SEISMIC VULNERABILITY AND PRIORITIZATION RANKING OF DAMS IN CANADA

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ABSTRACT:

This paper presents a method for a seismic vulnerability screening analysis of dams in Canada and its application to rank Canadian hydropower dams in order of apparent vulnerability. In total 133 dams were considered. These included concrete gravity dams, earth-fill dams, and rock-fill dams. The seismic vulnerability for each dam was determined by combining the probabilities of various levels of the seismic hazard at the dam location, with the damage probabilities to the dam-type corresponding to the seismic hazard levels considered. Seismic hazard was represented by the peak ground acceleration at the dam site, calculated from the latest national seismic hazard model developed by Geological Survey of Canada. The damage potential to the dams was represented by fragility curves. Different fragility curves were used for different types of dams. The construction periods (i.e., the age) of the dams were incorporated through approximate factors reflecting the improvements in seismic hazard estimation and dam design. The results from the analysis were used to rank the dams according to their apparent vulnerability. This study shows that depending on the dam type and construction period, some dams in lower seismic regions appear to be more vulnerable to seismic motions than other dams in regions with higher seismicity. The ranking of the hydropower dams developed in this study is of special importance for energy reliability and can be used by decision-making authorities to ensure that owners of the apparently highest risk dams respond with detailed assessments and/or remedial actions for those dams.

KEY WORDS: seismic vulnerability, hazard, fragility curves, risk ranking, Canadian dams.

1. INTRODUCTION

There are 933 large dams in Canada based on the latest Canadian Dam Register (CDA 2003). About 60% of the dams were built before 1970, and have been in service for more than 40 years. Dam design and construction practice has evolved over time. The older dams, especially those built before 1930, were designed with no seismic considerations. The dams built between 1953 and 1985 also might be considered deficient for seismic resistance, because the seismic hazard levels they were designed for were much lower than those based on the current understanding of the seismic hazard. The Fourth Generation of seismic zoning maps prepared by the Geological Survey of Canada (GSC) (Adams and Halchuk 2003) were developed using the latest knowledge of the Canadian seismicity, seismotectonics and strong motion relations. Given the foregoing considerations, it is wise to evaluate the damage consequences of dams in Canada which might be subjected to earthquake excitations predicted by the GSC's latest hazard estimates.

The objective of this study is to develop a methodology for estimating seismic vulnerability for dams in Canada, and to rank the dams according to their vulnerabilities.

Seismic vulnerability analyses were conducted for a number of dams in eastern and western Canada. The selected dams are mainly for hydropower purpose. A sample of risk ranking is presented in this paper. Two types of dams, i.e., concrete gravity dams and earth/rock-fill dams were considered in this study.

2. SEISMIC HAZARD COMPUTATION

For the purpose of the risk ranking of the dams due to earthquake excitations, seismic vulnerability analysis was conducted first. It combines the effects of the seismic hazard of the dam location and the fragility of the dam for seismic loads.

In this study, the seismic hazard is represented by peak ground acceleration (PGA). Seismic hazard analyses were performed using the latest seismic hazard model developed by Geological Survey of Canada (Adams and Halchuk 2003). For each location, annual probabilities of exceedence were computed for a range of PGA values for the 50% (median) confidence level. This is the same confidence level as that used in the seismic provisions of the latest edition of the National Building Code of Canada (NBCC 2005).

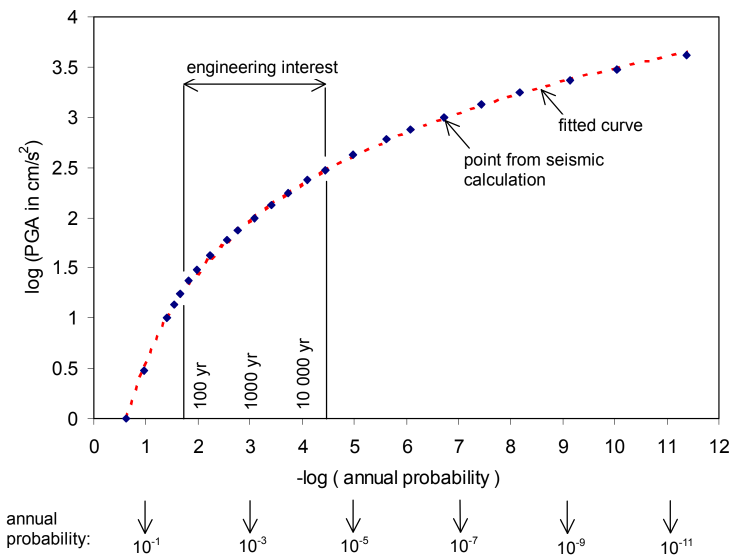

Figure 1. Relationship between PGA and annual probability for one of the selected sites (Lin and Adams 2007)

For illustration, Figure 1 shows hazard results for one of the dam sites considered in this study. Based on the seismic model calculations by Geological Survey of Canada for all the selected locations, it was found that the function fitting the discrete points obtained from model calculations can be represented by Eq.2.1, where p.a. (per annum) is the annual probability, and PGA is in units of cm/s^2.

$$\log(PGA)=K_1*\log(-\log(p.a.))+K_2 \tag{2.1}$$

For the function shown in Fig. 1, K_1 is 2.90, and K_2 is 0.5861. It can be seen that the 2-parameter function fits the model results very well, even for extremely low probabilities ($<<10^{-4}$) for which we recognize that the hazard model may be mathematically precise but giving physically unreasonable values. For example, Figure 1 shows that the annual probability for PGA of 1g at this site is 10^{-7}, whereas the seismic hazard computation is unlikely to be reliable much beyond 10^{-4} (Adams and Halchuk 2004).

3. DEVELOPMENT OF FRAGILITY CURVES FOR DAMS

The damage probability for the dams is represented by fragility curves. The development of fragility curves was based on the ATC-13 Report (ATC 1985). It should be mentioned that the damage probabilities presented in the ATC-13 Report (ATC 1985) were originally intended for the earthquake damage evaluation of structures in California. Because of the similar characteristics of the design codes, construction methods, and seismic conditions in California and western Canada, it is considered that the California parameters can be applied directly to western Canadian facilities. In this study, the development of fragility curves for the dams in western Canada was based on the data in ATC-13 Report. However, the fragility curves for the dams in eastern Canada were obtained by adjustments of the western fragility curves in order to take into account the different seismic motion characteristics in eastern Canada (see section 2.2.2).

3.1. Damage Probability Matrices in ATC

In ATC-13, damage probabilities are expressed in terms of mean damage probability matrices which describe the probabilities of the facilities having a certain damage state at a given ground shaking intensity. Modified Mercalli Intensities (MMI) from VI to XII are used to represent the intensity of the earthquake ground shaking. The damage states are divided into six levels, i.e., slight, light, moderate, heavy, major and destroyed. The definitions for these damage states are listed in Table 1.

Table 1. Definitions of damage states (ATC 1985)

Damage state	Definition
Slight	Limited localized minor damage not requiring repair
Light	Significant localized damage of some components generally not requiring repair
Moderate	Significant localized damage of many components warranting repair
Heavy	Extensive damage requiring major repair
Major	Major widespread damage that may result in the facility being demolished or repaired
Destroyed	Total destruction of the majority of the facility

As an example, Table 2 shows the damage probability matrix (DPM) for concrete gravity dams given in ATC-13. The damage factor range and the central damage factor (CDF) for each damage state are also shown in the table. The damage factor represents the ratio of dollar loss to replacement cost. The damage matrix in Table 2 can be interpreted as follows, for example, if shaking at the site of a given concrete dam reaches MMI=VIII, the expected loss for the dam is 3.1% (i.e. 42.5%*0.5%+57.5%*5%=3.1%) of the replacement value.

Table 2. Damage probability matrix (DPM) for concrete dams (ATC 1985)

Damage state	Damage factor range (%)	CDF (%)	MMI						
			VI	VII	VIII	IX	X	XI	XII
None	0	0	100	57.2	—	—	—	—	—
Slight	0 - 1	0.5	—	42.8	42.5	3.9	0.3	—	—
Light	1 -10	5	—	—	57.5	95.8	88.5	19.3	0.5
Moderate	10 - 30	20	—	—	—	0.3	11.2	75.2	52.9
Heavy	30 - 60	45	—	—	—	—	—	6.5	46.4
Major	60 - 100	80	—	—	—	—	—	—	0.2
Destroyed	100	100	—	—	—	—	—	—	—

—denotes very small probability

3.2 Development of Fragility Curves

3.2.1 Fragility curves for dams in western Canada

Fragility curves describe the probability of *reaching or exceeding* different damage states for every MMI level. The cumulative log-normal probability functions representing each of the damage states, are expressed by Eq.3.1 (NIBS 1999), in which *DS* represents damage state, and the parameters *A* and *B* represent the mean and standard deviation of *ln(MMI)* respectively. The matching function is obtained by changing the values of A and B to fit the DPM points, and the curves representing the best matching functions are called fragility curves.

$$p(damage \geq DS \mid MMI) = \int_0^{MMI} \frac{1}{MMI \times B \times \sqrt{2\pi}} \times \exp\left[-\frac{1}{2}\left(\frac{\ln(MMI) - A}{B}\right)^2\right] d(MMI) \qquad (3.1)$$

Currently, the seismic hazard is normally represented by peak ground acceleration (PGA), spectral acceleration (Sa), or spectral displacement (Sd), rather than by MMI. In this study, the PGA was used as a hazard parameter, and fragility curves were developed as a function of PGA. This was done by applying the relationships between MMI and PGA (shown in Table 3) as used in the HAZUS software.

Table 3. Conversion table for MMI to PGA (NIBS 1999)

MMI	VI	VII	VIII	IX	X	XI	XII
PGA (g)	0.12	0.21	0.36	0.53	0.71	0.86	1.15

It is necessary to mention that the use of PGA as seismic intensity measure may overestimate the damage probabilities for the dams which have long vibration period. Refinement of the fragility curves in terms of a more suitable ground motion parameter together with additional experience incorporated from recent code documents might improve the results, but are beyond the scope of the present paper.

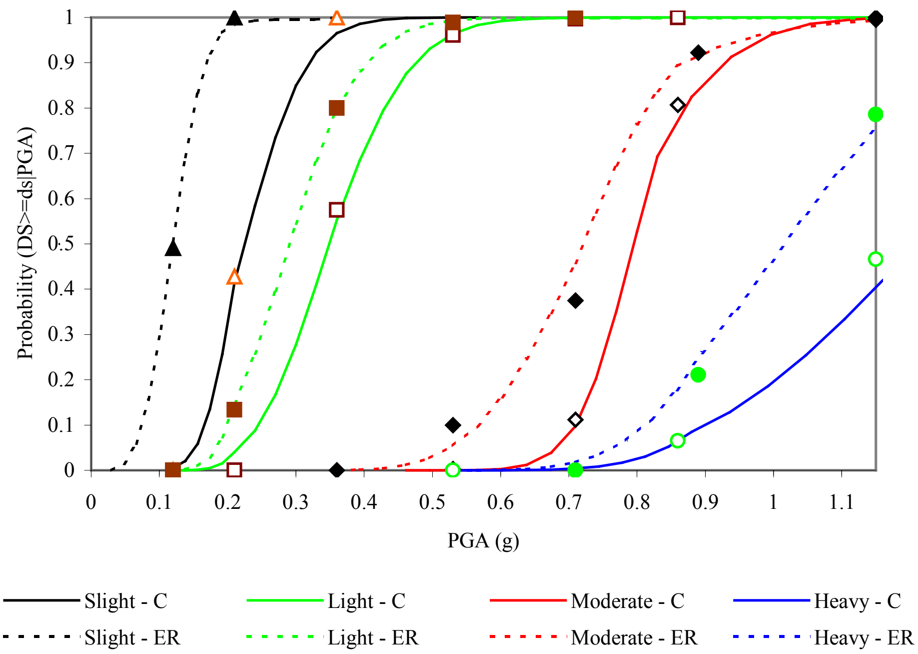

Figure 2. Fragility curves for concrete dams (C) and earth/rock-fill dams (ER) in western Canada

Figure 2 shows the fragility curves for concrete dams and earth/rock-fill dams in western Canada used in this study. The solid lines represent the curves for concrete dams while the dotted lines represent the curves for earth/rock-fill dams. The discrete points are from DPM given in ATC-13 (e.g., see Table 2 for concrete dams). It can be seen that the damage probabilities for earth/rock-fill dams are higher than those for concrete dams, i.e., earth/rock-fill dams are considered more vulnerable to earthquakes than concrete dams.

3.2.2 Fragility curves for dams in eastern Canada

It is known that the characteristics of seismic motions in eastern Canada (east of the Rockies) are different than those of motions in western Canada (Adams and Halchuk 2003). This is because of different physical properties of the crust and different mechanisms in the generation of ground motion in eastern and western Canada. Given this, the fragility curves developed for dams in western Canada should be adjusted by considering the characteristics of seismic motions in eastern Canada in order to derive the corresponding fragility curves for eastern Canada.

Peak acceleration values from western sites such as California are a reasonable measure of damage potential because the western crust rapidly attenuates the peak motions and a high PGA value comes only from a large earthquake with a long duration of shaking. However, the crust in eastern Canada attenuates the peak motions very slowly, and high PGA values can come from quite small earthquakes. The shaking from these small earthquakes is typically of very short duration (a few cycles), so that it has less damage potential than western shaking with the same peak value. For these reasons, if we are to compare the damage consequences of PGA shaking Canada-wide, we need to adjust the eastern PGA values.

The response characteristics of seismic motions are best represented by spectral acceleration. We investigated the relationship between spectral accelerations and peak ground accelerations in western and eastern Canada. Spectral acceleration at period of 0.2 s (Sa(0.2)) was used as representative of the response of short period structural systems. Median values for PGA and Sa(0.2) for a probability of 2% in 50 years for selected locations in western and eastern Canada (Adams and Halchuk 2003) were used. Considering the Sa(0.2)/PGA ratios for the selected locations, it was found that the average Sa(0.2)/PGA ratio was 1.94 for the western sites, and 1.66 for the eastern sites. This means that for the same Sa(0.2) value (i.e. the same damage potential) in western and eastern Canada, the average PGA value in eastern Canada is 1.94/1.66 or about 1.2 times larger than that in western Canada. Based on this, fragility curves for the dams in eastern Canada were developed by multiplying the PGA values associated with the western fragility curves by a factor of 1.2. Thus, in the east, the PGA values needed to cause the same damage are 20% larger than PGA values in the west.

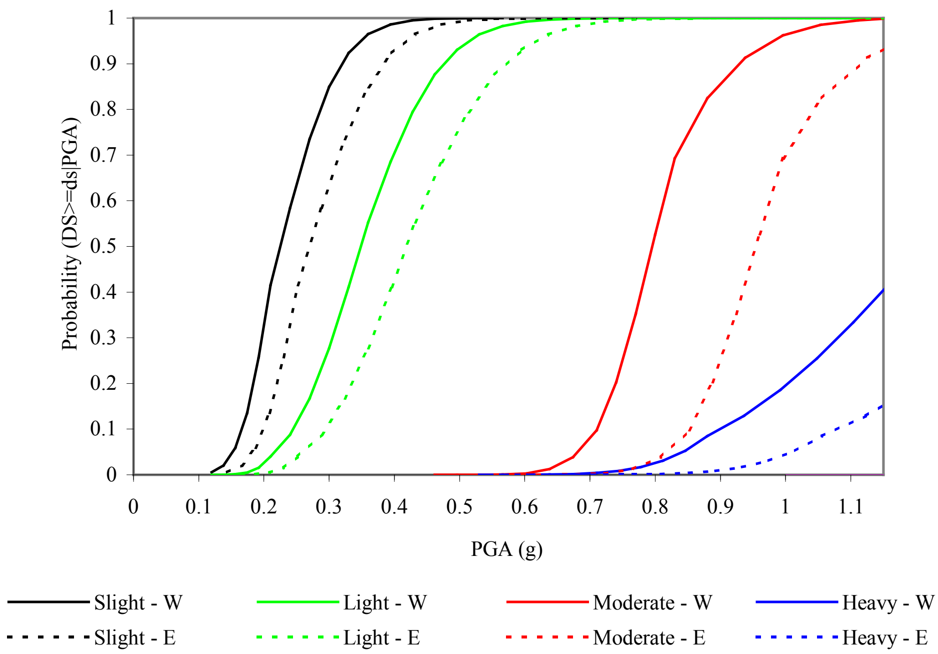

Figure 3. Fragility curves for concrete dams in western and eastern Canada

Figure 3 shows the fragility curves for concrete dams for western Canada (solid lines) and the derived fragility curves (dashed lines) for eastern Canada. As it is seen in the figure, the separation of the solid and dashed lines indicates that for the same PGA value, dams in eastern Canada are less vulnerable to earthquakes than those in western Canada.

4. FRAGILITY CURVES FOR DIFFERENT DESIGN/CONSTRUCTION DATES

Since the dams considered in this study were constructed between 1910 and 1996, it was necessary to take the age of the dams into account in the vulnerability analysis. This is because many aspects have changed during that period, including construction methods, seismic design codes, and our knowledge about seismic hazard levels. Obviously, older dams are characterized by higher fragility than newer ones, i.e., on average older dams sustain more damage when a severe earthquake occurs.

ATC (1985) does not provide fragility curves for different design/construction periods for dams. The fragility curves in the ATC-13 Report, and those for Canadian dams discussed above (e.g., Figs. 2 and 3) are considered "standard fragility".

In order to develop fragility curves for different design periods for dams, the approach used by ATC (1985) for buildings, and that of NIBS (1999) applied in the HAZUS software, were followed. ATC (1985) provides standard fragility curves for buildings, and recommends that the fragility curves for a given damage state for older and newer buildings be derived by shifting the standard fragility curve horizontally by one (or two) intensity level(s) of MMI. According to the ATC recommendations, the fragility curve for a given damage state for older buildings is obtained by shifting the standard fragility curve to the left, i.e., by decreasing the MMI values, and that for newer buildings is obtained by shifting the standard fragility curve to the right, i.e., by increasing the MMI values. In HAZUS, different fragility curves for buildings are incorporated for four different design ages and are referred to as the "pre-code", the "low code", the "moderate code", and the "high-code" fragility curves.

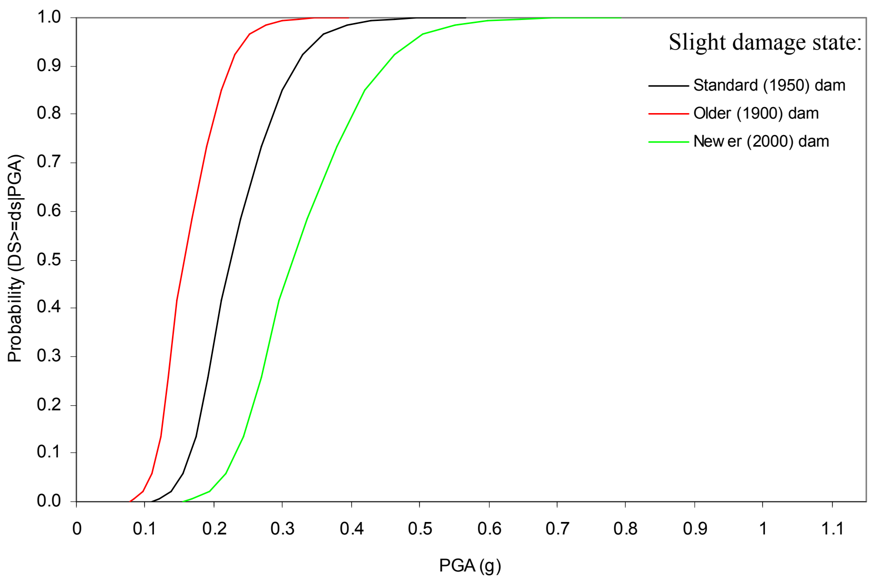

Figure 4. Fragility curves for different ages of concrete dams in western Canada

Similar to the approaches used for buildings in ATC-13 and HAZUS, we also defined fragility curves for older and newer dams relative to the standard fragility curves. The standard fragility curves were assumed to be representative of the design/construction practice in 1950. This is quite reasonable because the designation of the "standard construction" in ATC-13 pertains to structures built between 1940 and 1976. Old dams were considered those designed/constructed in 1900, and new dams were considered those of 2000. The fragility curves for *old* dams were obtained by shifting the corresponding standard fragility curves along the PGA axis, which was done by dividing the PGA values associated with the standard fragility curves by $\sqrt{2}$. The fragility curves for *new* dams were obtained by multiplying the standard fragility curves by $\sqrt{2}$. Together, the range of PGA values for dams constructed between 1900 and 2000 is a simple factor of 2, representing an approximate estimate. Using this approach, fragility curves for old and new dams in western and eastern Canada were developed for each damage state. For illustration, Figure 4 shows the fragility curves for the slight damage state for old, standard, and new concrete dams in western Canada. For the dam constructed in a given date, the fragility curves can be derived by interpolation of those corresponding to 1900 and 2000.

5. VULNERABILITY ANALYSIS AND SAMPLE OF RANKED RESULTS

Seismic vulnerability analyses were conducted for each dam considered in this study in order to determine the damage probabilities and to rank the dams according to their seismic risks. The seismic damage probabilities were determined by considering the seismic hazard at the locations and the vulnerability of the dam represented by the fragility curves.

Damage probabilities were computed for PGA values between 0.03g and 1.15g, representing the range of seismic shaking. For each shaking level, the damage probability was computed by multiplying the annual probability of the PGA by the corresponding probability from the fragility curves. The graphs of damage probabilities plotted as functions of PGA represent the damage probability distributions for a given dam.

It is useful to discuss the general shapes of the probability distributions (see Fig. 5). For PGA values larger than the dominant values, the damage probabilities decrease. This is related to the seismic hazard at the location of the dam, i.e., the probabilities that seismic motions with large PGA values will occur at the locations are very small, and hence, the risk from such motions also is very small (Fig. 5).

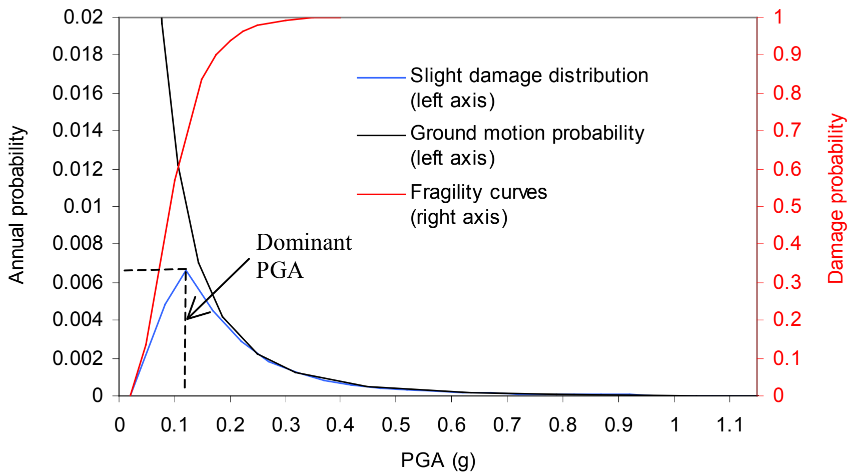

Figure 5. General relationship between seismic hazard, fragility curve and resultant annual probability of damage, illustrated for slight damage to a specific concrete dam in western Canada.

Using the foregoing approach, a large number of dams located in British Columbia, Quebec and Ontario were ranked according to their vulnerabilities. Their locations represent high, medium, and low seismicity regions in Canada. A sample of ranking results from the full analysis of the dams considered in the study is shown in Table 4. Due to confidentiality issues, the actual dam names are not shown in the table. It should be noted that the ranking was based on seismic vulnerability analyses for the "slight damage" state.

According to the ranking results shown in Table 4, some dams in Quebec and Ontario have higher seismic risk than other dams in British Columbia, even though their locations have lower seismic hazard. This is because the eastern dams are relatively older than those in B.C. It is necessary to mention that the damage probabilities in Table 4 do not represent the actual risk, and they were used for ranking purpose only, i.e., the values just indicate the relative risk level of each dam in the sample.

6. CONCLUSIONS

A probabilistic method for seismic ranking of Canadian hydropower dams was established in this study. The method considers the probability contributions from the seismic hazard computations at the dam site, the fragility curves associated with the dam type, and the construction period of the dam.

Table 4. Sample of risk ranking results (slight damage)

Name of dam	Province	Year of completion	Structure type	Seismic hazard	Risk analysis results		
				PGA @ 2%/50ys (g)	Dominant PGA (g)	Damage annual probability @ dominant PGA	Risk ranking
Dam A	Que.	1924	Earth-fill	0.43	0.17	0.00126	1
Dam B	Que.	1927	Concrete	0.42	0.30	0.00115	2
Dam C	Que.	1933	Earth-fill	0.43	0.17	0.00114	3
Dam E	Ont.	1931	Earth-fill	0.42	0.17	0.00110	4
Dam I	B.C.	1930	Concrete	0.46	0.22	0.00089	5
Dam H	B.C.	1911	Concrete	0.43	0.22	0.00089	6
Dam K	Ont.	1959	Rock-fill	0.41	0.17	0.00080	8
Dam D	B.C.	1953	Earth-fill	0.31	0.12	0.00112	9
Dam L	Ont.	1948	Earth-fill	0.39	0.17	0.00079	11
Dam F	B.C.	1947	Earth-fill	0.28	0.12	0.00095	13
Dam G	B.C.	1955	Rock-fill	0.28	0.12	0.00091	15
Dam G	B.C.	1957	Earth-fill	0.31	0.12	0.00088	17

In the study, the seismic hazard is represented by peak ground acceleration (PGA). The calculation was based on the latest seismicity models developed by Geological Survey of Canada. The annual probability of occurrence for median (50%) confidence level was used. The damage probability was computed using fragility curves for the dams. The development of the fragility curves was based on the ATC-13 Report (ATC 1985) prepared by Applied Technology Council. The damage probabilities were obtained by considering the seismic hazard of the dam sites and the fragility curves. Since the dams were constructed at different periods, the effects of the age of the dams were taken into account in the damage estimates.

Based on the established method, a sample of ranking results for hydropower dams in British Columbia, Quebec and Ontario was presented. The results showed that some dams in lower seismicity regions, such as Quebec and Ontario, are more vulnerable to earthquakes than those in British Columbia which is considered a high-seismicity region of Canada. The results also indicate that attention should be given to the seismic vulnerability of Canadian dams in low to moderate seismicity regions. The ranking of seismic vulnerabilities is also intended to ensure that any possible safety or reliability issues posed by the top-ranked (apparently most vulnerable) dams are raised earlier rather than later.

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