Canada's 6th Generation Seismic Hazard Model, as Prepared for the 2020 National Building Code of Canada

John Adams[1], Trevor Allen[2], Stephen Halchuk[1], Michal Kolaj[1]
[1]Seismologist, Natural Resources Canada, Ottawa, Canada
[2]Seismologist, Geoscience Australia, Canberra, Australia

ABSTRACT

Canada's 6th Generation seismic hazard model has been developed to generate seismic design values for the 2020 National Building Code of Canada (NBCC2020). The model retains most of the seismic source model from the 5th Generation, but updates the earthquake sources for the deep inslab earthquakes under the Straits of Georgia and adds the Leech River Valley - Devil's Mountain faults near Victoria. The rate of Cascadia megathrust earthquakes is also increased to match an improved paleoseismic record. Two major changes in the ground motion model (GMM) are A) adoption of modern Ground Motion Models (GMMs), together with a classical weighted-GMM approach replacing most of the three-branch representative suites used in NBCC2015. and B) direct calculation of hazard on various site classes using representative Vs_{30} values, rather than provision of hazard values on a reference Class C site and then applying F(T) factors. Computations are now being performed with the OpenQuake engine, which has been validated through the replication of the 5th Generation results. Seismic design values (on various Soil Classes) for PGA, and for Sa(T) with T = 0.2, 0.5, 1.0, 2.0, 5.0 and 10.0 s are proposed for NBCC2020 mean ground shaking at the 2% in 50-year probability level. The paper discusses chiefly the change in Site Class C values relative to 2015 in terms of the changes in the seismic source model and the GMMs, but the changes in hazard at other site classes that arise from application of the direct-calculation approach are also illustrated.

Keywords: probabilistic, seismic hazard, Canada, National Building Code, Cascadia

INTRODUCTION

A national seismic hazard model is a fundamental component of the most effective approach to reducing human casualties and economic losses from future earthquakes. To be useful, a national map must estimate hazard with a consistent methodology across the country, so earthquake-resistant design can be distributed equitably according to the hazard. This requires an assessment of earthquake sources and occurrence, selecting an appropriate probability level, and a wise choice of shaking intensity measures. As the knowledge of, and sophistication in, probabilistic seismic hazard analyses have grown, Canada's national mapping efforts have moved from a qualitative assessment towards probabilistic assessment at lower probabilities using spectral acceleration parameters (Table 1; [1]).

Table 1 ─ Evolution of the choice of probability level per annum (p.a.) and ground shaking intensity measures used in key NBCC editions.

PGA ─ peak ground acceleration,
PGV ─ peak ground velocity,
Sa(T) ─ spectral acceleration at period T

Year	Probability (p. a.)	Ground shaking intensity measure
1953	qualitative	
1970	0.01	PGA
1985	0.0021	PGA, PGV
2005 **2010**	0.000404	Sa(0.2), Sa(0.5), Sa(1.0), Sa(2.0), PGA
2015 **2020**	0.000404	Sa(0.2), Sa(0.5), Sa(1.0), Sa(2.0), Sa(5.0), Sa(10.0), PGA, PGV

NBCC2010 was based on the same 4th Generation seismic hazard model, but with an improved Ground Motion Model (GMM) for earthquakes in eastern Canada. The 5th Generation model used for NBCC2015 [2] incorporated a significant increment of earthquake data, recent research on source zones and earthquake occurrence, together with complementary research on strong ground motion relations. This model was the first to be entirely probabilistic, replacing the "robust" combination of deterministic (Cascadia) and probabilistic models used in NBCC2005.

In this paper we outline the new features of the 6th Generation hazard model and discuss some of its consequences. Companion 6th Generation papers at this conference are Kolaj et al. [3] on the ground motion models and site-class modelling, and Halchuk et al. [4] which discusses the seismic hazard contribution of the Leech River Valley Fault near Victoria.

METHOD

We apply the same Cornell-McGuire methodology [5] as for Canada's 5th Generation model used for NBCC2015, but use the OpenQuake platform [6] to compute the hazard. Our implementation of the 5th Generation model in OpenQuake replicated NBCC2015 values to within 3-4% [7], with the larger deviations chiefly reflecting differences in how areal source zones are discretized. The 5th Generation OpenQuake implementation was the starting point for the 6th Generation model, with additional improvements described below.

Regionalization of Canada

Of necessity, eastern and western Canada must be treated slightly differently because of the different propagation of seismic waves in the crust [3]. Figure 1 illustrates both the earthquake history and the regionalization used. Seismic hazard for most of the area to the west of the leftmost dashed line on Figure 1 has been calculated using western GMMs (eastern GMMs are used for the Rocky Mountain foothills) while eastern GMMs are used for the remaining regions.

NBCC2020 continues the use of 5%-damped horizontal spectral acceleration values, denoted by Sa(T), where T is the period. As with the 5th Generation model, the 6th Generation model will provide 0.05, 0.1, 0.2, 0.3, 0.5, 1.0, 2.0, 5.0 and 10.0 s spectral accelerations plus PGA and PGV. Of these, the 0.2, 0.5, 1.0, 2.0, 5.0 and 10.0 second Sa(T) are used in NBCC2020. While PGA was used in the calculation of site amplification in NBCC2015, hazard values for the 6th Generation model are now directly provided for each site class [3]. Nevertheless, PGA continues to be a useful parameter for liquefaction and other geotechnical analyses. PGV is not explicitly used by NBCC2020 (or NBCC2015), but will be provided by 2020 as it is a useful parameter for predicting damage. We express the values in units of g and report them to two significant figures (an appropriate level of precision), except for small long-period values for which one significant figure is appropriate.

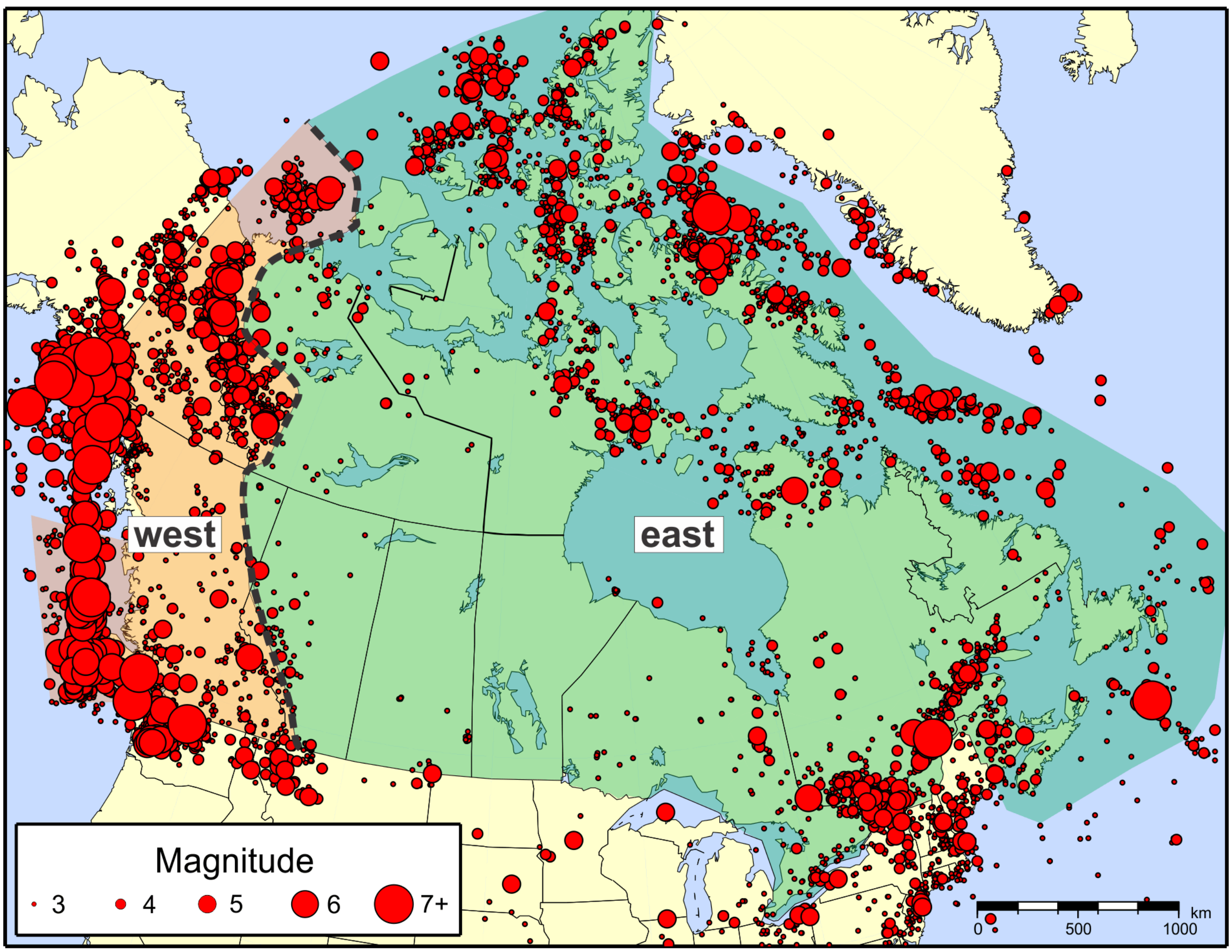


Fig. 1 — Map of Canada showing the earthquake catalog used for the 6th Generation model together with dashed lines delimiting the eastern and western seismic regions.

Probability Level and Choice of Confidence Level

In North America the *de facto* standard probability level for national seismic hazard maps is the 2% chance of exceedance in 50 years (2%/50 years), equivalent to an annual probability of 0.000404; this is the key probability for 6th 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, 2019), and so will be provided by a web calculator like the one on the EarthquakesCanada web site [8]. The 6th 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 to developing 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. The model provides the mean hazard (used in NBCC2015 and NBCC2020) and percentiles of the distribution. For most locations in Canada, the mean-hazard value lies between the 60th and 85th percentiles of the hazard distribution [2,9].

Earthquake Catalog and Seismic Source Models

The 6th Generation model uses most of the same seismic source model as the 5th Generation model. The moment magnitude catalog and magnitude recurrence curves were not updated for the 6th Generation model as their hazard consequences are relatively insensitive to added earthquakes, and the focus was on other more consequential parts of the model. Nevertheless, updating the activity should be a priority for the 7th Generation model. The main source changes from the 5th Generation model are:

- **Cascadia.** The paleoseismic history of the Juan de Fuca segment of the Cascadia subduction zone has been improved from that used in the 5th Generation model. Our implementation of recent results [10] now adds 4 extra complete-rupture earthquakes to the 18 included in NBCC2015. The added earthquakes reduce the average inter-event period from 532 to 432 years, and increase the seismic hazard from the Juan de Fuca segment to southern British Columbia by about 8% for all periods and probabilities. In addition, the evidence for event clustering now appears weaker than previously thought, supporting the 2013 decision not to implement a clustered seismicity model. The great earthquakes are still satisfactorily modelled as time-independent events, but a time-dependent model should be considered for the 7th Generation model.

- **Inslab deep seismicity under Straits of Georgia.** In the 5th Generation model the inslab source GTP was set at a depth of 50 km and had a uniform distribution of earthquakes. In the 6th Generation model, GTP is replaced by three sources (western, central and eastern) set at 50, 55, and 60 km depths to better model the dip of the inslab source and the spatial activity rate. The consequence is a 5-10% increase in short-period hazard for Victoria and Vancouver.

- **Leech River Valley and Devil's Mountain Faults near Victoria.** As discussed in [4] studies have identified a potentially active crustal fault system in the southern Vancouver Island region, near Victoria. Given the proximity of both of these faults to Victoria, they were included, with details of their relatively-minor hazard contribution given in [4].

As in the 5th Generation model, both standard Gutenberg-Richter and pseudo-characteristic MFDs are used for fault sources [11]. Additional details on the retained 5th Generation model sources are given in [1, 12, 13]. The implementation of pseudo faults with the OpenQuake engine requires new decisions about seismogenic thickness, hypocentral depths and various rupture parameters (e.g., magnitude-area relations, aspect ratio, orientation) and these details are discussed and included in [14].

Ground Motion Models, Reference Ground Condition and Adjustment to Other Soil Conditions

A major change is the adoption of modern Ground Motion Models (GMMs), together with a classical weighted-GMM approach replacing most of the three-branch representative suite of Atkinson & Adams [15]. 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 [16]. The NBCC2015 chose V_{S30} = 450 m/s to represent the reference condition and introduced period-dependent factors, F(T), to adjust hazard to other site classes. It is recommended that in NBCC2020 the adjustment be replaced by the direct calculation of hazard on each site class. These changes are described in detail in [3]. Although Site Class C has lost its "reference" status, 6th Generation Site Class C hazard values will be used below to simplify comparison to NBCC2015.

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 3A-B). Table 2 provides a summary of Class C hazard for selected localities and Figure 4 shows the corresponding uniform hazard spectra (UHS) for major cities. The UHS for Winnipeg is representative of many localities in low-seismicity parts of Canada. The additional consequences of the direct calculation of seismic hazard for Site Classes A through E are illustrated for Vancouver on Figure 5.

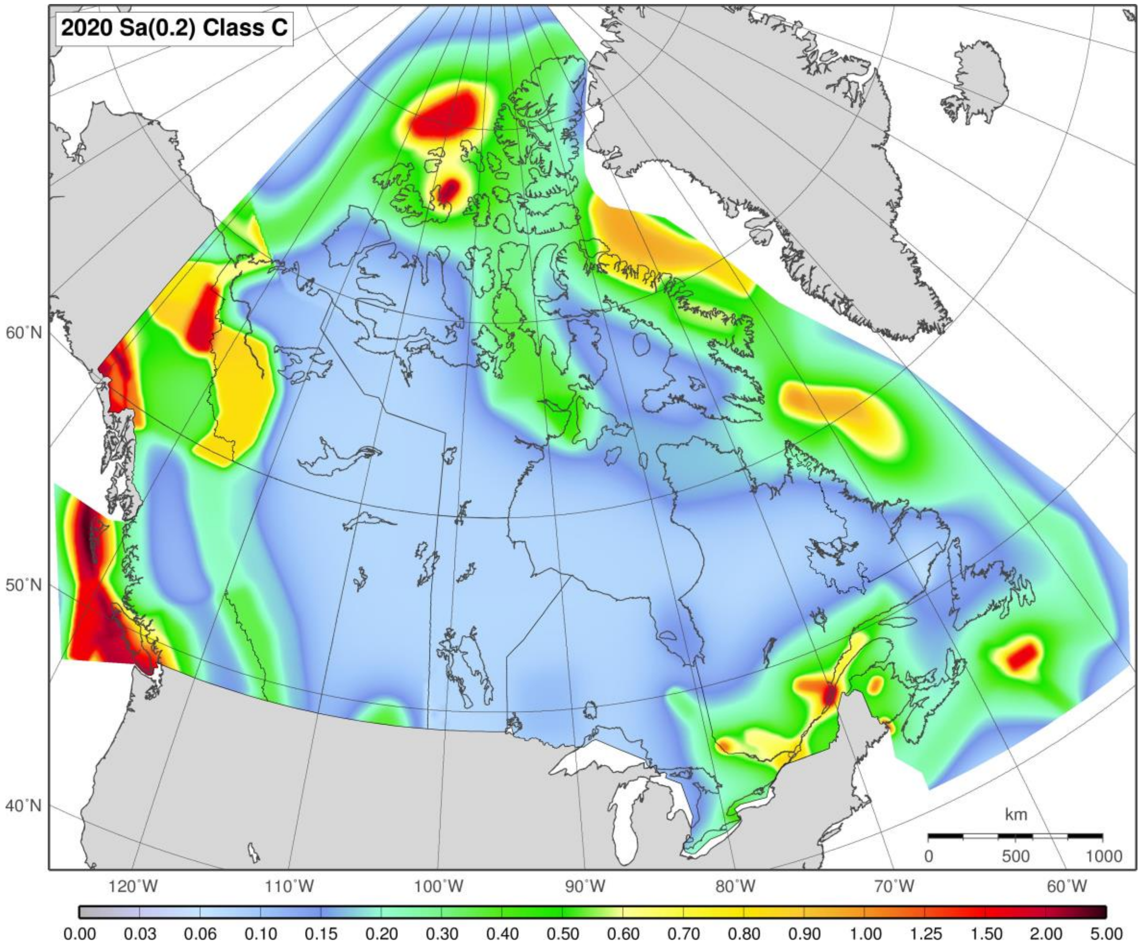


Fig. 2 Sa(0.2) for Canada (mean values of 5% damped spectral acceleration for Site Class C and a probability of 2%/50 years, units = g).

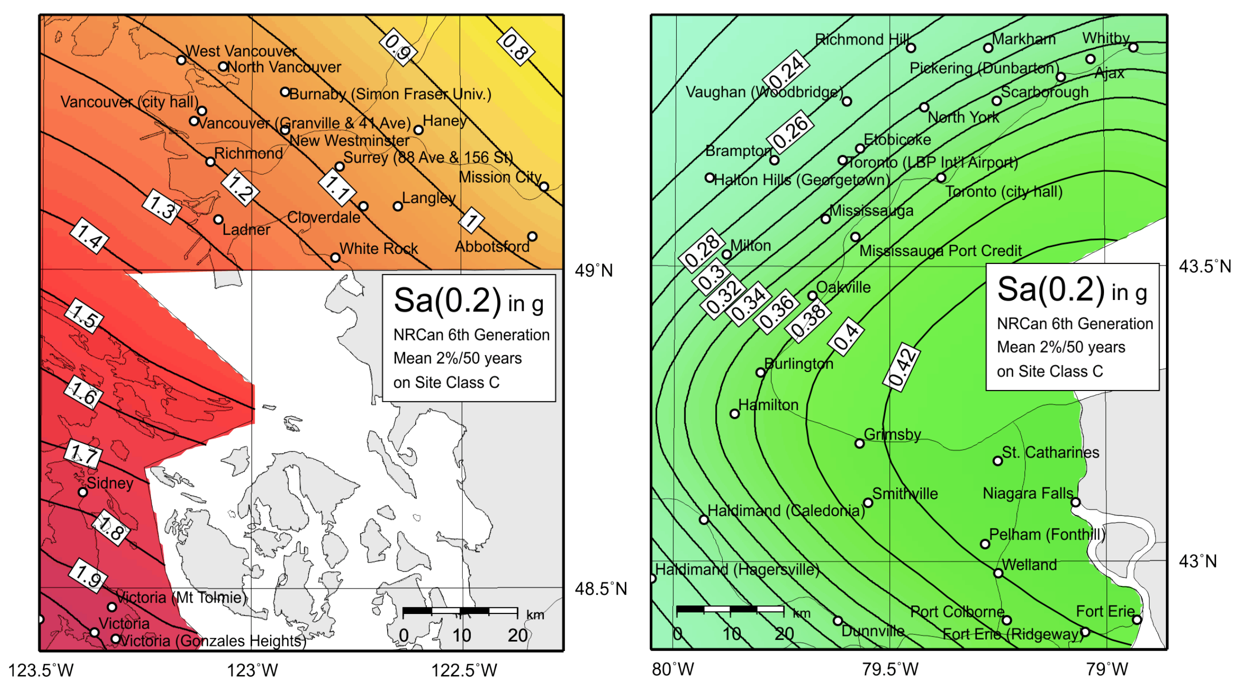
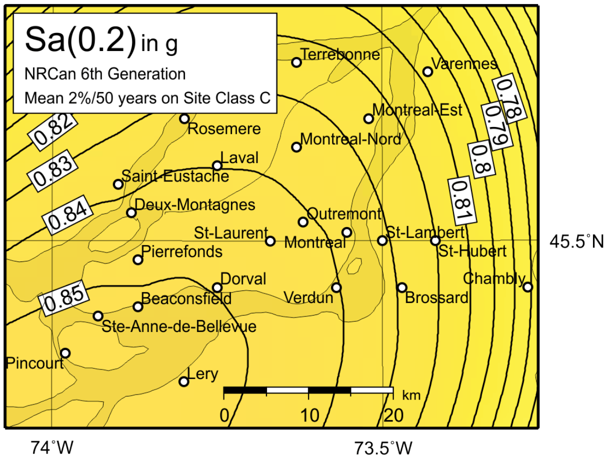


Fig. 3A ─ Detailed maps of Sa(0.2) hazard in the vicinity of Vancouver-Victoria and Toronto-Niagara. Mean values of 5% damped spectral acceleration for Site Class C and a probability of 2%/50 years.



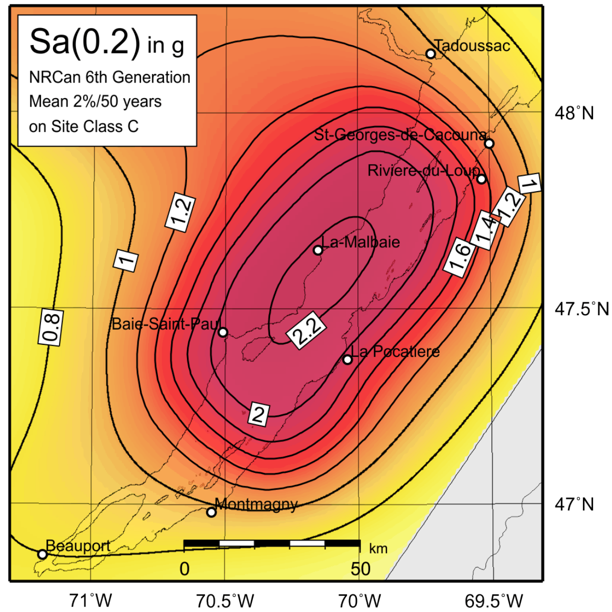


Fig. 3B — As for Figure 3A, but for Montreal and Charlevoix (Quebec).

Table 2 — 6th Generation seismic hazard values for selected localities in Canada, from east to west. Mean hazard values, reported to 2 significant figures, are given for 2% in 50 year probability on Site Class C (units=g).

	Lat.N	**Long.W**	**Sa(0.2)**	**Sa(0.5)**	**Sa(1.0)**	**Sa(2.0)**	**Sa(5.0)**	**Sa(10.0)**	**PGA**
St. John's	*47.57*	*52.72*	0.18	0.13	0.079	0.041	0.012	0.0044	0.072
Halifax	*44.65*	*63.60*	0.21	0.14	0.082	0.042	0.012	0.0043	0.085
Moncton	*46.10*	*64.78*	0.29	0.17	0.10	0.047	0.013	0.0047	0.13
Fredericton	*45.95*	*66.65*	0.38	0.21	0.12	0.056	0.016	0.0055	0.17
La-Malbaie	*47.65*	*70.15*	2.2	1.2	0.61	0.26	0.060	0.018	1.1
Québec	*46.80*	*71.23*	0.77	0.41	0.21	0.10	0.026	0.0087	0.38
Trois-Rivières	*46.35*	*72.55*	0.60	0.32	0.17	0.082	0.022	0.0077	0.29
Montréal	*45.51*	*73.55*	0.84	0.43	0.22	0.10	0.025	0.0084	0.43
Ottawa	*45.42*	*75.69*	0.66	0.34	0.18	0.082	0.022	0.0073	0.33
Niagara Falls	*43.10*	*79.07*	0.44	0.22	0.10	0.045	0.011	0.0038	0.24
Toronto	*43.65*	*79.38*	0.36	0.19	0.093	0.042	0.011	0.0037	0.19
Windsor	*42.30*	*83.02*	0.17	0.10	0.049	0.022	0.0052	0.0018	0.071
Winnipeg	*49.89*	*97.15*	0.080	0.044	0.020	0.0080	0.0016	0.0005	0.036
Edmonton	*53.55*	*113.47*	0.15	0.080	0.040	0.021	0.011	0.0075	0.073
Calgary	*51.05*	*114.08*	0.23	0.14	0.068	0.033	0.015	0.010	0.10
Kelowna	*49.88*	*119.48*	0.18	0.13	0.090	0.067	0.029	0.018	0.083
Kamloops	*50.67*	*120.32*	0.18	0.13	0.090	0.068	0.030	0.018	0.083
Vancouver	*49.25*	*123.12*	1.1	0.82	0.47	0.28	0.075	0.032	0.49
Victoria	*48.43*	*123.37*	2.0	1.5	0.87	0.51	0.12	0.047	0.83
Tofino	*49.12*	*125.88*	1.8	1.7	1.0	0.66	0.15	0.060	0.76
Village of Q. Charlotte	*53.26*	*132.08*	2.3	1.8	1.1	0.60	0.16	0.068	0.96
Inuvik	*68.35*	*133.72*	0.39	0.26	0.15	0.077	0.029	0.018	0.16

DISCUSSION

Improved understanding of seismic sources in southwestern British Columbia and changes in ground motion models has led to significant changes in estimated hazard relative to those of the 5th Generation maps (Figure 6). The changes depend on the period of the ground motion measures, so not all changes are apparent from the values in Table 3, which compares 2015 and 6th Generation seismic hazard values across Canada for just two periods important for building design. 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. In most places the new hazard estimate is higher than in 2015. The main reasons for the changes for Site Class C hazard at each site are summarized in Table 3.

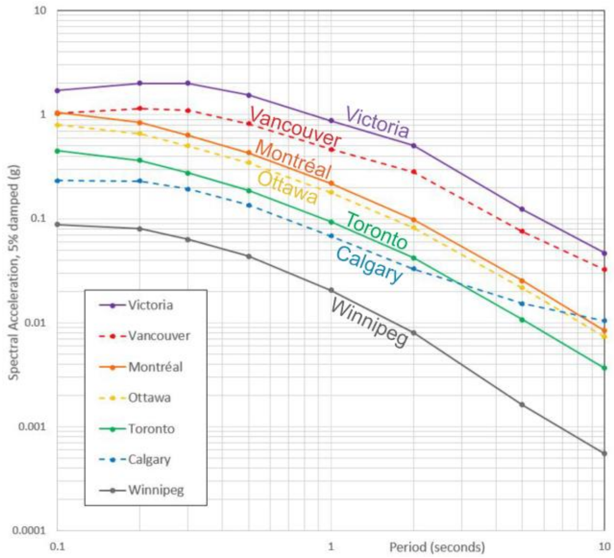


Fig. 4. Uniform Hazard Spectra for mean 2%/50 year ground motions on Site Class C for key cities.

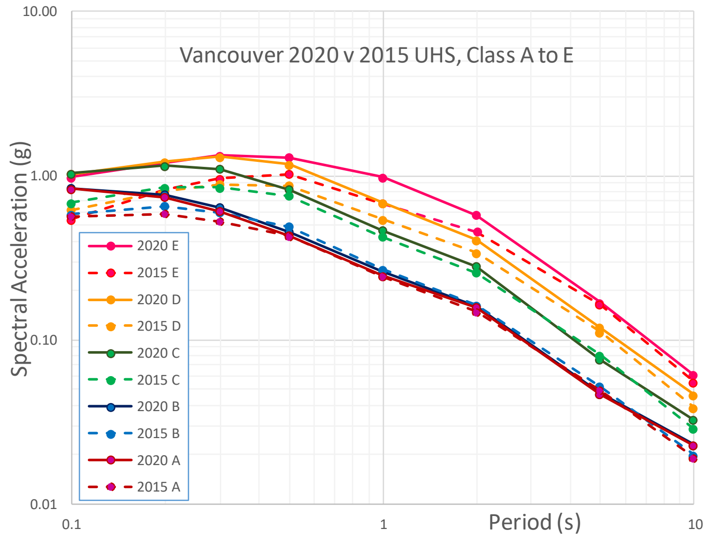


Fig. 5. Comparison of proposed-2020 UHS for Vancouver on Site Classes A, B, C, D, and E with NBCC2015 values.

Table 3 — 6th Generation seismic hazard values for selected localities in Canada, from east to west, compared with NBCC2015 values. Values are given for mean hazard at 2% in 50 years on Site Class C (units=g).

	Sa(0.2) 2015	**Sa(0.2) 2020**	% Change	Reason	Sa(2.0) 2015	**Sa(2.0) 2020**	% Change	Reason
St. John's	0.090	**0.18**	106	B	0.027	**0.041**	52	B
Halifax	0.11	**0.21**	90	B	0.029	**0.042**	45	B
Moncton	0.16	**0.29**	81	B	0.031	**0.047**	53	B
Fredericton	0.21	**0.38**	80	B	0.036	**0.056**	55	B
La-Malbaie	1.73	**2.2**	29	B	0.203	**0.26**	28	B
Québec	0.49	**0.77**	57	B	0.064	**0.097**	52	B
Trois-Rivières	0.36	**0.60**	63	B	0.052	**0.082**	57	B
Montréal	0.60	**0.84**	41	B	0.068	**0.098**	44	B
Ottawa	0.44	**0.66**	50	B	0.056	**0.082**	46	B
Niagara Falls	0.32	**0.44**	36	B	0.032	**0.045**	40	B
Toronto	0.25	**0.36**	46	B	0.030	**0.042**	42	B
Windsor	0.10	**0.17**	72	B	0.017	**0.022**	25	B
Winnipeg	0.05	**0.080**	47	B	0.007	**0.008**	23	B
Edmonton	0.10	**0.15**	46	B	0.019	**0.021**	10	B
Calgary	0.19	**0.23**	20	B,C	0.036	**0.033**	-9	B,C
Kelowna	0.14	**0.18**	27	B,C	0.063	**0.067**	6	A,B,C
Kamloops	0.15	**0.18**	25	B,C	0.064	**0.068**	7	A,B,C
Vancouver	0.85	**1.1**	36	B,C,D	0.256	**0.28**	10	A,B,C
Victoria	1.30	**2.0**	53	A,B,C,D,E	0.399	**0.51**	27	A,B,C,E
Tofino	1.46	**1.8**	23	A,B,C	0.535	**0.66**	23	A,B,C
Village of Q.C.	1.61	**2.3**	42	B,C	0.450	**0.60**	34	B,C
Inuvik	0.31	**0.39**	27	B,C	0.072	**0.077**	6	B,C

Reasons: A = Juan de Fuca activity rate, B = New GMMs, C = Sigma in new GMMs, D = Changes in inslab (GTP) source, E = Addition of Leech River Valley Fault.

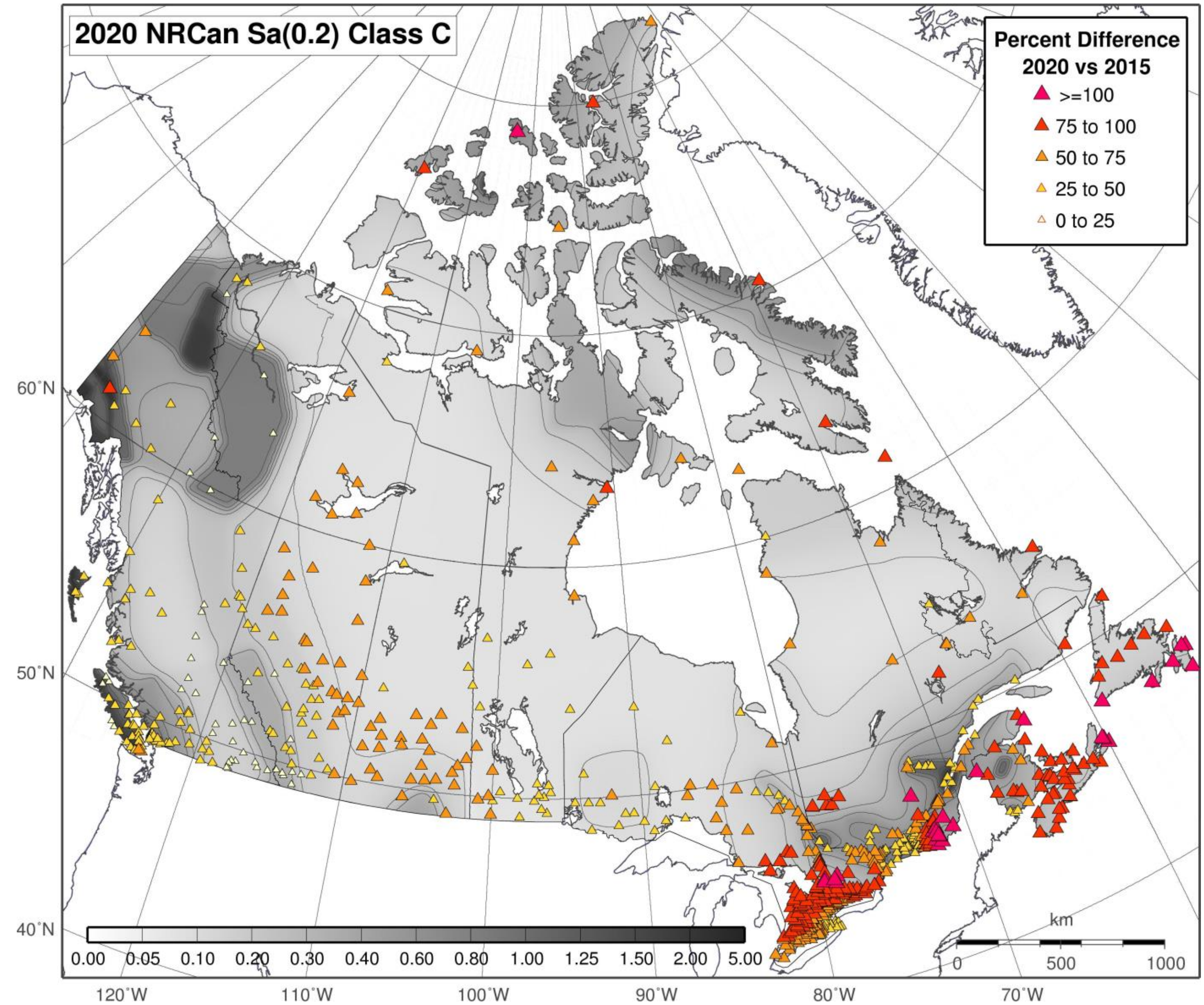


Fig.6. Change in Sa(0.2) hazard from NBCC2015. Red-scale triangles indicate the percentage change from NBCC2015 for specific localities, while grey shading indicates the 6th Generation Sa(0.2) hazard across Canada (in g).

Some differences from NBCC2015 arise due to the direct calculation of hazard for the standard Site Classes [3]. Moreover, as there are no national amplification factors (comparable to NBCC2015's F(T)), the amplification in a particular locality depends on the amplification term of the GMMs and their relative contributions to mean hazard. For example, considering the hazard for Vancouver (Figure 5), the hazard increase at Site Class C is due to a combination of updated seismic sources and the new GMMs [2]. At Site Class B the increase due to source changes still exists, but the overall increase is mitigated by a reduction in net amplification factors (relative to Site Class C). Conversely, at Site Classes D and E there is an additional increase due to a net increase in amplification factors relative to the 2015 F(T) factors (through a combination of reduced levels of non-linear deamplification and higher linear amplification factors at smaller V_{s30}, [3]).

The stated reasons necessarily over-simplify the net effect of many changes, some acting to increase and some to mitigate (or decrease) the estimated hazard. For particular sites, the 6th Generation hazard values may have changed in different ways from Vancouver because of the cumulative effect of the improvements detailed above.

CONCLUSIONS

We have summarized the basis for the 6th Generation hazard model and its results as prepared for NBCC2020. The principal changes to the seismicity model are: 1) updated recurrence of large Cascadia earthquakes from an inter-event period of 532 to 432 years, 2) three independent sources for GTP to better reflect the dip of the inslab source, and 3) inclusion of the Leech River Valley - Devil's Mountain fault system near southern Vancouver Island. These source changes have increased the estimated hazard in southwestern B.C by roughly 7-21%. In addition to the updated seismicity model, there have been substantial changes to the GMMs (as described in [3]) that have led to significant increases in Class C seismic hazard, particularly in eastern Canada. Among the changes, hazard is now calculated directly for each of the standard site classes, improving the results and removing the need for site amplification look-up tables in the building code. The overall effect of calculating hazard at each site class depends on the locality in question, as the relative contribution between the site terms of each GMM varies. The combination of these new data and methodological advances is consistent with global best practice and evidence-based science for undertaking national-scale earthquake hazard assessments.

ACKNOWLEDGMENTS

Hazard models like this are a team effort, and we thank our present and past colleagues at NRCan for their assistance and criticism while they worked with us. Gail Atkinson provided valuable advice during the work. We also thank members of the Standing Committee on Earthquake Design, and especially those of SCED's Seismicity Task Group, for their input. We thank Nick Ackerley for a thorough review.

REFERENCES

1. Adams, J. (2019). Evolution of seismic hazard estimates in Canada. *12th Can. Conf. Earthquake Engineering*, Quebec City, paper 192-cSSQ-149, 8 pp.
2. Adams, J., Halchuk, S., Allen, T., Rogers, G. (2015). Canada's 5th Generation seismic hazard model, as prepared for the 2015 National Building Code of Canada, *11th Canadian Conference on Earthquake Engineering*, 21–24 July 2015, Victoria, Canada, Paper 93775, 11 pp.
3. Kolaj, M., Allen, T., Mayfield, R., Adams, J., and Halchuk, S. (2019). Ground-motion models for the 6th Generation Seismic Hazard Model of Canada. *12th Can. Conf. Earthquake Engineering*, Quebec City, paper 192-hHtH-159, 9pp
4. Halchuk, S., Allen, T., Adams, J. and Onur, T. (2019). Contribution of the Leech River Valley - Devil's Mountain fault system to seismic hazard for Victoria B.C. *12th Can. Conf. Earthquake Engineering*, Quebec City, paper 192-WGm8-169, 8 pp.
5. McGuire R.K. (1993). Computations of seismic hazard in Giardini D, and Basham P.W., Editors. Global Seismic Hazard Assessment Program. *Annali di Geofisica* Vol. 34, pp. 181-200.
6. Pagani, M, Monelli, D, Weatherill, G, Danciu, L, Crowley, H, Silva, V, Henshaw, P, Butler, R, Nastasi, M, Panzeri, L, Simionato, M, Vigano, D (2014): OpenQuake Engine: An open hazard (and risk) software for the Global Earthquake Model, *Seism. Res. Lett.*, **85** (3), 692–702, doi: 10.1785/0220130087.
7. Allen, T.I., Halchuk, S., Adams, J., Rogers, G.C. (2017): Canada's 5th generation seismic hazard model: 2015 hazard values and future model updates, *16th World Conference on Earthquake Engineering*, Santiago, Chile, Paper 3494.
8. http://www.earthquakescanada.nrcan.gc.ca/hazard-alea/interpolat/index-en.php Last Accessed January 2019.
9. Adams, J., and Halchuk, S. (2019). Uncertainty spread in the 5th Generation seismic hazard results used in NBCC2015. *12th Can. Conf. Earthquake Engineering*, Quebec City, paper 192-H39s-279, 8 pp.
10. Goldfinger, C., Galer, S., Beeson, J., Hamilton, T., Black, B., Romsos, C., Patton, J., Nelson, C.H., Hausmann, R., Morey, A. (2016): The importance of site selection, sediment supply, and hydrodynamics: A case study of submarine paleoseismology on the northern Cascadia margin, Washington USA, *Mar. Geol.*, doi: 10.1016/j.margeo.2016.06.008.
11. Allen, T., Adams, J., Rogers, G., and Halchuk, S. (2015). New seismic hazard model for north-western Canada, *11th Canadian Conference on Earthquake Engineering*, 21–24 July 2015, Victoria, Canada, Paper 93782.
12. Halchuk, S., Allen, T.I., Adams, J., and Rogers, G. C. (2014). Fifth generation seismic hazard model input files as proposed to produce values for the 2015 National Building Code of Canada, *Geological Survey of Canada Open File* 7576, 15 pp, https://doi.org/10.4095/293907
13. Halchuk, S., Allen, T.I., Adams, J., and Rogers, G.C. (2014). Fifth Generation seismic hazard model input files as proposed to produce values for the 2015 National Building Code of Canada. Geological Survey of Canada, Open File 7576, 18 pages, https://doi.org/10.4095/293907
14. Halchuk, S., Allen, T.I., Kolaj, M., and Adams, J. (2019). Sixth Generation seismic hazard model input files as proposed to produce values for the 2020 national building code of Canada. Geological Survey of Canada, Open File.
15. Atkinson, G.M. and Adams, J. (2013). Ground motion prediction equations for application to the 2015 Canadian national seismic hazard maps, *Can. J. Civ. Eng.*, Vol. 40, pp. 988–998, doi: 10.1139/cjce-2012-0544.
16. Finn, W.D.L., and Wightman, A. (2003). Ground motion amplification factors for the proposed 2005 edition of the National Building Code of Canada, *Can. J. Civ. Eng.*, Vol. 30, pp. 272–278, doi: 10.1139/L02-081.