of BC Hydro's embankment dams on Vancouver Island, British Columbia, Canada. Earthquake records were selected and matched to the developed target spectrum using CMS-ε technique. Dynamic analyses were performed using the records spectrally matched to the CMS-ε target spectrum to evaluate the performance of the dam and to assess the applied load on the wall of the powerhouse downstream of the dam shell. The analyses were re-run using records linearly scaled to the UHRS at the period of interest and also using the records spectrally matched to the entire UHRS. All the analyses were run with and without applying the vertical ground motion excitation. This paper compares the results of the dynamic analyses using the three methods of ground motion record scaling and the effect of vertical ground motion on the results.

INTRODUCTION

To provide guidance for selection of ground motion time histories for the dynamic analysis of structures, site-specific response spectra can be generated by means of a deterministic seismic hazard analysis (DSHA) or a probabilistic seismic hazard analysis (PSHA). Due to its comprehensive nature, there is a greater tendency to use PSHA to develop site specific response spectra. The response spectrum developed from a PSHA is referred to as Uniform Hazard Response Spectrum (UHRS) because there is an equal probability of exceeding the spectral value of ground motion at each period. Since the hazard is computed independently for each spectral period, a uniform hazard spectrum does not represent the spectrum of any single earthquake.

Selection of appropriate time histories is usually based on the design earthquake and ground motion characteristics including tectonic environment, design earthquake magnitude, fault characteristics, source to site distance, subsurface conditions, and significant duration. These parameters are usually determined from the results of de-aggregation of the probabilistic hazard calculations at the target annual frequency of exceedance and the period(s) of interest. In the current state of practice, one of two scaling methods is generally used: 1) linear scaling of record to fit the UHRS at the natural period or period range of significance for the structure, or 2) spectrum matching of record to fit the entire UHRS.

When linear scaling, each selected time-history is multiplied by a single factor so that the response spectrum of the scaled record is approximately at the level of the UHRS in the period (or period range) of significance for the structure (USACE, 2003). Since the recorded time histories contain peaks and valleys at different periods, the level of the agreement of the scaled time histories with the UHRS may vary significantly with period. For spectrum matching of the selected time histories, the records should first be scaled linearly to the approximate level of the UHRS in the period range of significance of the structure. The linearly scaled records will then be modified to match the UHRS at all periods using spectrum matching techniques in either the frequency domain or the time domain.

Spectrum matching of the records to the UHRS may seem to eliminate the disagreement between the UHRS and the time histories' response spectra. However it should be noted that the UHRS is constructed by conducting a hazard analysis for each spectral period independently and such a spectrum is unlikely to represent the spectrum of any one single earthquake. Baker and Cornell (2005, 2006a, 2006b) presented a method to develop a design "target spectrum" specific to a structure's period range of significance. The spectrum that results from applying their method is called the conditional mean spectrum considering epsilon, or (CMS-ε). For single degree of freedom structures the developed target spectrum for earthquake ground motions with low exceedance rates matches the UHRS at the natural period of the structure but is lower than the UHRS at other periods,. For multi degree of freedom structures, or structures with nonlinear behaviour, i.e. where a range of periods is significant for structure response, the developed target spectrum is always lower than the UHRS for earthquake ground motions with low exceedance rates. Therefore it can be concluded that spectrally scaling an earthquake record to match the entire UHRS may be unnecessarily conservative. Development of the scenario target spectrum does not require hazard analysis at all periods and only requires the spectral accelerations in the period range of significance for the structure.

This paper assesses the significance and advantages of using the scenario target spectrum (CMS-ε) and record scaling and selection method proposed by Baker and Cornell on the seismic response of an earthfill dam. Dynamic analysis was carried out on a 64m high cross section of an earthfill dam located in a high seismic hazard area using a set of three earthquake record time histories. The dynamic analyses were carried out using the time histories linearly scaled to the UHRS at the period range of significance, spectrally matched to the entire UHRS, and spectrally matched to the CMS-ε. The results of the dynamic analysis using these three approaches to scale time histories are presented in this paper.

GEOTECHNICAL DESIGN PARAMETERS

The dam being analyzed is part of a hydro-electric facility on Vancouver Island, owned and operated by BC Hydro. As part of BC Hydro's ongoing dam safety assessment program, dynamic analysis of the dam, power intake tower, spillway, and powerhouse, was performed to help determine the likely performance in the Maximum Design Earthquake (MDE). These various components of the power facilities all have different horizontal natural periods of vibration, and moreover they physically interact; the intake tower (long period) is partially embedded in the upstream toe of the dam (medium period), the dam fill abuts the spillway wall (short period), and the rear wall of the powerhouse (short period) is embedded in the downstream toe of the dam fill (medium period). It was decided early in the project that computer models of each facility component should be excited with a suite of earthquake records that were tuned to the natural frequency of the structure, and that interaction of components, such as earth pressures on the powerhouse wall, would be assessed by taking the worst case from models excited, separately, by two suites of appropriate earthquake records. Thus, rather than match one suite of records to the UHRS for all analyses, three different suites of records were developed for each period class of structure using the CMS-ε technique. For the actual project six or more time history records were selected and scaled for each of the three period classes. For purposes of this paper, which deals only with the response of one section of the dam, results from only three time histories are discussed.

The section of the dam used for dynamic analyses in this study is shown in Fig. 1. The dam at this left abutment section is 64m high and founded on bedrock. Strength, stiffness, and hydraulic conductivity properties of the materials, required for numerical modelling of the dam, were selected based on field testing, laboratory testing, and back calculations, and are summarized in Table 1. A dilation angle of 9˚ for drained condition and 3˚ for undrained condition was assigned to all materials.

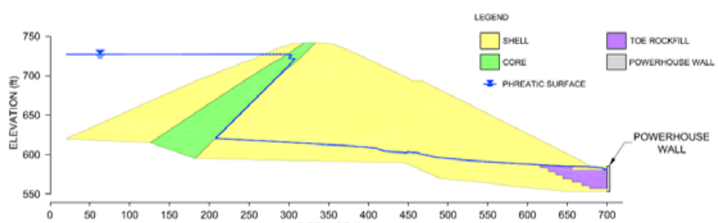

Fig. 1. Dam Cross Section and Identified Material Zones.

The constitutive model developed by UBC Professor Emeritus Dr. P.M Byrne and his students, referred to as UBCHYST, was used in dynamic analyses. In this model the modulus reduction and damping with strain, prior to yield, conforms to a hyperbolic stress-strain relationship and is set to match the shape of standard curves found in the literature that are based on laboratory tests. The modulus degradation and damping characteristics of dense shell and core materials were modelled using the data presented by Seed and Idriss (1970) for sands. The modulus degradation and damping characteristics of toe rock was modelled using the data presented by Rollins et al. (1998) for gravels. For numerical stability at very small strains, a small amount of Rayleigh damping, typically 0.1 % was also included.

Table 1. Summary of Typical Material Properties

Material Name	D_r (%)	Φ_{cv}	K_{2max} (1)	Hydraulic Conductivity (cm/s)	
				K_h	K_v
Dense Shell (2)	85	32˚	145	5.00E-05	5.00E-06
Core (2)	85	30˚	145	5.00E-06	5.00E-07
Toe Rockfill	- (3)		90	5.00E-04	5.00E-05

Notes:

1. A factor depending on relative density of the soil for estimation of shear modulus.
2. Dependency of friction angle on confining stress is based on Bolton (1986).
3. Dependency of friction angle on confining stress is based on the minimum value for rockfill suggested by Leps (1970).

Numerical analysis to estimate the earthquake performance of the dam was completed using the commercially available program, FLAC^{2D} 5.0 (Itasca Consulting Inc.) and the non-linear hysteretic soil stress-strain relationship, invoking the Mohr Coulomb failure criterion, described above. The dynamic analysis involves two steps. Prior to applying the earthquake/dynamic loading, a static analysis including steady state seepage analysis was carried out to determine the in-situ static stress state in the finite difference dam model. The phreatic surface resulting from the seepage analysis is overlain in Fig. 1.

The seismic response analysis was then commenced from the static stress state, simulating an undrained condition. In FLAC dynamic analyses, the undrained response of a saturated soil unit (i.e. soil units below the water table) was modelled by assigning an appropriate bulk modulus for the pore water and switching off the seepage flow during earthquake shaking. In this case, any changes that occur in the mean normal stress in a saturated soil element during earthquake shaking will be transferred directly to the pore water as in the real undrained loading case. The non-saturated soil units (i.e. soil units above the water table) will behave as drained and any changes in the mean normal stress will directly be transferred to the soil element. The shear induced pore water pressures in a saturated soil unit and volume changes in a non-saturated soil unit were modelled by assigning appropriate dilation angles for each material unit.

EARTHQUAKE RECORD SELECTION AND SCALING

This hydroelectric dam is categorized as a "very high" consequence facility requiring an earthquake ground motion with an annual frequency of exceedance of 10^{-4} for safety evaluation. A probabilistic seismic hazard assessment was completed for the site by BC Hydro. This analysis made use of four ground motion prediction equations for crustal earthquakes: Campbell and Bozorgnia (2003), Abrahamson and Silva (1997), Boore, Joyner, and Fumal (1997) and Sadigh et al. (1997). Two equations were used for subduction earthquakes; Youngs et al. (1997) and Atkinson and Boore (2003). The peak ground acceleration (PGA) with a mean annual exceedance frequency (AEF) of 10^{-4} is 0.8g. The Uniform Hazard Response Spectrum (UHRS) of the horizontal ground motion for AEF of 10^{-4} and for 5% damping is presented in Fig. 2. The vertical UHRS derived from the horizontal UHRS based on the empirical procedure recommended by the US Army Corps of Engineers (USACE, 2003) is overlain in Fig. 2. Deaggregation results for selected periods are shown in Table 2. The modal and mean values of distance and magnitude are in the same range, indicating that the earthquake hazard is controlled by a single area source rather than multiple sources. The dominant scenario is a crustal earthquake with magnitude greater than 6.9 and distance less than 15 km.

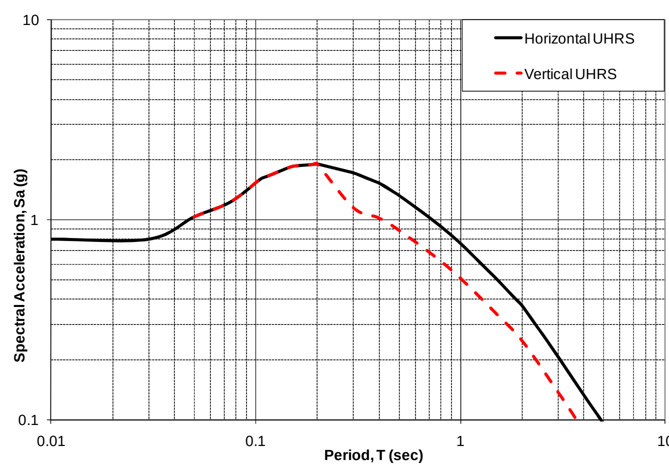

Fig. 2. Horizontal and Vertical Uniform Hazard Response Spectra.

The horizontal natural period of the earth fill dam can be estimated using Equation (1) below (Gazetas, 1987).

$$T_s = \frac{2.6 \times H}{V_s}$$
$$V_s = \sqrt{G_{\max}/\rho} \tag{1}$$

where:
H = height of the embankment dam (64 m),
V_s = average shear wave velocity, and
G_{max} = maximum soil shear modulus
ρ = material mass density

Table 2. Probabilistic Seismic Hazard Assessment, Deaggregation Results

Period (sec)	M_{mean}	D_{mean} (km)	M_{modal}	D_{modal} (km)
0.01 (PGA)	7.09	6.66	7-7.2	0-5
0.10	6.87	6.07	7-7.2	0-5
0.15	6.90	6.50	-	-
0.20	6.99	6.78	7-7.2	5-10
0.30	7.12	7.22	-	-
0.40	7.22	7.65	-	-
0.50	7.28	8.19	-	-
0.75	7.36	9.02	-	-
1.00	7.41	9.95	7-7.2	0-5
1.50	7.48	11.03	-	-
2.00	7.50	12.11	7-7.2	5-10

The average shear wave velocity and horizontal natural period of the embankment dam are estimated as 600 m/s and 0.27 sec respectively. Softening of material will happen during the earthquake shaking which increases the natural period of the dam. Therefore the period range of interest for this dam is assumed to be 0.25 sec. to 0.5 sec.

The scenario earthquake for the period range of interest of the structure (0.25 sec. to 0.5 sec.) has a mean magnitude in the range of 7.0 to 7.3 and a mean source to site distance of less than 10 km. Based on the current state of the practice, the following criteria should be considered in the selection of the acceleration time histories for dynamic analysis (USACE 2003):

Tectonic environment of the selected time histories should be similar to that of the scenario earthquake.

Magnitude of the earthquakes of the selected time histories should be within +/- 0.5 of that of the scenario earthquake.

The type of faulting of the earthquake of selected records should preferably be similar to that of the scenario earthquake.

When the mechanism of the design earthquake is unknown, attempts should be made to select recorded time histories from various fault mechanism to cover the range of possible mechanisms.

Earthquake source to site distance for selected time histories should be similar to the design source to site distance. For design source to site distances of less than 10 km, time histories recorded at distance of less than 10 km should preferably be selected to keep the near-source characteristics of the time histories.

Subsurface condition of the selected earthquake recording should be preferably similar to the site subsurface condition for which the hazard analysis was performed.

Duration of strong shaking should be generally within a factor of 1.5 of the duration of the design earthquake.

Guidelines suggest that at least five records should be used for nonlinear dynamic analysis. Six or more were used for the actual project but for brevity and comparison purposes, only three records were selected in this study. Table 3 summarizes the parameters of the selected ground motion time histories along with the design earthquake parameters.

Table 3. Summary of Selected Time History Characteristics

Parameter	Design Earthquake	Record 1	Record 2	Record 3
Earthquake	-	Chichi	Tabas	Kocaeli
Station	-	TCU089	Tabas	Izmit
Tectonic Environment	Shallow Crustal	Shallow Crustal	Shallow Crustal	Shallow Crustal
Mechanism	Unknown	Reverse/ Oblique	Reverse	Strike Slip
Magnitude	7.1 to 7.3	7.6	7.35	7.5
Source to Site Distance	7 to 8.5 km	8.9 km	6.8 km	7.4 km
Subsurface Condition	Rock	Rock	Rock	Rock
Significant Duration	10 to 40 sec	25 sec	17 sec	15 sec

Linear scaling of the records
One approach for scaling of the records is linearly scaling of the selected time histories so that the response spectrum of the records matches the UHRS in the period range of significance of the structure. Recommendations are provided in the USACE (2003) and other guidelines for linearly scaling of the records. Table 4 shows the selected component of recorded time histories and scaling factor used in linearly scaling of the

time histories to match the UHRS. The horizontal component of the ground motion is assumed as the primary component for linear scaling. The same scaling factor is used for scaling of the vertical component as suggested in USACE (2003). Response spectra of the scaled time histories are shown in Figures 3 to 5.

Table 4. Scaling Factors for Linear Scaling and Initial Scaling Factors for Spectrum Matching of Records

		CHICHI-TCU089	TABAS-Tabas	KOCAELI-Izmit
Horizontal Comp.	Component	CHICHI-TCU089-N	TABAS-LN	KOCAELI-IZMIT-090
	Linear to UHRS	2.7	0.95	2.8
	Spectrum Match to UHRS	3.0	0.95	3.5
	Spectrum Match to CMS-ε	2.6	0.8	3.0
Vertical Comp.	Component	CHICHI-TCU089-V	TABAS-UP	KOCAELI-IZMIT-UP
	Linear to UHRS	2.7	0.95	2.8
	Spectrum Match to UHRS	3.3	1.2	4.5
	Spectrum Match to CMS-ε	2.0	0.8	3.0

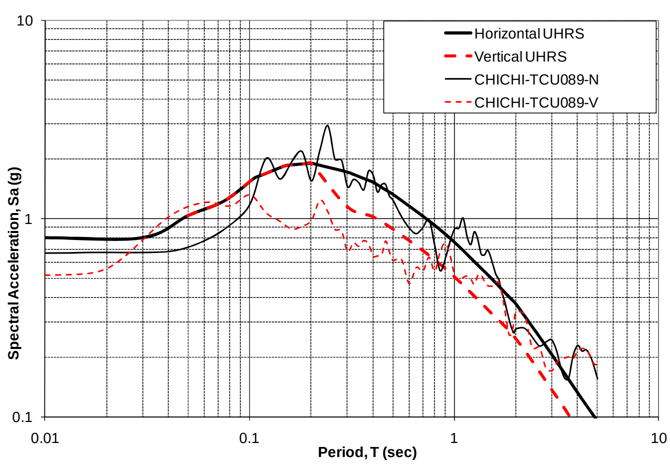

Fig. 3. CHICHI-TCU089 Record Scaled to the UHRS between 0.25 and 0.5 Seconds (Scale Factor = 2.7)

Spectrum matching of the records to the UHRS

The second common approach to scale earthquake records, is spectrally matching them to the entire UHRS. Spectrum matching can be done either in the frequency domain by adding sine waves to the recorded ground motion or in the time domain by adding short wavelets. The RSPMATCH computer software (Abrahamson, 1992) was used in this study for spectrum matching of the records. This program uses a time domain scaling approach which is believed to preserve non-stationary characteristics of the time histories (Abrahamson, 1992). The closer the spectral shape of the seed record is to the target spectrum, the less wavelets need to be added to the time history during the spectral matching process, and the non-stationary characteristics of the record will be better preserved. To minimize the changes that occur to the time history during the spectrum matching process, the time histories were linearly scaled to the approximate level of the target spectra prior to the spectrum matching process. Initial linear scaling factors used for spectrum matching of the records to the UHRS are presented in Table 4.

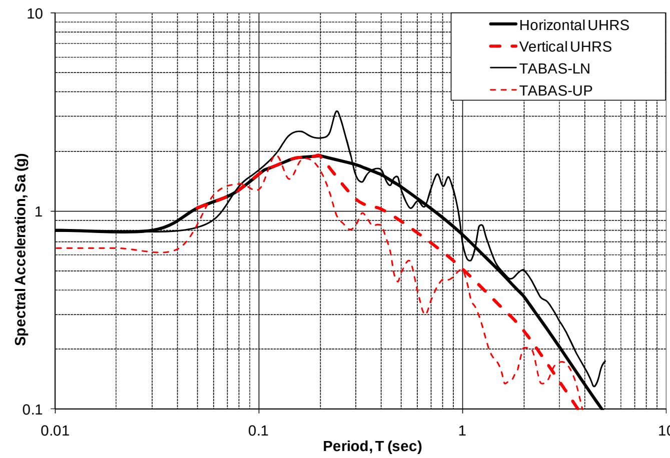

Fig. 4. TABAS-Tabas Record Scaled to the UHRS between 0.25 and 0.5 Seconds (Scale Factor = 0.95)

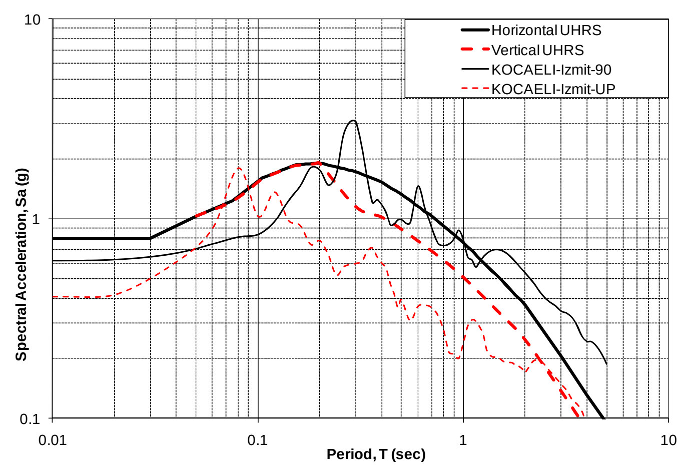

Fig. 5. KOCAELI-Izmit Record Scaled to the UHRS between 0.25 and 0.5 Seconds (Scale Factor = 2.8)

Matching of records to the CMS-ε target spectrum

The method proposed by Baker and Cornell (2005, 2006a, 2006b) to develop site specific design spectra is used here to produce target spectra for a structure with a period range of significance of 0.25 to 0.5sec. The spectrum that results from applying this procedure is called the conditional mean spectrum considering epsilon, or CMS-ε. Epsilon is the number of standard deviations on the ground motion prediction equation(s) that is required to match the UHRS in the period range of significance. For low probability hazard, such as is the case for this site at 10^{-4} frequency of exceedance per annum, the ground motion will invariably have a positive epsilon value, i.e. the hazard is dominated by earthquake shaking that may be several standard deviations above the median.

The same ground motion prediction equations used in the hazard assessment were used here to develop the horizontal CMS-ε target spectrum. Full implementation of the CMS- ε technique to develop target spectrum for a period range of significance requires re-running the seismic hazard analysis to obtain median values of distance, magnitude, and the new intensity measure Sa_{avg}(T1, T2,…Tn) as described by Baker and Cornell (2006b). When the earthquake hazard is controlled by a single source (as is the case in this study) rather than multiple sources, a simpler approach can be used. In this approach, due to the small variation in median values of distance and magnitude in the period range of significance, average values were selected as the median values of magnitude and distance for target spectra development. The value of the new intensity measure can also be conservatively selected so that the target spectrum barely touches the UHRS. The horizontal CMS-ε target spectrum developed for this site is presented in Fig. 6. The horizontal CMS-ε spectrum developed using the simplified method touches the UHRS at one point and has slightly lower spectral acceleration values than the UHRS at other points in the period range of significance. The difference between spectral acceleration in the CMS-ε and UHRS increases when moving away from the period range of significance. This is an inherent characteristic of the CMS-ε with positive epsilon values, as the target spectrum decays to the median spectrum derived from the ground motion prediction (attenuation) equation(s). The average of the median horizontal spectrum values of ground motion prediction (attenuation) models is also presented in Fig. 6 for comparison purposes.

Two of the ground motion prediction models, Campbell and Bozorgnia (2003) and Abrahamson and Silva (1997), which provide equations for vertical component of ground motions, were used to develop the vertical CMS-ε target spectrum. The vertical CMS-ε target spectrum developed for this site is presented in Fig. 6. This target spectrum is noticeably below the vertical UHRS. This is mainly due to the weak correlation between horizontal and vertical components of ground motion (Baker and Cornell, 2006a).

Once the CMS-ε target is determined, it is preferable to select natural records that have the same shape as the target, and then linearly adjust for the best match. It is argued that for use in structural response analyses the shape is the most important selection criterion, and that other factors such as magnitude, distance etc., are already accounted for by the CMS-ε determination procedure (Baker and Cornell, 2006b). The geotechnical engineer, however, may need to pay attention to such issues as duration and equivalent number of uniform stress cycles when selecting records for the analysis of soil structures, especially where subsoil liquefaction is an issue. For simplicity in this study, however, to avoid a multiplicity of earthquake records, the same records that were selected for linear scaling were scaled to the CMS-ε target spectra using the time domain matching procedure described above. Initial linear scaling factors used for spectrum matching of the records to the UHRS are presented in Table 4.

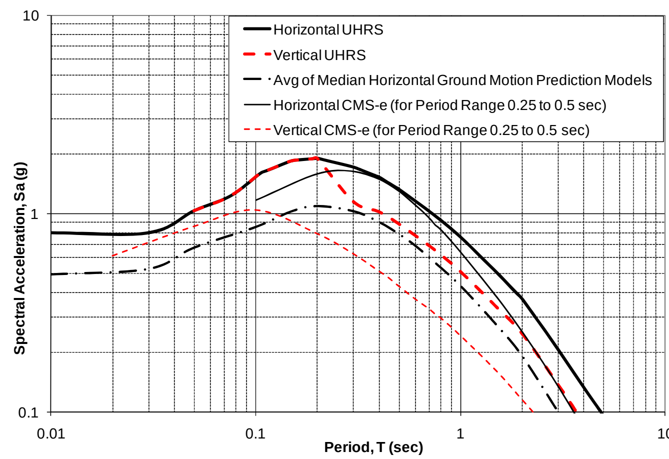

Fig. 6. Horizontal and Vertical CMS-ε

DYNAMIC ANALYSIS RESULTS

Dynamic analyses were carried out on the dam cross section described above using three sets of scaled records. The first set of analyses was carried out using only the horizontal components of ground motion, in keeping with conventional geotechnical practice. Time histories of displacements at the crest centre and downstream edge of the crest were recorded, and the ultimate values are presented in Table 5. As expected and intended, the average displacement values of the records spectrally matched to the CMS-ε are consistently lower than those spectrally matched to the UHRS and those linearly scaled to the UHRS at period range of significance. The order of the results is consistent with the fact that the linearly scaled records contain excursions above the UHRS, whereas the spectrum matched records do not, and the CMS-ε records, by definition, are significantly below the UHRS except in the period range of interest. The differences in results between the scaling techniques are arguably not geotechnically significant. For structural response, however, this may not always be the case.

For the second set of analyses, the models were run with the same suite of earthquake records, but including the appropriate vertical components. A summary of these results is provided in Table 6. Again, as expected, the records scaled to the CMS-ε target provide the lowest estimates of displacement. The order of the remaining two techniques is reversed in this case when compared to the runs with only the horizontal component. This is no doubt due to the fact that the vertical UHRS determined using the USACE (2003) procedure is a more aggressive spectrum than that of the natural records linearly scaled. This can be seen in Figures 3 to 5. An additional reason for the CMS-ε records to provide the lowest displacement estimates is the fact that the target vertical spectrum is lower than that derived from the USACE method, and also generally lower than those for the naturally scaled records. This is due to relatively weak correlations between spectral acceleration of horizontal and vertical components of ground motion (Baker and Cornell, 2006a), resulting in vertical scenario target spectrum noticeably lower than the vertical UHRS. Despite these recognizable differences between the results from different scaling techniques, overall the variations from one to the other technique may not be significant geotechnically.

Table 5. Summary of Dynamic Analysis Results with Only Horizontal Component

		Disp. at crest centreline		Disp. at D/S slope crest		Average Earth Pressure (kips/ft^2)
		Hor. (ft)	Ver. (ft)	Hor. (ft)	Ver. (ft)	
Linearly Scaled to UHRS	CHICHI-TCU089	2.3	-1.8	7.6	-3.2	9.1
	KOCAELI-Izmit	1.5	-1.4	5	-2.3	11.1
	TABAS-Tabas	2.6	-1.7	6	-2.8	8.8
	Average	***2.1***	***-1.6***	***6.2***	***-2.8***	***9.7***
Spectrum Matched to UHRS	CHICHI-TCU089	1.9	-1.6	7.8	-3.3	9.7
	KOCAELI-Izmit	1.5	-1.3	4.9	-2.2	8.1
	TABAS-Tabas	1.7	-1.2	4.2	-2.0	8.3
	Average	***1.7***	***-1.4***	***5.6***	***-2.5***	***8.7***
Spectrum Matched to CMS-ε	CHICHI-TCU089	2.3	-1.6	7.4	-2.9	8.7
	KOCAELI-Izmit	1.1	-1.1	3.9	-1.9	7.7
	TABAS-Tabas	1.4	-1.0	3.5	-1.7	8.3
	Average	***1.6***	***-1.2***	***4.9***	***-2.2***	***8.2***

Table 6. Summary of Dynamic Analysis Results with Horizontal and Vertical Components

		Disp. at crest centreline		Disp. at D/S slope crest		Average Earth Pressure (kips/ft^2)
		Hor. (ft)	Ver. (ft)	Hor. (ft)	Ver. (ft)	
Linearly Scaled to UHRS	CHICHI-TCU089	4.7	-3.1	9.2	-4.4	11.0
	KOCAELI-Izmit	3.8	-1.7	7.4	-2.9	11.8
	TABAS-Tabas	4.3	-2.6	7.4	-3.3	10.2
	Average	***4.3***	***-2.5***	***8***	***-3.5***	***11.0***
Spectrum Matched to UHRS	CHICHI-TCU089	6	-2.9	11	-4.3	11.6
	KOCAELI-Izmit	5.2	-2	8.4	-3.1	10.1
	TABAS-Tabas	5.4	-2.8	8.1	-3.1	10.8
	Average	***5.5***	***-2.6***	***9.2***	***-3.5***	***10.8***
Spectrum Matched to CMS-ε	CHICHI-TCU089	4.7	-2.4	9.3	-3.5	10.6
	KOCAELI-Izmit	4.1	-1.8	7.1	-2.7	8.7
	TABAS-Tabas	3.6	-2.1	5.9	-2.5	10.2
	Average	***4.1***	***-2.1***	***7.4***	***-2.9***	***9.8***

No major difference is observed in the deformation of the downstream edge of the crest with and without the vertical component, which is mainly controlled by failure of a thin layer close to the downstream face. This is in accord with the study performed by Gazetas (2008) on Newmark's (1965) sliding block model which showed that the inclusion of the vertical component of ground motion does not have a noticeable effect on displacement of a sliding block model. However, post earthquake performance of a dam is usually assessed by the settlement of the dam crest (vertical deformation of the dam crest), because a minimum freeboard is required to be maintained for safe performance. Comparing the vertical deformation of the dam crest centre in Tables 5 and 6 indicates a significant difference between the results obtained with and without the inclusion of the vertical component of ground motion. An increase of approximately 55% to 85% is evident in the results in Tables 5 and 6. It can be explained by the fact that the settlement of the dam crest is not controlled by slope skin sliding, but by overall deformation and bulging of the dam. The reason, originally, for including the vertical component was that the evaluation of the intake tower at the upstream toe of the dam involved the assessment of the response of mechanical and electrical equipment on the upper deck of the tower, and also an assessment of the rocking response of the tower when retrofitted with dampers. The effect of the vertical component was then seen to be important in the response of the dam and also in the evaluation of lateral earth pressures on the spillway wall and the rear wall of the powerhouse.

In assessing the earthquake induced earth pressures on the rear wall of the powerhouse an initial estimate was made using the rigid wall relationship provided by Wood (1973), and the design charts developed by Wu and Finn (1999), which incorporate the seismic response of the backfill. These methods identify the potential for earth pressures much higher than those predicted by the Mononobe-Okabe relationship for flexible/sliding walls, but they are applicable to the case of dry backfill with a horizontal surface, excited by horizontal ground shaking. The configuration of the dam and powerhouse in this site includes a potentially high ground water level due to the connection with the tailrace, and the possible influence of the nearby downstream toe of the dam slope. To evaluate the effect of these influences, the interaction of a rigid wall with the slope and backfill was included at the right boundary of the model (see Fig. 1.).

The analyses performed for the actual project using records scaled to short period, medium period, and long period target spectra showed that the records scaled to the medium period target spectrum apply the highest soil pressure to the rigid wall of the powerhouse. The time history of the earth pressure on the powerhouse wall was recorded during the analyses at eight equidistant locations up the wall. Peak horizontal earth pressure values on the powerhouse wall are presented in Tables 5 and 6 for analysis without and with the vertical component of ground motion respectively. The values presented are maximum earth pressure averaged up the wall. Peak earth pressure up the wall averaged for each set of earthquake records, are also presented graphically in Figures 7 and 8 for sets of records without and with the vertical component of ground motions respectively.

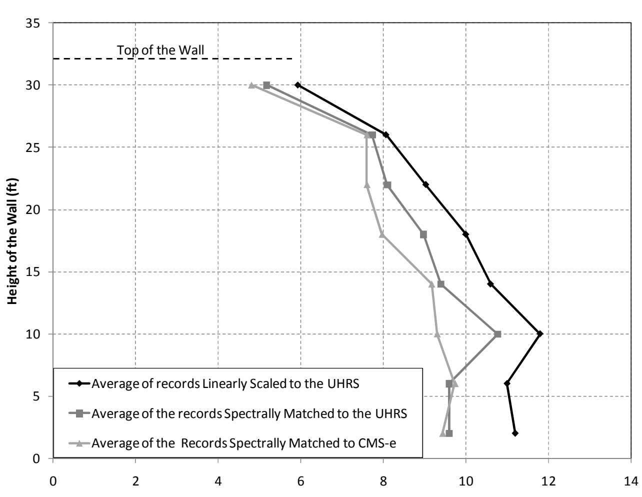

Fig. 7. Peak Soil Pressure on the Wall – Results of Analysis with Only Horizontal Component

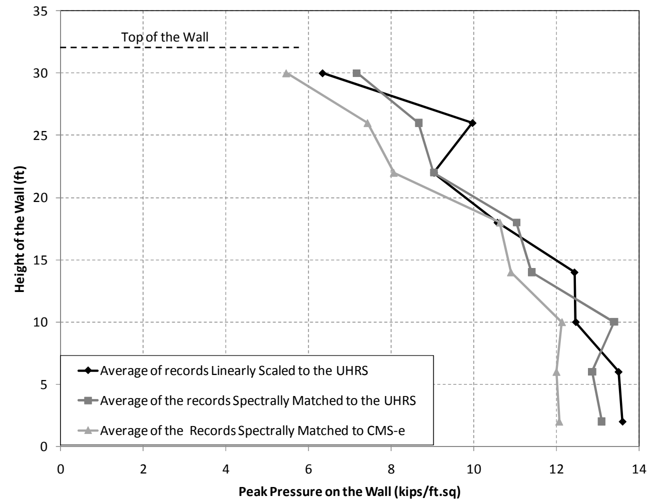

Fig. 8. Peak Soil Pressure on the Wall – Results of Analysis with Horizontal and Vertical Components

The resulting maximum earth pressures were somewhat higher than predicted by Wu and Finn for the dry level ground case. Similar to the crest displacements, the CMS-ε records provide the lowest soil pressure on the powerhouse wall. The results also showed that inclusion of the vertical component of ground motions causes an increase of approximately 15% to 25% of the maximum soil pressure on the powerhouse wall.

SUMMARY AND CONCLUSIONS

In summary, this study has confirmed that records scaled to a CMS-ε target will result in lower embankment displacement estimates, when compared to UHRS matching or linear scaling methods. The differences may be of the order of 20%. A similar conclusion can be reached with respect to lateral earth pressures on rigid walls.

The most significant result, however, is to demonstrate the effect of adding the vertical component of acceleration. This results in an increase in settlement of the crest centre by as much as 85%. Even for the CMS-ε records, which arguable represent a more realistic portrayal of the vertical component, given the selection of a high epsilon horizontal component, the difference between models with and without the vertical component is, on average, approximately 75%.

Inclusion of vertical component of the ground motion also results in an increase of approximately 20% on the soil loads on the powerhouse wall. Although such increase is not geotechnically significant, it can be noticeable for structural design of the wall.

Side benefits of using the CMS-ε technique, not discussed in the paper, include the ability to develop target spectra for orthogonal horizontal components for use in 3 –dimensional analyses, in addition to the vertical component discussed above.

REFERENCES

Abrahamson, N.A. [1992]. "*Non-Stationary Spectral Matching*". Seismological Research Letters Vol. 63, No. 2, 1992, pages 30.

Abrahamson, N.A. [2006]. "*Seismic Hazard Assessment: Problems with Current Practice and Future Developments*". First European Conference on Earthquake Engineering and Seismology, Geneva, Switzerland, 3-8 September 2006.

Abrahamson, N.A. and W.J. Silva [1997]. "*Empirical Response Spectral Attenuation Relations for Shallow Crustal Earthquakes*". Seismological Research Letters, Vol. 68, No. 1, January/February 1997, pp. 94-127.

Atkinson, G.M. and D.M. Boore [2003]. "*Empirical Ground-Motion Relations for Subduction-Zone Earthquakes and Their Application to Cascadia and Other Regions*". Bulletin of the Seismological Society of America, August 2003, Vol. 93, No. 4, pp. 1703-1729.

Baker, J.W. and C.A. Cornell [2005]. "*A Vector-Valued Ground Motion Intensity Measure Consisting of Spectral Acceleration and Epsilon*". Earthquake Engineering and Structural Dynamics, April 2005, Vol. 34, No. 10, pp. 1193-1217.

Baker, J.W. and C.A. Cornell [2006a]. "*Correlation of Response Spectral Values for Multicomponent Ground Motions*". Bulletin of the Seismological Society of America, February 2006, Vol. 96, No. 1, pp. 215-227.

Baker, J.W. and C.A. Cornell [2006b]. "*Spectral Shape, Epsilon and Record Selection*". Earthquake Engineering and Structural Dynamics, April 2006, Vol. 35, No. 9, pp. 1077-1095.

Bolton, M. D. [1986]. "*The Strength and Dilatancy of Sands*". Geotechnique, 36, No.1, pp. 65-78.

Boore, D.M., W.B. Joyner and T.E. Fumal [1997]. "*Equations for Estimation of Horizontal Response Spectra and Peak Acceleration from Western North American Earthquakes: A Summary of Recent Work*". Seismological Research Letters, Vol. 68, No. 1, January/February 1997, pp. 128-153.

Campbell, K.W. and Y. Bozorgnia [2003] "*Updated Near-Source ground Motion (Attenuation) Relations for the Horizontal and Vertical Components of Peak Ground Acceleration and Acceleration Response Spectra*". Bulletin of the Seismological Society of America, February 2003, Vol. 93, No. 1, pp. 314-331.

Gazetas, G. [1987]. "*Seismic response of Earth Dams: Some recent Developments*". Soil Dynamics and Earthquake Engineering, Vol. 6, No. 1, pp. 1-48.

Gazetas, G. [2008]. "*Effects of Near-Fault Ground Shaking on Sliding Systems*". Proceedings of Geotechnical Earthquake Engineering and Soil Dynamics IV, Sacramento, CA.

Leps, T.M. [1970]. "*Review of Shearing Strength of Rock Fill*". Journal of the Soil Mechanics and Foundations Division, Proceedings of the American Society of Civil Engineers, pp. 1159 – 1169.

Newmark, N.M. [1965]. "*Effects of Earthquakes on Dams and Embankments*". Fifth Rankine Lecture, Geotechnique, Vol. XV, No.2, The institute of Civil Engineers, London, England, pp. 139-160.

Rollins, K.M., M.D. Evans, N.B. Diehl and W.D. Daily [1998]. "*Shear Modulus and Damping Relations for Gravels*". ASCE Journal of Geotechnical and Geoenvironmental Engineering, Vol. 124, No. 5, pp. 396-1998.

Sadigh, K., C.Y. Chang, J.A. Egan, F. Makdisi and R.R. Youngs [1997]. "*Attenuation Relationships for Shallow Crustal Earthquakes Based on California Strong Motion Data*". Seismological Research Letters, Vol. 68, No. 1, January/February 1997, pp. 180-189.

Seed, H.B. and I.M. Idriss [1970]. "*Soil Moduli and Damping Factors for Dynamic Response Analysis*". Report No. EERC 70-10, Earthquake Engineering Research Center, University of California, Berkeley.

USACE [2003]. "*Engineering and Design – Time History Dynamic Analysis of Concrete Hydraulic Structures*". US Army Corps of Engineers Manual EM 1110-2-6051, December 2003

Wood, H.R. [1973]. "Earthquake Induced Soil Pressures on Structures". Ph.D. Thesis, The California Institute of Technology, Pasadena, California.

Wu, G. and W.D.L. Finn [1999]. "*Seismic Lateral Pressures for Design of Rigid Walls*". Canadian Geotechnical Journal. Vol. 36, No. 3, pp. 509-522.

Youngs, R., S. Chiou, W. Silva and J. Humphrey [1997]. "*Strong Ground Motion Attenuation Relationships for Subduction Zone Earthquakes*". Seismological Research Letters, Vol. 68, pp. 58–73.