



CANADA'S 5TH GENERATION SEISMIC HAZARD MODEL, AS PREPARED FOR THE 2015 NATIONAL BUILDING CODE OF CANADA

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ABSTRACT: Canada's 5th Generation seismic hazard model was developed to generate seismic design values for the 2015 National Building Code of Canada (NBCC2015). The model updates the earthquake catalog, consistently expresses earthquake magnitudes in terms of moment magnitude, revises earthquake source zones, and includes probabilistic treatment of Cascadia and other fault sources, and so estimates mean ground shaking at the 2% in 50-year probability level. Hence it takes advantage of contemporary scientific knowledge and replaces the 4th Generation 'robust' combination of alternative models used for NBCC2010 (for example, the hazard in southwestern BC was the higher of the H-probabilistic, the R-probabilistic or the Cascadia-deterministic model) by a fully probabilistic model. The ground-motion prediction equations (GMPEs) used represent a major advance over those used for the 4th Generation. Seismic design values (on Soil Class C at $V_{S30}=450$ m/s) for PGA, PGV and for Sa(T) for T = 0.2, 0.5, 1.0, 2.0, 5.0, and 10.0 s are proposed for NBCC2015. Values for the longer two periods are possible because of the modern GMPEs, and they replace the $\frac{1}{2}Sa(2.0)$ value used for T>4 s in 2010. In general, for locations in eastern Canada, the estimated seismic hazard at long periods has increased while the seismic hazard at short periods has decreased - in some places significantly. For locations in western Canada, the seismic hazard at long periods has increased significantly for areas affected by great Cascadia interface earthquakes. In Haida Gwaii and the Yukon, the explicit inclusion of fault sources has also raised the estimated hazard.

1. Introduction

A national seismic hazard model forms the fundamental basis of the most effective way that we can reduce human casualties 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 earthquake sources, but it also needs the selection of the probability level for the assessment and a wise choice of earthquake parameters. As the knowledge of, and sophistication in, probabilistic seismic hazard analyses have grown, Canada's national mapping efforts have moved from qualitative assessment in 1953, to probabilistic assessment at 0.01 per annum (p.a.) using peak horizontal ground acceleration (PGA) in 1970, to probabilistic assessment at 0.0021 p.a. using both PGA and peak horizontal ground velocity (PGV) in 1985, and to the 4th Generation assessment at 0.000404 p.a. using spectral acceleration parameters which was the basis for the 2005 edition of the National Building Code of Canada (NBCC2005; Adams and Halchuk (2003)).

NBCC2010 seismic hazard values were based on the same 4th Generation seismic hazard model as the 2005 values, but with seismic hazard values updated by replacing the quadratic fit to the ground motion relations used in NBCC2005 for earthquakes in eastern, central and north-eastern Canada by an 8-parameter fit. It was recognized that, while the quadratic fit provided a good approximation in the high-hazard zones, it was rather conservative at short periods for the low-hazard zones; however, because the design values are small in the low-hazard regions, the approximation was accepted for NBCC2005. The 8-parameter fit gave a good fit across all zones. In general, NBCC2010 PGA and short-period spectral values dropped in most regions, while long-period values slightly increased from their NBCC2005 values (Adams, 2011).

In this paper we lay out the new features of the 5th Generation hazard model and discuss some of its consequences. 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. The model's numerical parameters are given in Halchuk et al. (2014), and detailed documentation of the model and its results are in Adams et al. (2015).

Companion papers at this conference include: Allen et al. (2015a) on the new seismic hazard model for northwestern Canada; Halchuk et al. (2015a) which compares the seismic hazard results from the 5th Generation model to the 2014 US hazard models along Canada's southern border; and Rogers et al. (2015) which discusses the seismic hazard in southwestern British Columbia and illustrates the magnitudes and distances of the earthquakes making the largest contribution to the seismic hazard for the more densely populated region of southwest British Columbia including Vancouver and Victoria.

2. Method

2.1. Overview

We apply the same Cornell-McGuire methodology (McGuire, 1993) as was adopted by Adams and Halchuk (2003) for Canada's 4th Generation model and NBCC2005, using a customized version of the FRISK88 hazard code in order to incorporate uncertainty. FRISK88 is a proprietary software product of Risk Engineering Inc. The 5th Generation seismic hazard model for Canada considers two types of uncertainty: aleatory uncertainty due to randomness inherent in natural processes 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 et al. (2015).

2.2. Regionalization of Canada

Of necessity, eastern and western Canada must be treated slightly differently because of the different propagation properties of seismic waves in the crust. Figure 1 shows the earthquakes and the regionalization used and identifies in a general way the low-seismicity central region of Canada we refer to as "stable Canada". Seismic hazard for most of the area to the west of the leftmost dashed line on Figure 1 has been calculated using western GMPEs (eastern GMPEs are used for the Rocky Mountain foothills); eastern GMPEs are used for the remaining regions.

2.3. Ground Motion Parameters

The 2005 maps for NBCC2005 used 5% damped horizontal spectral acceleration values for the 0.2, 0.5, 1.0, and 2.0 second periods plus values for PGA. The spectral acceleration parameters are denoted by $S_a(T)$, where T is the period. The 5th Generation model provides 0.05, 0.1, 0.2, 0.3, 0.5, 1.0, 2.0, 5.0 and 10.0 second periods plus PGA and PGV. Of these, the 0.2, 0.5, 1.0, 2.0, 5.0 and 10.0 second periods are proposed for use in NBCC2015. PGA is used in the calculation of site amplification (see 2.11), and for liquefaction and other geotechnical analyses. PGV is not explicitly used by NBCC2015, but is a useful parameter for predicting damage. We express the values in units of g (m/s for PGV) and report them to two significant figures (an appropriate level of precision), except for one small long-period value for which one significant figure is appropriate.

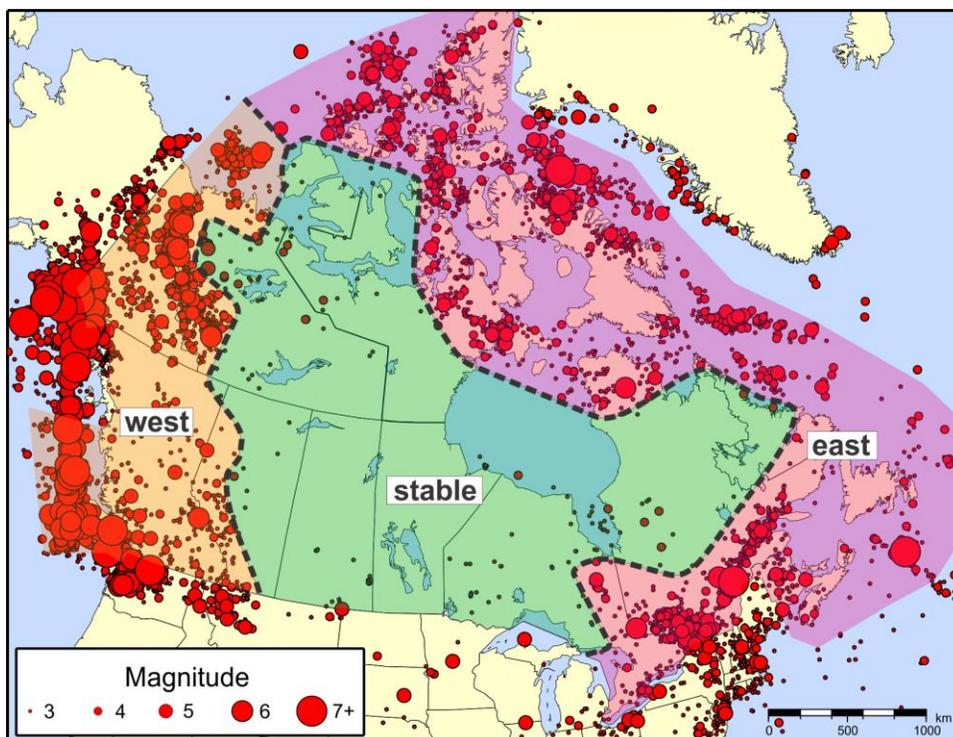


Fig. 1 – Map of Canada showing the earthquake catalog used for the 5th Generation model together with dashed lines delimiting the eastern and western seismic regions and the “stable Canada” central region.

2.4. Probability Level

The *de facto* standard for national seismic hazard maps is the 2% chance of exceedance in 50 years probability level (2%/50 years), equivalent to an annual probability of 0.000404; this is key probability for 5th Generation seismic hazard model. Hazard values at other, higher probability levels are also needed, such as by the Canadian Highway Bridge Design Code (CSA-S-6, 2014), and so will be provided by a web calculator on the EarthquakesCanada.ca web site. The 5th Generation model is not, however, intended for lower probability calculations, such as 0.0001 p.a. sometimes used for dam and nuclear power plant design. In many places the attention given in the model and the detail of the model itself may be insufficient for reliably computing such low probabilities, and site-specific analyses should be performed.

2.5. Choice of Confidence Level

The 4th Generation model provided a first assessment of uncertainty, presenting the percentiles of the distribution instead of just a single “best estimate” value (representing the single result of our best estimate of the input parameters) given by the 3rd Generation model. The median (50th percentile) hazard values were used in NBCC2005 because the median is less sensitive to the exact amount of uncertainty included in the model. It was felt at the time that the treatment of uncertainty was too preliminary to estimate mean-hazard values (for example we a crude factor of 2 was used on the western GMPEs). For the 5th Generation we feel more confident in our treatment of the uncertainty, and estimate mean-hazard values, which are preferred for most uses. The model can also provide the median hazard and percentiles of the distribution. For most locations in Canada, the mean-hazard value typically lies between the 65th and 75th percentiles of the hazard distribution.

2.6. Earthquake Catalog and Magnitude-Frequency Distribution

The 5th Generation model uses a catalog to the end of 2010 compiled by Halchuk et al. (2015b) from Canadian, U.S., and international sources. Magnitudes in the catalog are as-determined moment magnitudes (M_w) or given as equivalent M_w s using regional conversion equations for the original magnitude type. Completeness start years are adjusted from, but are similar to, the 4th Generation model. Upper bound magnitudes (M_{max}) are assigned based chiefly on global analog regions for areal zones and on length-magnitude relations for faults with fault slip rates. For areal sources, magnitude-

frequency distributions (MFD) are computed using maximum-likelihood statistics together with uncertainty bounds on the best-fit relation. For fault sources, both standard Gutenberg-Richter and pseudo-characteristic MFDs are used (Allen et al., 2015a).

2.7. Seismic Source Models

The seismic source zones used for the 4th Generation consisted of two models, which were distinguished primarily as historical cluster (H) and regional seismotectonic (R) models. For the 5th Generation model in northeastern Canada, we use new H and R models. In southeastern Canada, an additional type of source - hybrid between H and R - is used with the new H and R models. In western Canada, a single set of source models is used, but it includes variations in the source geometry as appropriate (for example, in the closest approach of the Cascadia subduction zone to southwestern British Columbia). Boundaries of the individual source zones were revised to reflect new information, and their seismicity parameters were recalculated. For the relatively aseismic central part of Canada, a “stable Canada” source with arbitrary boundaries was used to integrate knowledge about earthquake activity rates in similar parts of the world’s continents. The source – similar to the 4th Generation F model - provides a “floor” value to seismic hazard for all parts of Canada, and source zones populated with its rate of earthquakes are added to each regional model to represent otherwise-unmodelled regions.

The 2005 model included one probabilistic fault source (the Queen Charlotte fault) plus a single deterministic treatment (“C” model) of the Cascadia subduction zone. The 5th Generation model includes fault sources for three low-angle subduction thrusts in the Cascadia subduction zone, an updated treatment of the faults offshore of Haida Gwaii (Queen Charlotte Islands), and adds 5 onshore strike-slip and reverse faults in the Yukon-Alaska region (Allen et al., 2015a). The modelled faults appropriately concentrate the earthquake occurrence near the faults, instead of averaging it out over a wider area (as was done for NBCC2010). The coordinates of the source zones are given in Halchuk et al. (2014) and further details of the choices are given in Allen et al. (2015a) and Adams et al. (2015).

2.8. Combining Hazard Results from Various Seismic Source Models

For the 4th Generation the results from four seismicity models (H, R, C and F) were combined using the method termed “robust” by Adams et al. (1995). This method - choosing the highest value from the four models for each grid point across Canada - was used because it was felt that there was insufficient information to make a valid judgment on the relative merits of each model (particularly H and R), as is necessary to create a fully probabilistic model. Designing for the higher of the H and R models was generally (but not always) conservative, and thus the adopted robust median was likely closer to the true mean value than the probabilistic median in many localities. However, the combination was clearly unconservative in localities (and periods) where the C and F models gave similar hazard to the H or R model. For example, in NBCC2005 and NBCC2010 design shaking for Vancouver and Victoria was taken from the H or R model (see Adams and Halchuk, 2003, Table 6) ignoring the smaller amplitude, but still significant shaking, contribution of the Cascadia subduction earthquakes. The 5th Generation model is now fully probabilistic, as it applies relative weights to the various source models given above. For northeastern Canada the new H and R models are equally weighted, for western Canada the model is fully weighted but has weighted alternatives for variations of geometry. For southeastern Canada the new H model gets 40%, the hybrid model 40%, and the revised R model the remaining 20%. Thus overall the weight is about 2:1 between historical seismicity and a seismotectonic generalization of that seismicity.

2.9. Ground Motion Models

A major change is the adoption of modern Ground Motion Prediction Equations (GMPEs). In the three decades since the publication of the first national Canadian GMPEs (Hasegawa et al., 1981) new GMPEs for North America have incorporated a better understanding of the magnitude- and distance-scaling of earthquake ground motions, a wealth of new data, and the use of finite-fault ground motion simulations to generate synthetic time histories to fill-in for the absence of data from large eastern North American earthquakes.

The different physical properties of the crust in eastern and western Canada and the different nature of the earthquake sources in southwestern Canada require the use of separate GMPEs, as detailed by Atkinson and Adams (2013). Unlike the 4th Generation model which used a single published relation (with rather arbitrary uncertainty bounds) for each region, the 5th Generation uses representative suites of relations (Atkinson et al., 2014). For eastern Canada we used a suite of crustal relations based on the hazard values from five appropriate eastern GMPEs. For the western Canadian crustal source zones, as well as the crustal faults, we used a suite based on the Boore and Atkinson (2008) GMPEs. For subcrustal, chiefly normal-mechanism, earthquakes within the subducting slab under Puget Sound and west of Vancouver Island we centred on the Zhao et al. (2006) inslab relation with a representative depths of 50 km and 30 km respectively. For the Cascadia and Haida Gwaii subduction earthquakes we used a 50/50 weight for simulation- and empirical-based interface relations. For all sources the closest approach of the rupture (R_{rup}) was used as the distance metric. For fault sources R_{rup} was used directly, but for area sources the R_{rup} from the GMPEs was adjusted to include the average effect of finite fault length from a point source (see Atkinson 2012). Finally, we adjusted all suites to give the ground motions on “firm ground” (see 2.10).

2.10. 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 (RGC) is needed in order to make the 2015 hazard values both numerically comparable between east and west, and roughly comparable in intent to the past (1985 and 2005) hazard models. NBCC2005 adopted “Site Class C”, defined by a 360 to 750 m/s time-averaged shear wave velocity in the uppermost 30 m (V_{S30}) for the Canada-wide reference ground condition (Finn and Wightman, 2003). A back-calculation of the 2005 RGC factors using the Boore and Atkinson (2008) NGA-West relations indicates that those factors were applicable to $V_{S30} \sim 450$ m/s, slightly slower than the midpoint of Class C. Therefore $V_{S30} = 450$ m/s was taken as the RGC for 5th Generation, and the GMPEs used in the 5th Generation model have been modified to give hazard at $V_{S30}=450$ m/s.

2.11. Adjustment to Other Soil Conditions

As proposed for NBCC2015 the short- and mid-period amplification factors, F_a and F_v of NBCC2010, are replaced by period-dependent factors, $F(T)$, for fundamental periods 0.2, 0.5, 1.0, 2.0, 5.0, and 10.0 seconds, as well as for PGA and PGV. For each period, T , the values of $F(T)$ differ by soil class and by the expected intensity of shaking. The measure of ground motion intensity used to enter these tables has been changed from the $S_a(0.2)$ and $S_a(1.0)$ spectral values used with F_a and F_v in NBCC2010; they now use an adjusted measure of PGA, PGA_{ref} . The attenuation of short-period ground motion in Eastern Canada is less than in the West. The direct use of PGA would give $F(T)$ values with larger non-linear de-amplification effects in the east than is appropriate for their sustained level of shaking. This would be unconservative and thus have potential safety implications. Consequently an adjustment factor of 0.8 is needed to provide appropriate foundation factors for sites with UHS shapes typical of eastern Canada.

3. Results

Seismic hazard values were calculated for a grid extending over Canada and used to create national-scale contour maps such as shown in Figure 2. Additional maps demonstrate the pattern of seismic hazard across selected urban areas (Figure 3). Adams et al. (2015) give the 5th Generation values for over 679 localities across Canada, of which Table 1 is a summary for selected cities. The spectral values were used to construct Uniform Hazard Spectra (UHS) on Site Class C for a few major cities to illustrate the range and period dependence of seismic hazard across Canada (Figure 4). Other UHS are given by Adams et al. (2015), and yet more can be constructed from the tabulated values therein or from the online hazard calculator. The UHS for Winnipeg is representative of many localities in low-seismicity parts of Canada. The change of $S_a(0.2)$ hazard as a function of probability (“hazard curve”) for selected cities is illustrated in Allen et al. (2015b).

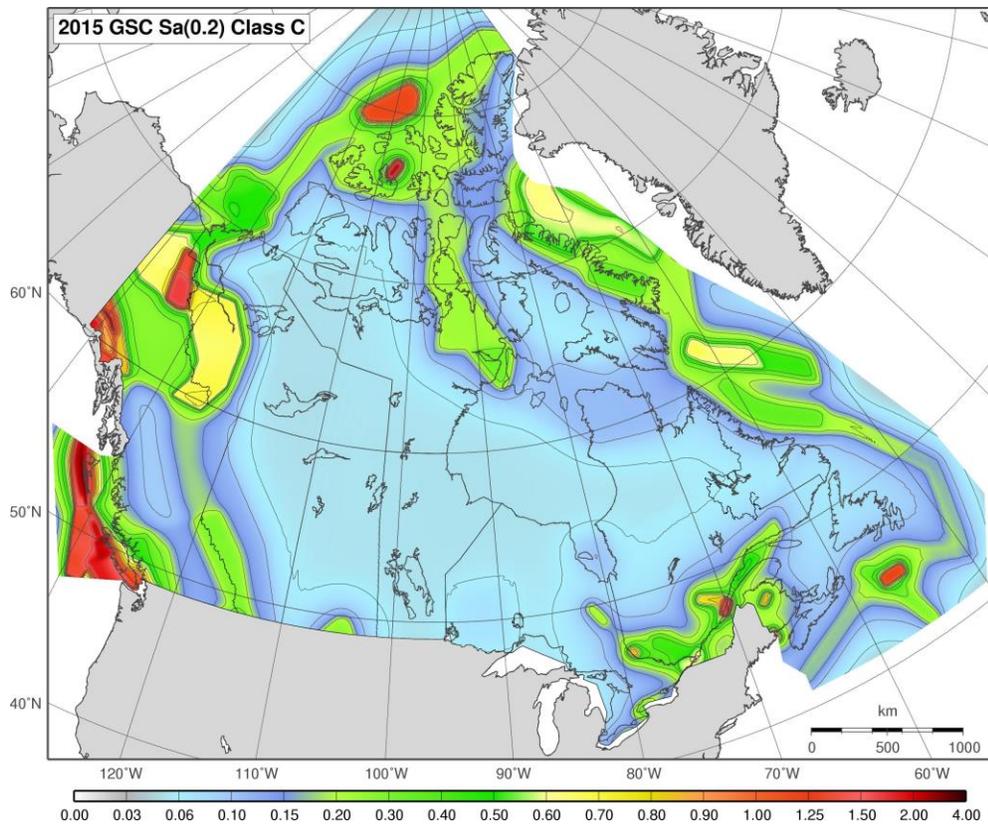


Fig. 2 — Sa(0.2) for Canada (mean values of 5% damped spectral acceleration for Site Class C and a probability of 2%/50 years), in g.

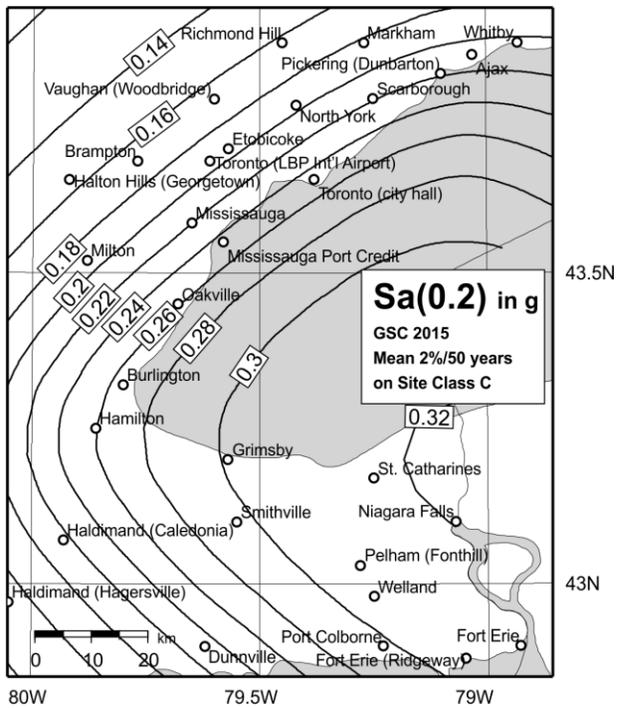
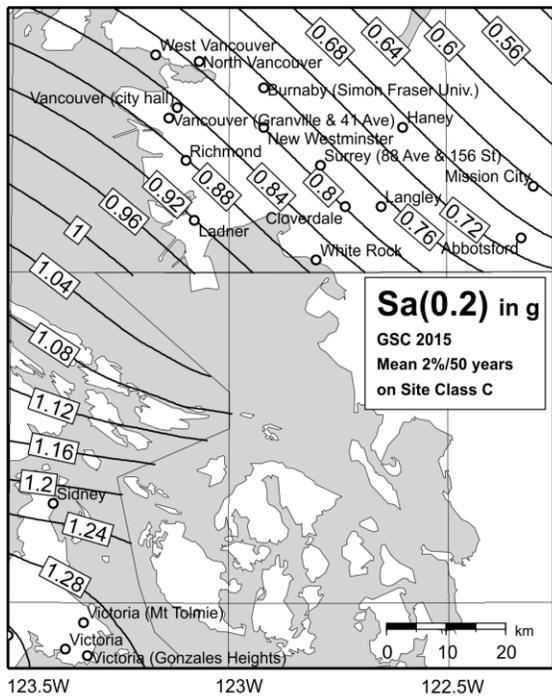


Fig. 3A — Detailed maps of Sa(0.2) hazard in the vicinity of Vancouver-Victoria and Toronto-Niagara. Mean values of 5% damped spectral acceleration for Site Class C and a probability of 2%/50 years.

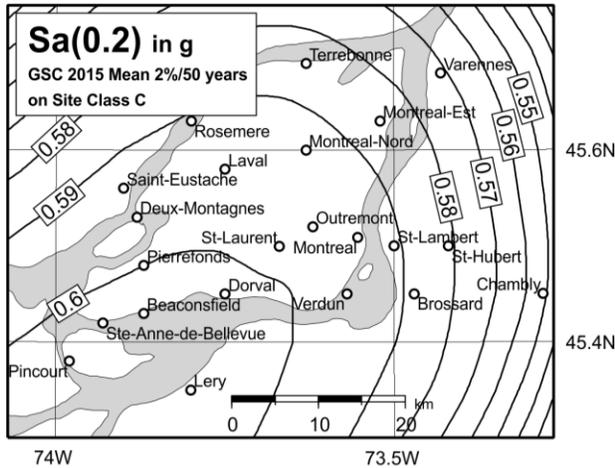


Fig. 3B – As for Figure 3A, but for Montreal and Charlevoix (Quebec).

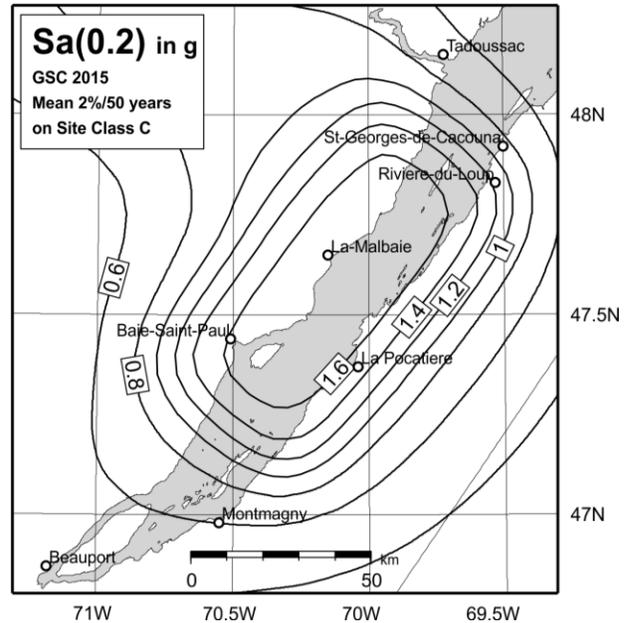


Table 1 – 5th Generation seismic hazard values for selected Canadian cities. Mean hazard values, reported to 2 significant figures, are given for 2% in 50 year probability on Site Class C (units=g, except m/s for PGV).

	Lat.N	Long.W	Sa(0.2)	Sa(0.5)	Sa(1.0)	Sa(2.0)	Sa(5.0)	Sa(10.0)	PGA	PGV
St. John's	47.57	52.72	0.090	0.073	0.049	0.027	0.0071	0.0032	0.052	0.064
Halifax	44.65	63.60	0.11	0.082	0.053	0.029	0.0077	0.0033	0.064	0.070
Moncton	46.10	64.78	0.16	0.10	0.059	0.031	0.0080	0.0034	0.098	0.084
Fredericton	45.95	66.65	0.21	0.13	0.072	0.036	0.010	0.0039	0.13	0.11
La-Malbaie	47.65	70.15	1.7	0.95	0.45	0.20	0.049	0.014	1.0	0.81
Québec	46.80	71.23	0.49	0.26	0.13	0.064	0.017	0.0062	0.32	0.22
Trois-Rivières	46.35	72.55	0.36	0.20	0.11	0.052	0.014	0.0054	0.23	0.17
Montréal	45.51	73.55	0.60	0.31	0.15	0.068	0.018	0.0062	0.38	0.26
Ottawa	45.42	75.69	0.44	0.24	0.12	0.056	0.015	0.0054	0.28	0.20
Niagara Falls	43.10	79.07	0.32	0.16	0.072	0.032	0.0076	0.0030	0.21	0.12
Toronto	43.65	79.38	0.25	0.13	0.063	0.030	0.0071	0.0029	0.16	0.10
Windsor	42.30	83.02	0.10	0.063	0.035	0.017	0.0040	0.0017	0.057	0.048
Winnipeg	49.89	97.15	0.054	0.032	0.016	0.0065	0.0013	0.0007	0.032	0.022
Edmonton	53.55	113.47	0.10	0.062	0.037	0.019	0.0057	0.0026	0.064	0.045
Calgary	51.05	114.08	0.19	0.13	0.072	0.036	0.013	0.0047	0.098	0.077
Kelowna	49.88	119.48	0.14	0.12	0.091	0.063	0.029	0.0091	0.066	0.12
Kamloops	50.67	120.32	0.15	0.12	0.091	0.064	0.029	0.0092	0.067	0.12
Vancouver	49.25	123.12	0.85	0.75	0.42	0.26	0.081	0.029	0.37	0.55
Victoria	48.43	123.37	1.3	1.2	0.68	0.40	0.12	0.044	0.58	0.83
Tofino	49.12	125.88	1.5	1.4	0.88	0.54	0.17	0.060	0.70	0.94
Village of Q. Charlotte	53.26	132.08	1.6	1.4	0.84	0.45	0.12	0.041	0.76	0.99
Inuvik	68.35	133.72	0.31	0.22	0.14	0.072	0.025	0.0096	0.14	0.15

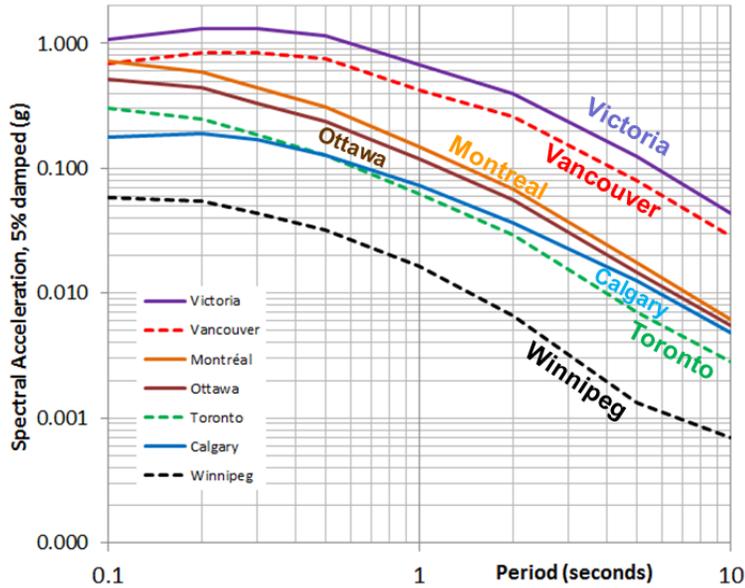


Fig. 4 – Uniform Hazard Spectra for mean 2%/50 year ground motions on Site Class C for key cities.

4. Discussion

Improved understanding of seismicity patterns, their cause and recurrence rates, and increased knowledge of ground motion attenuation has led to significant changes in estimated hazard relative to those of the 4th Generation maps (Figure 5). The changes depend on the period of the ground motion measures, so not all changes are apparent from the values in Table 2, which compares 2010 and 5th Generation seismic hazard values for the periods of most importance to buildings across Canada. The percent differences need to be considered in conjunction with the hazard values, as a large percentage change in a low hazard value can be of less consequence than a smaller percentage change in a high hazard value. Brief reasons for the changes in our estimate of hazard are given in Table 2. The stated reasons necessarily over-simplify the sum effect of many changes, some acting to increase and some to decrease the estimated hazard. For particular sites, the 5th Generation ground motion values may have changed in very different ways because of the cumulative effect of the improvements detailed above.

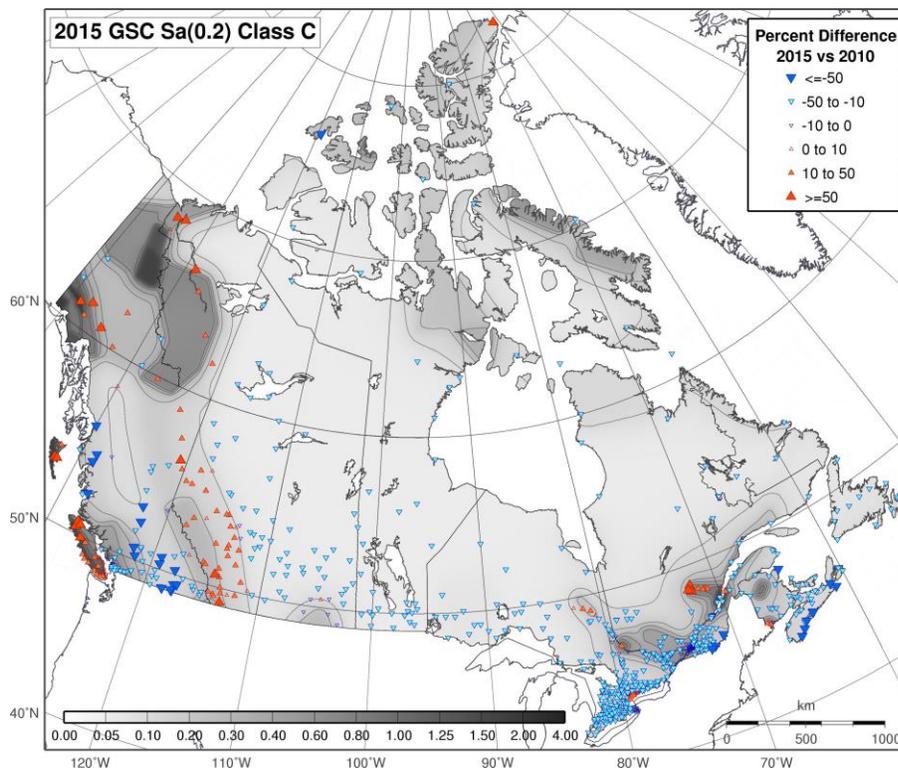


Fig. 5 – Change in Sa(0.2) hazard from NBCC2010. Grey shading indicates the 5th Generation Sa(0.2) hazard (in g), while red and blue triangles indicate the percentage change from NBCC2010.

Table 2 – 5th Generation seismic hazard values for selected Canadian cities compared with NBCC2010 values. Values are given for mean hazard at 2% in 50 years on Site Class C (units=g)

	Sa(0.2)	Sa(0.2)	%			Sa(2.0)	Sa(2.0)	%		
	2010	2015	Change	Change	Reason	2010	2015	Change	Change	Reason
St. John's	0.17	0.090	-47	down	B,G,E,C	0.025	0.027	8	slight	-
Halifax	0.23	0.11	-52	down	B,G,E,C	0.027	0.029	7	slight	-
Moncton	0.25	0.16	-37	down	B,C	0.029	0.031	7	slight	-
Fredericton	0.33	0.21	-36	down	B,C	0.034	0.037	9	slight	-
La-Malbaie	2.3	1.7	-25	down	D,B	0.16	0.20	27	up	B
Québec	0.55	0.49	-10	slight	-	0.052	0.064	23	up	B
Trois-Rivières	0.59	0.36	-38	down	C,B	0.045	0.052	16	up	B
Montréal	0.64	0.60	-7	slight	-	0.048	0.068	42	up	B
Ottawa	0.64	0.44	-32	down	C,B	0.046	0.056	22	up	B
Niagara Falls	0.34	0.32	-6	slight	-	0.023	0.032	39	up	B
Toronto	0.22	0.25	13	slight	-	0.021	0.029	38	up	B,F
Windsor	0.15	0.10	-36	down	B,E	0.014	0.017	21	up	B
Winnipeg	0.095	0.054	-43	down	H,B,E	0.008	0.007	-18	down	H
Edmonton	0.095	0.10	8	slight	-	0.008	0.018	120	up	B,F,J
Calgary	0.15	0.19	28	up	B,F	0.023	0.036	57	up	B,F,J
Kelowna	0.28	0.14	-49	down	G,F	0.056	0.063	13	up	A,B
Kamloops	0.28	0.15	-48	down	G,F	0.061	0.064	5	slight	-
Vancouver	0.94	0.85	-10	slight	F,B	0.17	0.26	51	up	A,B
Victoria	1.2	1.3	9	slight	-	0.18	0.40	120	up	A,B
Tofino	1.2	1.5	22	up	A	0.21	0.54	150	up	A,B
Village of Q. Charlotte	0.62	1.6	160	up	I,B	0.24	0.45	88	up	I,B
Inuvik	0.10	0.31	210	up	D,F	0.26	0.72	180	up	D,F

Reasons:

A	Probabilistic addition of Cascadia fault source	F	Change in source zone boundary position
B	New ground motion prediction relations used	G	Seismicity rate in underlying zone
C	More weight on historical activity rates	H	Lower activity rate for stable Canada
D	More weight on seismotectonic sources	I	Addition of Haida Gwaii thrust fault source
E	Mmin in the east expressed in Mw	J	Larger upper-bound magnitudes used

5. Conclusions

We have summarized the basis for the 5th Generation hazard model and its results as prepared for NBCC2015. The improved seismicity model developed and the new ground motions adopted give an improved distribution of estimated hazard across Canada. Any seismic hazard model produces an *estimate* of the (unknown) true hazard values. Model deficiencies (for example the choice of 0.01 p.a. in 1970, the too-low values of Mmax in 1985) have been progressively identified, often using lessons from “unexpected” Canadian and foreign earthquakes or simply through the adoption of international norms. We believe that the seismic hazard estimates are improving and that, as a consequence, the structures we design and build today and tomorrow will be better able to resist the effects of future earthquake shaking. That in turn should lead to safer communities.

6. Acknowledgments

Hazard models like this are a team effort, and we thank our present and past colleagues in GSC, especially Lan Lin and Helena Greene, for their assistance and criticism while they worked with us. Paul Somerville acted as external reviewer of the model to the SCED committee, and we thank him for his thoughtful inputs. The improvements from the 4th Generation model have been reviewed by many concerned engineers who took the time to learn about the issues and ask penetrating questions that have improved our seismologist's product. We thank them. ESS contribution number 20150117.

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