CDA ACB
CANADIAN DAM ASSOCIATION
ASSOCIATION CANADIENNE DES BARRAGES

CDA 2004 Annual Conference
Congrès annuel 2004 de l'ACB
Ottawa, Ontario, Canada
September 25 – September 30, 2004
25 Septembre – 30 Septembre, 2004

IMPLICATIONS OF CANADA'S 4th GENERATION SEISMIC HAZARD MODEL FOR CANADIAN DAMS

John Adams, Earthquakes Canada, Geological Survey of Canada, Natural Resources Canada, 7 Observatory Crescent, OTTAWA, K1A 0Y3 Canada (email: adams@seismo.nrcan.gc.ca)
Stephen Halchuk, (address as for Adams, email: halchuk@seismo.nrcan.gc.ca)

ABSTRACT: We summarize the methods being used for the new seismic hazard maps of Canada and estimate median ground motion on firm soil sites for a probability of exceedence of 2% in 50 years (1/2475 per annum). Spectral acceleration at 0.2, 0.5, 1.0 and 2.0 second periods and peak acceleration will form the basis of the seismic provisions of the 2005 National Building Code of Canada. The future design of common buildings to 1/2475 p.a. may raise public concerns about dams designed to "only" 1/1000 p.a. shaking, unless their expected performance is shown to be substantially better. NBCC2005 hazard values may be useful for screening dam projects. However, as seismic hazard may be very sensitive to the choice of input parameters site-specific evaluation remains essential for 1/10,000 p.a. designs.

RÉSUMÉ: Nous résumons les méthodes utilisées pour les nouvelles cartes d'aléa séismique du Canada et nous estimons le mouvement moyen du sol sur sol ferme pour une probabilité d'excédence de 2% en 50 ans (1/2475 par année). L'accélération spectrale de 0,2, 0,5, 1,0 et 2,0 secondes et l'accélération maximale seront la base des dispositions séismiques du Code National du Bâtiment du Canada de 2005. La future conception des bâtiments communs à 1/2475 p.a. peut évoquer des inquiétudes publiques concernant des barrages conçus pour des mouvements de "seulement" 1/1000 p.a., à moins que leur exécution prévue est considérablement meilleure. Les valeurs d'aléa du CNBC2005 peuvent être utiles pour examiner des projets de barrages. Cependant, comme l'aléa séismique peut être très susceptible au choix de paramètres, l'évaluation spécifique par site reste encore essentielle pour des conceptions de 1/10.000 p.a.

1. INTRODUCTION

A national seismic hazard map forms the fundamental basis of the most effective way that we can reduce deaths and economic losses from future earthquakes. To be useful, a national map must estimate hazard fairly across the country, so future protection can be distributed equitably according to the hazard. This clearly requires a good assessment of the earthquakes sources, but it also needs the selection of the probability level for the assessment and a wise choice of earthquake parameters. Canada's national mapping efforts have moved from qualitative assessment in 1953, to probabilistic assessment at 0.01 p.a. using peak horizontal ground acceleration (PGA) in 1970, and to probabilistic assessment at 0.0021 p.a. using both PGA and peak horizontal ground velocity (PGV) in 1985. With the 4th Generation assessment at 0.000404 p.a., Canada will use spectral acceleration parameters as the basis for the 2005 edition of the National Building Code of Canada (NBCC2005). In this paper we set out the new features of the 4th Generation hazard assessment and discuss some of its consequences for dam design.

2. METHOD

The new hazard model incorporates a significant increment of earthquake data, recent research on source zones and earthquake occurrence, together with complementary research on strong ground motion relations. Detailed information on the model's parameters is given by Adams and Halchuk (2003), and an overview is provided by Adams and Atkinson (2003). The April 2003 special issue of the Canadian Journal of Civil Engineering also contains 12 papers related to NBCC2005. We apply the same Cornell-McGuire methodology (McGuire 1993) that was adopted by Basham et al. (1982, 1985) for Canada's 3rd generation maps and NBCC1995 (1995), but we have used a customized version of the FRISK88 hazard code (FRISK88 is a proprietary software product of Risk Engineering Inc.) in order to incorporate uncertainty. The new seismic hazard model for Canada considers two types of uncertainty - aleatory uncertainty due to randomness in process and epistemic uncertainty due to uncertainty in knowledge; the former cannot be reduced by collecting additional information, but the latter can be (Adams and Atkinson 2003). The treatment of uncertainty is detailed in Adams and Halchuk (2003).

2.1 Regionalization of Canada

Of necessity, eastern and western Canada must be treated slightly differently because of the different properties of the crust. Figure 1 shows the earthquakes and the regionalization used and identifies in a general way the low-seismicity central part of Canada we discuss later as "stable Canada". Seismic hazard to the west of the leftmost dashed line on Figure 1 has been calculated using western strong ground motion relations; eastern relations are used for the remaining regions.

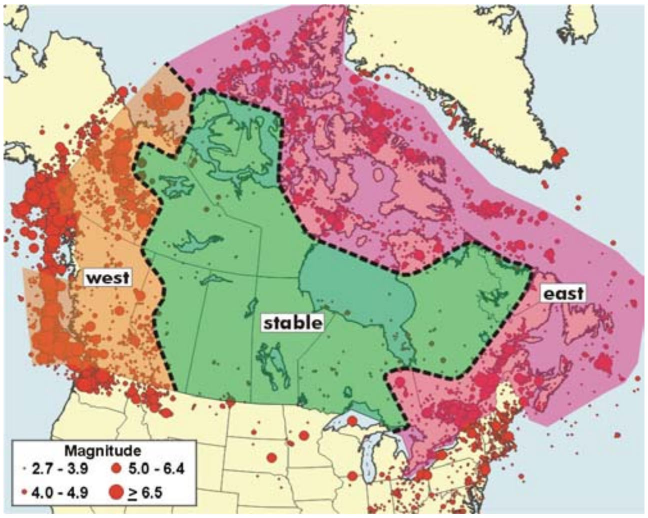

Figure 1. Map of Canada showing the earthquake catalog used for the 4th Generation model together with dashed lines delimiting the eastern and western seismic regions and the "stable Canada" central region.

2.2 Ground Motion Parameters

In contrast to the 1985 maps used in NBCC1995, which gave values for PGA and PGV, we present 5% damped horizontal spectral acceleration values for the 0.2, 0.5, 1.0, and 2.0 second periods that will be used in NBCC 2005. The spectral acceleration parameters are denoted by Sa(T), where T is the period. We also present PGA values, which are used only for liquefaction analyses. We express the values in units of g and report them to 2 significant figures (an appropriate level of precision), except for some small 2.0 s values for which one significant figure is appropriate.

2.3 Probability Level

The new code will use hazard computed at the 2% in 50 year probability level (1/2475 per annum) instead of the 10% in 50 year (1/475 p.a.) level of the 1995 code. This change is consistent with expected building performance i.e., although buildings were apparently being designed to 1/475 p.a. in NBCC1995, engineering judgment suggests 1/2500 p.a. performance was attained (Heidebrecht 2003). It was necessary to calculate hazard at the new lower probability because the distribution of hazard across Canada at 1/475 p.a. differs from that at 1/2475 p.a. Thus applying a constant conservatism (= implied Factor of Safety in the 1995 code) did not achieve the same reliability across the country. For example if the reliability in Vancouver was 1/2475 p.a., the reliability in Montreal was only 1/1600 p.a. (Figure 2). For backward comparability, Adams and Halchuk (2003) give some 10%/50 year values computed using the new hazard model.

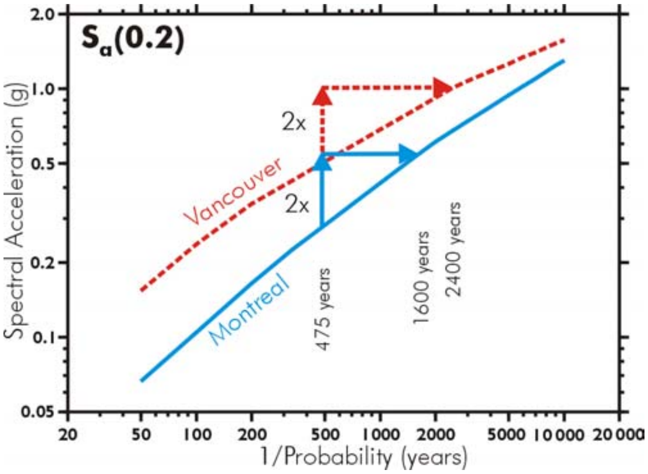

Figure 2. Sa(0.2) hazard curves for Vancouver and Montréal, showing how increasing the 10%/50 year hazard by a factor of two produces different increases in safety.

Incidentally, for most common buildings the general increase in ground motions from NBCC1995 to NBCC2005 is by a factor of 2 +/- 0.3, but the increase is taken into account in the design process through the use of new R_o factors that explicitly quantify overstrength (Heidebrecht 2003). Thus in a general way the large increases in ground motions due the drop in probability level do not lead to a proportional increase in building "strength" or robustness.

2.5 Choice of Confidence Level

The 4th Generation model provides an assessment of uncertainty, and so instead of presenting just the value for a given probability level (representing the result of our best estimates of the input parameters) it provides the percentiles of the distribution. While typical choices include the mean (which is the expected value given the uncertainty) and the 84th percentile (which uses the uncertainty to provide a higher confidence that the specified ground motion will not be exceeded), we recommended the 50th percentile - the median - ground motions for NBCC2005 as it is less sensitive to the exact amount of uncertainty included in the model. For typical seismic hazard computations in Canada the mean hazard value typically lies between the 65th and 75th percentiles of the hazard distribution.

2.5 The Four Seismicity Models - H, R, F, and C

To capture epistemic uncertainty in source, two complete probabilistic seismic hazard models were created for Canada, an "**H**" model that uses relatively small source zones drawn around historical seismicity clusters, and a "**R**" model that establishes larger, regional zones reflecting seismotectonic units.

Both models are composed chiefly of areal sources, with only the Queen Charlotte Fault being modeled as a fault source. Standard methods were applied to define the source zone boundaries, select the earthquakes that pass completeness, choose upper bound magnitudes, and fit the magnitude-recurrence curves. Details of the method and listing of the parameters chosen are given in Adams and Halchuk (2003).

For the relatively aseismic central part of Canada a "stable Canada" probabilistic "**F**" model with arbitrary boundaries was used to integrate knowledge about earthquake activity rates in similar parts of the world's continents. The **F** model provides a "floor" value to seismic hazard for all parts of Canada.

A great earthquake occurred off Vancouver Island on the Cascadia subduction zone in 1700 A.D., and is expected to repeat. We chose to adopt a realistic scenario for this earthquake involving a line source with magnitude 8.2 (2003, Fig. 6), and so provide a deterministic ("**C**" model), rather than probabilistic, estimate of its ground motions.

2.7 Strong Ground Motion Relations

The different physical properties of the crust in eastern and western Canada and the different nature of the earthquake sources in southwestern Canada required the use of four separate strong ground motion relations. For eastern and central Canada, east of the leftmost dashed line on Figure 1, we used the relations of Atkinson and Boore (1995) adjusted to represent the ground motions on "firm ground" (see below). For the western Canadian shallow source zones, including the subcrustal transition zones west of Vancouver Island as well as the Queen Charlotte Fault, we adapted the ground motion relations from Boore et al. (1997) to include a period-dependent anelastic attenuation term for distances beyond 100 km. For subcrustal, normal-mechanism earthquakes within the subducting slab under the Straits of Georgia and Puget Sound we used the Youngs et al. (1997) intraslab relations adjusted to "firm soil" with a representative depth of 50 km. For the Cascadia subduction earthquake scenario we used Youngs et al. (1997) interface relations with a magnitude of 8.2 and depth of 25 km, and with the closest approach of the rupture zone to establish distances to each site.

2.7 Reference Ground Condition for Canada

For the preparation of national hazard maps it is essential to present seismic hazard levels on the same ground condition. Thus a "reference" ground condition is needed in order to make the 2005 hazard values both numerically comparable between east and west, and roughly comparable in intent to the past (1985) hazard maps. NBCC2005 has adopted "Site Class C", defined by a 360 to 750 m/s average shear wave velocity in the uppermost 30 m (Finn and Wightman 2003) for the Canada-wide reference ground condition because it: represents the larger number of strong motion recordings in well-instrumented places like California; is in the mid-range between very hard and very soft ground (thus minimizing uncertainty in the amplification or deamplification factors); and is close to the ground conditions that were implied by the strong ground motion relationships used in for the 1985 maps. The strong ground motion equations we use, such as the hard-rock relations of Atkinson and Boore (1995), have been modified to Site Class C.

2.8 Combining Hazard Results from Various Seismicity Models

For NBCC 2005 the results from the four seismicity models are combined using the method termed "robust". The "robust" model is just choosing the highest value from the four models for each grid point across Canada. The actual procedure is to compare the **H**, **R** and **F** models for the east and choose the higher value, compare the **H**, **R** and **F** models for the west and choose the higher value, compare these eastern and western value sets and choose the higher value (this ensures a robust join in Saskatchewan and the western Arctic), then lastly compare the Canadian **H**+**R**+**F** values for southwestern Canada with the values from the **C** model.

3. RESULTS

Adams and Halchuk (2003) give the NBCC2005 values for over 650 localities across Canada. Seismic hazard values were calculated for a grid extending over Canada and used to create national contour maps such as Figure 3. The four spectral values used by NBCC2005 (together with values at a few other periods) were used to construct Uniform Hazard Spectra (UHS) for a few major cities to illustrate the range and period dependence of seismic hazard across Canada (Figure 4).

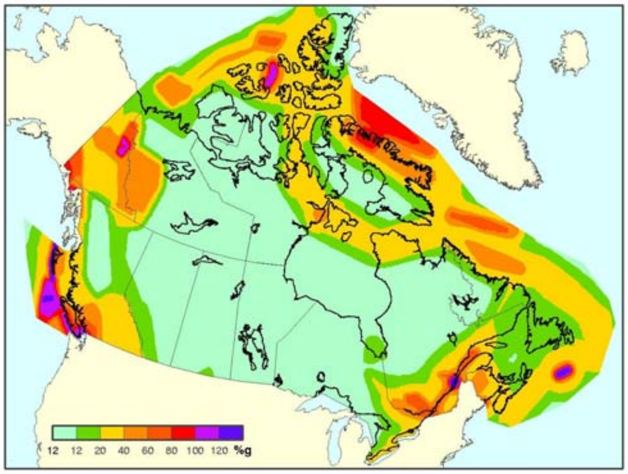

Figure 3. Sa(0.2) for Canada (median values of 5% damped spectral acceleration for Site Class C and a probability of 2%/50 years).

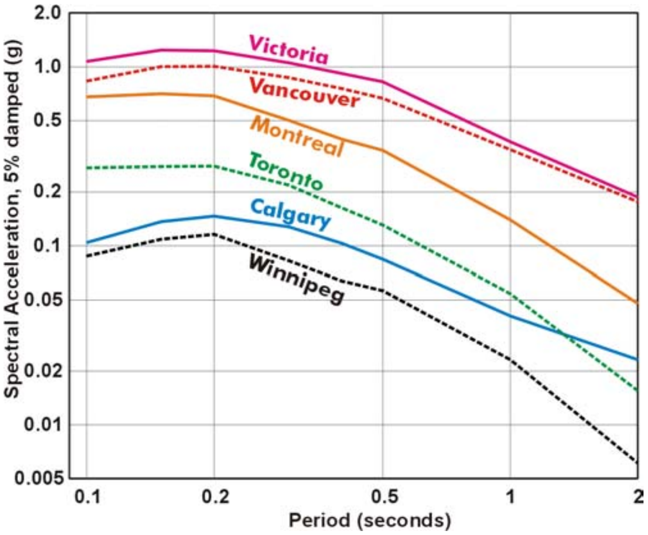

Figure 4. Uniform Hazard Spectra for median 2%/50 year ground motions on Site Class C for key cities.

Other UHS are given by Adams and Halchuk (2003), and yet more can be constructed from the tabulated values therein. The UHS for Winnipeg is representative of many localities in low-seismicity parts of Canada where the F model dominates. The change of Sa(0.5) hazard as a function of probability ("hazard curve") for selected cities is illustrated in Figure 5. Other hazard curves are given in Adams and Halchuk (2004a). Figure 6 shows that the slopes of the hazard curves also vary considerably within one geographic area.

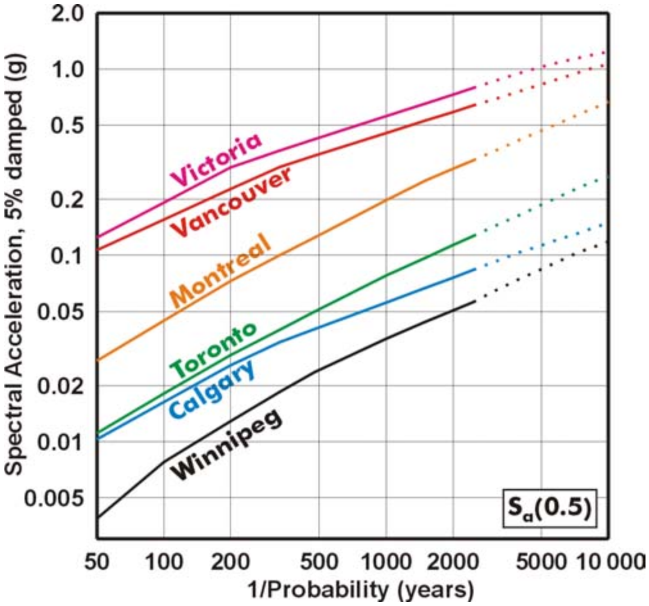

Figure 5. Sa(0.5) hazard curves for key cities.

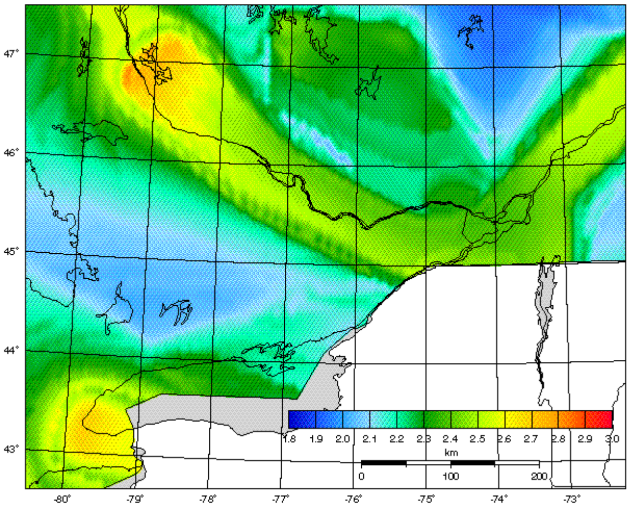

Figure 6. Ratio of 2%/50 year to 10%/50 year robust hazard for Sa(0.2) in southeastern Canada.

Halchuk and Adams (2004) discuss the deaggregation of Canadian seismic hazard and illustrates the magnitudes and distances of the earthquakes making the largest contribution to the seismic hazard for selected cities. An example is given in Figure 7.

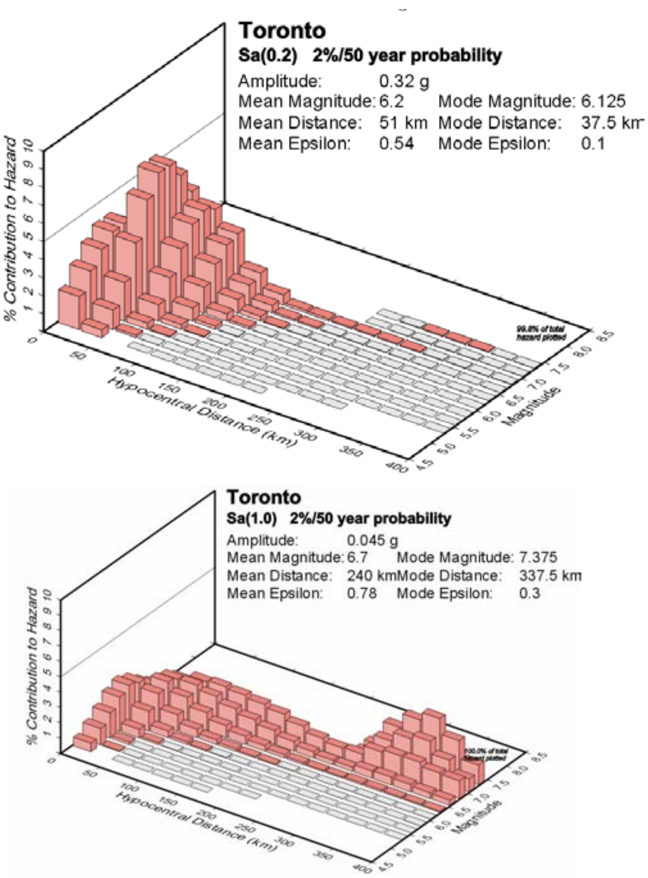

Figure 7. Deaggregation of Sa(0.2) (top) and Sa(1.0) (bottom) hazard for Toronto, showing the relative contributions of magnitude-distance combinations (from Halchuk and Adams (2003).

4. DISCUSSION

4.1 Improvements already considered in site-specific dam design.

NBCC 2005 implements several improvements already considered standard for dam design: the use of site-specific values instead of zonal average values, the use of uniform hazard spectra instead of a standard spectrum scaled to PGV and partially adjusted by PGA, and use of a probability reflecting required performance. Furthermore, the use of site-specific geotechnical values and soil-response modeling for dam foundations already exceeds the new NBCC soil classification and its generic handling of ground motion amplification and non-linear effects at strong shaking.

4.2 Improvements in estimated hazard because of new knowledge about earthquake distribution

While the general pattern of earthquakes in the two decades since the 1985 maps were compiled has not changed, there have been a few significant earthquakes that have caused re-evaluation of the earthquake sources together with an upward revision of many upper bound magnitudes. Two completely new components have been added in the 2005 maps: the Cascadia subduction earthquake, and the occurrence of earthquakes in the "stable" part of Canada. These two additions have increased the estimated hazard along the Pacific edge of Vancouver Island and throughout many areas of Canada hitherto thought to be aseismic respectively. While only a small increment of earthquakes has been added to the 1985 active zones, the approach used for the R model has increased estimated seismic hazard at places that lie near potentially-seismogenic features with few historical earthquakes, such as the St. Lawrence valley near Trois-Rivières.

4.3 Changes in estimated hazard from the 1985 maps

Improved understanding of seismicity patterns, their cause and recurrence rates, and increased knowledge of strong ground motion has led to significant changes in estimated hazard from NBCC1985, both in absolute terms and relative to other city values (Fig. 8). Table 1 of Adams and Halchuk (2004b) compares 1985 and 2005 seismic hazard values for PGA at 10%/50 year.

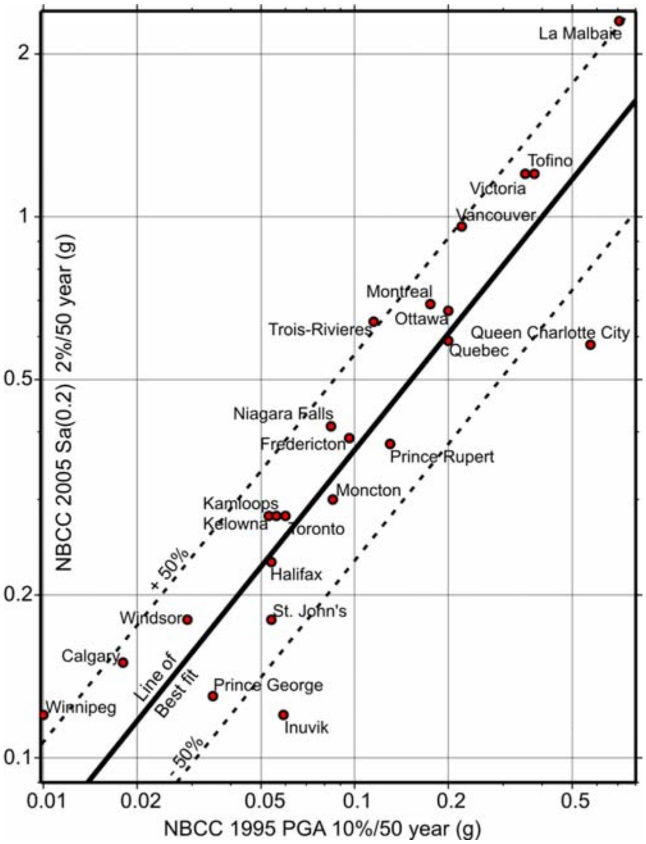

Figure 8. Relative change in short-period seismic hazard for selected Canadian cities. Most places lie within ∀50% of the line of average change.

The comparison is not ideal because PGA is a short-period measure that captures the damage potential of ground motions much more poorly than spectral acceleration at short or long periods. The changes arise from: new strong ground motion relations used, new earthquake sources (discussed above), changes in source zone boundaries, increases in upper bound magnitudes, and lowered impact of large historical earthquakes thought less likely to reoccur. They represent the net result of many effects, some acting to increase and some to decrease the estimated hazard.

4.4 Some unresolved consequences

4.4.1 Consistency of other standards with the new, lower NBCC2005 probability level

Some existing codes and standards were written in the context of NBCC1985, i.e. seismic hazard estimated for common buildings at 10%/50 years. For example, CSA Z289-01 (2001) defines the "safe shutdown earthquake" for Liquefied Natural Gas (LNG) plants to be 5%/50 years, and so requiring design to a hazard probability half that required for common buildings in 2001. However this now seems out of step, in that common buildings in 2005 will be designed for hazard levels half the probability of the CSA standard for these critical structures. As many common buildings may be as reliable under NBCC2005 as under NBCC1995 (because of the inclusion of R_o factors to reflect actual building performance), it appears that although the CSA standard intended LNG plants to be designed to be safer than common buildings, that might not have been the outcome. In a similar fashion there may be concern about dams designed to "only" 1/1000 p.a., unless the expected performance for the 1/1000 p.a. design can be shown to be substantially better.

4.4.2 Parameters for liquefaction design

NBCC1995 was based on the philosophy that the foundation should not fail before the structure that it supports. Resistance to soil liquefaction was often based on Seed's criteria which uses the site NBCC PGA together with a representative magnitude. The move to 2%/50 year hazard has had two effects that seem likely to result in more conservative anti-liquefaction designs than NBCC1995. Firstly the firm ground 2%/50 year ground motions are about twice the 10%/50 year motions. Secondly, deaggregation of hazard at the 2%/50 year probability level Halchuk and Adams (2004) reveals that more of the hazard is coming from the larger earthquakes than before, thus leading to larger modal (or mean) magnitudes (which may be those chosen for the liquefaction assessment).

These increases are only partially offset by the smaller amplification of surface ground motions on soft soil sites in high-seismic regions. The net effect is an increase in design ground motions of about 30% in the high-seismicity Vancouver/Richmond area (A. Wightman, pers. comm., 2004), but an increase of 60% or more for eastern sites in areas of low seismicity.

The problem is compounded by basing liquefaction analysis on the PGA ground motion parameter. Eastern earthquakes generate shaking that is rich in short-period motions that control the amplitude of PGA, and the crust of eastern Canada attenuates them slowly. Hence PGA values that in California represent strong earthquakes capable of causing liquefaction can be produced in eastern Canada by moderate earthquakes that lack the shaking duration needed to induce liquefaction. Clearly a thoughtful analysis of the problem is required to ensure that application of California-based experiential rules to eastern NBCC2005 ground motions does not produce unduly conservative designs. Site specific analyses (or model solutions for certain cities) appear to be appropriate.

4.5 Some thoughts on possible revisions to the 1999 CDA Dam Safety Guidelines

(*The following is the current personal view of the authors and is presented for the purposes of discussion by the dam-design community*).

4.5.1 Inappropriateness of the 1985 maps for design and screening

We applaud the intent of the 1999 guidelines, with their focus on performance and averting consequences. The intent (CDADCG section 5.0) is that a site-specific seismic analysis be performed to determine the seismic parameters. Increasingly this involves the probabilistic evaluation (perhaps with a deterministic "sanity check") performed by a competent authority. However, certain "well-built embankment dams" (8.2.7) can be designed using (at minimum) a pseudostatic analysis, using "zoning maps created for *that* purpose" (*our emphasis*). As the only provided reference is the Basham et al. 1982/1985 seismic hazard maps, these are probably the ones commonly used to provide the seismic coefficients, even though those maps were intended for the design of common buildings, not dams. Low-consequence dams in low seismic zones do not require any analysis (and again the Basham et al. maps are used to define the "low seismic" regions).

Probably the greatest problem with this approach is that the Basham maps are for 0.0021 p.a. (circa 1/475 years) hazard, a probability likely too high for all but the lowest-consequence dams. Also the new assessment for seismic hazard in the "stable Canada' means that there are now design values for these "low seismic" regions, which previously were listed as zero hazard.

4.5.2 Applicability of 4th Generation results to the design of high-reliability structures

Past NBCC seismic provisions have formed a guide for the seismic design of "non-buildings" that require reliable performance. For example, the Canadian Dam Association Safety Guidelines (1999) suggest dams be designed for one of three levels of safety, dependant on consequences, and associated with probability levels of 0.01-0.001 p.a., 0.001-0.0001 p.a., and 0.0001 p.a. As the first and perhaps often the second are now above the NBCC2005 probability level of 0.000404 p.a., one might ask if the 4th Generation model provides sufficiently reliable estimates for the design of low-risk dams. The answer is "maybe", since while the hazard can be estimated at the correct probability level, there is no certainty that all the factors relevant to the specific dam have been considered by the national model. Chief among these factors are the choices made in associating relevant earthquakes into source zones and in the position of nearby source-zone boundaries. The site value for a short-period structure close to a high-seismicity zone is often sensitive to the position of the zone boundaries because of the rapid attenuation of short-period motion with distance (e.g., the gradients across Toronto and Vancouver, Figure 9). A shift of 10 km in the boundary used in the model could change the ground motions for Sa(0.2) by 30%. Hence site-specific evaluation becomes essential for critical designs.

While the 4th Generation model could also be run to produce lower probability estimates (e.g., 0.0001 per annum) these probabilities are normally only required for special facilities such as nuclear power plants or dams which have a large consequence if they were to fail. These probabilities are beyond the scope of the National Building Code of Canada. Extrapolation of the hazard model to lower probability results is mathematically possible (i.e. precise), but represents an unreliable (i.e. possibly inaccurate) extrapolation of the model with respect to a) the seismic source zones used to develop the seismic hazard model and b) the uncertainty in the strong ground motion prediction equations and other inputs, hence the dashed lines on

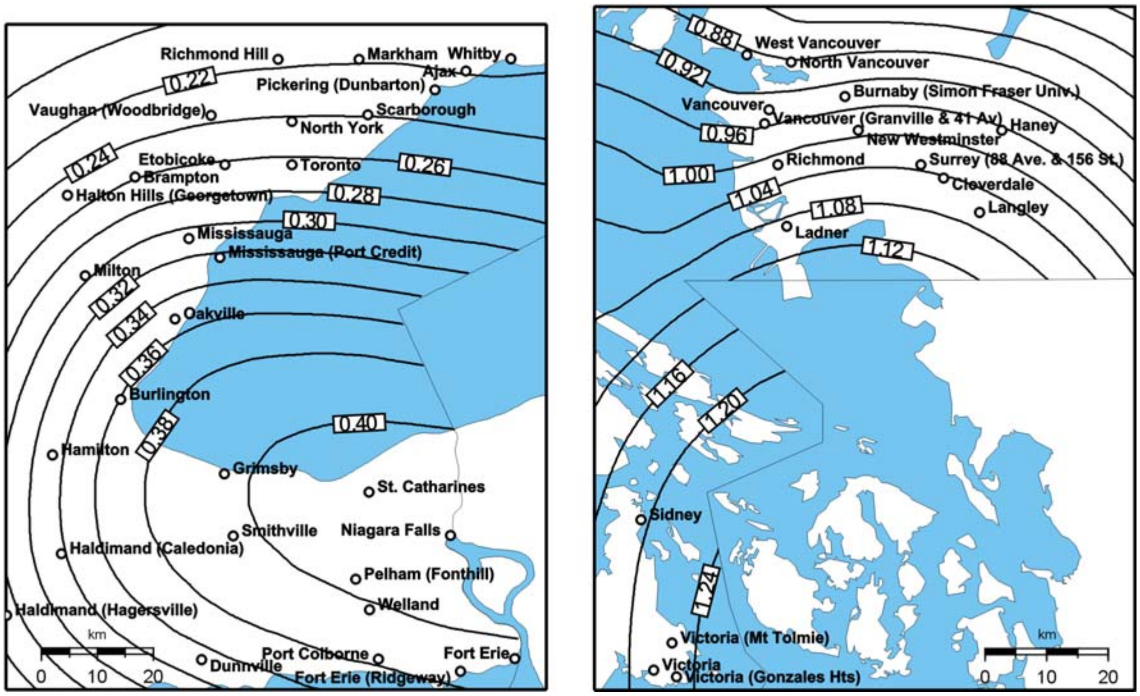

Figure 9. Detailed maps of Sa(0.2) hazard in the vicinity of Toronto-Niagara and Vancouver-Victoria (units=g) showing relatively steep gradients.

Figure 5. We strongly caution that the national scope of the model means it cannot adequately address all uncertainties at all sites. Hence site-specific evaluation becomes essential for critical designs.

4.5.3 Screening

For screening purposes, it might be possible to provide guidance regarding low-probability hazard by a procedure such as the following: (i) plotting the 10%/50 year and 2%/50 year NBCC2005 median values on a log-log scale and linearly extrapolating them out to the required return period; (ii) increasing the median value from (i) by a factor to estimate the mean; and (iii) if the boundary of a source zone generating higher hazard than the zone containing the site lies within 100 km of the site, applying a second period-dependent factor to the value from (ii) to represent the possibility that the nearby source zone boundary is incorrectly placed too far from the site (this factor would need to be larger for short periods, because short-period ground motions fall off more rapidly with distance than do long period motions). The suggested screening procedure is conservative in four ways: the actual hazard curves have slopes that flatten as one moves to lower probabilities (Figure 5); an estimate of the mean is used here to incorporate a measure of epistemic uncertainty; the true source boundary may be more distant from, rather than closer to, the site; and a closer zone boundary would normally be associated with a larger source zone and hence a reduced earthquake density and lower hazard. However the intent of a *screening* is to give conservative results such that we have high confidence a "pass" is a valid outcome. A "fail" at the screening level is just encouragement for a detailed site-specific analysis. The greatest benefit of the screening could be for moderate consequence dams in the lower seismicity regions, such as most of the region dominated by the **F** model.

4.6 On "conservative" design

In considering the seismic hazard design for high-reliability structures such as dams, it is well to consider the consequences of conservative design. Conservative design comes with increased costs, making the value of the project less worthwhile (to both the proponent and society). A problem is that the benefits of "just-right" design are largely realized by the proponent in the short term, while the costs of under-design are often borne by society in the long term.

A design to a higher level of conservatism allows satisfaction of a job well done; and may allow a project to cope with future upward reassessment of seismic hazard (such as might happen after an "unexpected" earthquake occurred nearby). Such intentional over-design may be economically justified, when the initial cost of the higher design is much less than the plausible costs of retrofit plus the loss of revenue during shutdown (McGuire, 1987).

Costs of appropriate or over-design may be quickly recovered should shaking near the design level occur. A recent success was the 1972 design of the Alaska oil pipeline at its crossing of the Denali Fault (USGS press release, 2002). The fault moved about 5 m during the 2002 earthquake, but the pipeline was built on sliders to accommodate 6 m of motion and was undamaged. The pipeline was shut down for just a few days for precautionary inspection. Had the pipeline ruptured, economic losses would have been considerable as the pipeline carries $US25M of oil per day. More importantly, such a catastrophic oil spill might have proved almost impossible to remediate and environmental considerations might have prevented the re-opening of the pipeline.

However, recent work on low probability (10^{-6} to 10^{-9} per annum) design for nuclear reactors and radioactive waste repositories has identified some of the pitfalls of conservative design (Reiter 2004) which may also have relevance for high consequence dams:

- We cannot capture all uncertainty – so we tend to put a lot of effort into the quantification of uncertainty in known processes, while ignoring "unknown" processes.
- "Compounding conservative assumptions does not always lead to conservative results" (a worst case may result from some other combination).
- Conservatism introduced because of a fear of the unknown or lack of knowledge can compromise society's confidence in the rational basis for the risk analysis.
- Conservative estimates may not be physically realistic (is 20 g a realistic PGA design level?).
- Conservatism may result in major design changes and/or unjustifiably high costs.
- An overconservative estimate, say for an earthquake, may distort the significance of other key trigger events and their consequences for plant operation, thus impeding understanding of the total risk.
- Conservatism can lead to unwarranted effort into incidents and consequences for which we have no practical experience (since they are in fact so unlikely that only a few - or none - of the world's dams has ever experienced them).
- If, later in the design process, the project may appear unable to proceed, public pressure may make it impossible to justify sane reductions to the ground motion estimates previously made public.

4.7 Estimating seismic hazard differently

New methods of estimating seismic hazard are being developed that would allow the simulation of site-specific ground motions at levels of engineering interest. Seismograph recordings of small earthquakes made at the site of interest are used as "seeds" to simulate the effects of hypothetical large earthquakes occurring at the epicentres of the small ones. The method thus replaces the regional estimates from standard strong ground motion relations with source-specific ground motions. It should prove especially valuable for sites near active faults or set back from highly-active source zones. Some of the work on conservative hazard estimation suggests that these types of results might have lower variance than standard strong motion relations which rely on the "ergodic" assumption – that we can use many earthquake recordings at many different sites during a short period of time to estimate the variance of all earthquake recordings at a single site over a long period of time (Anderson 2004). Although the method requires advance planning to install a seismograph for a handful of years in advance of project design, it might pay for itself in terms of less uncertainty in the estimates of ground motions the dam will face in the future.

5. CONCLUSIONS

We have summarized the basis for the 4th generation model and shown how it should enable improved dam design across Canada through the use of spectral parameters that permit site-specific uniform hazard spectra to be constructed for each site. The incorporation of the "stable Canada" model should mean that dams in the large central part of Canada can be designed for realistic probabilistic shaking and not for a deterministic event that might be very improbable. The future design of common buildings to 1/2500 p.a. may raise public concerns about dams designed to "only" 1/1000 p.a. ground motions, unless their expected performance can be shown to be substantially better. Finally, site-specific evaluation of seismic hazard remains essential for 1/10,000 p.a.

6. ACKNOWLEDGMENTS

We thank Peter Basham and Dieter Weichert and many of our colleagues who have been involved in the 4th Generation seismic hazard maps.

7. REFERENCES

(papers by Adams and Halchuk can be downloaded from www.EarthquakesCanada.ca)

Adams J., Atkinson G.M. 2003. Development of Seismic Hazard Maps for the 2005 National Building Code of Canada. *Canadian Journal of Civil Engineering* 30: 255-271.

Adams J., 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. *Geological Survey of Canada Open File* 4459: 1-155. Also available from http://www.seismo.nrcan.gc.ca/hazards/OF4459/

Adams J., Halchuk S., 2004a. Fourth generation seismic hazard maps of Canada: Hazard curves for selected Canadian cities. *Geological Survey of Canada Open File XXXX*, for release summer 2004.

Adams J., Halchuk S., 2004b. Fourth generation seismic hazard maps for the 2005 National Building Code of Canada. *Proceedings of the 13th World Conference on Earthquake Engineering, Vancouver, Canada. Paper 2502 on CD-ROM.* Vancouver: 2004.

Anderson, J.G., and Brune, J. N., 2004. Possible importance of the Ergodic assumption for probabilisitic seismic hazard analysis. *Seismological Research Letters* 74:284.

Atkinson G.M., Boore D.M. 1995. New ground motion relations for eastern North America. *Bull. Seism. Soc. Am.* 85: 17-30.

Basham P.W, Weichert D.H, Anglin F.M., and Berry M.J. 1982. New probabilistic strong seismic ground motion maps of Canada: a compilation of earthquake source zones, methods and results". *Earth Physics Branch Open File* 82-33: 1-202.

Basham P.W., Weichert D.H., Anglin F.M., and Berry M.J. 1985. New probabilistic strong seismic ground motion maps of Canada. *Bull. Seism. Soc. Am.* 75: 563-595.

Boore D.M., Joyner W.B., Fumal T.E. 1997. Equations for estimating horizontal response spectra and peak acceleration from western North American earthquakes: A Summary of Recent Work. *Seismological Research Letters* 68: 128-153.

Canadian Dam Association Dam Safety Guidelines. *Canadian Dam Association*, Edmonton, 1999: 1-118.

Canadian Standards Association Z276-01 Liquefied Natural Gas (LNG) - Production, Storage and Handling. *Canadian Standards Association*, Toronto, 2001: 1-78.

Finn W.D.L., Wightman A. 2003. Ground motion amplification factors for the proposed 2005 edition of the National Building Code of Canada. *Canadian Journal of Civil Engineering* 30: 272-278.

Halchuk S., Adams J. 2004. Deaggregation of seismic hazard for selected Canadian cities. *Proceedings of the 13th World Conference on Earthquake Engineering, Vancouver, Canada. Paper 2470 on CD-ROM.* Vancouver: 2004.

Heidebrecht A.C. 2003. Overview of seismic provisions of the proposed 2005 edition of the National Building Code of Canada. *Canadian Journal of Civil Engineering* 30: 241-254.

McGuire R.K., 1987. Seismic hazard uncertainty and its effects on design decisions in F.H. Wittmann (ed) *Transactions 9th International Conference on Structural Mechanics in Reactor Technology*, Lausanne 3-12.

McGuire R.K., 1993. Computations of seismic hazard. Giardini D, and Basham PW, Editors. *Global Seismic Hazard Assessment Program. Annali di Geofisica* 34: 181-200.

National Building Code of Canada 1995. *National Research Council of Canada*, Ottawa, NRCC 38726: 1- 571.

Reiter, L., 2004. When are ground motion estimates too high? *Seismological Research Letters* 74:282.

Youngs R.R., Chiou,S-J., Silva W.J., Humphrey J.R. 1997. Strong ground motion relationships for subduction zone earthquakes. *Seismological Research Letters* 68:58-73.