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PROBABILISTIC METHOD FOR SEISMIC VULNERABILITY RANKING OF CANADIAN HYDROPOWER DAMS

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ABSTRACT:

A probabilistic method was developed for ranking Canadian hydropower dams according to their seismic vulnerability. The method is based on the probabilistic seismic hazard at the dam location, the seismic fragility of the dam, and the construction date of the dam. The seismic hazard is represented by the peak ground acceleration of seismic motions at the dam location for a specified probability of exceedance. The seismic fragility of the dams is included through fragility curves, which describe the experience-based probability of the dam reaching or exceeding different damage states as a function of the peak ground acceleration. Different fragility curves are used for different types of dams. The construction periods of the dams are incorporated through approximate factors reflecting the improvements in seismic hazard estimation and dam design. The method was applied to rank a sample of hydropower dams in Canada. These included a range of different types of dams, construction periods, and seismic hazard conditions. The ranking of seismic vulnerabilities is 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.

RÉSUMÉ:

Une méthode probabiliste a été élaborée pour le classement des barrages hydro-électriques canadiens en fonction de leur vulnérabilité aux séismes. Cette méthode est basée sur l'aléa sismique probabiliste à l'emplacement du barrage, sur la fragilité sismique du barrage et sur la date de construction du barrage. L'aléa sismique est représenté par l'accélération maximale du sol attribuable aux secousses sismiques à l'emplacement du barrage pour une probabilité de dépassement donnée. Il est tenu compte de la fragilité sismique du barrage au moyen de courbes de fragilité décrivant la probabilité fondée sur l'expérience que surviennent ou soient dépassés différents états d'endommagement du barrage en fonction de l'accélération maximale du sol. Des courbes de fragilité différentes sont utilisées pour différents types de barrages. Les périodes de construction des barrages sont intégrées d'après des facteurs approximatifs reflétant les améliorations de l'estimation de l'aléa sismique et de la conception des barrages. Cette méthode a été appliquée au classement d'un échantillon des barrages hydroélectriques au Canada. L'échantillon couvrait toute une gamme de types de barrages construits à différentes époques et exposés à différentes conditions d'aléa sismique. Le classement des vulnérabilités aux séismes est effectué pour s'assurer que tous les aspects possibles de la sécurité et de la fiabilité des barrages au plus haut niveau de ce système de classement (apparemment les plus vulnérables) sont abordés avec une tendance d'être plus tôt au lieu d'être plus tard.

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).

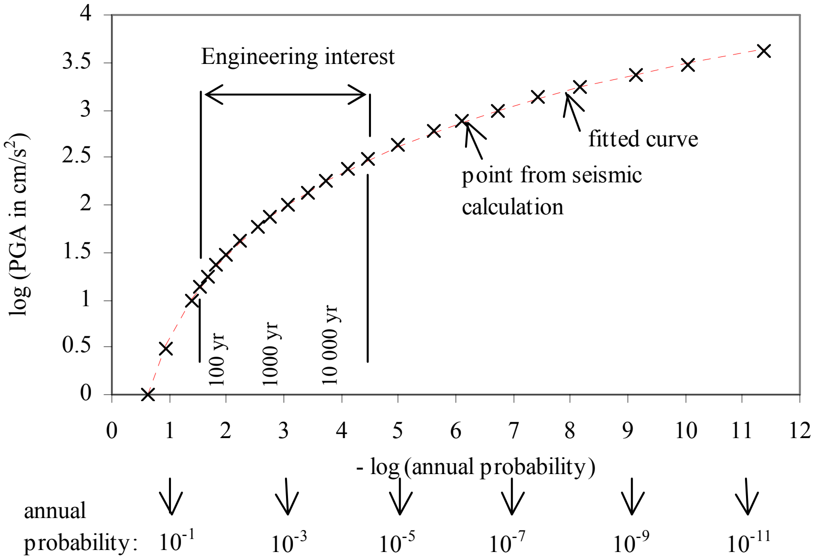

Figure 1: Relationship between PGA and annual probability for one of the selected sites (Lin and Adams 2007)

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.1, where p.a. (per annum) is the annual probability, and PGA is in units of cm/s^2.

$$\log(PGA)=K_1*\log(-\log(p.a.))+K_2 \tag{1}$$

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 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.

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

Due to limited data on earthquake damage to various types of facilities, the damage probability matrices in ATC-13 were developed using "expert-opinion" approach. A panel of 71 professional engineers and professors were invited to participate in the questionnaire process. Each of the participants was asked to provide an estimate of the damage probability for different types of structures when subjected to ground motions with MMI intensities from VI to XII. Their answers were statistically analyzed to determine the damage probability matrices.

The ATC-13 damage probability matrices (DPM) for concrete gravity dams and earth/rock-fill dams are given in Table 2 and Table 3. These tables also include the damage factor range and the central damage factor (CDF) for each damage state. The damage factor represents the ratio of dollar loss to replacement cost. The damage matrices 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 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

Table 3: Damage probability matrix (DPM) for earth/rock-fill dams (ATC 1985)

Damage state	Damage factor range (%)	CDF	MMI						
			VI	VII	VIII	IX	X	XI	XII
None	0	0	50.9	—	—	—	—	—	—
Slight	0 — 1	0.5	49.1	86.6	20.0	1.1	—	—	—
Light	1 — 10	5	—	13.4	80.0	88.9	62.5	7.8	—
Moderate	10 — 30	20	—	—	—	10.0	37.5	71.1	21.4
Heavy	30 — 60	45	—	—	—	—	—	21.1	74.1
Major	60 — 100	80	—	—	—	—	—	—	4.5
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. 2 (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.

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

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 4) as used in the HAZUS software.

Table 4: 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 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 shown in Tables 2 and 3. 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 more vulnerable to earthquakes than concrete dams.

Table 5 lists the values for the parameters A and B used for the development of the fragility curves. The values for A and B are employed only for fitting the discrete points from damage matrices, and they do not need to have any statistical or physical meaning.

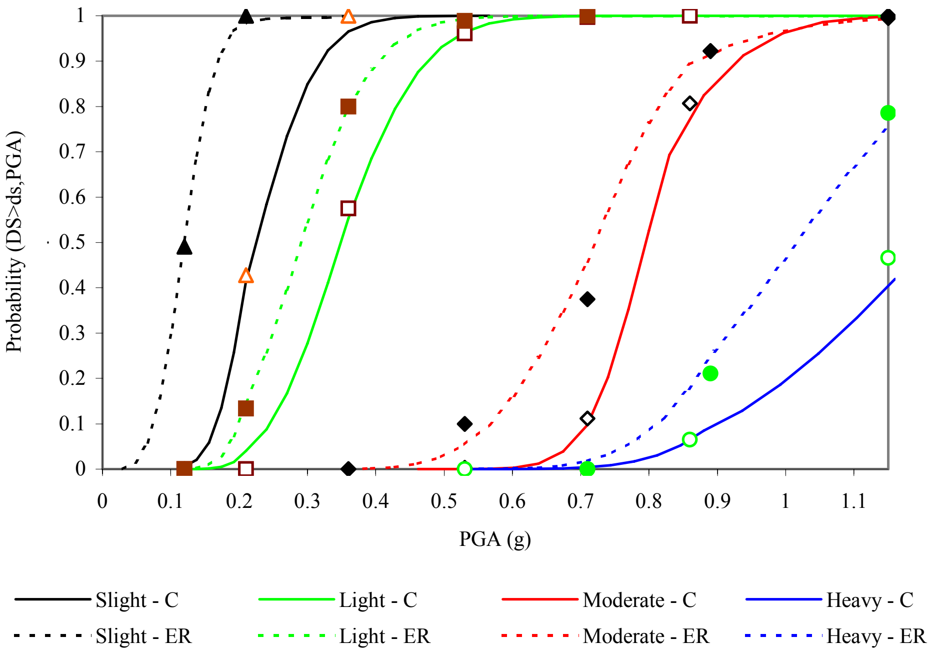

Figure 2: Fragility curves for concrete dams (C) and earth/rock-fill dams (ER) in western Canada

Table 5: Values for parameters A and B

Type	Slight damage		Light damage		Moderate damage		Heavy damage		Major damage	
	A	B	A	B	A	B	A	B	A	B
Concrete	1.960	0.065	2.070	0.070	2.358	0.042	2.500	0.074	2.400	8.0
Earth/rock-fill	1.790	0.066	2.020	0.070	2.310	0.070	2.440	0.065	2.540	2.2

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 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.

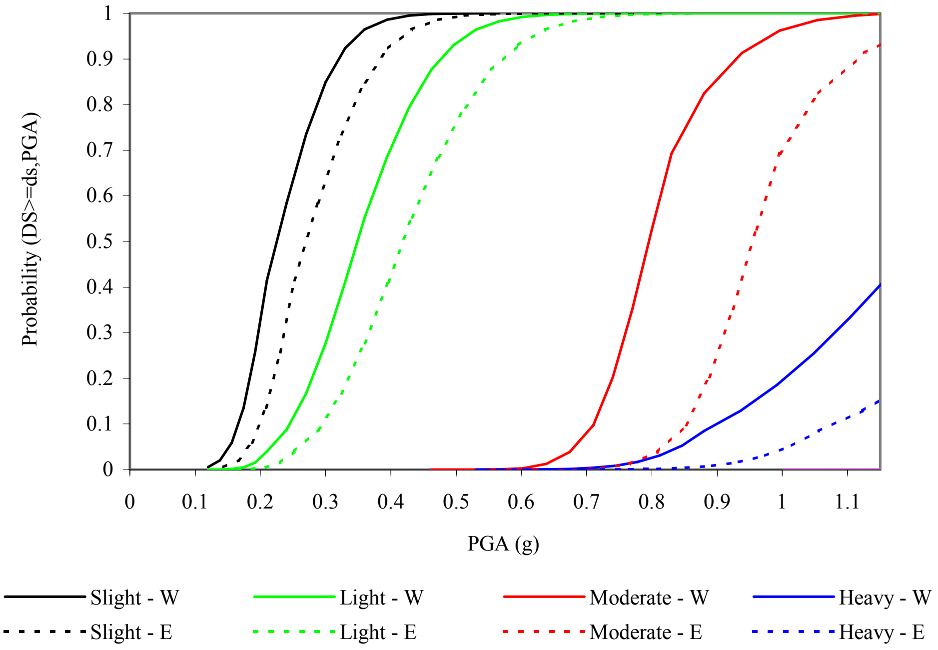

Figure 3: Fragility curves for concrete dams in western and eastern Canada

4 VULNERABILITY CONSIDERATIONS DUE TO DAM CONSTRUCTION PERIOD

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., older dams sustain more damage when a severe earthquake occurs.

4.1 Fragility curves for different design/construction dates

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) 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.

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 √2. The fragility curves for *new* dams were obtained by multiplying the standard fragility curves by √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.

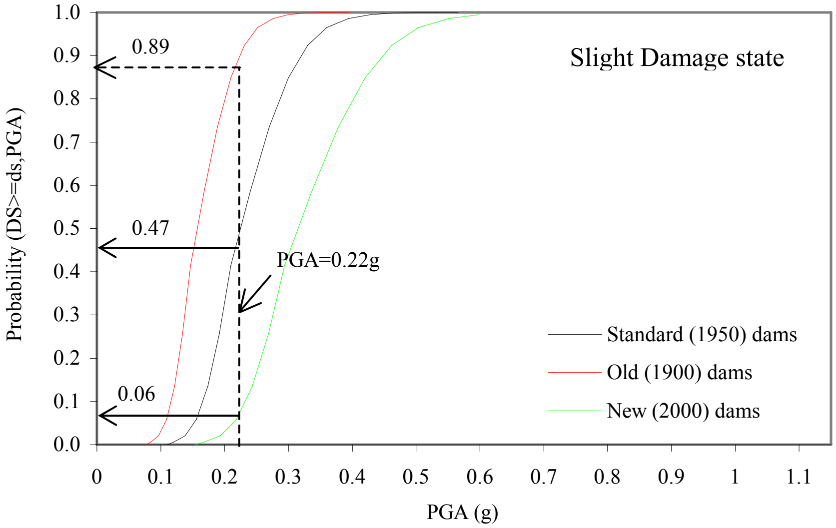

Figure 4: Fragility curves for different ages of concrete dams in western Canada

4.2 Defining construction-date factors

To determine the construction-date factor for a dam designed or constructed at a specific date, *date factors* for old dams, standard dams, and new dams were defined first. These factors represent the construction-date factors for the dams constructed in 1900, 1950, and 2000 respectively. It is necessary to mention that the construction-date factors can be defined for different damage states. In this study, the construction-date factors were developed for just the "slight damage" state according to the following procedure:

(1) Calculation of seismic vulnerability for the dams for slight damage state.

The seismic vulnerability was expressed as the expected probability of damage for each ground motion. Each discrete damage probability was computed by multiplying the annual probability of the PGA obtained from seismic hazard calculation by the corresponding probability from the *standard* fragility curves. For illustration, Fig. 5 shows discrete damage probability distributions for a sample of concrete dams in western Canada.

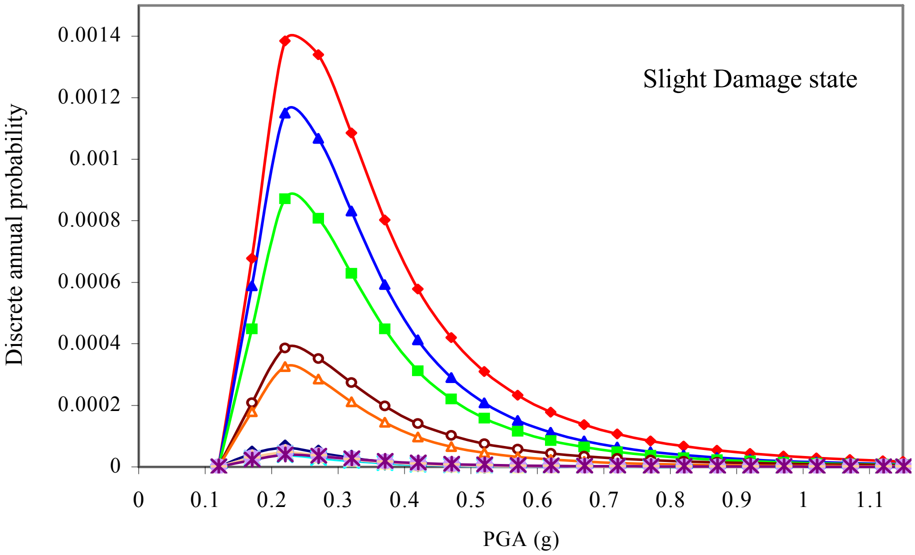

Figure 5: Discrete damage probability distribution for some concrete dams in western Canada

(2) Determination of dominant PGA values.

The dominant PGA value is the ground shaking level associated with the largest damage potential. This value can be found from the discrete damage probability distribution. For example, in Fig. 5, it can be seen that the dominant PGA value for the concrete dams for slight damage state in western Canada is about 0.22g. Using the same approach, it was found that the dominant PGA value for earth/rock-fill dams in western Canada was 0.12g. For eastern Canada, it was 0.30g and 0.17g for concrete dams and earth/rock-fill dams respectively.

(3) Computation of the damage probabilities.

The damage probabilities are associated with the fragility curves for old, standard, and new dams (concrete and earth/rock-fill) corresponding to the dominant PGA values obtained in the previous step. For example, the damage probabilities for old, standard and new concrete dams in western Canada are 0.06, 0.47 and 0.89 (see Fig. 4). Note that these values correspond to the dominant PGA value of 0.22 g as discussed above.

(4) Definition of *date factors.*

Table 6 lists the damage probabilities for concrete dam and earth/rock-fill dam in western Canada and eastern Canada at the dominant PGA value. Each value was derived by a method like that shown on Fig. 4. In other work we found that the ranking of dams is not very sensitive to the exact date factors used so for simplicity and to be congruent with the crude factor of 2 used we defined *date factors* as 0.85 for old dams, 0.50 for standard dams, and 0.15 for new dams. The *date factors* can be used for adjust the standard discrete damage probability (for slight damage) for dams other than those constructed in 1950. Note that these three points, i.e. 0.85 for 1900, 0.50 for 1950, and 0.15 for 2000 define a linear function that can be used to determine the date factor for any intermediate year of construction.

Table 6: Damage probabilities for dams in western and eastern Canada (slight damage)

Dam type	Damage probability Dominant PGA (g)	Old (1900)	Standard (1950)	New (2000)
Concrete – western	0.22	0.89	0.47	0.06
Earth/rock-fill – western	0.12	0.92	0.51	0.17
Concrete – eastern	0.30	0.96	0.63	0.17
Earth/rock-fill – eastern	0.17	0.98	0.73	0.31
Adopted Date factor		**0.85**	**0.50**	**0.15**

5 SAMPLE OF RANKED RESULTS

Only dams in British Columbia, Quebec and Ontario were ranked, but they included representatives of high, medium, and low seismicity regions; few dams in the lowest seismicity regions appear high on the ranking. From this ranking an “interesting” subset of dams with examples of dam type (gravity, earth-fill dams and rock-fill), location (west and east) and construction date (1911 to 1959) is shown in Table 7. The selection process means that certain other dams rank higher than some dams in Table 7. Due to confidentiality issues, the actual dam names are not shown here. It should be noted that the ranking was based on seismic vulnerability analyses for the “slight damage” state.

The *standard* discrete probabilities at the dominant PGA value in Table 7 were obtained by combining the seismic hazard at the dam sites, and the “standard “ fragility curves for the dam type (concrete or earth/rock-fill) and the location of the dam (western Canada or eastern Canada). The construction-date factors were calculated using linear interpolation among the reference factors, i.e., 0.85 for the dam constructed in 1900, 0.50 for the dam constructed in 1950, and 0.15 for the dam constructed in 2000. For example, the construction–date factor in Table 7 for Dam H, which was constructed in 1911, is 0.77, and for Dam K, which was constructed in 1959, is 0.44. The higher value of the construction–date factor indicates that the dam is relatively old, and more vulnerable to earthquake excitations. The modified discrete probabilities were obtained by the product of the standard probabilities and the associated construction-date factors. The dams were ranked based on the values of modified discrete damage probability.

According to the ranking results shown in Table 7, some dams in Quebec and Ontario have higher seismic risk even though parts of Quebec and Ontario have lower seismic hazard than parts of British Columbia. This is because these dams are relatively older than those in B.C. It should be noted that the modified discrete probabilities in Table 7 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.

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

Table 7: Sample of risk ranking results (slight damage)

Name of dam	Province	Year of completion	Structure type	Dominant PGA (g)	Standard discrete probability	Construction-date factor	Modified discrete probability	Ranking
Dam A	Que.	1924	Earth-fill	0.17	0.00185	0.68	0.00126	1
Dam B	Que.	1927	Concrete	0.30	0.00174	0.66	0.00115	2
Dam C	Que.	1933	Earth-fill	0.17	0.00185	0.62	0.00114	3
Dam D	B.C.	1953	Earth-fill	0.12	0.00234	0.48	0.00112	4
Dam E	Ont.	1931	Earth-fill	0.17	0.00174	0.63	0.00110	5
Dam F	B.C.	1947	Earth-fill	0.12	0.00183	0.52	0.00095	6
Dam G	B.C.	1955	Rock-fill	0.12	0.00195	0.46	0.00091	7
Dam H	B.C.	1911	Concrete	0.22	0.00115	0.77	0.00089	8
Dam I	B.C.	1930	Concrete	0.22	0.00139	0.64	0.00089	9
Dam G	B.C.	1957	Earth-fill	0.12	0.00195	0.45	0.00088	10
Dam K	Ont.	1959	Rock-fill	0.17	0.00183	0.44	0.00080	11
Dam L	Ont.	1948	Earth-fill	0.17	0.00153	0.51	0.00079	12

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 discrete 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.

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