Canadian Conference - Pacific Conference on Earthquake Engineering 2023

Vancouver, British Columbia

June 25th – June 30th, 2023

Deaggregation of NBCC 2020 Seismic Hazard for Selected Canadian Cities

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ABSTRACT

Natural Resources Canada's 6th Generation seismic hazard model (CanadaSHM6) for Canada forms the basis for the seismic design provisions of the 2020 National Building Code of Canada (NBCC). Deaggregation (also called disaggregation) unbundles the contributions of seismic hazard results to help understand the relative contributions of the earthquake sources. In southwestern Canada, hazard contributions come from three main sources of shaking – crustal, in-slab and interface earthquakes; deaggregations can help to identify the major contributions from each of these sources. By performing deaggregations for a range of probabilities (40% to 2% in 50 years) and spectral accelerations (0.2 to 10.0 seconds) we will examine in detail the hazard for two of Canada's largest urban centres at highest risk, Vancouver in the west and Montreal in the east. In most cases, as the probability decreases, the hazard sources closer to the site dominate. Larger, more distant earthquakes contribute more significantly to hazard for longer periods than for shorter periods. CanadaSHM6 provides hazard values for various site designations ($140 \leq V_{s30} \leq 3000$ m/s; Site Classes A to E), and the impact of non-linearity can be observed for soft site conditions. Seismic hazard deaggregations allow for better-informed choices of scenario events, and for the selection of representative time histories for engineering design.

Keywords: seismic hazard, national building code of Canada, deaggregation

INTRODUCTION

In 2020 Natural Resources Canada produced its 6th Generation seismic hazard model (CanadaSHM6), and from it produced a suite of seismic hazard maps for Canada. The model and a national grid of values can be accessed through Open Files 8924 [1] and 8950 [2], respectively. The results of CanadaSHM6 formed the basis for the seismic design values for the 2020 edition of the National Building Code of Canada (NBCC 2020, [3]). While comprehensive documentation on CanadaSHM6 is still being prepared, background information can be found in [4].

Deaggregation (also called disaggregation) unbundles the contributions of seismic hazard results to help understand the relative contributions of the earthquake sources. The process of deaggregation [5,6] has come to be an important tool for understanding seismic hazard. Allocating the total hazard into contributions based on distance and magnitude helps to close the gap between the thousands of earthquakes that go into the hazard models and the scenario design earthquake(s) required for engineering purposes. Identifying the predominant sources of hazard leads to better choices for design earthquakes' characteristics, as well as better choices for time histories. Performing deaggregations at more than one period also helps to determine if one source dominates at all periods, and also clarifies whether more than one design earthquake is needed. In this paper we deaggregate the CanadaSHM6 seismic hazard results for Vancouver and Montréal to gain insight on the relative contributions of earthquake sources in terms of distance, magnitude, epsilon and site designation.

METHOD

The NBCC2015 seismic hazard results were generated using GSCFRISK, a customized version of the FRISK88 hazard code (FRISK88 is a proprietary software product of Risk Engineering Inc.). For NBCC2020, the CanadaSHM6 model has been fully implemented in the OpenQuake platform [7,12] and deaggregations presented in this paper were performed using OpenQuake v.3.11.

Results in this paper are provided for six ground motion parameters, Sa(0.2, X), Sa(0.5, X), Sa(1.0, X), Sa(2.0, X), Sa(5.0, X), Sa(10.0, X) and PGA (X), where Sa(T, X) represents the 5% damped spectral acceleration for period T in seconds and site designation X. The site designation is a new term for NBCC 2020 and represents the site condition defined either via a site class or by the time-average shear wave velocity to a depth of 30 m (V_{s30}; further background on site designation is provided in NBCC 2020 [3] and [4]). PGA is the peak horizontal ground acceleration.

In this paper we provide deaggregations for Magnitude-Distance-Epsilon and the tectonic region type as calculated by OpenQuake. It is important to note that by default OpenQuake provides the conditional probability of observing at least one ground motion exceedance in a given time span given the occurrence of a rupture with specific characteristics. This definition is different than that of the formulation previously provided by NRCan for NBCC 2015 and earlier; it provided the conditional probability of observing a specific scenario given that a ground motion exceedance has occurred. These different definitions provide different probabilities. However, the OpenQuake output can easily be converted into the "traditional" format following the direction provided in [8]. The deaggregations presented in this paper have applied this conversion.

For NBCC 2015, deaggregations in terms of epsilon (ε) were not provided [9] as this was not possible with our modification to the GSCFRISK software. However, for NBCC 2020, epsilon is included. Epsilon represents the number of standard deviations ("sigma") that the ground motion deviates from the median value as predicted by the ground motion model implemented within the hazard model. For example, an $\varepsilon = 1$ indicates a contribution from the median plus one standard deviation. In OpenQuake, deaggregating for ε provides the conditional probability for each of the ε bins that meet the exceedance value. In contrast, an ε value that is occasionally used in the engineering community (and sometimes referred to as ε*) assigns the entire contribution to the minimum ε bin that meets the exceedance criteria. The outcome of these two definitions is largely to do with selecting representative scenarios for the hazard value whereby the ε* approach provides a scenario where the target ground motion is exactly matched. As described in [6], both approaches are valid and the usefulness of either depends on its application.

Further details on the technical details of deaggregations are provided in [8, 6].

Layout of NBCC 2020 deaggregation plots

Examples of the 2%/50 year deaggregation for PGA(X_{450}) (i.e., for a V_{s30} of 450 m/s) is given for Vancouver and Montréal in Figure 1. For NBCC2020 deaggregations, a bin size of 0.1 magnitude units (moment magnitude, Mw) and 20 km distance (closest rupture distance, Rrup) is used. Note that the adoption of the Rrup distance is new for NBCC2020 and reflects the adoption of ground motion models that use this distance metric and its improved ability to model the ground motions of faults with non-zero dimensions.

A further overview of the deaggregation figure layout is as follows:

- Title line: provides the common location name, followed by the probability of exceedance, the ground motion parameter and the associated hazard value.
- Pie chart: deaggregation of the tectonic region type. For eastern Canada, as there are only stable crust sources, all of the contributions are of this type. In western Canada (in particular southwestern British Columbia), this chart indicates the relative contributions of different source types (i.e., inslab, interface and crustal).
- Mean and modal statistics: summary statistics of the deaggregation mound. Note that the modal values are determined by the largest bin and are thus quantized by the bin increment.
- Colorbar legend: percent contribution of epsilon.
- Bar plot: 3D bar plot of the magnitude-distance-epsilon deaggregation showing the percent contribution of earthquake ruptures to the total hazard. Note that each bar is centered on the middle of its bin. In reality, each bar would span the entire width and length of its range (i.e., there would be no gaps in between the bars), but to assist with visual interpretations of the data the bar's dimensions are slightly reduced. Bottom right corner indicates the total % contributions displayed (small %-contributions are discarded to reduce visual clutter).
- Bottom right: Indicates the model used, the coordinates of the site, and the date the deaggregation was generated.

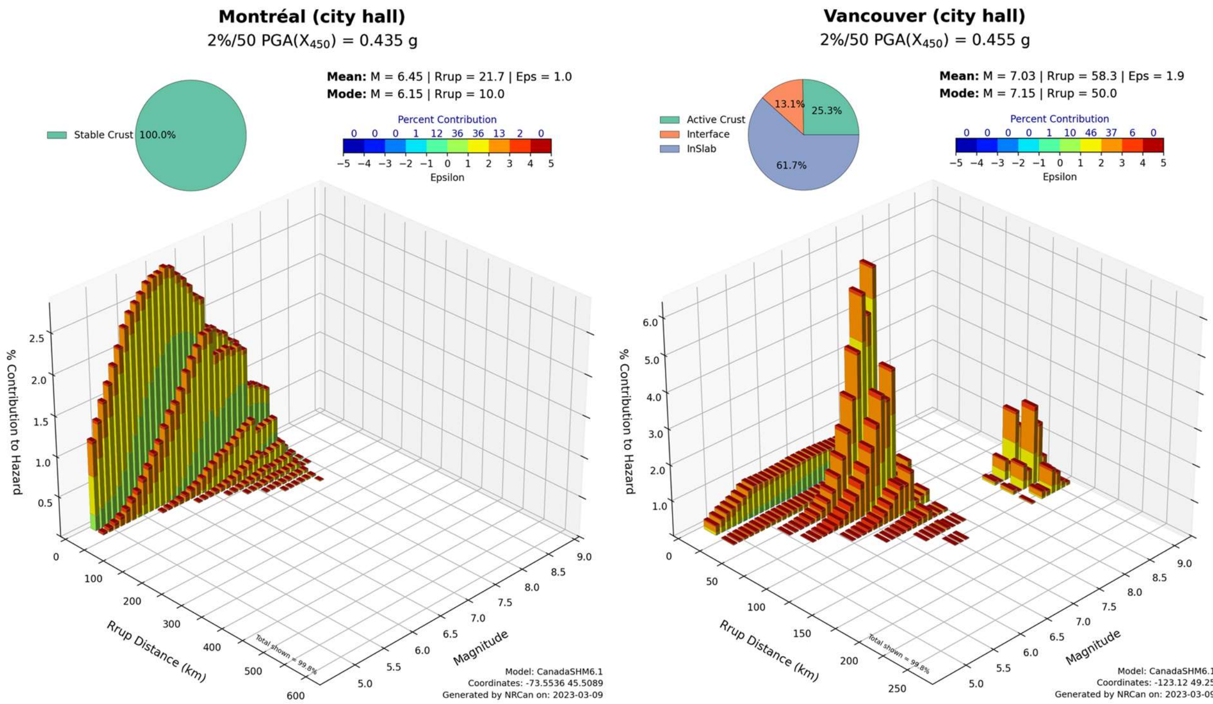

Figure 1. Deaggregation of Montréal and Vancouver PGA(X_{450}) for a probability of 2%/50 years.

RESULTS

Deaggregation as a function of probability level

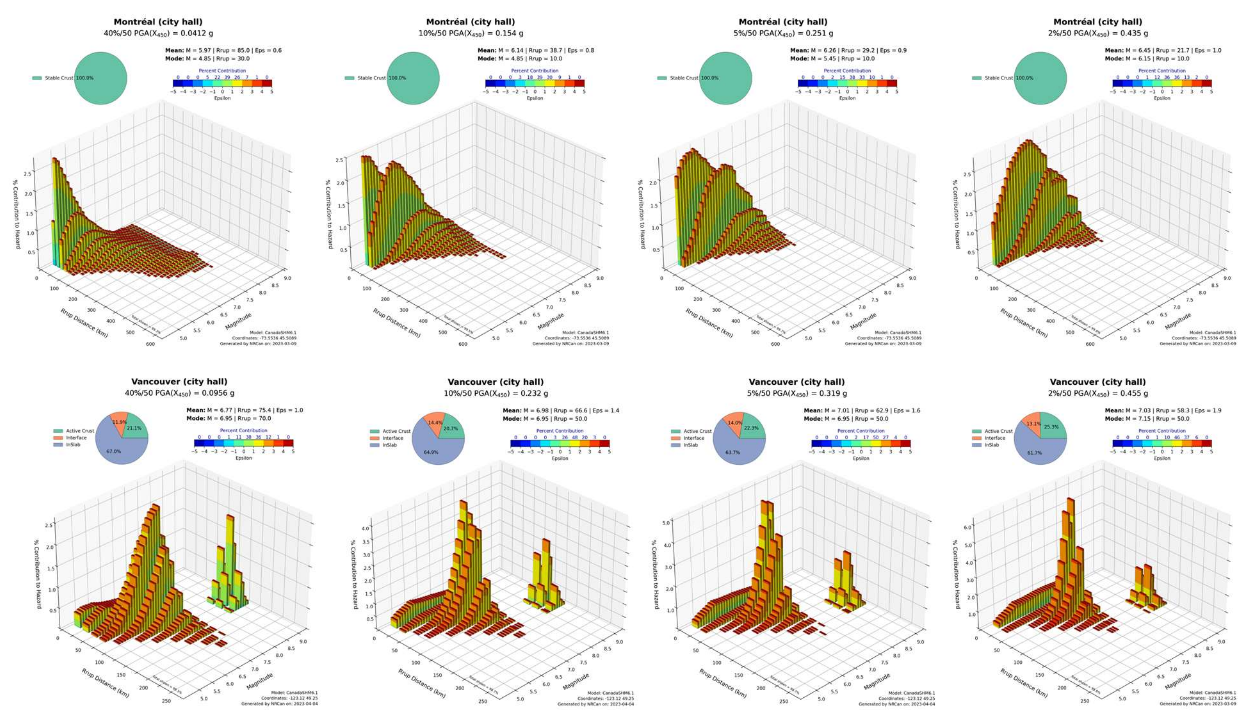

Figure 2. Deaggregation of Montréal and Vancouver PGA for increasingly lower probabilities. Note the vertical scale changes between Figures 2 and 4.

Typical simple deaggregations (e.g., Montréal) have a unimodal distribution, often with the modal peak close to the site and a "tail" that includes larger, more distant earthquakes. By contrast, some locations have multi-modal distributions, where the contribution of different earthquake sources can be seen. A multi-modal distribution is weakly expressed for PGA in Vancouver (Figure 1), but they occur more frequently in long-period deaggregations. An extensive discussion on multi-modal deaggregations is given in an accompanying paper [10]; most of its conclusions are likely to apply to the NBCC 2020 deaggregations, especially regarding the interpretation of the mean values in such cases.

Figure 2 depicts deaggregations for Montréal and Vancouver for PGA(X_{450}) for four probability levels: 40%, 10%, 5% and 2% in 50 years. Examination of Figure 2 shows that as the probability level is decreased (i.e., from 40% to 2% in 50 years) the dominant earthquakes contributing to the ground motion become larger and occur closer to the city. There is also a gradual increase in epsilon. For the particular case of Vancouver, the dominant contributions to hazard are from inslab (sub-crustal) sources whose earthquakes are modelled at depths of 50 km or greater, which constrains the decrease in mean Rrup distance. For Vancouver, there is a notable shift to larger magnitude inslab events and a large increase in epsilon.

Deaggregation as a function of ground motion parameter

Figures 3 and 4 show the 2%/50 year deaggregations for Sa(0.2, X_{450}), Sa(0.5, X_{450}), Sa(1.0, X_{450}), Sa(2.0, X_{450}), Sa(5.0, X_{450}) and Sa(10.0, X_{450}), for Montréal and Vancouver respectively.

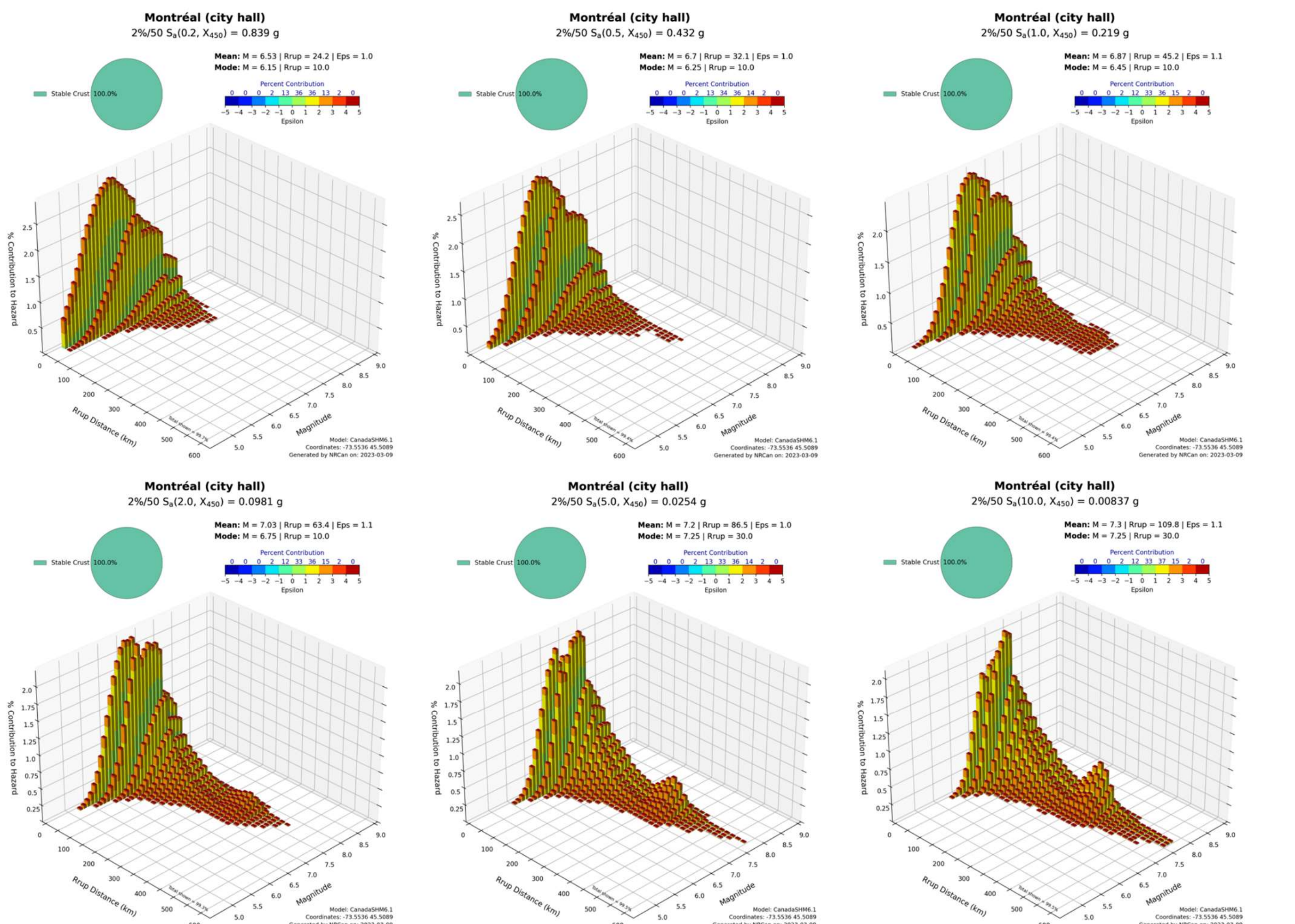

Figure 3. Deaggregation of Montréal at a probability of 2%/50 years and X_{450} for the six NBCC2020 spectral acceleration parameters.

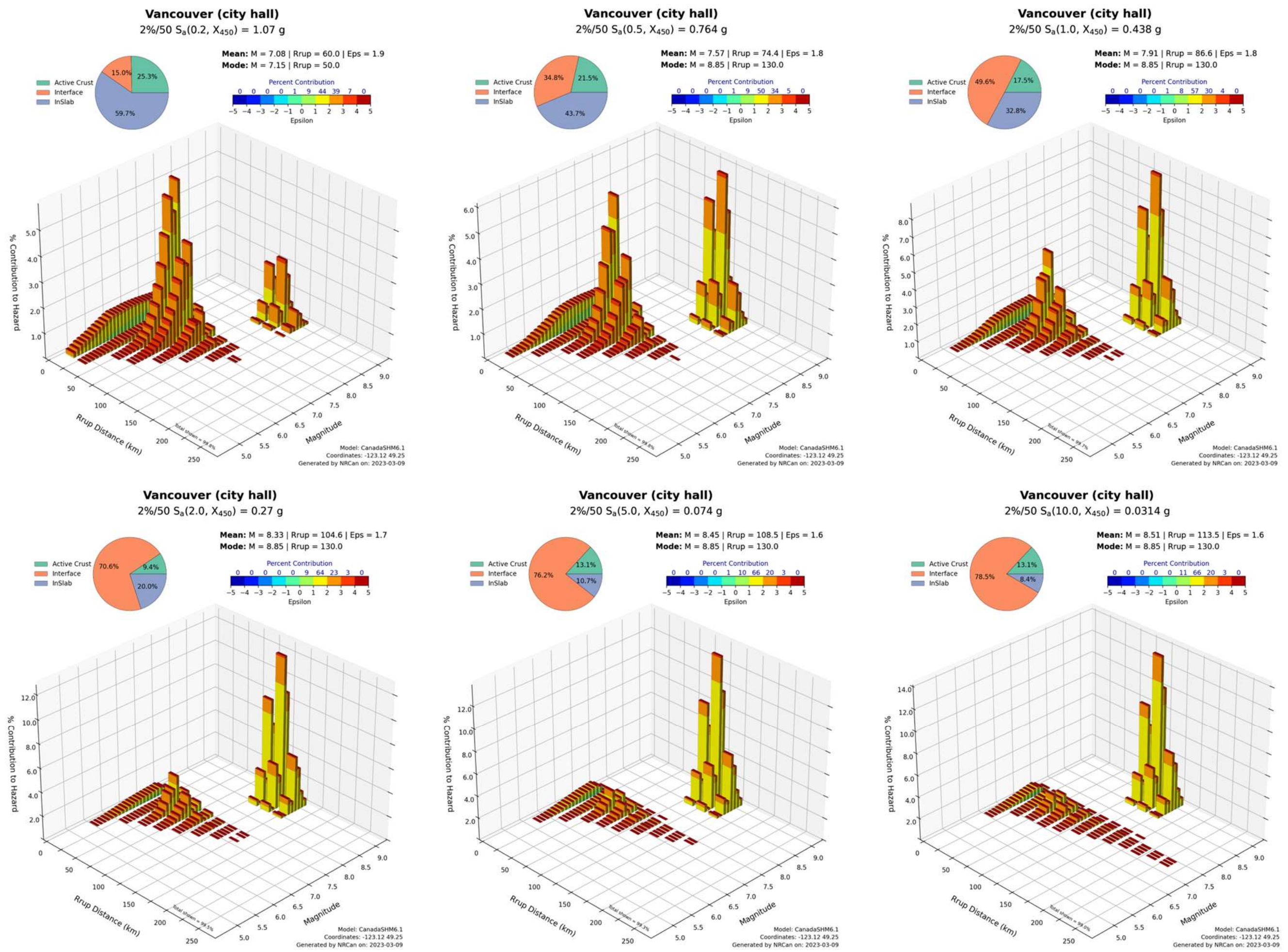

Figure 4. Deaggregation of Vancouver at *a probability of 2%/50 years and X_{450} for the six NBCC2020 spectral acceleration parameters.*

In Figure 3 Montréal shows the typical variation in deaggregation with spectral period for a site condition of X_{450} at a probability of 2%/50 years. As the period increases, larger and more distant earthquakes make an increasing contribution to the hazard. Table 1 shows how this transition is reflected in terms of mean magnitude and distance. The situation for Vancouver (Figure 4) is more complex due to the hazard coming from crustal, inslab, and subduction interface sources. The mean parameters for Vancouver can be taken from the figure but are not added to Table 1 as multi-modal distributions are observed in parts of southwestern British Columbia and need to be treated with caution (see Discussion). However, some general conclusions on the deaggregation shapes for Vancouver as a function of the ground motion measure can be made, namely, on how the dominant tectonic region type changes (can be seen in the %-contribution pie-chart); short-periods tends to be dominated by inslab events while long-periods are dominated by interface events. This is the expected result given the frequency-content of these event types (i.e., large magnitude interface events generate larger long-period ground-motions).

Table 1. Mean magnitude, distance and epsilon for each period (and PGA) for Montréal 2%/50 years, X_{450}.

Mean	PGA(X_{450})	Sa(0.2,X_{450})	Sa(0.5,X_{450})	Sa(1.0,X_{450})	Sa(2.0,X_{450})	Sa(5.0,X_{450})	Sa(10.0,X_{450})
Magnitude	6.45	6.53	6.7	6.87	7.03	7.2	7.3
Distance	21.7	24.2	32.1	45.2	63.4	86.5	109.8
Epsilon	1.0	1.0	1.0	1.1	1.1	1.0	1.1

Deaggregation as a function of site condition

Figures 5 and 6 show the 2%/50 year deaggregations for Sa(0.2) and Sa(2.0) Montréal and Vancouver for various site conditions.

A summary of the mean hazard, magnitude, distance and epsilon for Montréal is provided in Table 2. The deaggregations for Montréal are virtually unchanged from very-hard rock (X_{3000}) to firm ground (X_{450}). However, for softer conditions (below 450 m/s), the relative contributions of more distant sources and of smaller magnitudes is increased. This is largely due to the non-linear soil effect that is present at these site conditions. The non-linearity of these sites under moderate to strong ground shaking causes a reduction in ground motions. This reduces the ground motions from large nearby earthquakes and thus increases the relative contribution of smaller-magnitude and more distant earthquakes for which non-linear phenomena are reduced. Similarly, there is also an increase in the mean epsilon indicating that for the same exceedance probability there are larger contributions from ground motions further above the median level. Note that because non-linearity tends to impact short-period hazard, its impact is reduced and/or not as significant for longer periods for softer sites. For Sa(0.2) in Montréal, non-linearity and other contributing site-amplification effects [4] result in the hazard being largest for X_{450}.

Table 2. Mean hazard, magnitude, distance and epsilon for Montréal Sa(0.2) and Sa(2.0) for various site conditions.

Mean	**Sa(0.2,X_{160})**	**Sa(0.2,X_{250})**	**Sa(0.2,X_{450})**	**Sa(0.2,X_{760})**	**Sa(0.2,X_{1100})**	**Sa(0.2,X_{1600})**	**Sa(0.2,X_{3000})**
Hazard (g)	0.729	0.722	0.839	0.738	0.568	0.511	0.420
Magnitude (Mw)	6.46	6.50	6.53	6.53	6.53	6.53	6.53
Distance (km)	36.4	28.2	24.2	23.0	23.0	23.0	23.0
Epsilon	1.4	1.2	1.0	1.0	1.0	1.0	1.0

Mean	**Sa(2.0,X_{160})**	**Sa(2.0,X_{250})**	**Sa(2.0,X_{450})**	**Sa(2.0,X_{760})**	**Sa(2.0,X_{1100})**	**Sa(2.0,X_{1600})**	**Sa(2.0,X_{3000})**
Hazard (g)	0.180	0.141	0.0981	0.0669	0.0618	0.0571	0.0531
Magnitude (Mw)	7.11	7.06	7.03	7.03	7.03	7.03	7.03
Distance (km)	102.7	75.3	63.4	63.4	63.4	63.4	63.4
Epsilon	1.4	1.2	1.1	1.1	1.1	1.1	1.1

For Vancouver the impact is more complex due to the interaction of multiple tectonic types (i.e., subduction and crustal sources). This is also further complicated by the fact that each of tectonic types in southwestern British Columbia use unique ground motion models (GMMs) each with their own site-amplification models [11]. However, the general observations made for Montréal are still applicable. For example, you can observe a reduction in the contributions from crustal sources for Sa(0.2) for softer conditions (crustal sources only significantly contribute for distance less than 50 km and are sensitive to non-linear phenomena at short-periods). This is less obvious for Sa(2.0) due to a reduced prediction (by the CanadaSHM6 GMMs) of non-linear phenomena for crustal events at long-periods.

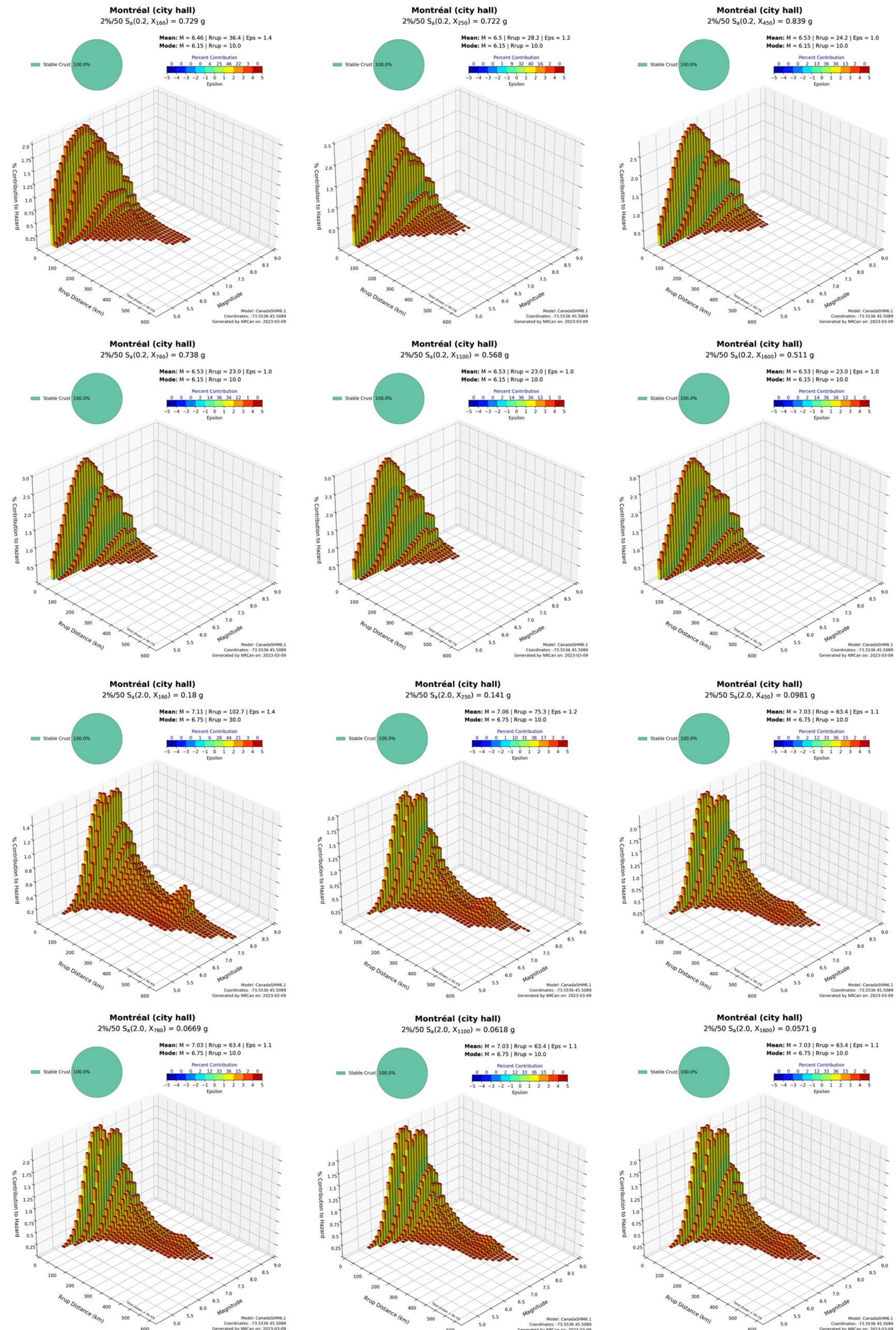

Figure 5. Deaggregation of Montréal Sa(0.2) and Sa(2.0) hazard for a probability of 2% in 50 years showing the variation of contributions with different site condition.

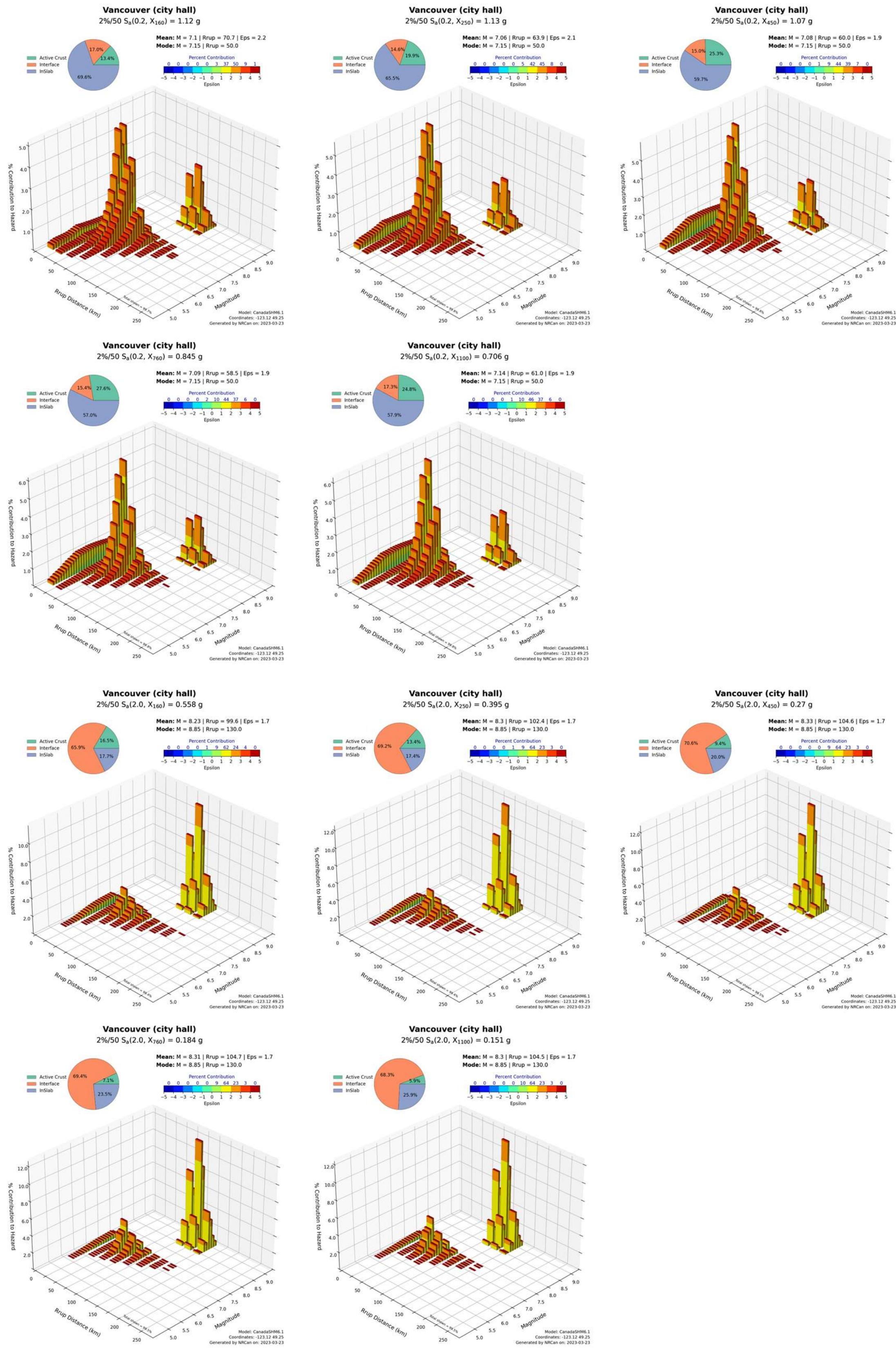

Figure 6. Deaggregation of Vancouver Sa(0.2) and Sa(2.0) hazard for a probability of 2% in 50 years showing the variation of contributions with different site condition. Deaggregations above 1100 m/s are omitted as they are very similar to the X_{1100} deaggregation.

DISCUSSION

Seismic hazard deaggregations are frequently only generated in order to determine mean or modal statistics which are used to guide earthquake rupture scenarios. However, this approach is predicated on the deaggregation being a simple unimodal distribution. As shown in the previous section, Vancouver poses a multi-modal distribution for some ground motions. Multi-modal distributions are observed for many locations both in western and eastern Canada. An accompanying paper [10] investigated this issue for NBCC 2015 and generated maps of zones where the deaggregations pose multi-modal characteristics. These types of automated or manual assessments must first be made prior to interpreting mean/modal characteristics as summary values such as mean magnitude or modal distance may indicate either unrealistic scenarios or not be fully representative of the significant scenarios which control hazard for a particular site.

Deaggregations in this paper were performed using an updated version of CanadaSHM6 termed CanadaSHM6.1. The CanadaSHM6.1 model is described in an accompanying paper ([13]). The CanadaSHM6.1 includes a corrected model for the Alaska interface subduction source in northwestern Canada. The design seismic hazard values for NBCC 2020, from CanadaSHM6, are unchanged. However, the CanadaSHM6.1 model is provided as an updated (non-NBCC) version of CanadaSHM6 because it removes unrealistic deaggregations in northwestern Canada. As this largely impacts only that region, the deaggregations and conclusions presented herein (for Vancouver and Montreal) are identical between the two models.

It is expected that deaggregations for additional cities (similar to those provided in [9]) will be released in a forthcoming Open File in late 2023. At this time, NBCC 2020 deaggregations are not available as an on-demand service, as is being provided for NBCC 2015. The NBCC 2020 availability is currently being examined and they may become available at a later date. In general, the deaggregations presented herein are very similar to those from NBCC 2015 ([9]). In the interim, it is recommended that users can perform deaggregations themselves (using OpenQuake and the files in [1]) following the guidance in this paper and the more complete documentation that will be released as a subsequent Open File.

CONCLUSIONS

The 6th Generation Seismic Hazard Model of Canada forms the basis for the seismic design values for the 2020 National Building Code of Canada. Deaggregations unbundle the contributions of seismic hazard results to highlight the relative contributions of the earthquake sources. This paper showcases deaggregations for two of Canada's largest urban centres at highest risk, Vancouver and Montreal. Deaggregations represent a further aspect of the 2020 NBCC design provisions that lead to better informed choices of scenario events and for the selection of representative time histories for engineering design, thus contributing to improved earthquake-resistant structures. NRCan contribution number 20230066.

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