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GENERATION OF VERTICAL ACCELERATIONS FOR SEISMIC SLIDING RESPONSE OF GRAVITY DAMS

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SUMMARY

This paper presents a general procedure to generate synthetic vertical accelerograms for both, Eastern North American (ENA) and Western North American (WNA) earthquakes. The incidence of vertical accelerations on the sliding response of a gravity dam is then investigated through parametric analyses. The sliding response is computed using a rigid-body model and assuming Mohr-Coulomb type friction. The analyses are carried out using both historical and synthetic records, generated with the proposed procedure. For the historical records the mean total sliding displacement was found to increase by 89% for the ENA input, and by 24% for the WNA input, when vertical components are included. The synthetic motions, generated by following the proposed procedure yielded results very similar to the historical records for both the ENA and WNA groups. The pseudo-static 30% load combination rule, commonly used in practice, yielded good approximations of the minimum safety factors against sliding computed from time-history analyses. It was also found that for ENA type earthquakes, a load combination consisting of the vertical PGA applied simultaneously with 30% of the horizontal PGA was more critical then the usual combination (100%H with 30% V) and represented more realistically the maximum response predicted from the time-history analyses.

INTRODUCTION

When generating synthetic accelerograms matching target spectra for the purpose of evaluating the seismic safety of structures through time-history analyses, the problem of incorporating vertical components in a simple and realistic way arises. Furthermore, the occurrence of the maximum responses for each of the components must be evaluated realistically to avoid too severe or insufficient correlation between these components. The seismic safety evaluation of existing gravity dams throughout North America has sparked great interest in the definitions and choices of accelerograms to perform dynamic analyses. A great deal of information is available concerning the horizontal components of ground motions, and published guidelines[1,2,3] offer engineers computational methodologies to estimate the seismic performance of gravity dam structures. CDSA[1] guidelines commentary state that 'It is a good practice to consider the impact of concurrent horizontal and vertical components of seismic input on the concrete structures, though not necessarily to include both in the calculation of sliding safety factors'. USACE[2] guidelines for gravity dams state that 'earthquake loading should be checked for horizontal earthquake acceleration and, if included in the stress analysis, vertical acceleration'. FERC[3] mention that vertical accelerations must be considered for buttress dams. Vertical accelerations alter the resistance of load-carrying systems designed to counter horizontally induced forces in many structures. This same concept is found when examining the effect of vertical seismic accelerations on the shear strength of reinforced concrete columns, or when examining the seismic response of base isolation devices for bridges. The main objective of this paper is to develop a simple procedure to generate vertical synthetic accelerograms typical of Eastern North American (ENA) intraplate earthquakes, usually rich in energy in the 10 Hz frequency range, and Western North American (WNA) interplate earthquakes, predominantly rich in energy in the 2 Hz frequency range, for the computation of the non-linear seismic response of civil engineering structures in general, and the sliding response of gravity dams in particular. The proposed method is an extension of the shift and reduced vertical spectrum developed by Bozorgnia et al.[4,5] for California earthquakes. This method recognises the differences in frequency content, as well as in amplitude, between the horizontal and vertical response spectra.

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To extend the method to non-linear problems, the effects of vertical accelerations on the seismic sliding response of gravity dams, and position the force resultant along the base, are then investigated through time-history analyses. Results computed using historical records are compared to results obtained with synthetic ground motion input. Safety factors against sliding computed with the commonly used pseudo-static 30 % load combination rule are compared to minimum safety factors against sliding obtained from time-history analyses.

STUDY AND GENERATION OF VERTICAL GROUND MOTIONS

Choice of historical earthquake ensembles

It is commonly accepted that the frequency content of horizontal and vertical earthquake ground motions are quite different, since the former propagate mainly as shear-waves (S-waves), while the latter propagate as tension-compression waves (P-waves). It is also recognised that ENA and WNA horizontal component ground motions have quite different characteristics, especially in terms of frequency content. To remain consistent with this fact, the historical earthquakes considered in this study were divided into categories according to the frequency content of the horizontal strong motion data. The current classification for seismic zones included in the 1995 edition of the National Building Code of Canada[6] (NBCC) was used in this study. According to the NBCC, the ratio of the peak horizontal acceleration (expressed in g) to the peak horizontal velocity (expressed in m/s), a/v, is directly related to the frequency content of earthquakes expected in a given region. In Eastern Canada, the a/v ratio is usually high (above unity), corresponding to high frequency earthquakes, and thus high energy content in the short period range. In Western Canada, the ratio is usually low or close to unity. Low a/v values indicate low frequency earthquakes and consequently higher amplitude ground motions. This classification was chosen herein, since an existing strong motion database[7], dividing selected historical records in these three categories, was available. In this study, 35 historical earthquake records from this database were considered. These records were obtained on firm ground in North America, Eastern Europe, and Japan. The selected records were divided into three categories according to their acceleration-to-velocity, a/v, ratio: i) high ($a/v \geq 1.2$), ii) intermediate ($1.2 > a/v \geq 0.8$), and iii) low ($a/v < 0.8$). Most of the previously published work on vertical accelerations and their characteristics is based on California earthquakes, with intermediate to low a/v. The selection of strong motion data considered herein is intended to extend this approach to a broader range of active seismic zones. It must be noted that because of the scarcity of strong motion recordings in ENA, the high a/v group is mostly composed of near-field WNA ground motions. The 1988 Saguenay earthquake in eastern Canada[8] confirmed high a/v values for ENA records.

Characteristics of historical ground motions

For each of the selected records, indices to compare the characteristics of the horizontal component to those of the vertical component were computed[9]. These indices mainly focus on the Peak Ground Acceleration (PGA), the duration, the frequency content, and the energy content of the accelerograms. The V/H ratios of the PGA had a mean value of 0.66 for the high and intermediate a/v groups, and 0.55 for the low a/v group. This could be explained by the fact that earthquakes in the high a/v group usually correspond to near fault events, where P-waves are predominant. The average distance to the fault for the records used in this group is 13.2 km. The vertical component of the earthquake motion is not significantly attenuated in near fault region, thus yielding vertical PGA values closer to the PGA values of the horizontal component. The intermediate and low a/v groups of records have average distances to the fault of 70.6 km, and 113 km, respectively. The increased distances from the fault cause P-waves to attenuate and thus reduce the vertical PGA (PGAV) comparatively to the horizontal PGA (PGAH). The value of 2/3, usually suggested by several building codes and dam safety guidelines seems to be a good approximation of the average of the PGAV/PGAH ratio. However, the scatter of values may lead to considerable underestimation of the PGAV for certain events. The maximum and minimum [max, min] envelopes of the PGAV/PGAH ratio for the three a/v groups are i) [1.76, 0.27] for the high a/v group, ii) [1.35, 0.34] for the intermediate a/v group, and iii) [1.02, 0.34] for the low a/v group. This indicates that the PGAV is predominant in some records. The number of zero crossings, and the predominant period of strong shaking, monitored the frequency content of the horizontal and vertical records. In all three a/v groups, the average V/H ratio of the predominant period is about 0.8. This is consistent with previous results stating that the frequency contents of the horizontal and vertical components are different, and that the vertical accelerations are richer in high frequencies. By definition, each a/v group of records presents a different frequency content for the horizontal component. Since the V/H ratio of the predominant period stays constant at 0.8 in all three groups, it seems that the vertical accelerations are affected in the same manner as the horizontal accelerations by the factors that influence the a/v ratio. The V/H ratios of the root mean square of the acceleration are also constant at a value of 0.6 for all three a/v groups. Furthermore, the V/H ratio of the pseudo-absolute acceleration spectral intensity[9] is also constant with a value of approximately 0.6 for the three a/v groups. These two results indicate that the total amount of energy generated by vertical accelerations is approximately 60 % of the amount of energy generated by horizontal accelerations. The correlation factor, θ, between the horizontal and vertical accelerograms expressed as the normalised dot product of two uni-dimensional vectors was also computed[9]. The highest correlation factor was obtained for the high a/v group with a value of $\theta = 0.25$, whereas the intermediate and low groups had $\theta = 0.13$ and $\theta = 0.11$, respectively. The higher value of θ for the high a/v group may be due to the shorter fault distances for this group. The P-waves are therefore less attenuated and more in phase with S-waves.

Characteristics of response spectra

For each earthquake record, the horizontal and vertical acceleration spectra were computed for 5% damping. The V/H ratio of spectral acceleration VSa/HSa was plotted as a function of period. All three groups exhibited peak VSa/HSa ratios in the small period range (T < 0.25 s) where the ratio was greater than 2/3. Observing the shapes of the horizontal and vertical spectra for each record, it becomes obvious that the peaks of the acceleration response spectra do not occur at the same periods. In fact, the VSa/HSa ratio gives an estimate of the relative importance of the vertical component compared to the horizontal one. This spectral ratio is not indicative of the potential damage to a structure by the combined effect of the horizontal and vertical components of an earthquake, since the modes that will be influenced by the vertical input motion will be at a much higher frequency than those influenced by the horizontal component. These ratios are examined as indicators of how to obtain realistic vertical spectra from corresponding horizontal ones.

Generation of vertical spectra

Following the idea proposed by Bozorgnia et al.[4,5], which suggest to define the vertical spectra by shifting the horizontal spectrum peak to lower periods and reducing its amplitude, two modification factors were defined. The period axis divider is defined as the shift factor, S_f, and the amplitude calibrating multiplier is defined as the reduction factor, R_f. These factors are illustrated in figure 1. To derive appropriate S_f and R_f values, the following steps were taken: i) the vertical and horizontal absolute acceleration spectra were computed for each earthquake, ii) the average acceleration response spectra were obtained for each a/v group, for all the horizontal and vertical components, iii) the values of S_f and R_f that minimised the sum of the squares of the errors between the shifted and reduced average horizontal spectra and the target average vertical spectra were determined, for different period ranges, iv) the values of S_f and R_f were compiled, and the statistics for each group of earthquakes were computed, v) these results were examined to determine S_f and R_f values that would result in an acceptable estimation of the real vertical spectra, from the horizontal spectra.

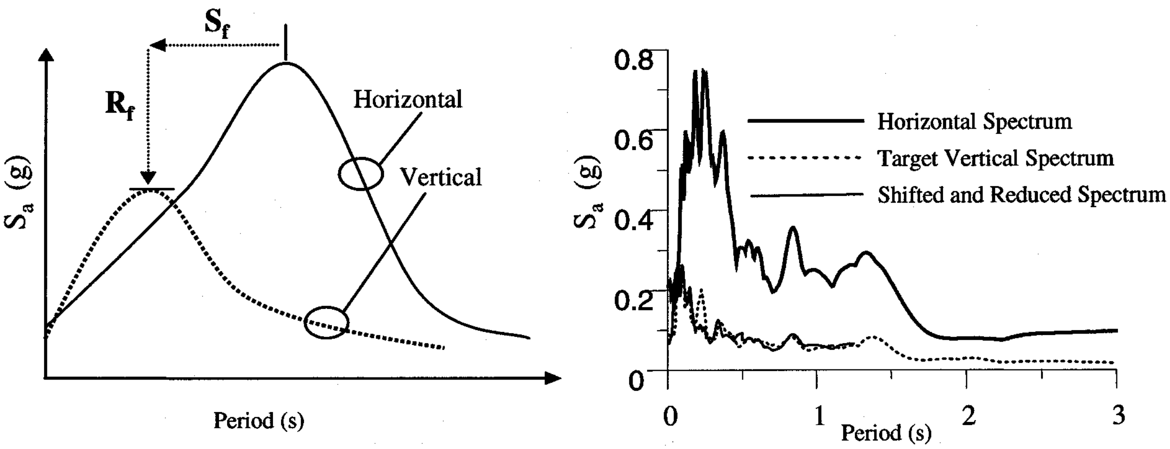

Figure 1: Shifted and Reduced Spectra (concept and example for 1971 San Fernando, Hol. storage record)

The average spectra for each group were used to compute S_f and R_f. Considering the proximity of the optimum values for the low and intermediate groups, it was decided to combine them to form a larger group of typical WNA ground motion. The high a/v values are representative of ENA ground motions. Based on the results obtained, and to simplify the proposed procedure, it was decided to use the same shift factor $S_f = 1.55$ for both groups of earthquakes, and to use the reduction factors $R_f = 0.80$ for the ENA ground motions and $R_f = 0.55$ for the WNA records. Figure 1 shows an example of application of the shift and reduced vertical spectrum method, based on optimal S_f and R_f values, for the individual record of the San Fernando earthquake (1971) in California recorded at the Hollywood storage parking lot which belongs to the intermediate a/v group. The derived spectra are compared to the target vertical spectra in figure 2. The spectra computed by simply reducing the horizontal spectra by 2/3 is also plotted for comparison purposes.

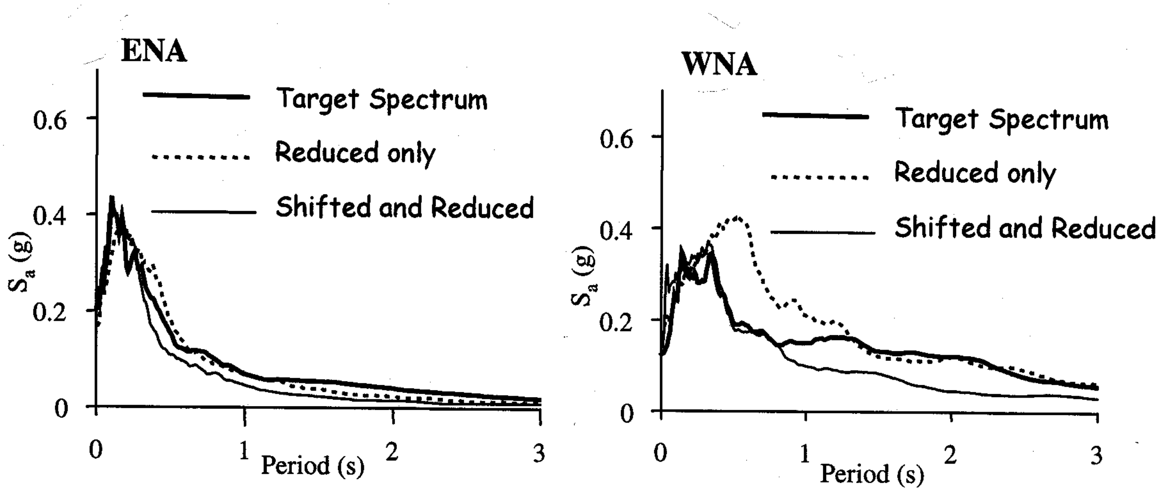

Figure 2: Vertical acceleration response spectra

Generation of vertical accelerograms

Once the vertical and horizontal spectra were computed, the well-known computer program SIMQKE was used to generate spectrum compatible ground motions. SIMQKE does not account for physical properties of wave propagation as included in advanced ground motion models recently developed. Nevertheless, this program is considered by many earthquake engineers as a simple and effective tool to generate ground motions, and is widely used in practice. In this program, time functions must be specified for the generation of synthetic accelerograms. Based on suggested duration for ENA and WNA earthquakes, an iteration procedure was used to derive time-functions that are compatible with the historical records considered[9].

SLIDING RESPONSE OF GRAVITY DAMS UNDER SEISMIC LOADS

SDOF rigid body sliding dynamic analysis

In the application example, the selected dam structure was considered as a rigid monolith supported without bond on a planar surface. This approach ignores the spectral amplification that could occur when the ground motion's predominant period is close to the fundamental period of the dam, as well as the effect of damping. However, it is generally used as a first step to bound the potential sliding that could occur when a dam or a cracked component is solicited by a severe earthquake.

The equations developed by Chopra and Zhang[10], which consist of treating the problem as a time-history of pseudo-static responses, is a simple and reliable way to compute the sliding response of rigid bodies subjected to seismic accelerations. A computer program was developed within the scope of this research project to assess the downstream sliding of rigid gravity dams under combined horizontal and vertical accelerations[9]. The program computes at every time step the downstream sliding critical acceleration, and compares it with the input seismic acceleration. Due to the presence of the hydrostatic thrust of the reservoir, upstream sliding of gravity dams is not relevant. As long as the critical sliding acceleration is not exceeded, the dam is responding in "stick mode", where no sliding is occurring, and the horizontal acceleration of the rigid block is equal to the horizontal ground acceleration. When the critical acceleration, at a given time step, is exceeded by the horizontal ground acceleration, the rigid sliding mode is engaged. When a_{hc} is exceeded, the rigid block is in motion, and the following dynamic equation of equilibrium must be satisfied at each time-step:

$$(M + M_{ao}) \cdot \ddot{s}(t) = -(M + M_{a0}) \cdot a_h(t) + H_{st} - F_R \quad (1)$$

where $\ddot{s}$ is the sliding acceleration of the block, a_h (t) is the horizontal component of the ground acceleration, M is the mass of the dam, M_{ao} is the added water mass (horizontal direction only), H_{st} is the horizontal hydrostatic force, and F_R is the maximum value of available friction at the dam-foundation interface. A Newmark $\beta = 1/6$, linear acceleration step-by-step scheme was used to compute sliding velocities and displacements. To assess the effectiveness of pseudo-static analysis of safety against sliding, a transient sliding safety factor, $F_s(t)$, was computed at each time step during the analysis:

$$F_s(t) = \frac{F(t)_{Resisting}}{F(t)_{Soliciting}} = \frac{[M \cdot (g + a_v(t)) - U] \cdot \tan\phi}{(M + M_{a0}) \cdot a_h(t) + H_{st}} \quad (2)$$

Where g is the acceleration of gravity, $a_v(t)$ is the vertical component of the ground acceleration, U is the uplift force at the base of the dam, and ϕ is the friction angle of the dam-foundation interface. Also, to assess the effect of vertical accelerations on the position of the resulting force at the base of the dam, the position of the resultant from the middle of the base, d, was computed at each time step. When the position of the resultant exceeds the middle third of the base, tensile stresses (crack) develop at the upstream face. Moreover, a position of the resultant computed outside the base indicates potential compressive overstressing. Dam safety guidelines[1,2] require that the force resultant remain within the base for gravity dams subjected to earthquakes.

System analyzed

The structure used in the analyses is a rigid representation of the Paugan Dam located in Quebec, Canada. Figure 3 shows the original section, along with the model used in the analyses with the computed loads and masses. After replacing the top openings by an equivalent concrete section, the effective height of the dam becomes 47.6 m in the model. The equivalent section maintains geometric and inertial properties of the initial section, but was used to simplify the calculations. The loads considered in the analyses are the weight of the dam, W, the hydrostatic forces acting horizontally on the upstream face of the dam, H_{st}, and the uplift force acting at the base of the dam, U. The uplift force was computed using a trapezoidal uplift pressure distribution, with a 50.7 m water head and a 10 m tailwater. In addition to these loads, the dam is subjected to seismic inertia forces through horizontal and vertical masses. In the horizontal direction, the added water mass, M_{ao}, accelerated with the dam is computed using Westergaard's approach. The effect of the water mass vibrating vertically due to the reservoir's bottom motion is neglected in this study. To resist the applied forces, the friction provided along the dam-foundation interface is determined by using a friction angle of $\phi = 45^o$, for both static and dynamic friction coefficients.

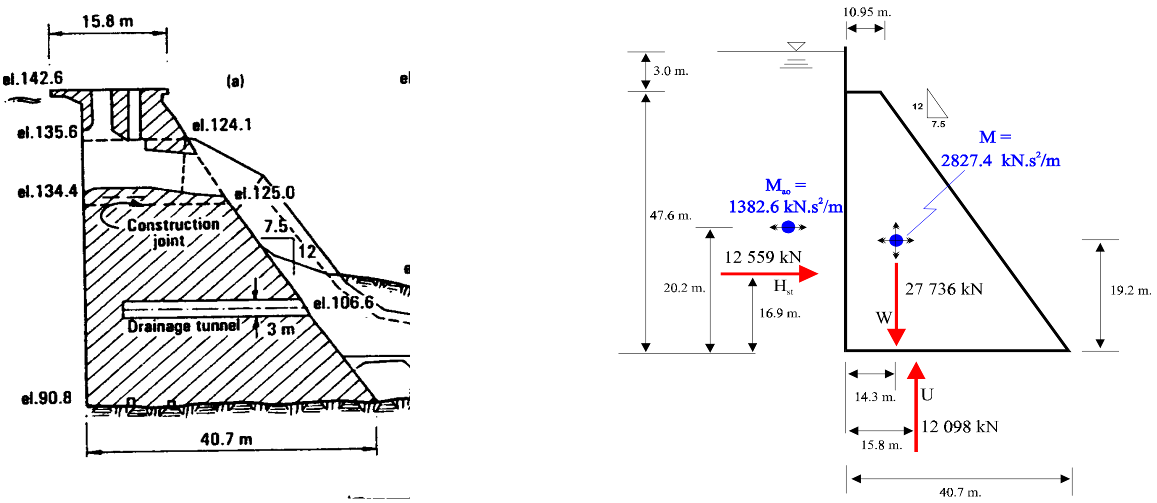

Figure 3: Paugan dam (real section, equivalent section)

Response analysis to historical earthquake records

The historical records were chosen amongst the initial data bank discussed earlier. Since the horizontal peak ground accelerations (PGAH) were quite scattered, all records were scaled to a PGAH of 0.25 g. The vertical accelerograms were scaled using the same scaling factor that brought the PGAH to 0.25 g, thus keeping unchanged the V/H ratio of the PGA of the historical records. Six historical records were chosen for each of the ENA and WNA groups[9]. A comparison of the total sliding of the dam when only the horizontal ground motion is used shows that for the western group historical earthquakes the sliding displacement is much larger then for the eastern earthquakes. This is due to the difference in frequency content between the eastern, higher frequencies, and western, lower frequencies ground motions as well as the difference in duration. In fact, it has been shown by numerical analyses and experimental shake table tests that the sliding is more sensitive to the duration of acceleration pulses, which is directly related to the frequency content, than to the PGA. Tinawi et al.[11] report that for the same PGA value, a total sliding displacement of three to four times greater is expected for WNA earthquakes than for ENA earthquakes. For the case of Paugan dam studied herein, the eastern group (horizontal excitation) yielded a mean total sliding displacement of 11.7 mm, compared to 71.0 mm for the western group (Table 1). This represents a total sliding 6 times larger for the western group, for a similar PGA of 0.25g. The results from the analyses show that the residual sliding displacement is substantially influenced by the presence of the vertical acceleration, for both groups. For the western group, the increase induced by vertical accelerations is smaller, since the mean total sliding reaches a value of 88.0 mm as compared to a value of 71.0 mm when the vertical component was omitted, representing a 24 % increase. For the eastern group, the total mean sliding reaches a value of 22.1 mm when the vertical accelerations are included, as compared to a value of 11.7 mm when the vertical component was omitted, which counts for an increase of 89 %. The difference between the groups in the total sliding displacement increase due to the inclusion of the vertical excitation can be explained by the computed values of S_f and R_f for each group. Since the value of S_f is the same for both groups, but the predominant period of the horizontal component of the ENA group is lower then that of the WNA group, the predominant period of the vertical component is much closer to that of the horizontal component for the ENA group. When the frequency content of both motions is similar, the probability that both solicitations will be in phase is greater, which can lead to larger sliding displacements. The amplitudes of the vertical motions for the ENA group are relatively larger then those of the WNA group, since the statistical study yielded values of R_f of 0.8 and 0.55, for ENA and WNA respectively. Figure 4 illustrates how the vertical acceleration affects the total sliding response and the safety factor F_s by 1) increasing the number of sliding events, and 2) by increasing the magnitude of sliding displacements within sliding events that are already present without the vertical accelerations. The increased sliding caused by the inclusion of the vertical component in the analyses is mostly due to the increase in the amount of sliding that occurs during a sliding phase. This indicates that during an earthquake a few simultaneous horizontal and vertical peak occurrences could be sufficient to greatly increase the non-linear sliding response even if a low correlation over the duration of the accelerograms exists between the two solicitations[9]. The safety factor against sliding, F_s, which corresponds to the lowest value of the safety factor computed during the time-history, was found to decrease on average over the 6 records by 21% for the ENA group and by 5 % for the WNA group (Table 1). The position of the resultant is downstream of the middle third for all records whether vertical accelerations are included or not in the analyses. Nonetheless, including the vertical accelerations in the analyses increased the eccentricity of the resultant. On average over six records, this increase was 5 % for the WNA group, and 54 % for the ENA group. For the ENA group, the mean value of the force resultant eccentricity exceeded the length of the base, which indicates a potential compressive overstressing when the vertical accelerations are included[9].

Response analysis to synthetic earthquake records

For the synthetic records, the same PGA value of 0.25 g used for the historical records was retained. Six eastern and six western synthetic horizontal earthquakes were generated from the mean horizontal historical spectra for each group[9]. The associated vertical accelerograms are generated according to three different procedures. The first, 'Synthetic 1', consisted of multiplying each horizontal accelerogram by 2/3 to generate the corresponding vertical component. The second, 'Synthetic 2', which is the most commonly used in practice, consists of calibrating the horizontal response spectrum to 2/3 of its value to obtain the vertical spectrum. Once the vertical target spectrum is defined, SIMQKE is used to generate the time-histories. The value of 2/3 is used because it is the most commonly accepted ratio of V/H peak ground accelerations. Although this method takes into account the lower spectral ordinates of vertical accelerations compared to the horizontal ones, it does not consider the difference in frequency content. The third, 'Synthetic 3'is based on the statistical analyses presented earlier on. This method uses the reduction factor, R_f, and a shift factor, S_f, on the horizontal spectrum to generate the vertical one. In this approach, the frequency content of the vertical spectrum is shifted towards the higher frequencies. SIMQKE is also used to generate the spectrum compatible accelerograms. It is important to note that when generating accelerograms with SIMQKE for non-linear time-history analyses, care must be taken to assure that indices like the predominant period, significant duration as well as energy content be representative of historical records. This was achieved by defining the frequency band accordingly for each group[9].

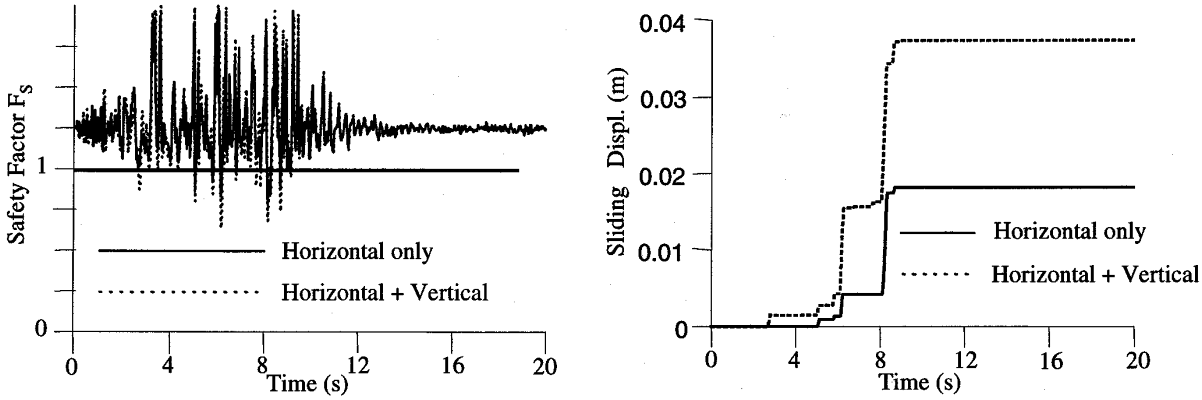

Figure 4: Safety factor and sliding displacement, 1966, Parkfield N65W component.

The synthetic records for both the ENA and WNA groups yields residual sliding displacements very similar to those obtained with the historical records corresponding to the same group (Table 1). The method to generate the accelerograms for the ‘synthetic 1’ series, that was included for illustrative purpose, is totally unrealistic and unrepresentative of the real interaction of horizontal and vertical seismic accelerations. The perfect correlation between the two accelerograms overestimates the effect of vertical accelerations. For both eastern and western records, the shifted and reduced method (‘synthetic 3’) yields better results than the reduced only method (‘synthetic 2’). For the WNA group the shifted and reduced method (‘synthetic 3’) is much more representative then the ‘synthetic 2’ method because the difference between the horizontal and vertical spectral peaks are further apart then for the ENA group. It must also be reminded that the calculations were performed assuming a rigid block model of the sliding structure. When performing the shift method, the spectrum peak is shifted to shorter periods, to account for the higher frequency characteristics of vertical accelerations. It could be expected that, considering the short natural period of the dam structure in the vertical direction, a more important dynamic amplification could occur for the shifted method. This effect would be more reliably described by the shifted vertical accelerogram. This needs to be investigated further for flexible structural systems.

Combination of H and V excitations in pseudo-static safety evaluation

Pseudo-static calculations are often used as a simple first assessment of, otherwise complex, problems. Similarly, applying equivalent static forces to the structure can initially assess the sliding safety of gravity dams. When considering both horizontal and vertical seismic accelerations in the analyses, the most critical load combination must be determined. In practice, the 30 % rule, which consists of applying simultaneously the forces induced by 100 % of the seismic input in the horizontal direction with 30 % of the forces induced by the vertical input, is commonly used. The safety factor against sliding was computed for each historical earthquake record by multiplying the PGA in both the horizontal (H) and vertical (V) directions by the mass of the dam to derive the value of the static forces. These forces were then combined by taking a) 100% H with 30 % V to compute the first safety factor, F_{S1}, and b) 100 % V with 30 % H to compute the second safety factor, F_{S2}. The safety factors computed from these pseudo-static analyses were then compared to the minimum value of the transient safety factor obtained during the time-history analyses (Table 1).

Table 1: Sliding response of Paugan dam to seismic loading (mean values)

ENA GROUP

	Residual Sliding (mm)			Minimum Safety factor		
	H	H+V	% incr.	H	H+V	% decr.
HISTORICAL	11.7	22.1	88.9	0.736	0.581	21.0
‘Synthetic 1’	12.0	78.4	553.3	-	-	-
‘Synthetic 2’	12.0	16.7	39.2	0.721	0.682	5.4
‘Synthetic 3’	12.0	19.3	60.8	0.721	0.697	3.3

30% rule $F_{S1\,(100\%\,H+30\%\,V)} = 0.605$ $F_{S2\,(100\%\,V+30\%\,H)} = 0.618$

WNA GROUP

	Residual Sliding (mm)			Minimum Safety factor		
	H	H+V	% incr.	H	H+V	% decr.
HISTORICAL	71.0	88.0	23.9	0.724	0.690	4.7
‘Synthetic 1’	75.1	234.3	212.0	-	-	-
‘Synthetic 2’	75.1	111.4	48.3	0.698	0.629	9.9
‘Synthetic 3’	75.1	93.8	24.9	0.698	0.649	7.0

30% rule $F_{S1\,(100\%\,H+30\%\,V)} = 0.639$ $F_{S2\,(100\%\,V+30\%\,H)} = 0.781$

The results obtained from the two different 30 % rules are quite close to the minimum results computed during the time-histories[9]. It was noted in the analyses, that for the ENA group, the F_{S2} factor, is sometimes more critical then the F_{S1}. It is therefore suggested that when computing the pseudo-static response to consider both load combinations for ENA type earthquakes.

CONCLUSIONS

The characteristics of vertical accelerations are different between eastern (ENA) and western (WNA) earthquakes. The ENA vertical accelerations are at higher frequencies and have higher structural significance for the sliding response of dams than the WNA vertical accelerations. The vertical accelerations influence the total sliding response much more for the ENA group, where the inclusion of vertical accelerations (historical records) increased the total sliding displacements by 89%. For the WNA group this increase was only 24%. The shifted and reduced method ('synthetic 3') accelerograms, yielded good results reproducing the effect of both the ENA and WNA historical vertical accelerations. Results indicate that the effect of vertical seismic loading can be reliably reproduced with synthetic ground motion by a) using the shifted and reduced method to derive the vertical spectrum and b) controlling the frequency band when generating the accelerograms with SIMQKE such that the significant indices (duration, energy and predominant period) match those of historical records. Combining the effects of 100% of the horizontal PGA with 30% of the vertical PGA for pseudo-static analyses represents a good approximation for the evaluation of the minimum safety factor against sliding computed during the time-history analyses. For the ENA group, combining 100% of the vertical PGA with 30% of the horizontal PGA was also found to be critical for some analyses. It is suggested that both these pseudo-static load combinations be considered when evaluating the seismic sliding response of gravity dams to ENA type earthquakes.

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