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Selection and Scaling of Ground Motions to Compute Residual Sliding Displacements of Gravity Dams

Aristide Razavet[1], Pierre Léger[2]

[1] M.A.Sc. Student, Department of Civil, Geological and Mining Engineering, Polytechnique, Montreal, QC, Canada.
[2] Professor, Department of Civil, Geological and Mining Engineering, Polytechnique, Montreal, QC, Canada.

ABSTRACT

Seismic safety assessment of gravity dams subjected to strong earthquakes requires an estimation of potential residual sliding displacements using dynamic time history response analyses. In Eastern North America (ENA), there is a lack of suitable historical ground motion records to perform these analyses. Herein, the NBCC 2015 guidelines are used to select and scale (i) eleven historical ground motion records, some originating outside of ENA, and (ii) eleven ENA synthetic records. Scaling is performed using either (i) scalar coefficients, or (ii) a time domain spectral matching procedure adding wavelets. Applications were then performed on an 80m gravity dam investigating base sliding displacements using rigid body dynamics and cracked upper crest block sliding displacements using linear time history analyses combined with rigid body dynamics. The ground motions cumulative absolute velocities (CAV) was found a good a priori indicator of residual sliding displacements. Overall, for the dam analysed, the use of spectrally modified accelerograms (wavelets) did not affect the sliding at the base of the dam as compared to the use of accelerograms scaled using scalar coefficients. However, crest block displacements were found more sensitive to the use of synthetic accelerograms as compared to the use of historical records, being smaller with synthetic records. On the other hand, the consideration of vertical accelerations causes an increase in residual displacements of 25% for historical records as compared to 40% in the case of synthetic records. The use of historical records is preferred if adequate spectral matching is achieved with proper CAV. Synthetic records could also be used but they may provide a lower bound estimate of residual sliding displacements.

Keywords: Concrete gravity dam; Ground motion selection; Ground motion scaling; Rigid body dynamics; Sliding

INTRODUCTION

The Quebec Dam Safety legislation [1] makes it possible to use data from the Geological Survey of Canada (GSC) to define seismic hazards that affect the earthquake response of concrete hydraulic structures located in Quebec. GSC data are used in the National Building Code of Canada (NBCC). Appendix J of NBCC (2015) [2] provides new detailed guidelines for the selection and scaling (S&S) of ground motion (GM) records to be used in linear or nonlinear time history analyses (LTHA or NLTHA). The NBCC is developed for buildings that, in most cases, have different dynamic characteristics from those of concrete gravity dams with short periods of vibration in the 0.03s - 0.30s range [3]. The key objective of this study is to investigate the incidence of different ground motions S&S procedures to achieve NBCC target spectrum compatibility requirements and compute related residual dam sliding displacements.

The paper first compares different S&S methods considering different aspects such as (i) the elaboration of several earthquake magnitude-distance (M-R) scenarios to cover the target spectrum period range, (ii) the use of historical versus synthetic seismic accelerograms; (iii) the use of vertical accelerations; and (iv) the use of spectrally modified accelerograms in the time domain to closely match the target spectrum ("spectral matching") using added wavelets. An 80m gravity dam, of typical cross-section, located in ENA is selected for applications. Two methods of increasing complexity are investigated in comparative studies to evaluate the residual seismic sliding displacements of the dam using different S&S procedures. (1) The sliding at the base of the dam is estimated using rigid body dynamics with the RS-DAM software [4] ("Rocking-Sliding of dams"). (2) The sliding of a cracked crest block is estimated with the combination of LTHA (using SAP2000, [5]) to compute and extract absolute accelerations that are applied to the base of a detached crest block rigid body model analysed using RS-DAM.

NBCC 2015 CODE REQUIREMENTS

Target spectrum and period range

According to the NBCC guidelines, for buildings S&S of ground motion records must be performed using a target design spectrum (DS) over a period range, T_R, that extends *from* $\mathbf{T_S}$ (i) the shortest of a period equal 0.15 T_1 or the period of the highest mode required to achieve 90% mass participation, *to* $\mathbf{T_L}$ (ii) the longer of a period equal to $2T_1$ or 1.5 s, with T_1 equal to the fundamental period. For the 80m gravity dam analysed, $T_1 \cong 0.22$s and $T_S \cong 0.005$s. Due to difficulty in scaling records in the very short period range, T_S was limited to 0.05s and no shorter. The longer period is taken as $T_L = 1.0$s to be more than 2 T_1 allowing for the unknown effective period elongation due anticipated cracking increasing the dam flexibility.

$$T_R = [0.05 - 1.0]\ s \tag{1}$$

The spectral ordinates values, Sa(T), of the target UHS used herein are shown in Table 1 and displayed in Figure 1.

Table 1. NBCC UHS DS for site class A .

T (s)	Sa(T); g
$\leq$ 0.01	0.105
0.05	0.159
0.1	0.169
0.2	0.132
0.3	0.099
0.5	0.073
1.0	0.043
2.0	0.023
$\geq$ 4.0	0.007

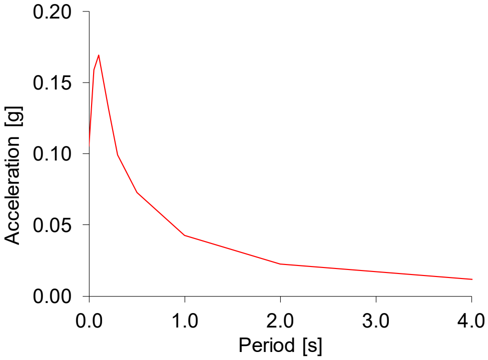

Figure 1. Target UHS for A class site (ξ=5%),

Selection of ground motion records

According to NBCC 2015 [2], the Target Response Spectrum (TRS) corresponds to the design spectrum Sa(T) within the period range of interest (T_R). Atkinson [6] suggested that magnitude M6.0 earthquakes could be used for periods shorter than 0.5 s whereas M7.0 events would be adequate for longer periods. Based on this information, and on Michaud & Léger [7], three magnitude/fault distance (M-R) scenarios were defined to cover the UHS period range of interest, as shown in Table 2.

Table 2. Selected M-R scenarios and corresponding scenario-specific period ranges.

Scenario	Scenario–Specific Period Range (s)	Historical GM		Synthetic GM	
		M	R (km)	M	R (km)
A	$0.05 \leq T \leq 0.15$	-	-	6	10 – 30
B	$0.1 \leq T \leq 0.5$	5.5 – 6.5	0 – 40	6	10 – 30
C	$0.5 \leq T \leq 1.0$	6.75 – 7.5	10 - 100	7	15 - 100

For ground motions selection, NBCC 2015 suggests the use of (i) historically recorded ground motions, or (b) synthetic (simulated) ground motions. The use of historical records is recommended when possible. As stated in Koboevic et al. [8] and supported by Michaud & Léger [7], the use of synthetic ground motions is adequate in non-linear analyses of ENA buildings.

As recommended in NBCC and confirmed in Soysal et al. [9], 11 historical and synthetic GM records were carefully selected for the site location as shown in Table 3. Historical ground motions were selected using the "PEER Ground motion database" web application [10]. At first, three M-R GM records on rock sites were selected from the East database considering that this database is still young and growing. The eight remaining GM records were selected from the West database that is more exhaustive using M-R-geological search characteristics similar to the East region. The synthetic ground motion database created to be compatible with the NBC 2005 by Atkinson [6] was used to select M6 and M7 ENA GM records for a class A site. The selected GM records are shown in Table 3, with their respective peak ground acceleration, PGA, and cumulative absolute velocity, CAV. The corresponding 5% damped acceleration spectra, before scaling, are displayed in Figure 2 by M-R scenarios.

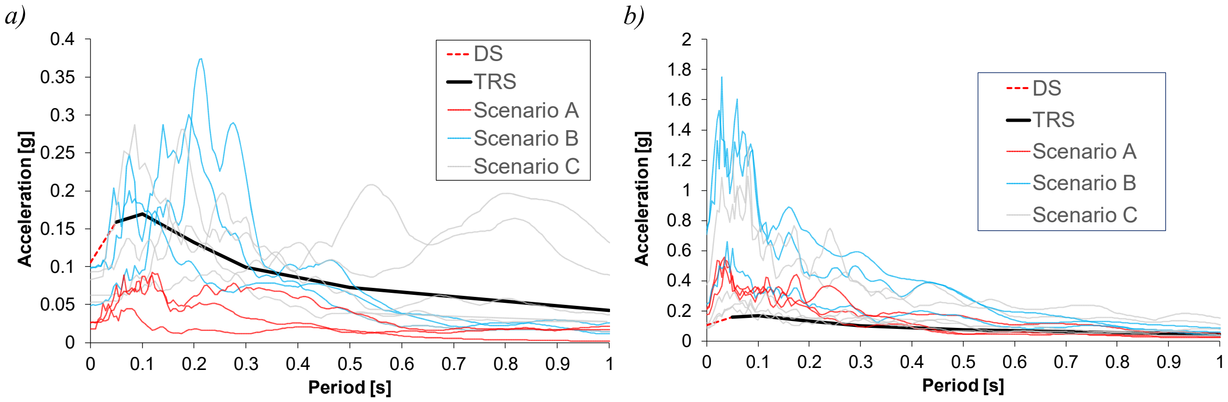

Figure 2. 5% damped acceleration spectrum of selected GM records before scaling: (a) historical; (b) synthetic.

Table 3. Selected historical and synthetic unscaled and scaled GM records: magnitude (M), peak ground acceleration (PGA in g) and cumulated absolute velocity (CAV in cm/s); o=original, MSE=Mean Square Error, SM=Spectral Matching.

	Historical								
Event	**Scen -ario**	**Year**	**M**	**PGA^{O}**	**PGA^{MSE}**	**PGA^{SM}**	**CAV^{O}**	**CAV^{MSE}**	**CAV^{SM}**
Val des Bois	A	2010	5.1	0.018	0.128	0.134	113	797	791
Sparks (1)	A	2011	5.68	0.027	0.082	0.066	127	385	379
Sparks (2)	A	2011	5.68	0.026	0.080	0.067	202	621	608
Morgan Hill	B	1984	6.19	0.099	0.095	0.069	175	168	150
Sierra Madre	B	1991	5.61	0.098	0.098	0.057	116	116	100
Whittier Narows	B	1987	5.99	0.049	0.081	0.057	66	109	102
Loma Pr. (1)	C	1989	6.93	0.062	0.035	0.028	195	110	102
Loma Pr. (2)	C	1989	6.93	0.093	0.049	0.045	224	117	114
Duzce, Turkey	C	1999	7.14	0.053	0.082	0.079	201	311	305
Iwate (1), Japan	C	2008	6.9	0.107	0.253	0.252	708	1670	1668
Iwate (2), Japan	C	2008	6.9	0.083	0.202	0.203	367	894	893
	Synthetic								
6a2, 21	A	2009	6	0.215	0.114	0.115	129	69	69
6a2, 31	A	2009	6	0.208	0.104	0.108	213	106	107
6a2, 40	A	2009	6	0.172	0.088	0.087	133	68	67
6a1, 35	B	2009	6	0.731	0.149	0.146	269	55	56
6a1, 38	B	2009	6	0.691	0.176	0.181	280	71	72
6a2, 35	B	2009	6	0.240	0.125	0.121	224	116	117
7a1, 31	C	2009	7	0.365	0.138	0.141	625	236	237
7a1, 42	C	2009	7	0.427	0.126	0.127	737	218	217
7a2, 24	C	2009	7	0.092	0.108	0.108	216	255	255
7a2, 40	C	2009	7	0.092	0.080	0.080	188	162	163
7a2, 45	C	2009	7	0.087	0.100	0.102	194	222	223

Ground motion scaling and spectral matching

Following GM records selection, scaling of GM records to match the TRS must be done. In NBCC 2015, the scaling method is left to the user's discretion. However, it is stated that "*time-domain spectral matching techniques intended to match the target spectrum may be used with caution, carefully evaluating the behaviour of the acceleration, velocity and displacement traces, including the presence of acceleration pulses, before and after spectral matching*". Different scaling methods were investigated in Michaud & Léger [7] and the "Mean Square Error" (MSE) was found very effective. The MSE equation is given below [11]:

$$MSE = \frac{\sum_i w(T_i)\cdot\{ln[Sa_{target}(T_i)]-ln[f\cdot Sa_{response}(T_i)]\}^2}{\sum_i w(T_i)} \tag{2}$$

Where $w(T_i)$ is a weight function allowing the user to apply different weights to some periods of greater interest, $Sa_{target}(T_i)$ is the spectral acceleration of the target spectrum, $Sa_{response}(T_i)$ is the spectral acceleration of the ground motion being scaled and f is a linear scaling factor applied to the entire response spectrum. As required in NBCC, the records were scaled to be over 90% of the design spectrum for each scenario-specific period range as shown in Figure 3. When comparing scenario-specific mean spectrum, the scaled synthetic ground motions have a better overall spectral matching with the target DS.

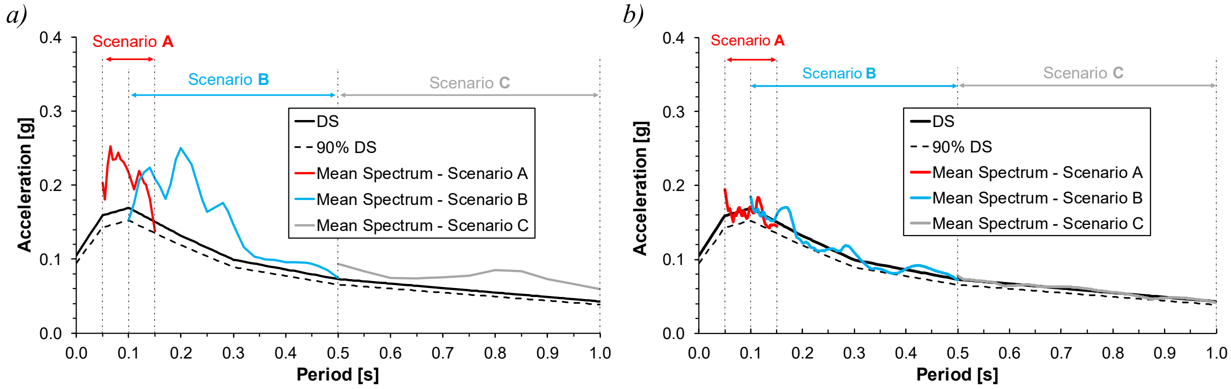

Figure 3. Design spectrum and mean response spectra for each suite of scenario specific records scaled using MSE: (a) historical; (b) synthetic.

In addition to the MSE scaling method, time domain (TD) spectral matching of GM was investigated. In TD spectral matching, wavelets are added or subtracted to the original GM records which modifies the intensity and frequency content of ground motions to better match the target DS. Spectral matching was done using the Seismosoft software [12] which is based on the methodology developed by Al Atik and Abrahamson [13]. When compared to Figure 3a, the mean response spectrum for each scenario specific historical records displayed in Figure 4 have a better matching with the target DS. Similar results were obtained for synthetic GM records.

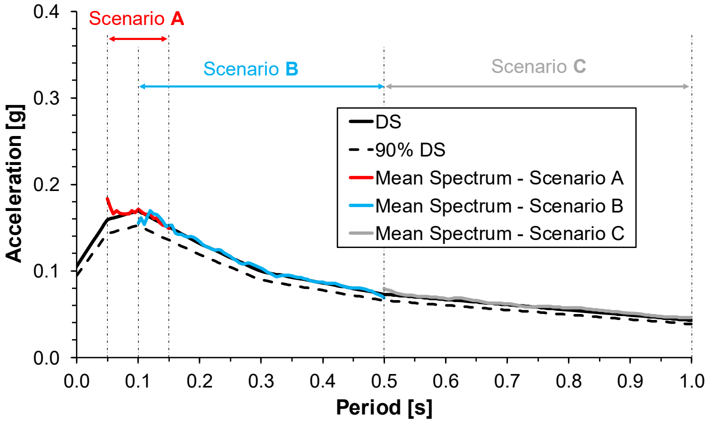

Figure 4. Design spectrum and mean response spectra for each suite of scenario specific historical records scaled using spectral modification.

GRAVITY DAM FOR APPLICATIONS

A concrete gravity dam located in Eastern Canada was chosen for applications. Only the highest monolith of the dam was considered for analysis as displayed in Figure 5. The monolith is 78.3 m high with a 14.2 m width. The water reservoir is 76.6 m high. The foundation rock under the dam is taken as a site class A and the fundamental period, T_1, including the Westergaard added mass from the reservoir was estimated to be 0.22 s.

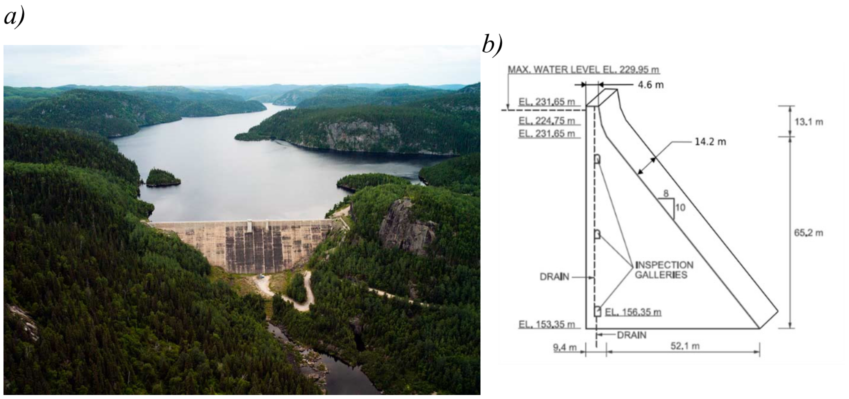

Figure 5. 80 m dam for application: a) aerial view; b) detailed isometric section from Bernier & al. [14].

At first, the monolith of the dam was modeled in RS-DAM as a rigid body to evaluate the dam residual sliding displacements at the base. A bilinear distribution was used to model the effects of uplift pressures considering the drain. The static uplift pressure distribution is considered unchanged during seismic excitations. For all the historical and synthetic seismic excitations (22 in total) both horizontal and vertical GM components were used in the analyses for a total of about a hundred analyses. The vertical ground motions were scaled / matched using 2/3 of the horizontal DS as recommended in NBCC 2015. Because RS-DAM is using rigid body dynamics, no dynamic amplification effect is considered and only rocking and sliding at the base of the monolith is considered using a zero rock-concrete tensile strength and a 45° residual friction angle (tan 45°=1). However, for sliding to occur, the critical acceleration causing the resulting downstream force resultant must be larger than the shear strength that could be mobilised. A dynamic amplification factor of 4 was applied to every GM record to induce sliding displacements and compare the results using different S&S methodologies on a common basis.

RIGID BODY SEISMIC SLIDING RESPONSES

In this section, the results of the parametric study on the residual base sliding of the dam using a rigid body model are used to compare and discuss three aspects: (a) the use of historical vs synthetic GM records, (b) TD spectral matching, and (c) vertical accelerations. Because the two historical records from Iwate event lead to residual sliding more than 10 times larger than the average, there were rejected. When special attention was drawn to their characteristics, their CAV and "Arias intensity" (AI not shown) were two to five times larger than the average (Table 2). Selection of GM records cannot be based solely on matching the DS spectral shape. Parameters as CAV and Arias Intensity that characterise strong shaking intensity and duration including the presence of strong acceleration pulses promoting sliding, should be examined.

Historical vs synthetic records

Figure 6a displays the residual base sliding displacements time histories of the monolith subjected to both historical and synthetic GM records. Even if sliding initiation does not take place at the time, the final residual sliding is about 4 mm for both GM records. As shown in Figure 6b, the average of residual sliding displacement induced by historical GM records is 0.95 mm compared to 1.16 mm for synthetic records, while standard deviation is respectively 1.28 and 1.12. Those are very small physical quantities. However, synthetic GM records appear appropriate to evaluate base sliding of a monolith when historical records aren't available.

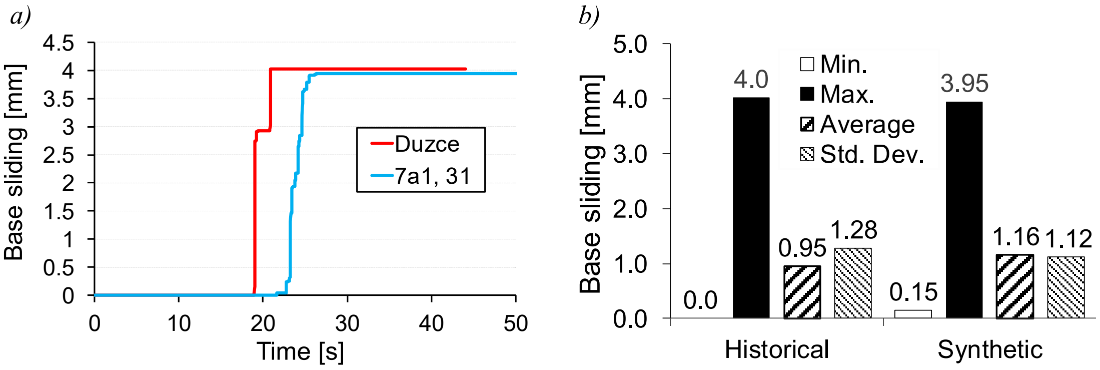

Figure 6. a) Comparisons of the residual base sliding of the dam using historical and synthetic ground motions (RS-DAM); b) Results of the parametric study (excluding Iwate 1 & 2).

Spectral matching effects

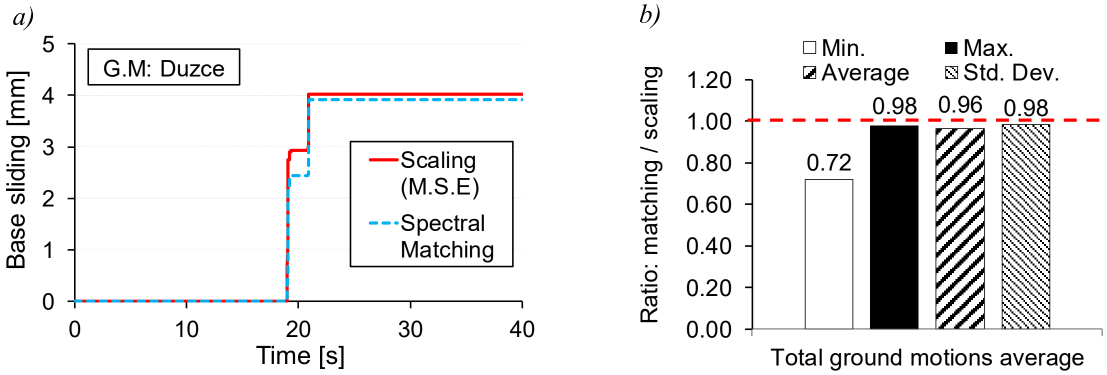

Figure 7. a) Comparisons of the residual base sliding using scaling and spectral matching (RS-Dam); b) Ratio of base sliding induced by TD spectrally matched and scaled ground motion records.

While using the TD spectral matching method, even though the original record is modified with addition or subtraction of wavelets, Figure 7a indicates no significant decrease in the residual base sliding of the monolith for the "Duzce" GM record. Figure 7b indicates that the residual sliding displacement ratio of the average value between all matched and scaled GM record is 0.96 while the standard deviation is 0.98. TD spectral matching evaluated on various records doesn't affect the residual base sliding displacements of the dam.

Vertical acceleration effects

When considering vertical accelerations, V, in seismic analyses, especially with synthetic GM records, users should consider the combination of horizontal, H and positive (+V) or negative (-V) vertical accelerations. As demonstrated in Figure 8a, the combination of H -V lead to larger dam sliding displacements. Figure 8b indicates that the dam base sliding ratios between the combinations of [H & V] and [H only] are on average 1.2 for historical and 1.4 for synthetic GM records. Considering these results, vertical acceleration plays an important role in the residual dam sliding displacements and should be considered in seismic analyses.

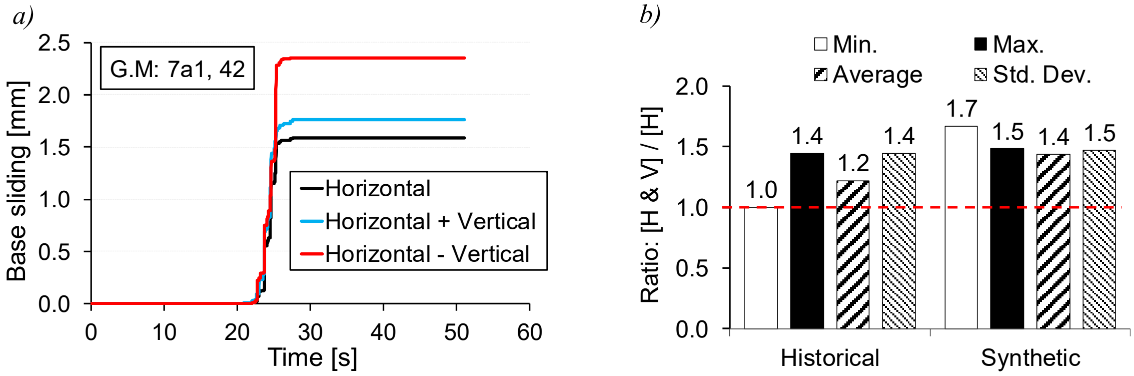

Figure 8. a) Comparisons of the residual base sliding using horizontal and vertical ground motions (RS-Dam); b) Ratio of the base sliding with and without vertical ground motion.

FLEXIBLE DAM SEISMIC SLIDING RESPONSES

The second method aimed at evaluating the residual seismic sliding displacements of the dam crest block is considering directly the dam flexibility and the related dynamic amplification effects [14-18]. A complete flexible 2D FE model (Figure 9a) of the dam is initially used to compute absolute horizontal and vertical accelerations at the "J" node located at the base of the block. These accelerations are applied to a crest block rigid body model using RS-DAM, as shown in Figure 9b following the procedure described in [17].

The FE model developed in SAP2000 is based on the geometry used in Bernier [14] and consists of 2D plane strain elements restrained by a nearly rigid foundation. The upstream hydrostatic forces and hydrodynamic forces with Westergaard added mass were used. Considering the large foundation stiffness, and the small dimensions used, the ground motion records were applied directly at the base of the foundation. The dam-foundation-reservoir system has 5% damping with a fundamental period of vibration of 0.22 s.

In RS-DAM, the geometry represents the cracked upper part of the dam, given that an upper crack tends to appear near the geometrical change of the downstream slope [17]. The selected material modelling parameters and applied reservoir forces were similar to those used for the full monolith rigid body model, except for the uplift pressures which followed a linear distribution.

GM records were applied to the flexible FE model. The resulting accelerations at the "J" node are applied in rigid body analyses of the crest model in RS-DAM. These accelerations were amplified by a factor of 1.5, an arbitrary scalar used in all analyses to induce significant sliding, which does not compromise comparisons among different S&S GM records methods. All the GM records were used and the average of the 5 records inducing the largest displacements were used to investigate vertical acceleration effects on the residual sliding displacements for a flexible dam.

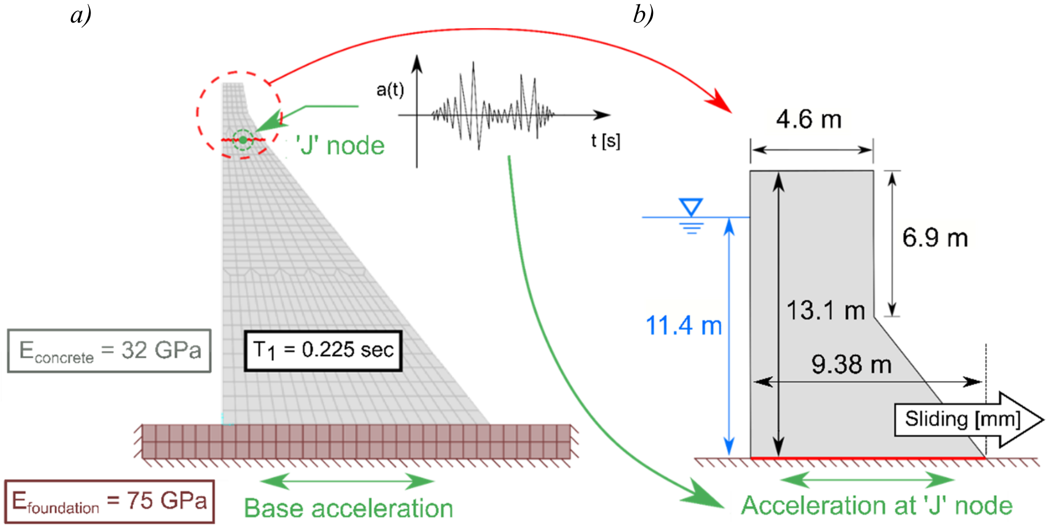

Figure 9. Seismic analysis of a concrete dam combining: a) Flexible elastic dam: linear time-history analyses (SAP2000); b) Rigid body dynamics of cracked component analysed with RS-DAM.

Figure 10a points out the important effect of considering the vertical acceleration on the residual sliding displacements for the cracked upper block. As shown in Figure 10b, the residual sliding displacements ratios between the combinations of [H & V] and [H only] are in average 1.57 for historical GM records and 2.33 for synthetic GM records. Not only is that the vertical acceleration should be considered in seismic sliding analysis of dams, but the dynamic amplification coming from the dam flexibility plays an important role in that matter and should therefore be taken into consideration.

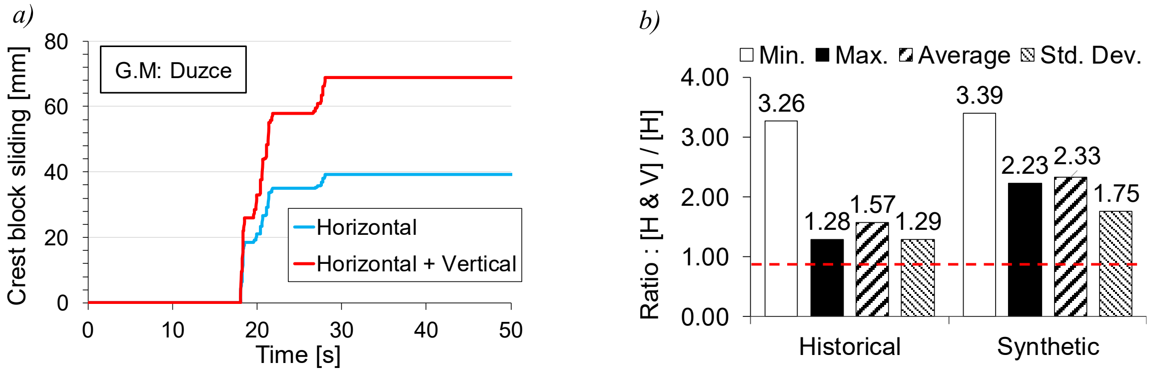

Figure 10. a) Comparisons of the residual crest block sliding using horizontal and vertical ground motions (SAP + RS-Dam); b) Ratio of the base sliding with and without vertical ground motions.

Additional studies were done using a non-linear FE model of the monolith using LS-Dyna [19] using tiebreak Mohr-Coulomb sliding contact elements producing results with somewhat larger dispersions. Further details can be found in Razavet [20].

CONCLUSIONS

The estimation of seismically induced residual seismic sliding displacements of gravity dams requires the selection and scaling (S&S) of suitable ground motion acceleration records. The CNBC 2015 provides guidelines suggesting different alternatives to do so. These guidelines were applied in the context of the seismic study of an 80m high gravity dam located in Eastern North America were there is a lack of historically recorded strong motion records. Therefore, synthetic ENA records were used in addition to historical records selected from different seismic events worldwide. The mean square error (MSE) scaling method indicated that it is difficult to fit the target spectrum in the short period range [0.05s-0.5s]. The variability of the residual sliding displacements shows that the selection of accelerograms cannot be based solely on the correspondence of the spectral ordinates with the target spectrum. Additional parameters such as Cumulative Absolute Velocity, CAV, and Arias Intensity, AI, must be used as complementary indicators reflecting the presence of long acceleration pulses inducing significant displacements. The modification of accelerograms by adding wavelets to achieve better "spectral matching" did not affect the sliding potential (CAV) characterizing seismic ground motions. Synthetic GM records have been found appropriate to evaluate base sliding of a rigid monolith when historical records aren't available, producing fairly similar results to those of historical GM records. However, crest block sliding displacements estimated using a flexible dam showed significant differences when using synthetic records as compared to historical records. Vertical accelerations increase the residual sliding displacement of the dam by up to 40% and should be considered in seismic stability assessment of dams. Considering the dispersion of the calculated displacements in each method, the use of eleven seismic accelerograms (recommended in NBCC) appears as the most appropriate approach in the context of dam seismic safety assessment using nonlinear dynamic time history analyses.

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