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Effects of selection and modification of ground motions on the seismic safety evaluation of gravity dams in Eastern Canada

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ABSTRACT

Assessing the structural safety of concrete gravity dams against earthquakes is often carried out through linear or nonlinear time history analyses using a limited number of ground motions. How the ground motions are selected and/or modified to correspond to anticipated seismic hazard in a given site can be critical for the seismic design and safety evaluation of structures. Different approaches have been proposed in several building codes and guidelines, but their appropriateness, performance and effectiveness in the context of the concrete gravity dams have been rarely studied. This paper utilizes different ground motion modification techniques that are commonly used in seismic design and evaluation of buildings and compares their effects on the prediction of seismic linear and nonlinear response of concrete gravity dams in Eastern Canada. For this purpose, two typical gravity dams located on two sites in Eastern Canada are studied. Ground motions from both simulated and historical databases are selected and scaled to site-specific seismic hazard levels. Linear and nonlinear analyses of the two dams under are conducted. Obtained engineering demand parameters such as dam crest displacement, dam sliding safety factors, and dam base residual sliding are compared and discussed.

Keywords: Gravity dams, Seismic stability, Dam safety, Scaling of ground motions, Eastern Canada

INTRODUCTION

The failure of critical structures such as dams can cause major human toll and economic loss. Among others, earthquake is one of the main natural hazards for most of concrete dams. Although Eastern Canada is situated in a stable intra tectonic plate region, it has been shaken by several moderate to strong historical earthquakes [1]. Seismic safety evaluations of concrete gravity dams are often carried out in forms of linear and nonlinear time history analyses. It is preferred to use real ground motions when performing time history analysis. When real records are limited, as the case in Eastern Canada, simulated records can be used [2]. Significant research efforts have been devoted to study various factors that contribute to the seismic response of dam monoliths [3-5]. However, the sensibility of predicted dam seismic demands to the input ground motions has rarely been studied. Soysal et al. [5] assessed the performance of different scaling procedures in predicting seismic demands on dams, using PEER NGA-West2 [6] ground motions. They concluded that scaling techniques commonly used for moment frames should not readily be applied to dam structures. It should be noted that the performance of different scaling methods in seismic stability analysis of concrete gravity dams located in Eastern Canada has not been studied.

The main objective of this study is to investigate effects of different ground motion modification techniques on the prediction of seismic linear and nonlinear response of concrete gravity dams in Eastern. In the next section, the studied dam monoliths and seismic hazard of the chosen dam sites are presented. Followed by a summary of the historical and simulated ground motion database used in this study. Different scaling techniques and the scaled ground motion suites for each case are presented. The effects of different scaling methods on the prediction of linear and nonlinear engineering demand parameters of gravity dams are compared and discussed. The adequate number of ground motions required in seismic safety analysis for concrete gravity dams is also investigated.

STUDIED DAMS, SEISMIC HAZARD AND GROUND MOTIONS

Dam properties and finite element models

As illustrated in Figure 1, two typical concrete gravity dam monoliths D1 and D2, with heights of 35 m and 90 m, respectively, are considered to investigate the influence of dam geometry on the results. A density and a modulus of elasticity of $\rho = 2400$ kg/m^3 and E = 25 GPa, respectively, are assumed for the concrete. Water in the reservoir is assumed incompressible and hydrodynamic loads are modeled using Westergaard added masses [7]. Uplift pressures are assumed constant during seismic excitation as recommended by most guidelines [8-10]. A drainage gallery at a height of 5 m and 5 m from the upstream face of the dam is considered with an efficiency of 66%. The dam foundation is assumed massless and infinitely rigid. The dam monoliths are modeled using 2D plane stress Finite Elements according to the meshes shown in Figure 1. A stiffness-proportional Rayleigh damping, equivalent to a modal damping of 5% critical, is considered. Nonlinearities are localized at the concrete-rock interface to investigate the stability of the dam against sliding along this interface. The sliding at the dam-rock interface is modeled using frictional contact elements programmed in ADINA [11] according to the Mohr–Coulomb rupture criterion. Different values of friction angle ϕ and cohesion c at the dam-rock interface are considered [4]. The analyses are carried-out using the finite element software ADINA [11].

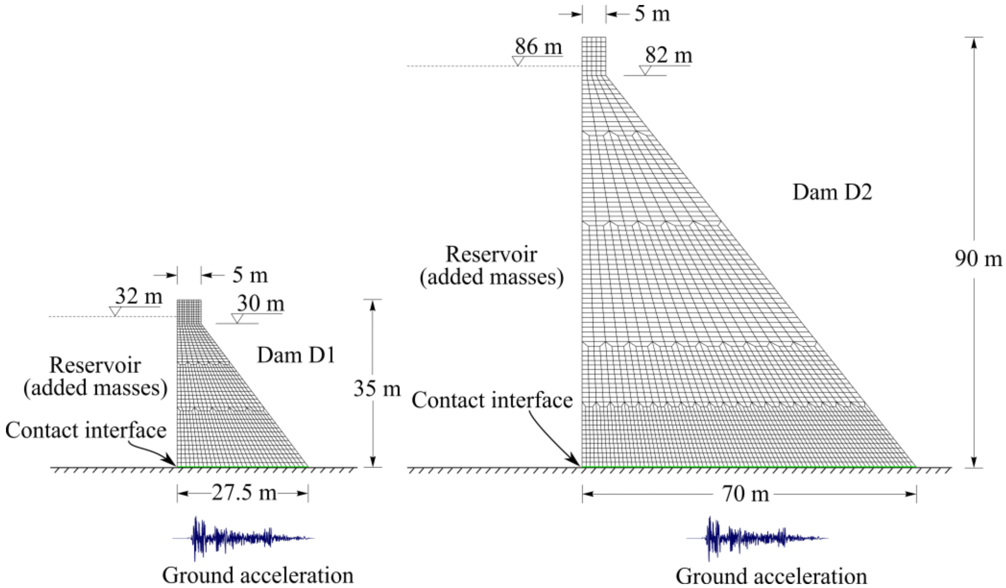

Figure 1 Geometry and finite elements model of D1 and D2 dam

Dam sites, seismic hazard and target spectra

Two dam locations with different seismic hazard levels in Eastern Canada are considered: Montreal and La Malbaie. Both locations are of soil type A (rock). A return period of 2475 years is assumed (corresponding to a probability of exceedance of 2% in 50 years) in this study. The corresponding Uniform Hazard Spectra (UHS) according to National Building Code of Canada (NBCC) 2015 [2] are shown in Figure 2 for both locations and will serve later as the target spectra for the ground motion scaling processes. The fundamental vibration periods T_1 of dam-reservoir systems D1 and D2 are 0.109 s and 0.280 s respectively. Table 1 shows the moment magnitude (Mw) and hypocentral distance (R) considered in this study. They are obtained based on the deaggregation of seismic hazard provided by Earthquakes Canada and the fundamental vibration periods T_1 of dam-reservoir D1 and D2.

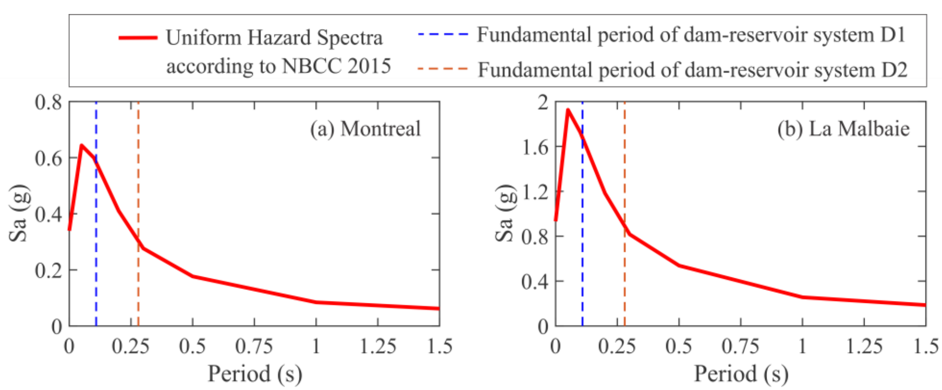

Figure 2 Target spectra of Montreal and La Malbaie for soil type A

Ground motion records used

Historical and simulated earthquakes were used in this work. The historical database consists 108 horizontal accelerograms recorded from eight historical earthquakes with magnitudes Mw varying from 4.5 to 6.9, and epicentral distances from 6.8 to

640 km were considered [12-14]. All ground motions were recorded on hard rock sites, i.e. NBCC 2015 [2] site class A ($V_{S30} \geq 1500\ \mathrm{m/s}$). A list of these earthquakes is provided in Table 2. The database of historical ground motions is supplemented by a suite of simulated, i.e. synthetic, ground motions. The suite was generated using stochastic finite-fault method for M-R scenarios that govern seismic demands in Eastern Canada [15]. The simulated database contains 180 accelerograms classified into four sets (45 accelerograms each) as a function of magnitude and fault distance, i.e. M6.0 at 10 to 15 km, M6.0 at 20 to 30 km, M7.0 at 15 to 25 km and M7.0 at 50 to 100 km. Historical and simulated ground motion databases were used separately to investigate their influences on the responses of dams. Each horizontal component is used individually when selecting the records for time history analysis. Ground motion candidates that are representative of the seismic hazard of dam sites were selected according to acceptable magnitude and distance ranges established for each M-R scenario presented in Table 1.

Table 1 Moment magnitude (Mw) and hypocentral distance (R) scenario for dam D1 and D2 in Montreal and La Malbaie

	Montreal		La Malbaie	
	Mw	R	Mw	R
D1	6.4	27 km	6.5	16 km
D2	6.5	32 km	6.7	18 km

Table 2 Historical ground motions studied [14]

Event	Magnitude	Number of records	Site class
Nahanni (11/1985)	4.5	2	A
Nahanni (12/1985)	6.9	4	A
Saguenay (1988)	5.8	18	A
Cap-Rouge (1997)	4.7	16	A
Pymatuning (1998)	5.0	2	A
Cote-Nord (1999)	4.7	18	A
Au-Sable-Forks (2002)	5.1	26	A
Rivire-du-Loup (2005)	5.0	16	A
Val-des-Bois (2010)	5.0	6	A

SCALING OF GROUND MOTION RECORDS

Ground motion scaling methods used

The ground motion scaling methods considered in this paper are: (i) scaling to the peak ground acceleration (PGA) of target spectra [16]; (ii) scaling to the target spectral acceleration $\mathrm{Sa}(T_1)$ at the fundamental vibration period T_1 of the structure [17]; (iii) scaling according to ASCE 7-16 specifications. Zimmerman et al. [18] suggest that each ground motion should be scaled to match the target spectrum on average over the period range of interest. ASCE 7-16 [19] suggests that the period range should be taken as $[\min(0.2T_1, T_{90\%}), 2T_1]$ where T_1 is the fundamental vibration period of the structure and $T_{90\%}$ is the period of the highest vibration mode required to cumulate a minimum participation of 90% of the structure's mass; (iv) scaling according to the guidelines of NBCC 2015 [20] by insuring the individual scaled response spectra equals or exceeds the target response spectra, on average, over a period range defined as $[\min(0.15T_1, T_{90\%}), \max(2T_1, 1.5\ \mathrm{s})]$. In addition, all records of each suite should be scaled by a second, common factor such that the mean response spectrum of the selected ground motion suite does not fall more than 10% below target spectral acceleration over the defined period range and (v) scaling to minimize the mean square error (MSE) between ground motion response spectra and the target spectra over a period range [21].

Most ground motion scaling methods, such as the NBCC 2015, the MSE and the ASCE techniques, require the definition of a period range of interest which is assumed to appropriately account for typical frequency content of seismic demands and the seismic response of the studied structure, including higher mode effects and period elongation due to nonlinear behavior [22-24]. To investigate the effects of different period ranges used in the scaling procedures on the response of a stiff structure such as concrete gravity dams, we applied, in methods (iv) and (v), three different period ranges adapted based on the guidelines of NBCC 2015 [2]. The applied period ranges are: $[\min(0.15T_1, T_{90\%}), \max(2T_1, 0.5\ \mathrm{s})]$, $[\min(0.15T_1, T_{90\%}), \max(2T_1, 1.0\ \mathrm{s})]$ and $[\min(0.15T_1, T_{90\%}), \max(2T_1, 1.5\ \mathrm{s})]$. In total, nine ground motion scaling procedures were used, and they are denoted as PGA, $\mathrm{Sa}(T_1)$, ASCE, $\mathrm{NBCC}^{(0.5\ \mathrm{s})}$, $\mathrm{NBCC}^{(1.0\ \mathrm{s})}$, $\mathrm{NBCC}^{(1.5\ \mathrm{s})}$, $\mathrm{MSE}^{(0.5\ \mathrm{s})}$, $\mathrm{MSE}^{(1.0\ \mathrm{s})}$, $\mathrm{MSE}^{(1.5\ \mathrm{s})}$ in the following sections.

Scaled ground motion suites

Using the above-mentioned scaling methods, a total of 72 suites of ground motion records were produced for different dam monoliths, dam sites and ground motions databases. Each suite contains 11 records. The mean value of scale factors and scaled PGA of each suite are summarised in Table 3 and Table 4. For illustration purposes, the mean scaled spectrums and individual scaled spectrums corresponding to different scaling methods for D2 dam in Montreal using simulated ground motions are presented in Figure 3.

Table 3 Mean value of scale factors in each ground motion suite

Scaling method	Historical				Simulated			
	Montreal		La Malbaie		Montreal		La Malbaie	
	D1	D2	D1	D2	D1	D2	D1	D2
PGA	3.04	3.08	6.64	6.52	1.24	1.3	1.62	1.57
$\mathrm{Sa}(T_1)$	2.57	2.37	5.95	6.65	0.87	1.1	2.17	1.63
ASCE	2.57	2.95	5.57	6.05	1.42	1.24	3.56	1.84
NBCC$^{(0.5\text{ s})}$	2.58	3.12	6.49	6.05	0.7	0.67	0.85	0.84
NBCC$^{(1.0\text{ s})}$	4.33	3.98	7.8	7.96	0.76	0.64	0.95	0.95
NBCC$^{(1.5\text{ s})}$	4.95	4.19	9.77	9.75	0.9	0.67	0.86	0.86
MSE$^{(0.5\text{ s})}$	2.58	2.92	9.03	6.03	1.55	1.34	2.16	1.84
MSE$^{(1.0\text{ s})}$	4.02	3.17	8.1	8.14	1.48	1.05	1.75	1.98
MSE$^{(1.5\text{ s})}$	4.53	4.48	8.86	9.52	1.85	1.13	1.79	1.72

Table 4 Mean value of scaled PGA (g) in each ground motion suite

Scaling method	Historical				Simulated			
	Montreal		La Malbaie		Montreal		La Malbaie	
	D1	D2	D1	D2	D1	D2	D1	D2
PGA	0.34	0.34	0.93	0.93	0.34	0.34	0.93	0.93
$\mathrm{Sa}(T_1)$	0.28	0.24	0.72	0.73	0.43	0.41	1.02	1.03
ASCE	0.32	0.39	0.92	0.98	0.3	0.31	0.87	0.92
NBCC$^{(0.5\text{ s})}$	0.34	0.36	0.97	0.98	0.42	0.38	1	0.99
NBCC$^{(1.0\text{ s})}$	0.43	0.41	1.12	1.15	0.46	0.36	0.99	0.99
NBCC$^{(1.5\text{ s})}$	0.47	0.4	1.29	1.3	0.56	0.35	1	1
MSE$^{(0.5\text{ s})}$	0.33	0.39	1.08	0.98	0.34	0.31	1.06	0.92
MSE$^{(1.0\text{ s})}$	0.37	0.33	1	1.01	0.35	0.3	0.98	0.99
MSE$^{(1.5\text{ s})}$	0.36	0.37	1.17	1.07	0.45	0.31	0.99	0.99

It can be seen from Table 3 that the scale factors for historical ground motions are generally larger than those for simulated ground motions. For example, using $\mathrm{Sa}(T_1)$ method, the mean value of scale factor for D1 dam in La Malbaie is 5.95 for historical records, almost 3 times larger than 2.17, which is the mean scale factor value for simulated records. This could be explained by the fact that some of the historical ground motions were recorded far from epicenter, thus having low amplitudes. These records require larger scale factors to match to the target spectra. Another observation is that the choice of the period range can affect the mean scaled seismic intensity. For example, in Table 4, the mean scaled PGA of historical ground motion suite for D1 dam in Montreal is 0.47 g when $[\min(0.15T_1, T_{90\%}), \max(2T_1, 1.5\text{ s})]$ is used in NBCC method. When the period range becomes narrower, the corresponding mean scaled PGA becomes smaller, i.e. 0.43 g and 0.34 g for $[\min(0.15T_1, T_{90\%}), \max(2T_1, 1.0\text{ s})]$ and $[\min(0.15T_1, T_{90\%}), \max(2T_1, 0.5\text{ s})]$, respectively. However, this observation is case dependent, for example, the mean scaled PGA for all NBCC suites are almost identical for both dams in La Malbaie when simulated ground motions are used. Figure 3 also shows the effect of period range on the scaled ground motion spectra. For both NBCC and MSE methods, i.e. Figure 3 (d) to (i), the mean scaled spectrum exceeds the target spectrum over corresponding period ranges. As the period range is wider, the over representation of site seismic hazard, as well as the dispersion between individual scaled spectra becomes more important. These results would suggest that for stiff structures such as concrete gravity dams, the period range recommended in building codes may not be appropriate.

RESULTS AND DISCUSSIONS

To investigate the effects of different scaling methods on the response of gravity dams in Eastern Canada, linear and nonlinear time history analyses were carried out using the abovementioned 72 ground motions suites for both D1 and D2 dams. Linear engineering demand parameters such as dam crest displacements and dam sliding safety factors (SSF) are obtained. Nonlinear residual sliding at dam base is also computed.

The mean and dispersion values of maximum dam crest displacements and SSFs are presented separately in Figure 4 and Figure 5, respectively. Both figures show that, when simulated ground motions are used, the linear responses are similar regardless of the scaling method. However, when historical ground motions are used, the responses tend to be more affected by the scaling techniques. When comparing the maximum dam crest displacement in Figure 4, it can be noted that the taller dam D2 has greater crest displacements during earthquake. Ground motion suites scaled by PGA and $\mathrm{Sa}(T_1)$ methods yield to smaller seismic demand comparing to other methods. The results in Figure 4 (d) and (h) also show that the effects of different period ranges are not significant when simulated ground motion are used. In the cases where historical ground motions are used, e.g. Figure 4 (b) and (f), a wider period range can result in a larger crest displacement. Figure 5 shows that both dams at Montreal site are rather stable against sliding: depending on the scaling methods, sliding may occur when friction angle $\phi = 45°$, dams are unlikely to slide when the friction angle $\phi = 55°$. At La Malbaie site though, both dams are susceptible to sliding no matter which scaling method is used. This observation is in line with the fact that La Malbaie has higher seismic hazard than Montreal, as shown in Figure 2.

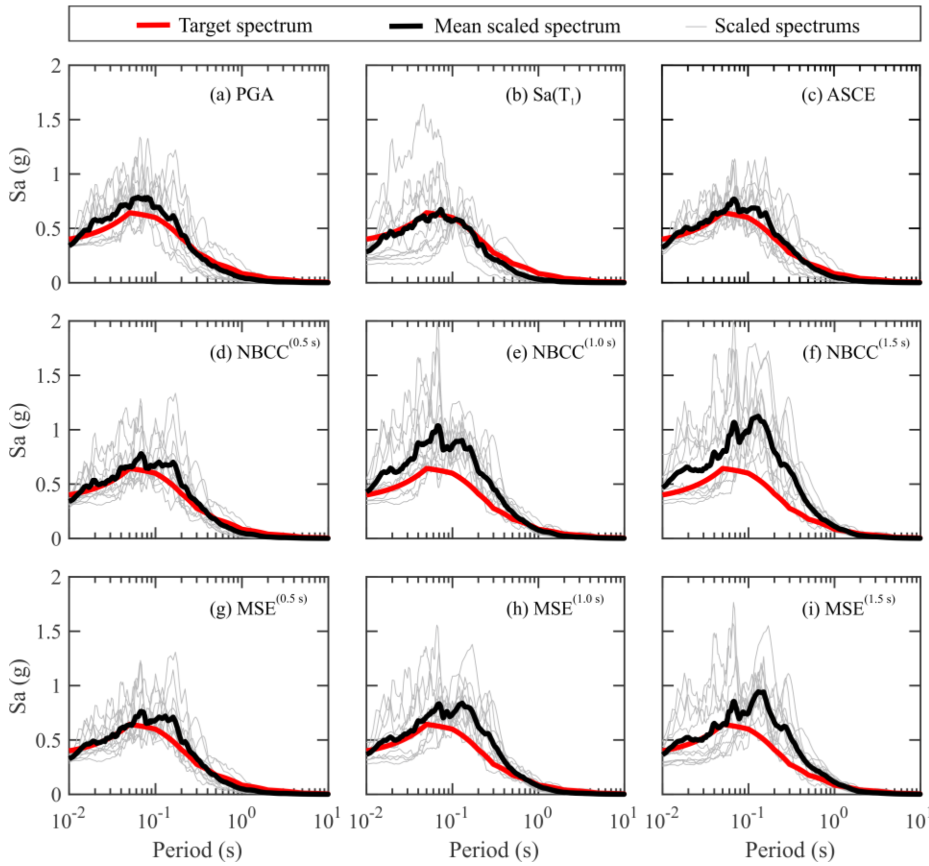

Figure 3 Mean scaled spectrum and individual scaled spectrum produced by different scaling methods for D1 dam in Montreal using historical ground motions

Figure 6 presents the mean sliding displacements of D1 and D2 dams considering different friction values, computed using ground motion suites scaled according to different methods, from historical database as well as simulated database. In contrast to the results shown in Figure 5, nonlinear analyses show that residual sliding occurs in all cases. The effect of friction angle on the dam sliding response can be observed, i.e. dam slides more with a smaller friction angle at dam-rock interface. Most of the time, the historical records used resulted in more residual sliding displacements than simulated ground motions. Also, when simulated records are used, e.g. Figure 6 (c), (d), (g) and (h), the different scaling methods lead to similar mean sliding displacements. The PGA method tends to be less conservative (i.e. induces less displacements) compared to the other methods. The choice of the period range has a slight effect on the mean response, but this observation cannot be generalized. For instance, in Figure 6 (c), the sliding displacements of D1 dam tend to increase when the period range becomes wider for both NBCC and MSE methods, but the results of D2 dam in Figure 6 (d) do not follow this trend. When historical ground motions are used, e.g. Figure 6 (a), (b), (e) and (f), larger differences between the different methods and larger dispersion within each method can be observed. The PGA and the $\mathrm{Sa}(T_1)$ methods give the least conservative results compared to other techniques. No definite trend could be identified for the ASCE method. For example, such approach leads to small mean displacements in Figure 6 (b), whereas in Figure 6 (f), it corresponds to larger mean displacements. The effects of the choice of period range are more apparent when historical ground motions are used. For all cases presented in Figure 6 (a), (b), (e) and (f), larder residual sliding displacements can be observed when the period range becomes wider.

To investigate the appropriateness of using a smaller ground motion suite, we compared the residual sliding displacements obtained using ground motion sets of 3, 7 and 11 records. Figure 7 compares the maximum response of the dams under the effects of sets of 3 records, their mean response under ground motion sets of 7 and 11 records, as well as the corresponding standard deviations. It is observed that for simulated ground motions, using only 3 records can lead to more conservative results in most of the cases, with exceptions of the $\mathrm{Sa}(T_1)$ method in Figure 7 (d) and the $\mathrm{MSE}^{(1.0\ \mathrm{s})}$ method in Figure 7 (f). Using ground motion sets of 7 records gives similar results to those obtained with sets of 11 records irrespective of the scaling method employed. For historical records, the maximum response of ground motion sets of 3 records seems to be not appropriate because it shows great variability compared to the results obtained using ground motion sets of 11 records. As for ground motion sets of 7 records, the mean responses are slightly lower than the results of under the effects of ground motion sets of 11 records.

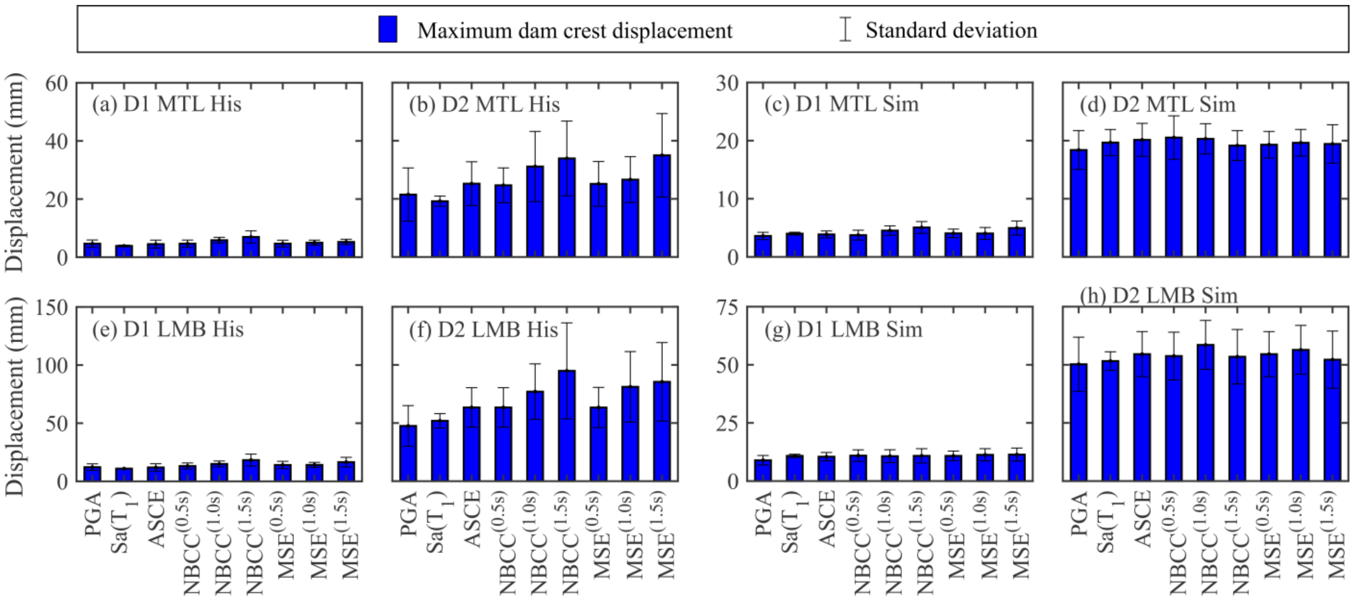

Figure 4 Mean value of maximum crest displacement of studied dams, computed using ground motion suites scaled according to different methods, from historical database as well as simulated database

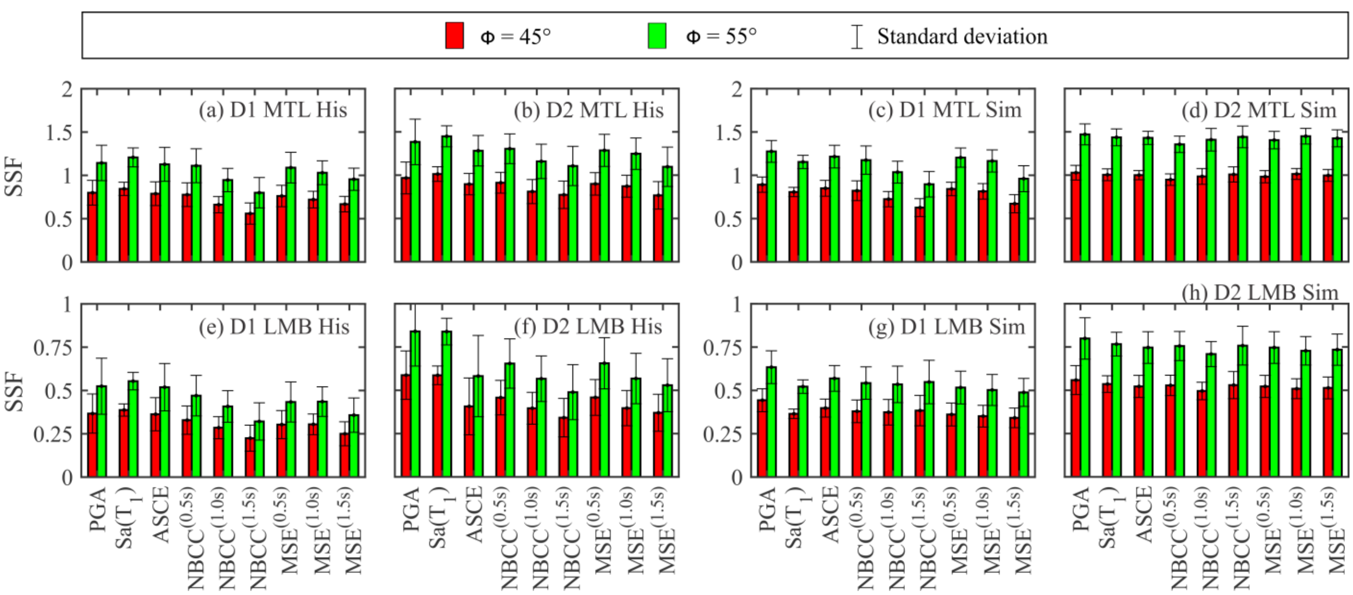

Figure 5 Mean value of SSF of studied dams considering different friction angles ϕ, computed using ground motion suites scaled according to different methods, from historical database as well as simulated database

CONCLUSIONS

This paper investigated the effects of different scaling methods on the evaluation of seismic linear and nonlinear response of concrete gravity dams in Eastern Canada. For this purpose, different ground motion scaling techniques that are commonly used in seismic design and evaluation of buildings were adapted and applied on two dam monoliths located on two sites in Eastern Canada. Historical and simulated ground motion databases were used in this study. Appropriate ground motions suites were selected and scaled to site-specific seismic hazard levels. Linear and nonlinear time history analyses were conducted using 72 scaled ground motion suites. The effects of different scaling methods on the prediction of seismic response were discussed in terms of engineering demand parameters such as dam crest displacement, dam sliding safety factors, and dam base residual sliding displacements. The effects of friction angle on the response of dams were also discussed. The appropriate number of ground motion required for dam seismic safety analysis was also examined.

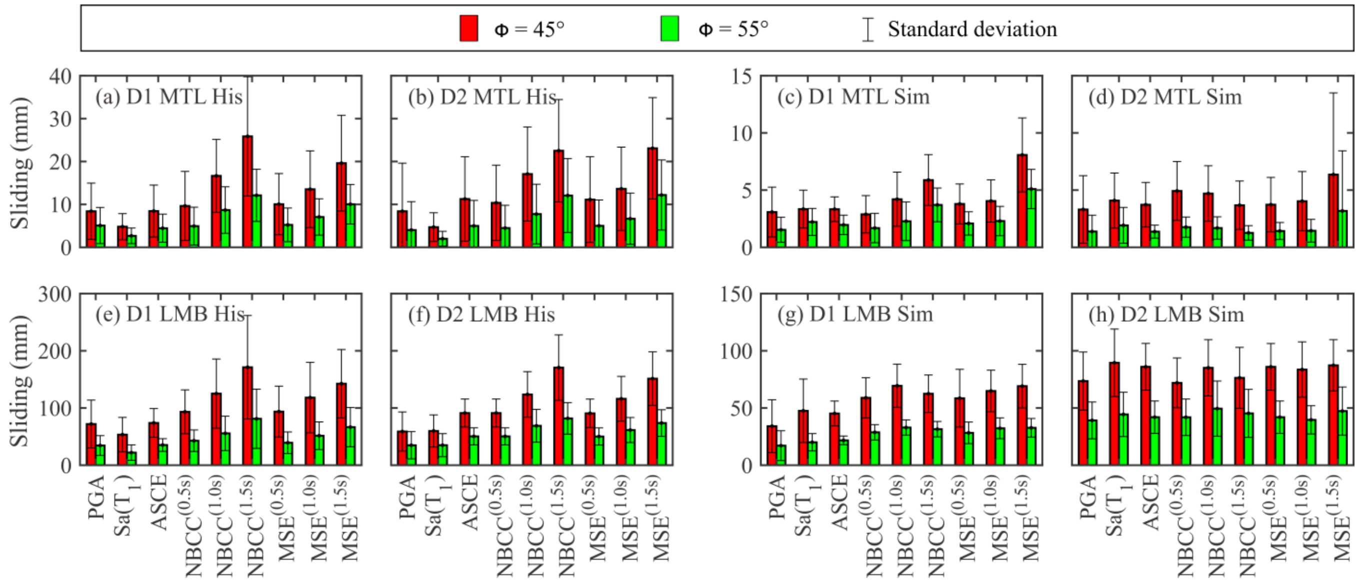

Figure 6 Mean residual sliding displacements of studied dams considering different friction angles \phi, computed using ground motion suites scaled according to different methods, from historical database as well as simulated database

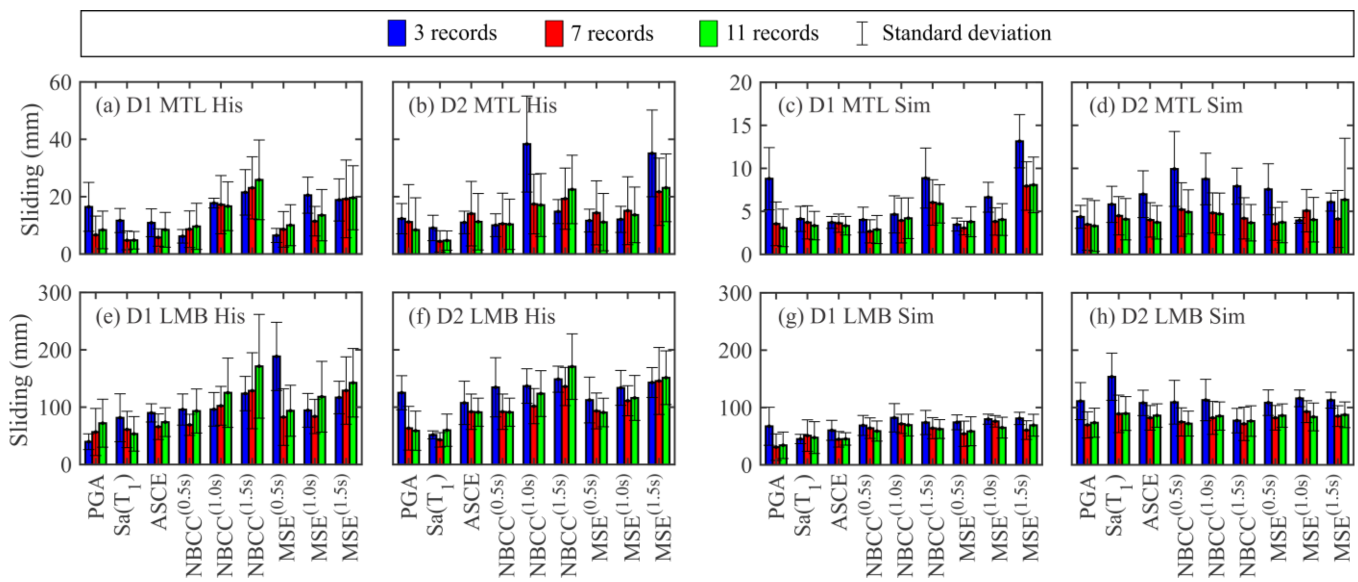

Figure 7 Comparison of sliding displacement estimated with maximum response of groups with 3 records, the mean response of groups with 7 records and groups with 11 records. Friction angle is taken as $\phi = 45°$.

The following conclusions could be drawn:

- Analyses results computed using historical ground motions are more sensitive to different scaling techniques than those using simulated ground motions.
- The historical ground motions used in this study tend to produce greater seismic demands than simulated ground motions for most of the scaling methods, with some exceptions when $\mathrm{Sa}(T_1)$ method is used.
- PGA and $\mathrm{Sa}(T_1)$ methods may not be suitable for seismic safety evaluation in the context of concrete gravity dam due to the lack of conservatism shown in the analyses.

- Attention should be paid when defining the period range for the scaling of ground motions. When historical ground motions are used, a wider period range can result in greater seismic demands for both dam monoliths in this study. When simulated ground motions are used, the effect of period range varies with dam size, dam site and the scaling method employed.
- Using sets of 3 records may not be suitable for seismic safety evaluation of gravity dams due to inconsistency of obtained results compared to those from sets of 11 records. For the ground motions used in this study, similar nonlinear seismic demands were obtained using either a set of 7 or 11 records.

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