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CANADA'S 5TH GENERATION SEISMIC HAZARD MODEL: 2015 HAZARD VALUES AND FUTURE MODEL UPDATES

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Abstract

The Geological Survey of Canada (GSC) has contributed earthquake hazard information for the National Building Code of Canada (NBCC) since the 1953 edition. The 2015 national hazard model update yields many important advances on its predecessors, including: probabilistic treatment of the Cascadia subduction zone; reconfigured seismic source zones and special consideration of rare large eastern earthquakes; explicit definition of crustal fault sources in the Yukon Territory and offshore western margin faults (north of Cascadia) based on GPS observations and paleoseismic slip rates; catalogue magnitudes expressed consistently in terms of moment magnitude for improved magnitude-frequency statistics; and the use of a suite of representative backbone ground-motion models. Seismic design values (on Soil Class C defined at V_{S30} = 450 m/s) are calculated for PGA and PGV, as well as spectral acceleration *Sa* at nine periods between 0.05 and 10 s. For locations in eastern Canada, the estimated seismic hazard at long periods has generally 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 (formally the Queen Charlotte Islands) and the Yukon, the explicit inclusion of fault sources has also raised the modelled hazard.

The GSC is now working towards the 2020 building code cycle with a view of rethinking the fundamental scientific questions and building on the advances made for the 2015 hazard model. In particular, we will: evaluate and adopt new hazard computation software; evaluate catalogue declustering techniques; examine, in more detail, the rationale for ground-motion model selection in specific tectonic environments; consider hazard from induced earthquakes; and explore the utility of risk-targeted ground motions for design.

Keywords: probabilistic seismic hazard, National Building Code of Canada, OpenQuake-engine

1. Introduction

The Geological Survey of Canada (GSC), part of Natural Resources Canada, is responsible for providing national-scale seismic hazard information to key stakeholders with the ultimate aim of safeguarding Canadians from the negative impacts of earthquakes. The 5th Generation Seismic Hazard Model of Canada (SHMC) has been prepared to underpin the seismic provisions for the 2015 National Building Code of Canada (NBCC) [1, 2].

Canada has had four epochal seismic hazard models (1953, 1970. 1985. and 2005), each of which were used in one or more editions of the NBCC [3]. The 1953 map of seismic hazard was a qualitative assessment [4], and was primarily a zoning map rather than a seismic hazard model. The 1970 model [5] was a true Probabilistic Seismic Hazard Analysis (PSHA), one of the earliest such national analyses. It depicted the peak horizontal ground acceleration (PGA) to be expected at 0.01 per annum (p.a.). The 1985 maps [6] were probabilistic at 0.0021 p.a. (or 10% exceedance in 50 years) and were given for both PGA and peak ground velocity (PGV). The 2005 (4th Generation SHMC) probabilistic assessment [7] was developed for 0.000404 p.a. (or 2% exceedance in 50 years), and provided four spectral acceleration parameters (at periods of 0.2, 0.5, 1.0, and 2.0 seconds) giving site-specific uniform hazard spectra for the first time. PGA was also provided to allow continuity for geotechnical designs. A schematic overview of the evolution of the SHMC is provided in Fig. 1.

The 2015 SHMC yields many important advances on its predecessors. The current contribution explores the development of the 2015 5th Generation SHMC, concluding with a discussion on research priorities and software requirements for the 6th Generation SHMC to be developed for the 2020 edition of the NBCC.

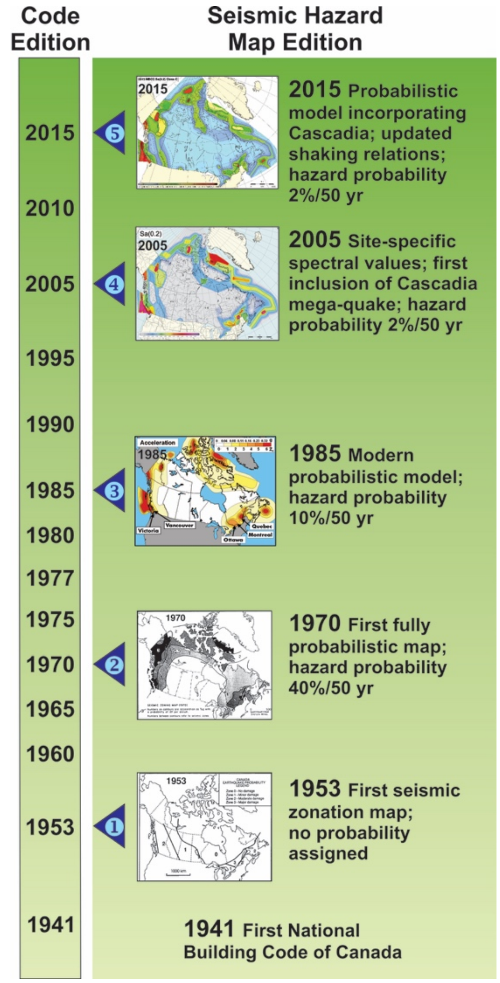

Fig. 1 – Evolution of the Seismic Hazard Model of Canada (SHMC).

2. The 5th Generation Seismic Hazard Model of Canada

The 5th Generation SHMC was developed to provide seismic design values for the 2015 NBCC [2]. The model updates the earthquake catalogue [8]; consistently expresses earthquake magnitudes in terms of moment magnitude; revises areal earthquake sources; includes probabilistic treatment of Cascadia and other fault sources; and estimates mean ground shaking at the 2% in 50-year probability level. The model takes advantage of state-of-the-art scientific knowledge and replaces the "robust" combination of alternative source models [7] used for the 2010 4th Generation SHMC with a fully probabilistic model. The ground-motion models (GMMs) used also represent a major advance over those used for the 4th Generation model. Seismic design values (on Soil Class C at V_{S30} = 450 m/s) for PGA, PGV and for $Sa(T)$ for periods T = 0.2, 0.5, 1.0, 2.0, 5.0, and 10.0 s were developed for the 2015 NBCC, as well as three additional periods not required for the NBCC (T = 0.05, 0.1, and 0.3 s). Specific highlights of the 2015 model are described below.

2.1 Seismic Source Models

Seismic source zones used for the 4th Generation SHMC consisted of two models, distinguished primarily as historical earthquake distribution (*H*) and regional seismotectonic (*R*) models. For the 5th Generation model, this framework is preserved in northeastern Canada. In southeastern Canada, an additional type of source – hybrid between *H* and *R* (see Adams [3] for rationale) – is used together with the updated *H* and *R* models. In western Canada, a single suite of area sources are used. However, this model includes variability in the source geometry as appropriate (for example, in the closest down-dip approach of the Cascadia subduction zone to southwestern British Columbia [9]). Boundaries of the individual areal source zones were revised to reflect new information, and their earthquake magnitude-frequency distributions were recalculated using the updated catalogue [8].

The 5th Generation model includes fault sources for three low-angle subduction thrusts in the Cascadia subduction zone (i.e., the Juan de Fuca, Explorer and Winona segments), an updated treatment of the faults offshore of Haida Gwaii (formally the Queen Charlotte Islands), and adds five onshore strike-slip and reverse fault sources in the Yukon-Alaska region [10]. The modelled sources appropriately concentrate the hazard near the faults, instead of averaging it out over a wider area (as was done for 2010 4th Generation SHMC). The methods for combining and weighting the source models in specific regions is detailed in Halchuk *et al.* [11].

2.2 Ground-Motion Models

A major enhancement is the adoption of modern ground motion models (GMMs). The modern GMMs for North America have incorporated an improved understanding of the magnitude- and distance-scaling of earthquake ground motions based on a wealth of new data [12], and the use of finite-fault stochastic simulations to account for the absence of ground-motion data from large eastern North American earthquakes [e.g., 13].

The different seismic propagation properties of the crust in eastern and western Canada and the diversity of the earthquake sources in southwestern Canada require the use of GMMs for different tectonic regions, as detailed by Atkinson and Adams [14]. Unlike the 4th Generation SHMC which used a single published relation (with rather arbitrary uncertainty bounds) for each region, the 5th Generation model uses representative suites of GMMs [15]. A suite of crustal relations based on the ground-motion values from five appropriate eastern GMMs was used for eastern Canada. For the western Canadian crustal source zones, as well as the crustal faults, a suite of models that use the Boore & Atkinson [16] GMM as the backbone model was used. For intraslab, chiefly normal-mechanism, earthquakes within the subducting slab under Puget Sound and west of Vancouver Island, the backbone GMM was centred on the Zhao *et al.* [17] intraslab relation with representative depths of 30 km and 50 km, respectively. For the Cascadia and Haida Gwaii subduction interface earthquakes, a 50/50 weight for simulation- and empirical-based interface GMMs was applied. Finally, the ground motions were adjusted so that hazard was calculated on "firm ground" site conditions, or Site Class C [18], defined as V_{S30} = 450 m/s for 2015 NBCC based on the site class factors used by Boore & Atkinson [16].

2.3 2015 Hazard Values

Seismic hazard values were calculated for a grid extending over Canada and used to create national-scale contour maps (Fig. 2). In general, for locations in eastern Canada, the estimated seismic hazard at $T \geq 2.0$ s has increased while the 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. Indicators of hazard change relative to the 4th Generation hazard model for *Sa*(1.0 s) on Site Class C are superimposed on Fig. 2. In Haida Gwaii and the Yukon, the explicit inclusion of fault sources has also raised the estimated hazard at some localities. The spectral values are used to construct Uniform Hazard Spectra (UHS) on Site Class C for selected major cities to illustrate the range and period dependence of seismic hazard across Canada (Fig. 3). The UHS for Winnipeg, Manitoba, is representative of many localities in the low-seismicity stable continental core. See Adams *et al.* [2] for further details on the rationale for changes to the seismic hazard estimates across Canada.

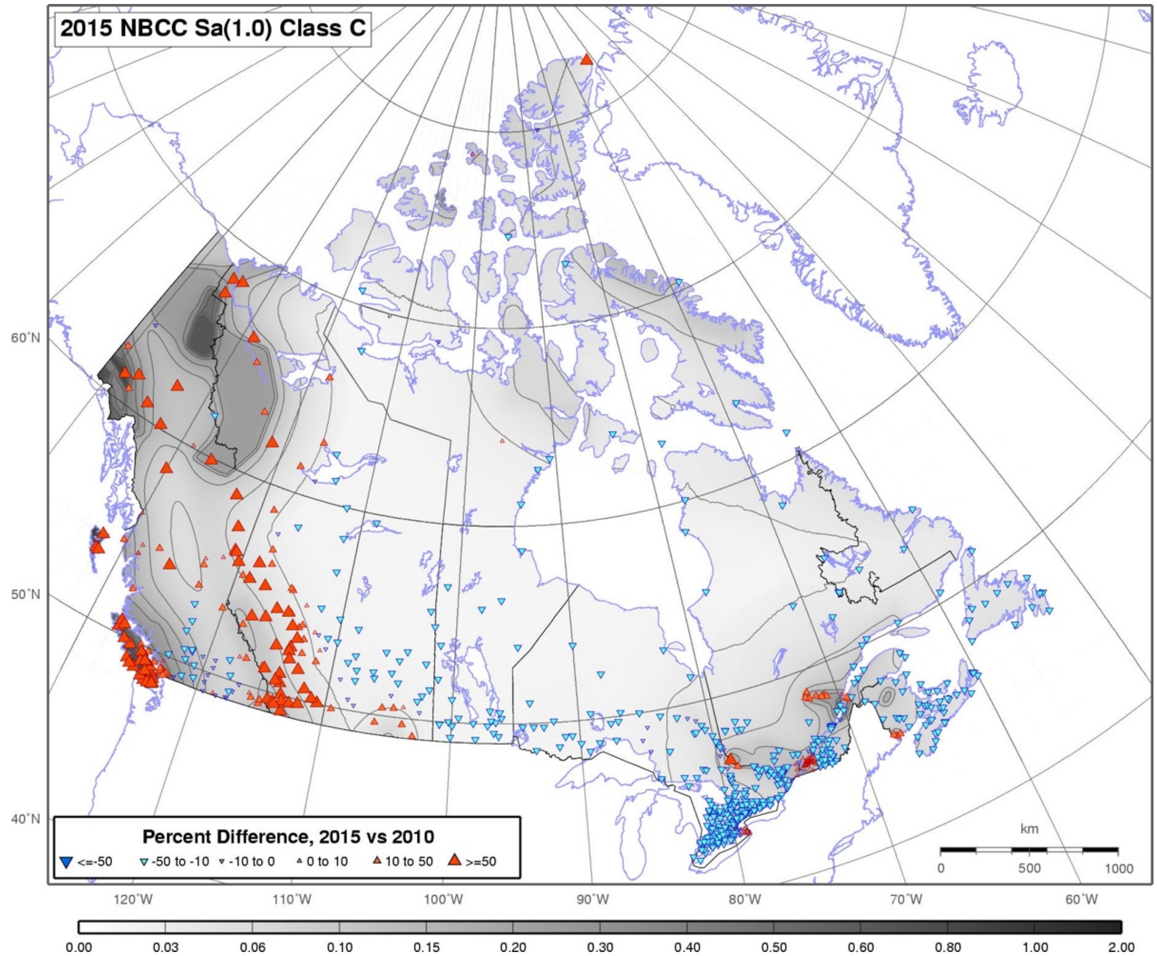

Fig. 2 – Calculated 2% in 50-year mean seismic hazard values for Canada. Hazard values are defined as 5% damped spectral acceleration at $Sa(1.0\ \mathrm{s})$ for Site Class C (defined as V_{S30} = 450 m/s) in g. Red and blue triangles indicate the percentage difference in hazard values relative to the 2010 4th Generation SHMC.

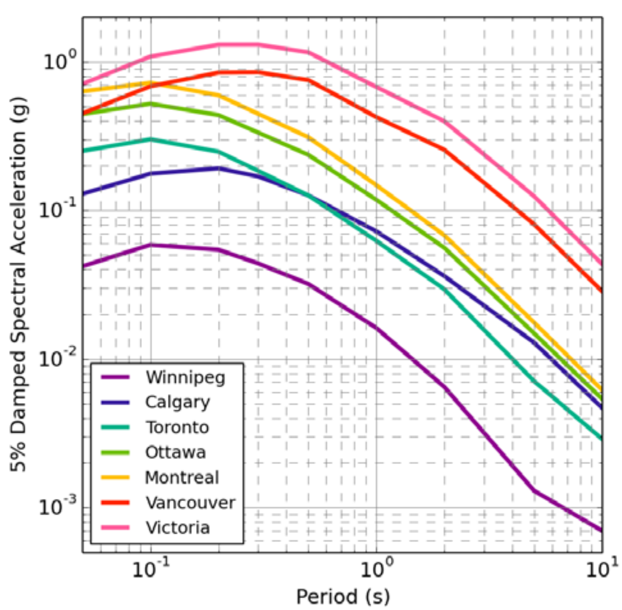

Fig. 3 – Uniform Hazard Spectra for mean 2% in 50-year ground motions on Site Class C for key cities.

Seismic hazard deaggregation partitions the calculated hazard into the relative contributions from various seismic sources that may affect a given site. For the first time in the SHMC, the GSC have included the Juan de Fuca subduction interface as a probabilistic source [2, 11]. The Juan de Fuca segment of the Cascadia subduction zone was previously considered as a deterministic source [7]. Exploring the deaggregated 5th Generation hazard estimated for Vancouver (Fig. 4), intraslab earthquakes in the subducted Juan de Fuca plate have the largest contributions to the hazard for shorter periods of ground shaking ($T \leq 0.5$ s). Hazard contributions from shallow crustal earthquakes in the North American plate and from subduction interface are significant but are relatively lower than intraslab events. However, at longer periods, interface earthquakes become the dominant source of hazard, primarily from the Juan de Fuca segment of the Cascadia subduction zone [9].

3. Towards the 2020 NBCC Hazard Models

There are several research priorities that will be investigated prior to the development of the 6th Generation SHMC. Paramount among these priorities is the need to migrate the hazard computational platform to modern open source PSHA software [e.g., 19]. In addition to the migration to modern PSHA software, other research priorities (some briefly discussed below) may include: incorporation and identification of additional crustal faults in Canada and adjacent U.S.; an enhanced earthquake catalogue; evaluation of the hazard sensitivity to catalogue declustering; evaluation of smoothed seismicity models; assessment and/or development of new GMMs; assessment of passive margin hazard from global analogues; improved site classification schemes; evaluation of risk-targeted hazard or; inclusion of induced seismicity.

Comparisons between the Canadian and U.S. national seismic hazard maps are often made for cross-border locations. Differences between the 2015 Canadian and the 2014 U.S. model [20] can largely be attributed to the definition of source zones, choice of ground motion prediction equations, the earthquake catalogue, and mode of incorporating Cascadia subduction earthquakes [21]. While there is general agreement in the pattern and relative hazard levels, we intend to continue working with our U.S. counterparts to minimise differences between the two national models.

3.1 Inclusion of Crustal Faults

The calculations for the 5th Generation SHMC were largely finalised by late 2013 for the inclusion in the 2015 NBCC. Since this time, two studies have identified potentially active crustal faults in the southern Vancouver Island region, near the British Columbia provincial capital of Victoria. Barrie and Greene [22] published a study based on recently collected marine geophysical data that reveals Holocene faulting in the Devil’s Mountain fault zone in the northern Strait of Juan de Fuca [23] that extends east to west from Washington State in the United States to just southeast of Victoria. Surveys are scheduled to investigate if Holocene faulting extends further to the west. There is also evidence that may suggest there is tectonically driven Holocene faulting in the Leech River Valley, a steep sided valley west of Victoria that is centred on the Eocene terrane bounding Leech River thrust fault [24]. Given the proximity of both of these structures to a major population centre on Vancouver Island, their inclusion as independent fault sources in future generations of the SHMC deserves consideration.

3.2 Catalogue Declustering

Previous sensitivity analyses of earthquake catalogue declustering for eastern Canada indicated little difference in hazard values when standard California algorithms were applied [e.g., 25]. However, studies suggest that aftershock sequences for large intraplate earthquakes can continue for longer durations than in seismically active regions [26, 27], rendering traditional declustering techniques unsuitable and providing non-Poissonian datasets for earthquake occurrence. Consequently, declustering parameters and methods will be reviewed for both active tectonic and intraplate regions.

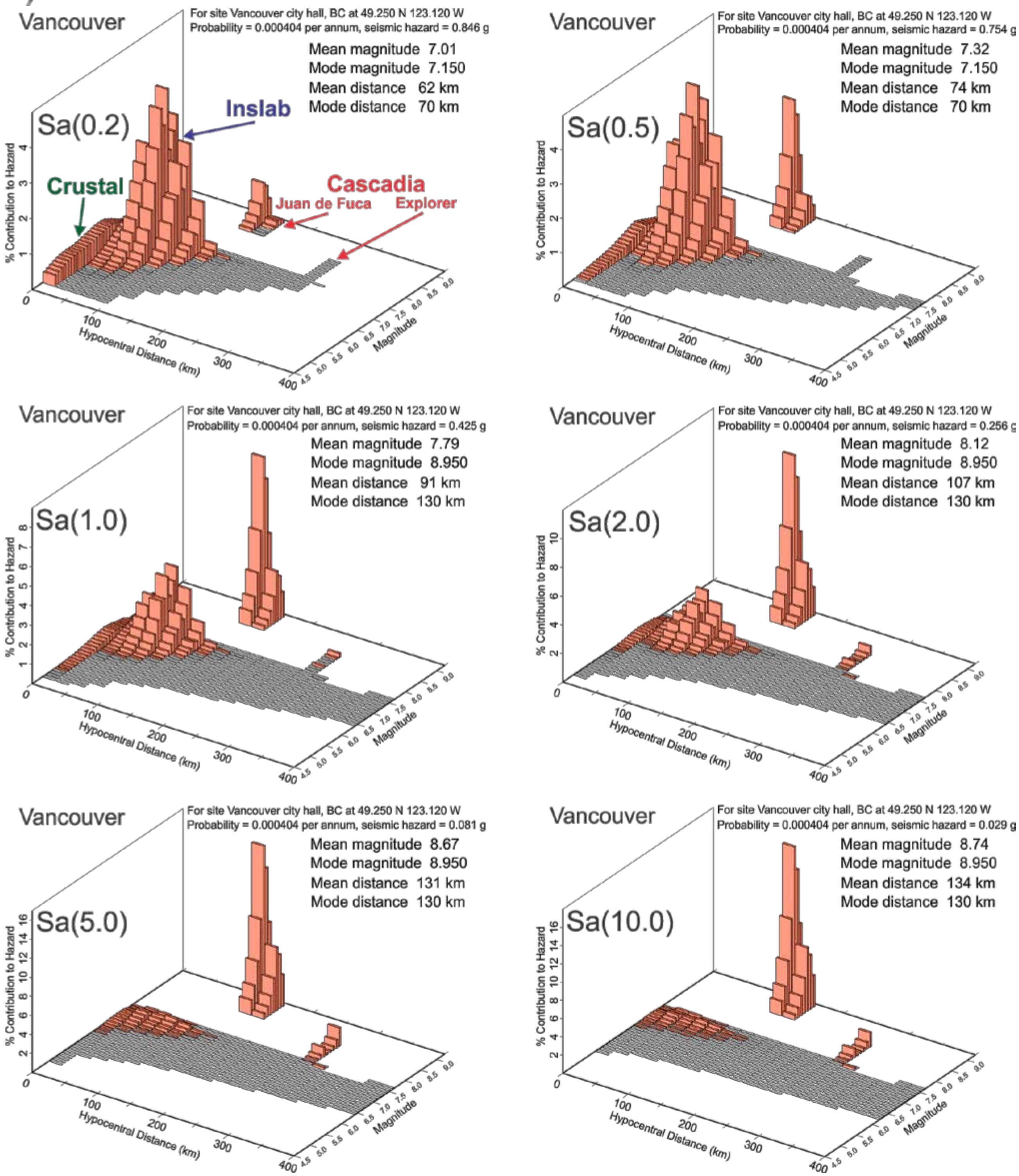

Fig. 4 – Deaggregation of seismic hazard for Vancouver. Contributions from various earthquake sources are indicated in the top left example for *Sa*(0.2s). The different contributions from these sources can be tracked for the periods proposed for 2015 NBCC (After Rogers *et al*. [9]).

3.3 Evaluating Smoothed Seismicity

The basis of the 5th Generation SHMC relies on areal source zones that assume a uniform rate of earthquake occurrence within a spatial region. The hazard in some regions is highly sensitive to the placement of source zone boundaries (e.g. Richardson Mountains, Yukon Territory). While every effort has been made to respect the knowledge base of seismotectonic and geophysical characteristics of the crust and historical seismicity, the definition of areal source zones remains somewhat subjective in nature. However, these areal sources do allow hazard modellers to forecast hazard in regions where there may be little evidence of earthquakes in the historical record, but where large earthquakes might reasonably be expected based on seismotectonic analogues. Consequently, their use will be retained for the 6th Generation SHMC.

Adaptively smoothed seismicity models offer a more objective method to determine seismicity distribution models based on historically-observed seismicity [e.g., 28]. Whilst the application of this technique might be better suited to active tectonic regions with shorter recurrence intervals, the method will be explored as an alternative earthquake spatial model for the 6th Generation SHMC.

3.4 Evaluation of Ground-Motion Models

Ground-motion models are often considered to contribute one of the largest sources of uncertainty in PSHA. The production of seismic hazard models requires assumptions on the selection and use of GMMs, often with little empirical evidence from local earthquakes. Preliminary assessment on the appropriateness of modern GMMs (including those used for the 2015 SHMC) for use in western Canada has begun using limited datasets from largely offshore earthquakes along the Pacific-North America tectonic plate boundary [29, 30]. While still preliminary, these assessments suggest that the use of modern GMMs tend to overestimate recorded ground motions from offshore earthquakes by factors of two or more. This work is ongoing for western Canada and efforts are underway to systematically process and evaluate ground-motion data for all earthquakes of $M_W \geq 4.0$ with moment tensor solutions, with an emphasis on deep subduction intraslab earthquakes and shallow crustal earthquakes within the North American plate.

A suite of GMMs has recently been completed for Central and Eastern North America (CENA) through the Next Generation Attenuation-East project [31]. The models developed through this research project have been tested and validated using CENA data. These models will likely be adopted in some fashion for the 6th Generation SHMC. Additionally, the nascent NGA-Subduction project [32] may also yield some valuable insights towards better characterising ground-motions for subduction zone earthquakes.

3.5 Risk-Targeted Hazard

Allen *et al.* [33] explored the utility of so-called “risk-targeted” ground motions for future editions of the NBCC. The risk-targeted approach described by Luco *et al.* [34] was adopted into the 2012 International Building Code for the United States. The method provides a framework for assessing hazard based on a uniform probability of collapse rather than uniform ground-motion exceedance probabilities. The risk coefficients (i.e., the proposed adjustment factors from 2% in 50-year mean hazard) presented in the study of Allen *et al.* [33] are necessarily dependent on the level of “acceptable risk,” or the collapse risk objective. This preliminary assessment indicates that there is moderate variability in the risk coefficient across Canadian localities, with all localities showing a slight reduction in design ground motions relative to the proposed 2015 NBCC 2% in 50-year hazard values. The largest potential changes in design ground motions are observed on the west coast of Vancouver Island near Tofino and Ucluelet, for example (Fig. 5). The adjustment factors observed in this region are commensurate with the changes seen in coastal regions in the United States Pacific Northwest that are affected by hazard from the Cascadia subduction zone. Risk coefficients of around 0.85 suggest that structures in these localities may be engineered to withstand ground-motions 15% larger than may be necessary. However, recent research suggests that the current approach in the United States – as also used by Allen *et al.* [33] – may lead to non-conservative design values in subduction environments [35]. This is because the median collapse capacity of buildings from subduction earthquakes is typically lower (because of longer duration shaking) than that assumed by the generic building collapse fragility curves used to determine the risk-targeted ground motions [36, 37].

Because the localities on the west coast of Vancouver Island represent a minor contribution to the nation's building stock (i.e., they are sparsely populated regions with low rise structures), there may be diminishing returns for adopting risk-targeted ground motions for future editions of the NBCC based solely on the numerical impacts to design values. This assumes that by not adopting the risk-targeted approach for the NBCC that there is little-to-no impact on life safety as a consequence of this decision. However, benefits for the adoption of risk-targeted ground motions for the NBCC include the explicit quantification of collapse prevention objectives in building design and mainstreaming the consideration of collapse risk into earthquake engineering practice. Ultimately, the decision to adopt risk-targeted ground motions, and at what collapse probability level, should be based on broad community consultation that involves structural engineers, hazard practitioners, sociologists and decision makers.

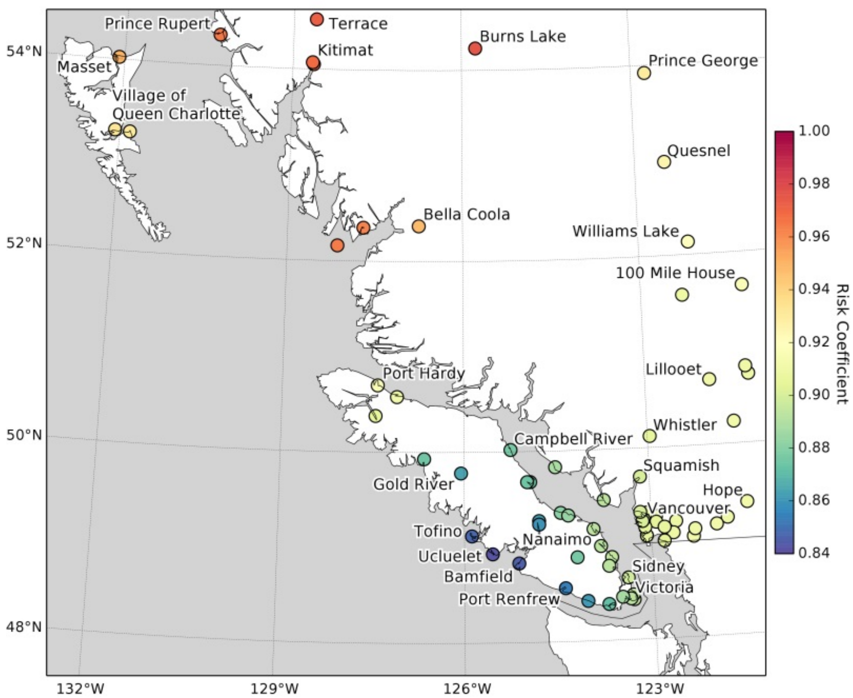

Fig. 5 – Calculated risk coefficients for *Sa*(1.0 s) at southwestern Canadian localities based on the hazard values proposed for the 2015 NBCC.

3.6 Induced Seismicity

The integration of seismic hazard triggered by earthquakes triggered through hydrocarbon-related industrial activity – either through hydro-fracturing or wastewater injection – into building design maps has become the subject of much debate in recent times [38]. Due to the transient and spatially variable nature of this hazard, its consideration presents a major challenge for typical exceedance probabilities of engineering interest (e.g., 2% in 50 years), which assume time-stationary earthquake behaviour. Furthermore, any potential changes in design requirements may result in trade-offs between public safety and economic benefits in regions affected by induced hazards.

There are now several documented cases of earthquakes potentially triggered by hydro-fracturing (*not* wastewater injection) in Canada [39, 40], the largest of these being a M_W 4.6 event in the Fox Creek, Alberta region (June 2015) and a M_W 4.5 event in northern British Columbia (August 2015). In a preliminary study for a typical site affected by induced earthquakes, Atkinson *et al.* [41] demonstrated that the hazard can greatly exceed the hazard from natural background seismicity at most probabilities of engineering interest; a finding that is supported by analogue studies in the United States [42]. Should the 6th Generation SHMC integrate hazard from potentially induced earthquakes, there are several philosophical issues and assumptions that need to be addressed. These include: 1) the appropriateness of the Poisson earthquake process; 2) catalogue declustering, earthquake rates, and *b*-value; 3) the maximum magnitude of induced events; 4) ground motions expected from shallow induced events; and 5) the frequency of hazard model updates in response to hydro-fracturing activities. As yet there is no consensus in how the hazard from induced earthquakes should be incorporated into design maps. Any move to do so in Canada will require broad stakeholder consultation in order to provide information and products that are useful for decision makers and users.

3.7 Implementation of the 2015 Model in the OpenQuake-Engine

The GSC has modified and maintained a commercial version of FRISK88 – a proprietary product of Risk Engineering, Inc. (now Fugro GeoServices Ltd.) – for national-scale seismic hazard calculations since the late 1980s. Dubbed GSCFRISK, this software has served the GSC well and has been used as the software engine to deliver the 2005 4th Generation seismic hazard model (with minor updates in 2010) and the 5th Generation hazard model in 2015. However, the software has become difficult to maintain over time as the science underpinning PSHA rapidly advances. With the emergence of new open source technologies, the GSC is exploring the use of the Global Earthquake Model's OpenQuake-engine [19] to deliver the next generation SHMC.

Prior to adopting the OpenQuake-engine as the primary hazard computation engine for future hazard modelling, it is necessary to first implement the GSC's 5th Generation SHMC to demonstrate that the OpenQuake-engine is able to generate seismic hazard values consistent with those generated by GSCFRISK. This step is required to show that future changes in the calculated seismic hazard are due to scientific advances and differences in modelling assumptions rather than the software engine itself. In order to implement the exiting GSCFRISK model as accurately as possible, it was necessary to overcome several challenges. One such challenge is the ability to support the selected ground motion models (GMMs) used by the GSC in the 5th Generation model, which are defined as lookup tables (requiring interpolation of the ground motion for a corresponding magnitude, distance and site class) rather than the more commonly adopted parametric form. This required the development of a new feature in the OpenQuake-engine that can not only support the ground motion tables required to represent the full GMM logic tree within the 2015 model, but can also apply modifications to the tables to take into account source and/or site-related amplification.

Preliminary hazard models implemented in the OpenQuake-engine generate hazard values generally within 2% of the 2015 NBCC hazard values for sites in the province of British Columbia (BC). However, sites near fault sources that assume "floating ruptures" [43] demonstrate significantly higher hazard when using the OpenQuake-engine (Table 1). Locations affected by these fault sources are limited to northern British Columbia and the Yukon Territory. Differences for low-hazard sites in eastern Canada are generally greater than in the west, but presently less than 10%. Differences in the treatment of the source zone cut-off distances between the two software engines have been identified as the major cause of these discrepancies, particularly for long period ground-motions (Table 1). However, uncertainties in the parameterization of the hazard (e.g. GMM selection, source zone definition, etc.) are likely to outweigh relatively the relatively minor hazard discrepancies between the computational engines. Table 1 compares the precision (not accuracy) of 2% in 50-year seismic hazard values (on Site Class C) for selected Canadian localities, as calculated in GSCFRISK (and those specified in the 2015 NBCC) and the OpenQuake-engine. The values calculated by the OpenQuake-engine are in good agreement with the 2015 NBCC national-scale hazard values, confirming that the GSC can use the engine for future calculations.

4. Concluding Remarks

The 2015 5th Generation SHMC yields many important advances on its predecessors, including: the probabilistic inclusion of the Cascadia subduction interface; updated seismic sources with special consideration of large rare eastern earthquakes; the use of a representative suite of ground-motion models, and; explicit definition of crustal fault sources in the Yukon Territory and offshore western margin faults (north of Cascadia) based on GPS and paleoseismic slip rates. The reasons for the changes to modelled hazard are well-described by Adams *et al.* [2]. The GSC is now looking forward to the 2020 building code cycle with a view of rethinking the fundamental scientific questions and building on the advances made for the 2015 model. Primary fields of investigation for the future hazard model include: sensitivity testing of hazard to various declustering algorithms; exploring the use of smoothed seismicity as an alternative earthquake spatial model; the evaluation and application of modern GMMs; exploring risk-targeted hazard for the NBCC; and investigating the need to consider hazard from induced seismicity.

Table 1 – Comparison of 2% in 50-year seismic hazard values (on Site Class C) for selected Canadian localities as calculated by GSCFRISK and the OpenQuake-engine.

Locality	*Sa*(0.2 s) g			*Sa*(1.0 s) g		
	GSCFRISK	OpenQuake	% Difference	GSCFRISK	OpenQuake	% Difference
Tofino, BC	1.46	1.53	4.8	0.883	0.921	4.1
Sandspit, BC*	1.31	1.48	12.0	0.727	0.815	11.4
Victoria, BC	1.30	1.30	0.68	0.677	0.681	0.53
Vancouver, BC	0.846	0.848	0.19	0.425	0.428	0.67
Montréal, QC	0.595	0.580	2.7	0.148	0.144	2.5
Québec City, QC	0.492	0.482	2.1	0.133	0.130	2.1
Ottawa, ON	0.401	0.387	3.6	0.110	0.107	2.4
Toronto, ON	0.249	0.247	0.83	0.063	0.062	1.7
Penticton, BC	0.158	0.160	1.2	0.102	0.104	2.7
Halifax, NS	0.110	0.108	1.5	0.053	0.050	6.3†

* Site affected by "floating ruptures" along fault sources

† Adjustment of source zone cut-off distances to 700 km (from 600 km) to fully include more active area sources significantly improves the long-period comparison.

5. Acknowledgements

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