Ninth Canadian Conference on
Earthquake Engineering
Ottawa, Ontario, Canada
26-29 June 2007

LESSONS FOR THE FRAGILITY OF CANADIAN HYDROPOWER COMPONENTS UNDER SEISMIC LOADING

L. Lin[1] and J. Adams[2]

ABSTRACT

This paper presents results from a seismic vulnerability analysis of the components of hydropower systems in Canada. A number of dams and their associated components (hydropower plants, switchyards, transmission towers, and supplementary equipment) at selected locations in western and eastern Canada were analyzed in the study. The seismic vulnerability for a given hydropower component was estimated by combining the probabilities of various levels of the seismic hazard at the component location, with the damage probabilities of the component corresponding to the seismic hazard levels considered. In this study, the seismic hazard was represented by the peak ground acceleration of the seismic motions. The calculation of the seismic hazard was based on the latest seismic hazard model developed by Geological Survey of Canada. The damage potential for the hydropower components was represented by fragility curves. The seismic vulnerability for each component was expressed by the damage probability as a function of peak ground acceleration. The results from this study show that the most vulnerable components of a hydropower system are the switchyards and the power plants.

Introduction

A hydropower system consists of a dam, reservoir, and electric power components, which include a power plant (turbines, generators and powerhouse), switchyards, transmission towers, and supplementary equipment, such as telecommunication systems. The purpose of the system is to transform water energy into electrical energy and to transmit that energy to consumers.

The failure of a dam would often have serious consequences to people, community structures and the environment. In Canada the likelihood of such failures is reduced by application of the Dam Safety Guidelines (CDA 1999). However, damage to electric power components may also result in a significant disruption of power supply, which can cause large indirect economic losses. Shinozuka et al. (2000) reported that the direct costs of full restoration of the electric power system due to 1994 Northridge earthquake and 1995 Kobe earthquake were $500 million and $4 billion respectively; indirect costs are harder to quantify but are likely to be of a similar order. Obviously, failure of any component of a hydropower system will affect the serviceability of the entire system as well as perhaps the national power supply.

The objective of this study is to investigate the vulnerability of hydropower components in Canada to earthquake excitations. Secondary earthquake-induced effects, such as landslides and tsunamis are not considered. The components considered in the study are the dam, power plant, switchyards and

---

[1] Graduate Research Assistant, Dept. of Civil Engineering, University of Ottawa, Ottawa, ON K1N 6N5
[2] Seismologist, Geological Survey of Canada, Natural Resources Canada, 7 Observatory Cres., Ottawa, ON K1A 0Y3

transmission towers. Each of these components is characterized by different damage potential, i.e., fragility curves.

Seismic vulnerability analyses were conducted for a number of selected hydropower components in eastern and western Canada. It should be noted that the components of each system analyzed were assumed to have the same seismic hazard and soil condition as the dam.

Seismic Hazard Computation

The seismic vulnerability analysis of a given component combines the effects of the seismic hazard of the location and the fragility of the component 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 four confidence levels, i.e. mean, 84%, 50% (median), and 16%. From these levels, the results for the 50% (median) confidence level were used in this study. 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).

For illustration, Fig. 1 shows hazard results for one of the hydropower 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.

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

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 gives physically unreasonable values. For example, Fig. 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).

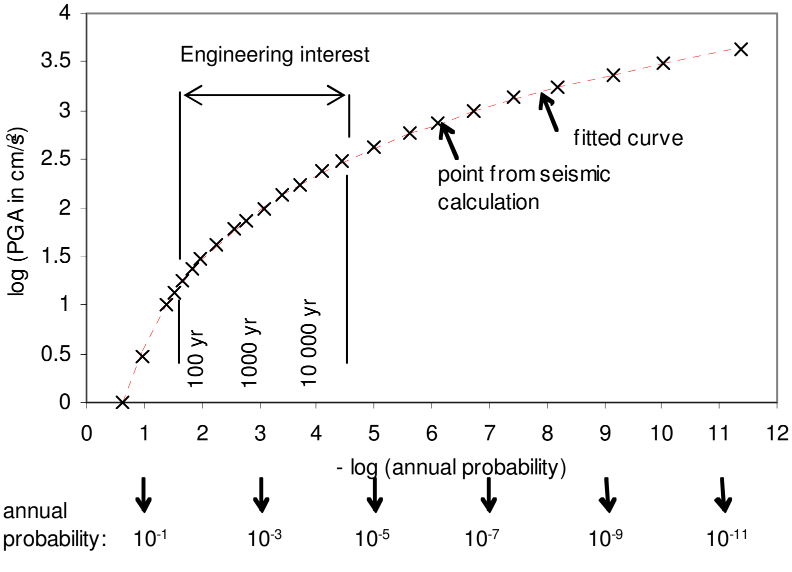

Figure 1. Relationship between PGA and annual probability for one of the selected sites.

Development of Fragility Curves for Hydropower Components

Each of the components of a hydropower system is characterized by a different damage potential, i.e. fragility curves. For the study, the development of fragility curves for the dam and transmission towers was based on the ATC-13 Report (ATC 1985), and for the power plant and switchyards, was based on HAZUS (NIBS 1999, using substation data for the switchyards). In this paper, only the development of the fragility curves for dams is presented; the fragility curves for the other hydropower components were developed using a similar approach.

Damage probability matrices

The damage probabilities presented in the ATC-13 Report (ATC 1985) were originally intended for the earthquake damage evaluation for 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 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 damage states are listed in Table 1. Table 2, which was extracted from ATC-13, shows damage probability matrices (DPM) for concrete gravity dams. This table also includes the damage factor (DF) 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 dam is 3.1% (i.e. 42.5%*0.5%+57.5%*5%=3.1%) of the replacement value.

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

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

Development of fragility curves

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.

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

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 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

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 motions in eastern and western Canada. Given this, the fragility curves developed for hydropower components for 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 Earth's crust in western North America 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 more 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 selected as representative of the response of short period structural systems (e.g., dams and substations). Median values for PGA and Sa(0.2) for a probability of 2% in 50 years (1:2475 years return period) for selected locations in western and eastern Canada (Adams and Halchuk 2003) were considered. The 2% in 50 years probability level is quite appropriate since the analyses showed that much of the contribution to the total damage comes from ground motions with probabilities of about 0.0004 p.a.. 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 for dams and transmission towers) 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.

For illustration, Fig. 2 shows the fragility curves for concrete dams for western Canada (solid lines) and the derived fragility curves (dashed lines) for eastern Canada. It can be seen in the figure that the solid curves fit the discrete points from the corresponding DPM (Table 2) well, and 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.

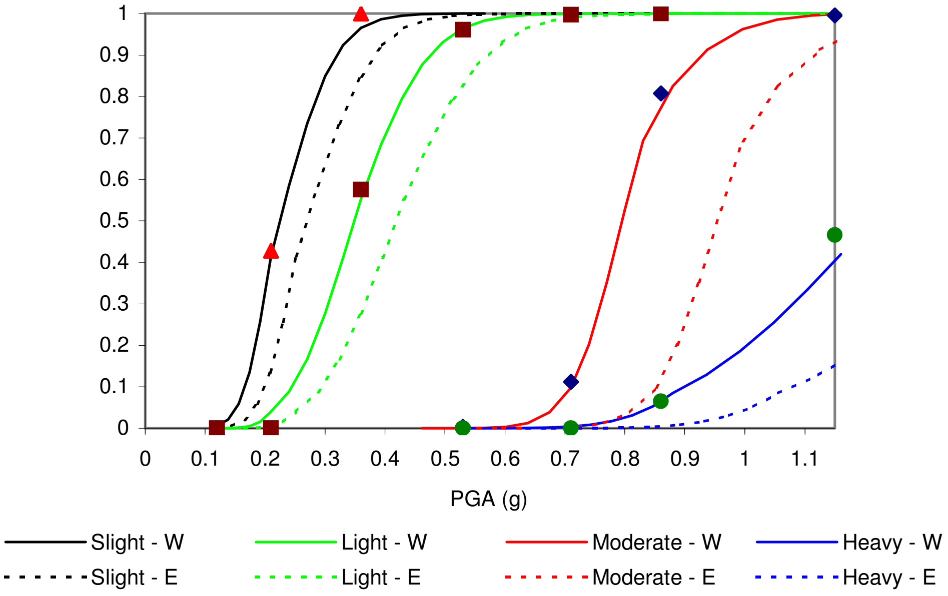

Figure 2. Fragility curves for concrete dams in western and eastern Canada.

Figure 3 shows fragility curves for hydropower components (western sites) for the slight damage state. The curves for eastern sites would be displaced to the right. An important observation from Fig. 3 is that substations are the most vulnerable components of the four considered. The figure also indicates that the dam and the transmission towers could resist stronger seismic motions compared to the switchyards and the power plant.

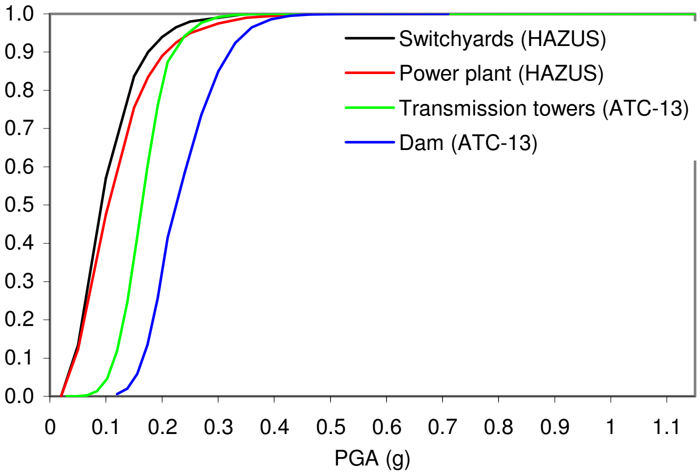

Figure 3. Fragility curves for slight damage state for hydropower components.

Fragility curves for different design/construction periods

Since the hydropower systems considered in the study were constructed between 1910 and 1996, it was necessary to take the age of the components 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 hydropower components are expected to be characterized by higher fragility than newer ones.

ATC (1985) does not provide fragility curves for different design/construction periods for hydropower components. The fragility curves in the ATC-13 Report, and those for Canadian hydropower components (discussed above) are considered to be “standard fragility”.

In order to develop fragility curves for different design periods for hydropower components, 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 hydropower components relative to the standard fragility curves. The standard fragility curves were assumed to be representative of the design/construction practice in 1950. This is considered to be reasonable because the designation of the “standard construction” in ATC-13 pertains to structures built between 1940 and 1976. Old hydropower components were considered those designed/constructed in 1900, and new components were considered those of 2000. The fragility curves for *old* hydropower components 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 hydropower components were obtained by multiplying the standard fragility curves by $\sqrt{2}$. Together, the range of PGA values for hydropower components constructed between the years 1900 and 2000 is a simple factor of 2, representing an approximate estimate. Fragility curves for old and new hydropower components in western and eastern Canada were developed for each damage state. For illustration, Fig. 4 shows the fragility curves for the slight damage state for old (1900), standard (1950), and new (2000) dams in western Canada. Fragility curves for hydropower components constructed at a specific year can be obtained by interpolation between these curves.

Vulnerability Analysis and Results

Seismic vulnerability analyses were conducted for each component of the hydropower system considered, in order to determine the damage probabilities and to rank the components according to their seismic risks. The seismic damage probabilities were determined by considering the seismic hazard at the locations and the vulnerability of the components represented by the fragility curves.

Damage probability values 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 component.

It is useful to discuss the general shapes of the probability distributions to be expected. For PGA values larger than the predominant values, the damage probabilities decrease. This is related to the seismic hazard at the location of the components, 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).

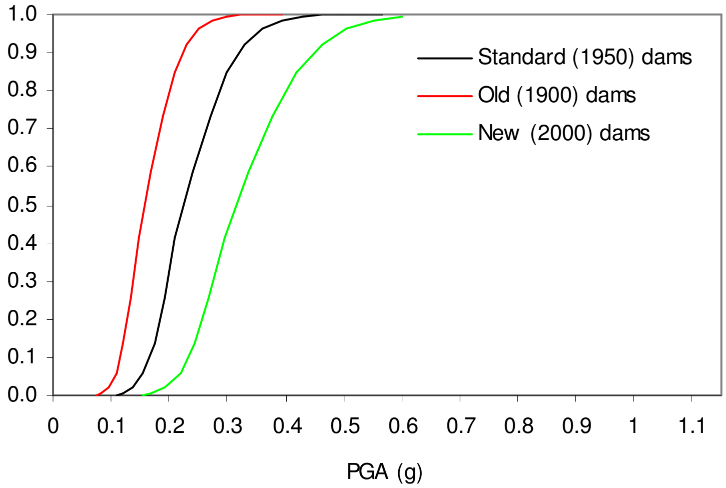

Figure 4. Fragility curves for different ages of concrete dams in western Canada (slight damage).

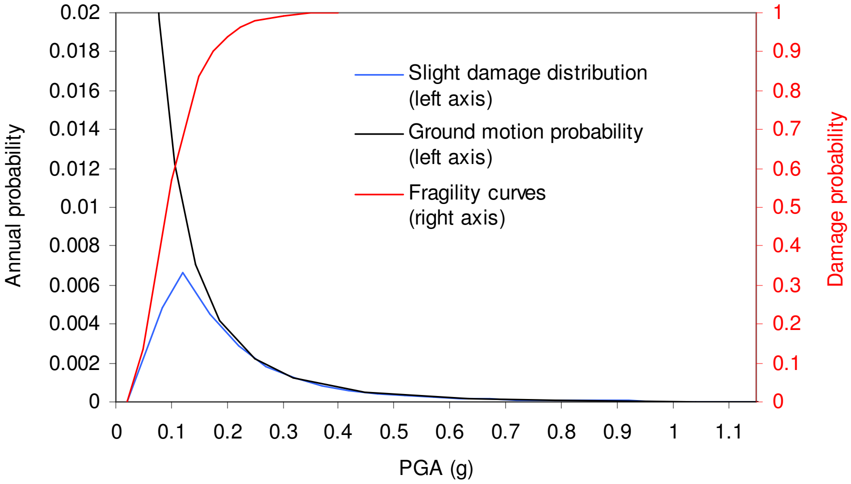

Figure 5. General relationship between seismic hazard, fragility curve and resultant annual probability of damage, illustrated for slight damage to a specific concrete dam in western Canada.

Using the foregoing approach, damage probability distributions were computed for the selected hydropower components using the “standard” fragility curves (i.e. for the standard-age components). In order to reduce the amount of computation, damage probabilities for the older and newer hydropower components were computed using a simplified method based on the application of “age factors” to the results for the standard-age components. Age factors for older and newer hydropower components were determined by conducting full vulnerability analysis for selected components with different ages. Based on these analyses, age factors were established as a function of the year of the design/construction of the hydropower components. These factors were applied to the damage probabilities of the standard-age components to obtain the probabilities for the older and newer components.

Within the constraints of this paper, only component damage probabilities for an example “standard-age” hydropower system can be presented. The damage probability distributions for the dam, the power plant, switchyards and transmission towers at one of the selected hydropower sites are shown in Fig. 6a-d for slight, light, moderate and heavy damage states. The system at this site was chosen because it is characterized by the largest chance of damage among the systems analyzed in this study. The results for the dam and transmission towers for moderate and heavy damage states are not presented in Figs. 6c and 6d because the probabilities for these damage states are extremely small. It should be mentioned that the probabilities in these figures are associated with the damage at the given damage state and

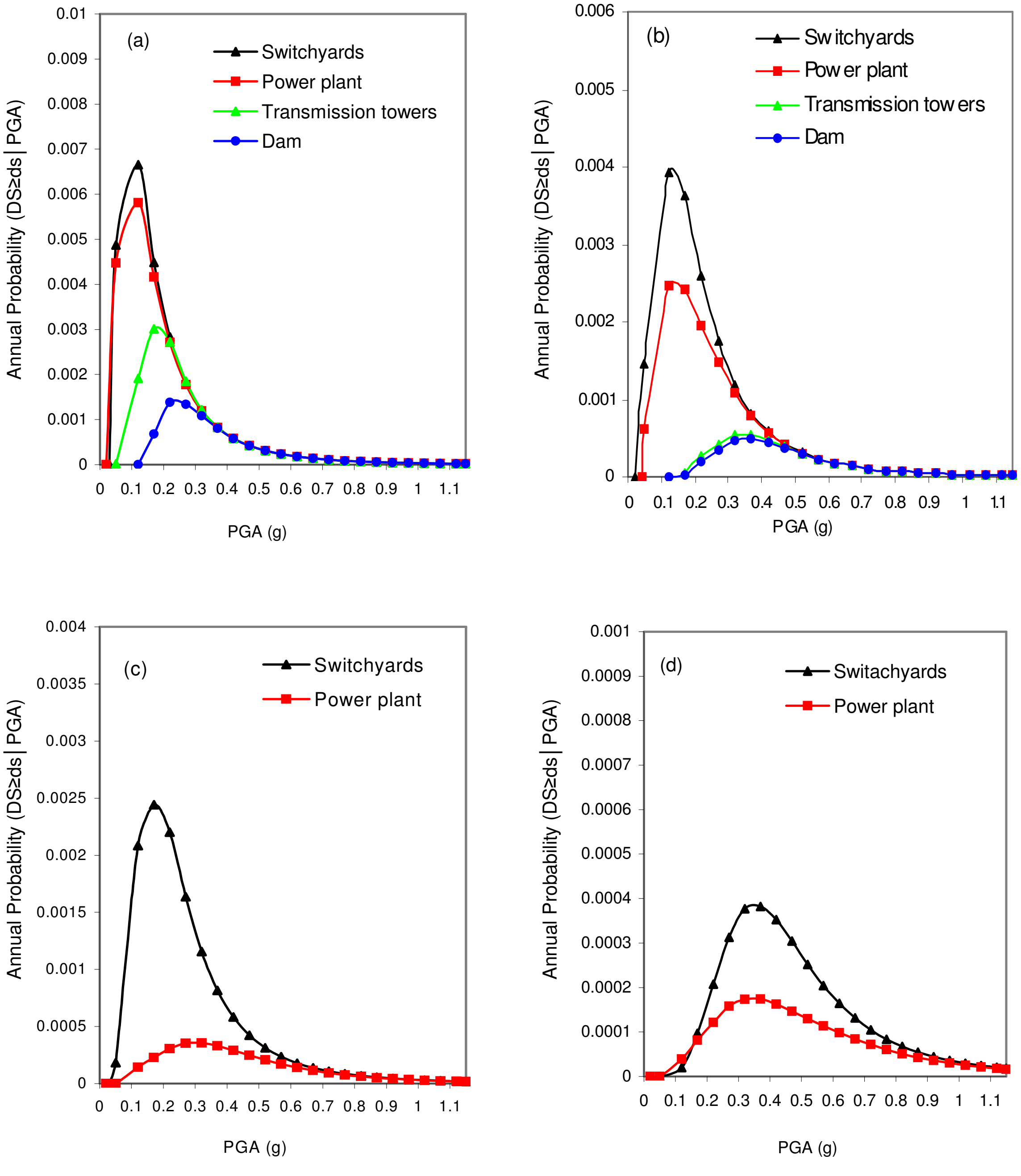

Figure 6. Probability distributions for hydroelectric components at the selected site. (a) Slight damage, (b) Light damage, (c) Moderate damage, (d) Heavy damage.

above that state, e.g. “slight damage” in Fig. 6a also includes occurrences where the damage exceeds “slight”, such as light, moderate and heavy damage. The main findings from the figures are as follows:

(1) The dominant PGA values for switchyards and the power plant are approximately 0.11g, 0.17g, 0.20g and 0.35g for slight, light, moderate and heavy damage state respectively.

(2) The dominant PGA values for transmission towers and the concrete dam are approximately 0.21g, 0.35g for slight and light damage state.

(3) The shifting of the predominant PGA values is associated with the shifting of the fragility curves (e.g., Fig. 3).

(4) For the considered site, the maximum damage probabilities range from 0.0004 to 0.007 p.a. for switchyards, 0.0002 to 0.006 for power plant, 0.0006 to 0.003 for transmission towers, and 0.0006 to 0.0014 for the dam.

Table 4 summarizes the maximum damage probabilities for hydropower components at the selected site. It clearly shows that substations are the most vulnerable components. The order of the vulnerability of the four components considered in the study is: substations, the power plant, transmission towers and the dam.

Table 4. Maximum annual damage probabilities for hydropower components.

Hydropower component	Slight damage	Light damage	Moderate damage	Heavy damage
Switchyards	0.0070	0.0040	0.0024	0.0004
Power plant	0.0060	0.0026	0.0004	0.0002
Transmission tower	0.0030	0.0006	–	–
Dam	0.0014	0.0006	–	–

– denotes very small probability

We consider the information above is sufficient to complete a ranking of hydropower components and facilities, but emphasize that the correctness of the damage probabilities in absolute terms depends entirely on the appropriateness of the DPMs and the conversion of these using the PGA parameter. For long-period structures, such as transmission towers, the use of PGA may overestimate the likelihood of damage. Refinement of the DPMs in terms of the most suitable ground motion parameter(s) together with additional experience incorporated from recent code documents would improve the results.

Conclusions

Seismic vulnerability analysis was conducted for major hydropower components (i.e. dams, power plants, transmission towers, and substations) at a number of selected locations in western and eastern Canada. The main conclusions that can be drawn from this study are as follows:

- The most vulnerable components of a hydropower system, when subjected to seismic motions, are the switchyards and the power plants.
- The highest vulnerability for switchyards and power plants is associated with seismic motions having peak ground accelerations (PGA) between 0.1g and 0.35g.
- The seismic vulnerability for dams and transmission towers is dominated by PGA values between 0.2g and 0.35g.
- The damage probabilities expressed as a function of peak ground accelerations are appropriate values for the vulnerability ranking of hydropower systems, even though this neglects the inter-actions among the individual components of the system.

Acknowledgements

This work was funded by NRCan as a contribution to assessing the reliability of Canada's energy infrastructure. We thank Stephen Halchuk for assistance with the seismic hazard calculations and Dieter Weichert for his review of the paper. Geological Survey of Canada contribution 20060442.

References

Adams, J., and Halchuk, S., 2003. Fourth generation seismic hazard maps of Canada: Values for over 650 Canadian localities intended for the 2005 National Building Code of Canada. Open File 4459, Geological Survey of Canada, Ottawa, Ontario, 155 pp.

Adams, J., and Halchuk, S., 2004. Implications of Canada's 4th generation seismic hazard model for Canadian dams. Paper 3B.1, (10 pp.) CDA 2004 Annual Conference, Ottawa, Ontario.

ATC, 1985. ATC-13: Earthquake damage evaluation data for California. Applied Technology Council, Redwood City, California, 492 pp..

CDA, 1999. Canadian Dam Association. Dam Safety Guidelines. http://www.cda.ca/

NBCC, 2005. National Building Code of Canada 2005. Document NRCC 47666, National Research Council of Canada, Ottawa, Ontario.

NIBS, 1999. National Institute of Building Science. Natural hazard loss estimation methodology. HAZUS 99. Federal Emergency Management Agency, Redwood City, California.

Shinozuka, M., Cheng, T.C., Jin, X., Dong, X., Penn, D., 2002. System Performance Analysis of Power Networks. Paper 00422, Seventh US National Conference on Earthquake Engineering, Boston July 21-25, 2002, 10 pp.