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Investigation of the Magnitude Lower Limit on the NBCC2020 Seismic Hazard

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ABSTRACT

Canada's 6th generation seismic hazard model (SHM6), as prepared for the 2020 National Building Code of Canada, was released in 2020. The seismic hazard model consists of both Cornell-type area sources and discrete fault sources. Sources are defined by their coordinates, depth, minimum and maximum magnitudes, and a magnitude-reoccurrence (M-R) relationship. M-R for each source is described in terms of an asymptotically truncated Gutenberg-Richter magnitude-frequency distribution.

Probabilistic seismic hazard analysis (PSHA) involves integration over distributions of three random variables: 1) magnitude (M), 2) source-to-site distance, and 3) the (logarithmic) standard deviation of the GMMs (ε). For each of these variables, an upper and lower limit of integration must be defined. For magnitude, the upper limit: M_{max} is defined by the largest earthquake a seismic source can generate; however, the lower limit: M_{min} is harder to define. For generating seismic hazard maps, M_{min} is typically taken as 4-5, as lower magnitudes are assumed to be unable to damage new buildings (e.g., do not increase the seismic risk). However, it is widely recognized that the inclusion of lower magnitude events in the PSHA may significantly increase the seismic hazard, particularly for short return periods and high frequencies.

The 2020 SHM6 considers events with $M \geq 4.85$ to develop seismic hazard maps. However, for lower levels of seismic hazard, there may be significant hazard contributions from events outside this range – particularly small magnitude events at close distances. While, typically not of concern for new buildings, such events may pose a realistic hazard to very low resistance structures, such as temporary structures, those designed without seismic considerations, or those under construction/retrofit.

In this paper, we estimate the effects on the seismic hazard from extending the magnitude range in the SHM6 M-R relationships to $M > 4.0$ in both Eastern and Western Canada. In Eastern Canada, the seismic hazard may be increased up to 40% for very short periods at the 40% in 50-year probability of exceedance (POE) level. The effect is much smaller (~10-15%) at the 2% in 50-year POE hazard level. The seismic hazard in Western Canada, which has large contributions from larger magnitude subduction inslab and interface events, is much less affected by this modification.

Keywords: Magnitude-reoccurrence, minimum magnitude, probabilistic seismic hazard analysis.

INTRODUCTION

Canada's 6th generation seismic hazard model (SHM6), as prepared for the 2020 National Building Code of Canada, was released in 2020 [1]. The seismic hazard model consists of both Cornell-type area sources and discrete fault sources. Area sources are defined by their coordinates, depth, minimum and maximum magnitudes, and a magnitude-reoccurrence (M-R) relationship. Fault sources are defined in a similar manner except with a surface trace and depths/dip angles instead of an area and depth, respectively. Area sources are used to capture the seismicity of an area where the exact faulting is unknown or ill-defined, but earthquake events have been observed. Fault sources are modeled where a faulting location is known or can be well estimated.

M-R for each source is described in terms of an asymptotically truncated Gutenberg-Richter magnitude-frequency distribution following:

$$N(m) = N_o e^{-\beta m}[1 - e^{-\beta(M_{max}-m)}] \quad (1)$$

where $N(m)$ is the cumulative number of earthquakes greater than magnitude m; N_o is the total number of earthquakes per year; M_{max} is the maximum magnitude considered possible for the source; and β is a constant that describes the relative number of small-to-large earthquakes, where $\beta = b\ln(10)$, and b is the Gutenberg-Richter (1944) b-value [2].

Ground motion models (GMMs) are used to predict shaking intensity (median and standard deviations) at a site(s) of interest for different possible scenarios (magnitude, distance, site class, etc.). Models useable over the entire magnitude/distance range needed for seismic hazard map calculation were selected. Several GMMs were selected for each source type to account for the epistemic uncertainty in ground motion prediction. These GMMs are weighted and combined into a logic tree for each distinct seismic source type [3].

M-R Lower Limit: M_{min}

Probabilistic seismic hazard analysis (PSHA) involves integration over distributions of three random variables: 1) magnitude (M), 2) source-to-site distance, and 3) the (logarithmic) standard deviation of the GMMs (ε). For each of these variables, an upper and lower limit of integration must be defined. For magnitude, the upper limit: M_{max} is defined by the largest earthquake a seismic source is capable of generating; however, the lower limit: M_{min} is harder to define. When proposing the basic formulation for PSHA, Cornell (1968) clearly states that M_{min} is an engineering, not seismological, parameter: "…and m_0 [M_{min}] is some magnitude small enough, say 4, that events of lesser magnitudes may be ignored by engineers" [4].

M_{min} therefore should be selected so that the ultimate seismic ***risk*** of structures in not affected by lower magnitudes, even though they still may increase the seismic ***hazard***. For generating seismic hazard maps, M_{min} is typically taken as 4-5, as lower magnitudes are assumed to be unable to damage new buildings (e.g., do not increase the seismic risk). However, it is widely recognized that the inclusion of lower magnitude events in the PSHA may significantly increase the seismic hazard, particularly for short return periods and high frequencies [5].

The 2020 SHM6 considers crustal events with M ≥ 4.85 and distance ≤ 600 km in Eastern Canada (distance ≤ 400 km in Western Canada) to develop seismic hazard maps [1]. However, for lower levels of seismic hazard (e.g., 40% probability of exceedance in 50 years) there may be significant hazard contributions from events outside this range - particularly small magnitude events at close distances. While, typically not of concern for new buildings, such events may pose a realistic hazard to very low resistance structures, such as temporary structures, those designed without seismic considerations, or those under construction/retrofit [6].

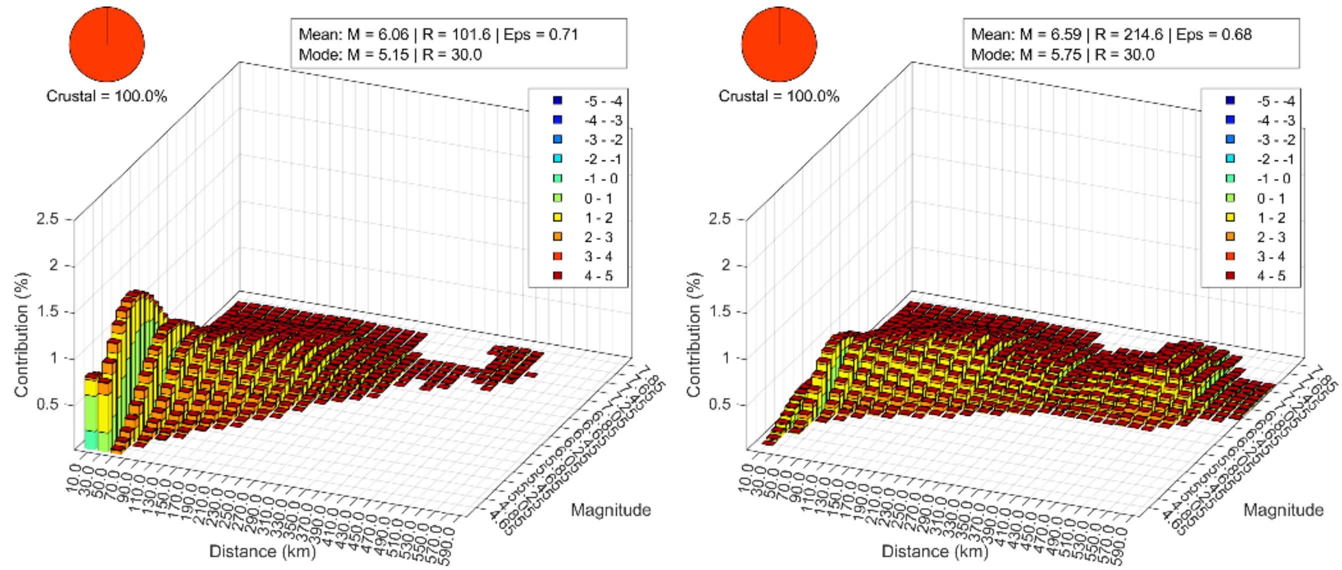
SEISMIC HAZARD IN EASTERN CANADA

The uniform hazard spectrum (UHS) for an example site in Eastern Canada (downtown Ottawa) was obtained from the SHM6 [1]. These values are summarized in Table 1 for a site with V_{S30} = 2000 m/s for different 50-year probabilities of exceedance (POE).

Seismic Hazard Disaggregation

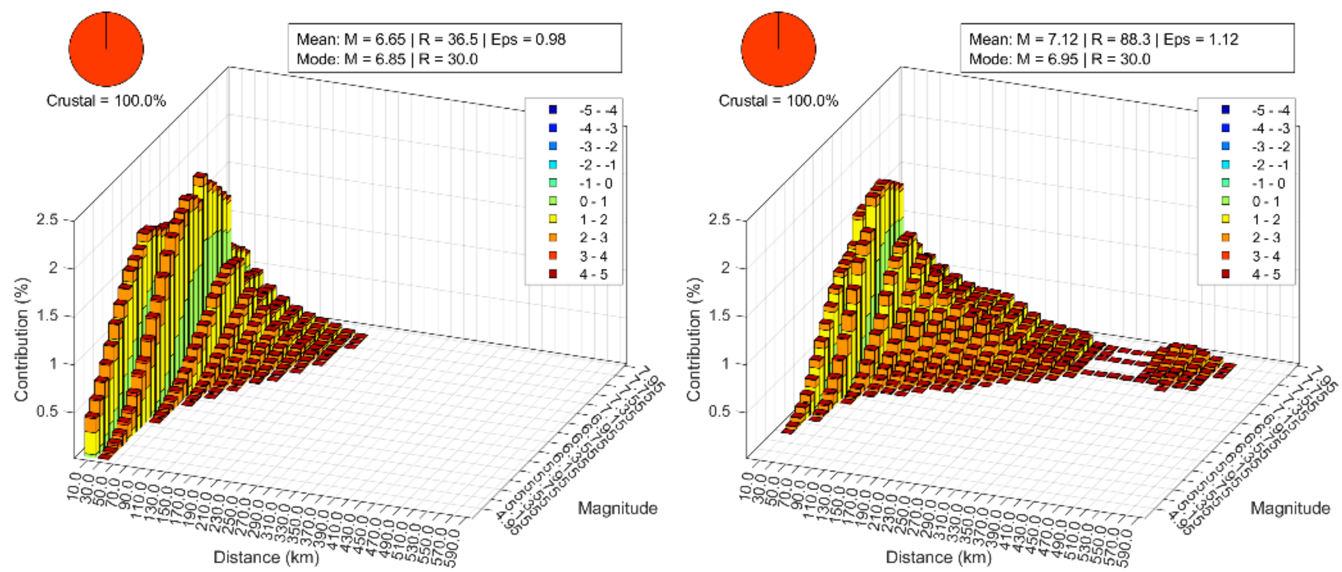
The seismic hazard at the site was disaggregated for several periods at different probabilities of exceedance in 50 years in order to determine the scenarios (magnitudes/distances) that contribute to the total seismic hazard. This is shown for periods of 0.2 and 2.0 s in Figure 1 for a 40% in 50-year POE, and Figure 2 for a 2% in 50-year POE.

From these plots it can be seen that the longer period (SA(2.0 s)) has more contribution from larger magnitude events at longer distances – while the SA(0.2 s) is dominated by small magnitude events at close distances. It can also be seen that there is a significant contribution to SA(0.2 s) from M = 4.85 events, which is the lowest magnitude defined in the M-R relationships for the sources used in the SHM6. Accordingly, if the M-R lower limit was decreased, there would be extra contribution to the SA(0.2 s) hazard from the lower magnitudes. This would not be as significant for SA(2.0 s), as the contributions to this hazard drop to ~0 at magnitudes < 4.85. The 2% in 50-year POE has more contribution from rarer, larger magnitude, events – thus, is less affected by very small magnitude events compared to the 40% in 50-year hazard.



(a) *(b)*

Figure 1: Seismic hazard disaggregation for Ottawa for a 40%/50 year POE obtained from the SHM6 for: a) SA(0.2 s), and b) SA(2.0 s).



(a) *(b)*

Figure 2: Seismic hazard disaggregation for Ottawa for a 2%/50 year POE obtained from the SHM6 for: a) SA(0.2 s), and b) SA(2.0 s).

Sensitivity to the M-R Lower Limit

For the "stable" crust of Eastern, Central and Arctic Canada, the 6th Generation model equally weights a) the AA13 GMMs used for the 5th Generation model [7], and b) the 13 NGA-East GMMs [3, 8]. The AA13 GMMs are not valid for magnitudes less than 4.5 – therefore, for the first case, the model was rerun with a M-R lower limit of 4.5. This was done by computing the slope (in linear-log space) of the M-R relationship and extrapolating it to M = 4.5. An example of this extrapolation process (to a M_{min} of 4.05) is shown in Figure 3. This model (SHM6_450) was used to generate UHS and ratios as summarized in Table 1.

Table 1 shows an increase in the seismic hazard by extending the M-R lower limit. The increase is larger for higher POEs and at shorter periods. Sample disaggregation results for this model are presented in Figure 4 and Figure 5. From the disaggregation results it can be seen that a large contribution of the hazard is still coming from M_{min} = 4.5, particularly for the short periods. This indicates that the magnitude range that significantly contributes to the hazard is still not fully captured, and that additional reductions in M_{min} will further increase the seismic hazard.

To further investigate a lower M-R limit, the model was modified again to only include NGA-East GMMs (with their respective weights doubled to account for discarding the AA13 GMMs), which are valid for magnitudes 4.0-8.2 and distances up to 1500 km. First, this modified model with a M-R lower limit of 4.85 (SHM6_NGAe485) was used to generate UHS as summarized in Table 2.

Next, the M-R relationship of the NGA-East GMM-only model was extended, for each source, to a lower limit of 4.05 (lower limit of the GMMs). An example of this extrapolation process is shown in Figure 3.

Although the Gutenberg-Richter M-R relationship may terminate at very low magnitudes [9], the magnitude at which this occurs would be much lower than magnitude 4 in Eastern Canada [10, 11]. Thus, this extrapolation is appropriate for this magnitude range (i.e., the Gutenberg-Richter relationship is valid for M > 4).

This model (SHM6_NGAe405) was used to generate UHS as summarized in Table 2. The ratio of SHM6_NGAe405/SHM6_NGAe485 was used to estimate the effect of lowering M_{min} from 4.85 to 4.05 for the SHM6 (with the unmodified GMM logic tree). As expected, the ratio is the largest for the shorter periods (as discussed previously) and lower for higher hazard levels (where such low magnitude events cannot generate large enough shaking levels to significantly affect the higher hazard). These ratios are slightly larger compared to the SHM6_450/SHM6 ratios from Table 1. Sample disaggregation plots for the SHM6_NGAe405 model are presented in Figure 6 and Figure 7.

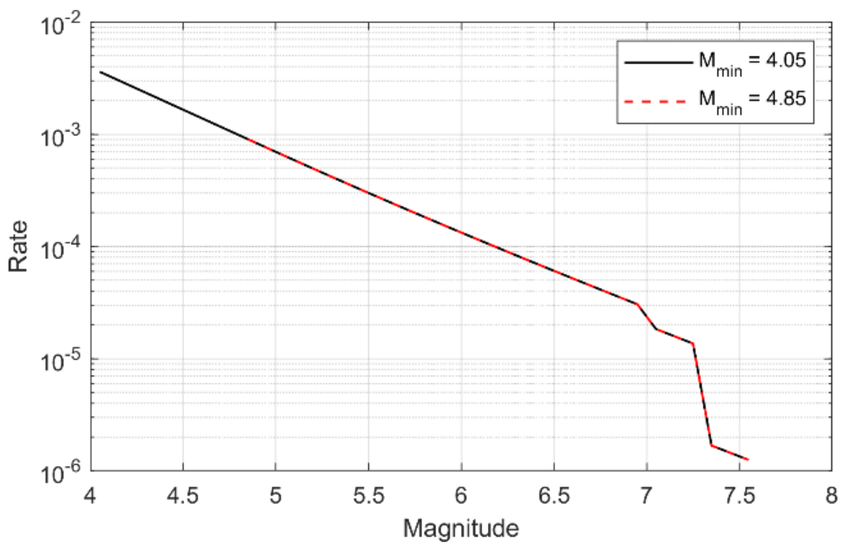
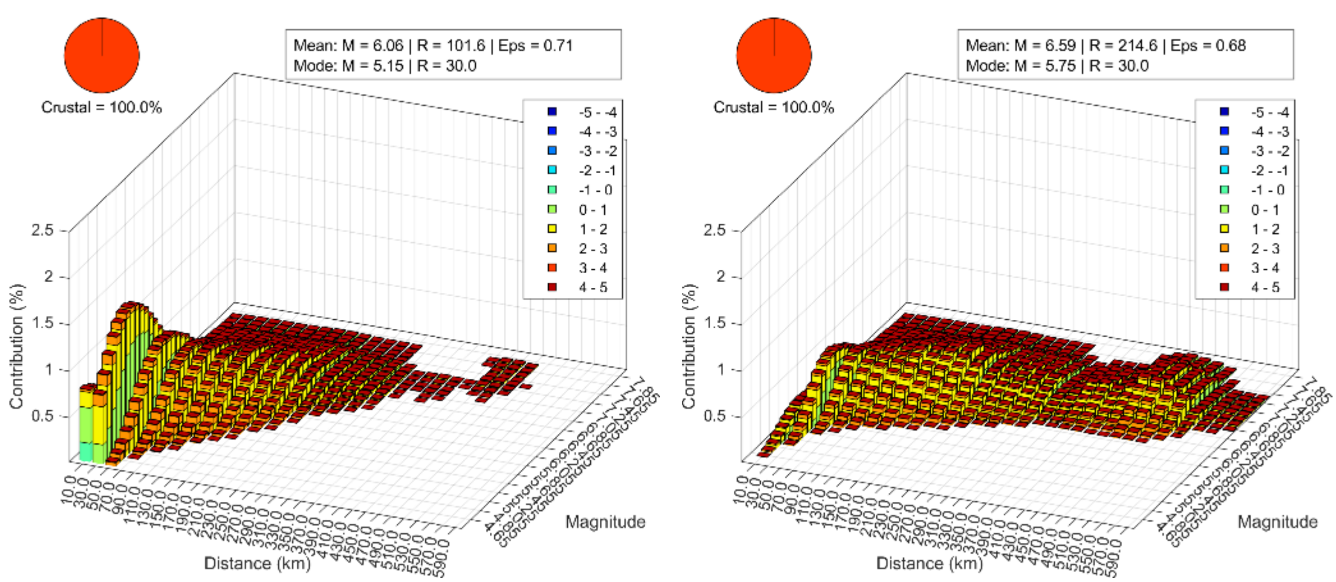


Figure 3: Example M-R extrapolation from M_{min} = 4.85 to M_{min} = 4.05.

Figure 1 presented the 40% in 50 year SA(0.2 s) disaggregation from the unmodified SHM6. Corresponding figures for SHM6_450 (with M_{min} = 4.5) and SHM6_NGAe405 (SHM6 with NGA-East GMMs and M_{min} = 4.05) are presented in Figure 4 and Figure 6, respectively. Comparing these figures clearly shows the additional contributions as M_{min} is progressively reduced, resulting in the hazard increases. Even with M_{min} = 4.05, it can be seen in Figure 6 that the complete contributing magnitude range is still not fully captured – however, the GMMs are not applicable for smaller magnitudes, and it is unlikely that events smaller than magnitude 4.05 would be of concern to even very low resistance structures [6].

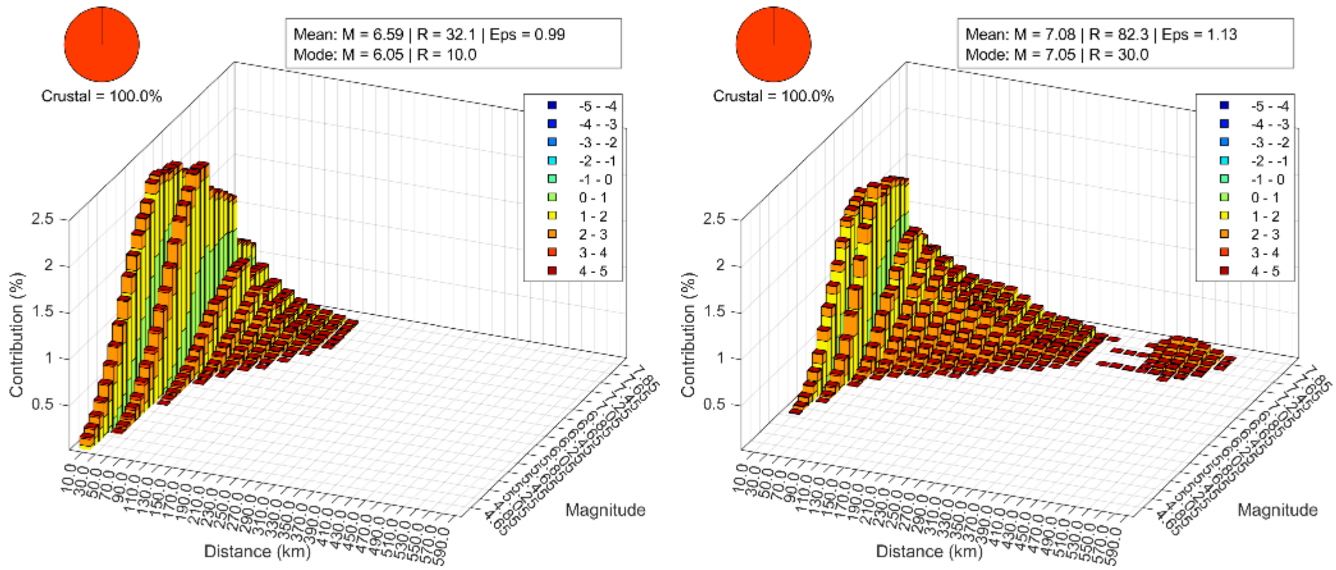
Table 1: UHS and ratios for Ottawa from the SHM6 with the two M_{min}.

POE	SA(0.1)	SA(0.2)	SA(0.3)	SA(0.5)	SA(1.0)	SA(2.0)	SA(5.0)	SA(10.0)	PGA
					SHM6				
2	0.5750	0.3630	0.2670	0.1840	0.0960	0.0453	0.0127	0.0048	0.3190
5	0.3210	0.2060	0.1520	0.1050	0.0535	0.0246	0.0066	0.0025	0.1760
10	0.1970	0.1290	0.0953	0.0657	0.0329	0.0147	0.0037	0.0015	0.1070
20	0.1140	0.0762	0.0566	0.0388	0.0190	0.0082	0.0019	0.0007	0.0610
40	0.0582	0.0401	0.0300	0.0203	0.0095	0.0039	0.0008	0.0003	0.0307
					SHM6_450				
2	0.6517	0.4045	0.2939	0.2004	0.1028	0.0477	0.0131	0.0049	0.3678
5	0.3726	0.2335	0.1695	0.1152	0.0579	0.0262	0.0069	0.0026	0.2089
10	0.2334	0.1482	0.1076	0.0730	0.0360	0.0159	0.0040	0.0015	0.1296
20	0.1376	0.0890	0.0647	0.0436	0.0210	0.0090	0.0021	0.0008	0.0753
40	0.0721	0.0478	0.0350	0.0232	0.0108	0.0044	0.0009	0.0004	0.0388
					Ratio				
2	1.13	1.11	1.10	1.09	1.07	1.05	1.03	1.02	1.15
5	1.16	1.13	1.11	1.10	1.08	1.07	1.05	1.03	1.19
10	1.18	1.15	1.13	1.11	1.09	1.08	1.07	1.05	1.21
20	1.21	1.17	1.14	1.12	1.11	1.10	1.10	1.08	1.23
40	1.24	1.19	1.17	1.14	1.13	1.14	1.14	1.14	1.26



(a) *(b)*

Figure 4: Seismic hazard disaggregation for Ottawa for a 40%/50 year POE obtained from the SHM6_450 for: a) SA(0.2 s), and b) SA(2.0 s).

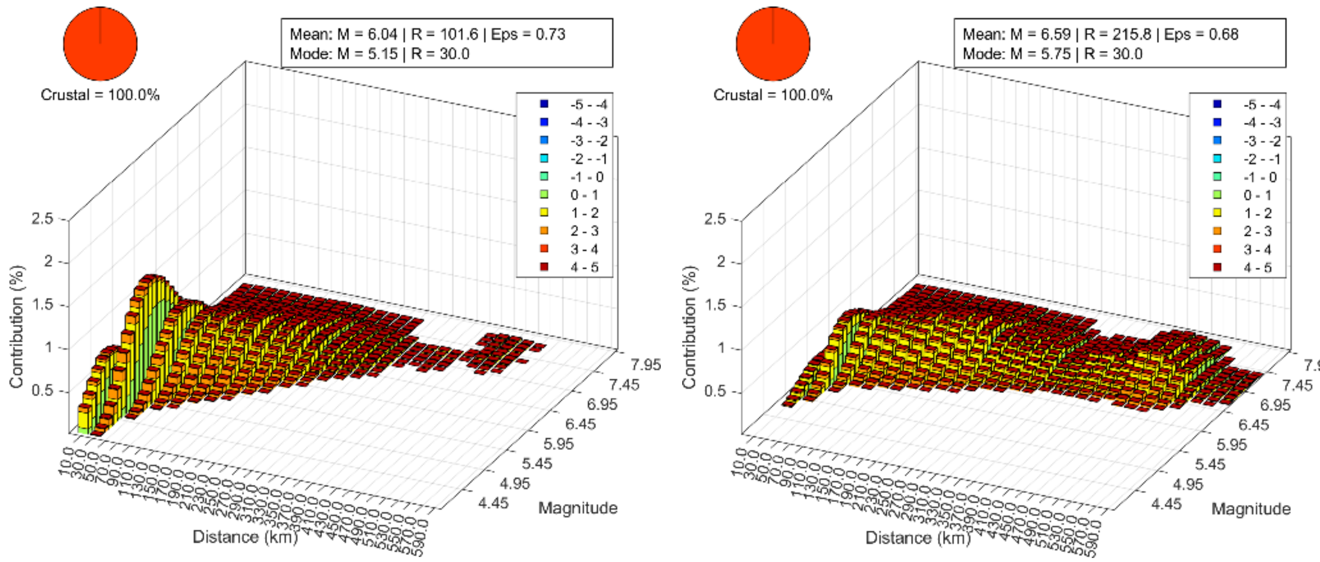


(a) *(b)*

Figure 5: Seismic hazard disaggregation for Ottawa for a 2%/50 year POE obtained from the SHM6_450 for: a) SA(0.2 s), and b) SA(2.0 s).

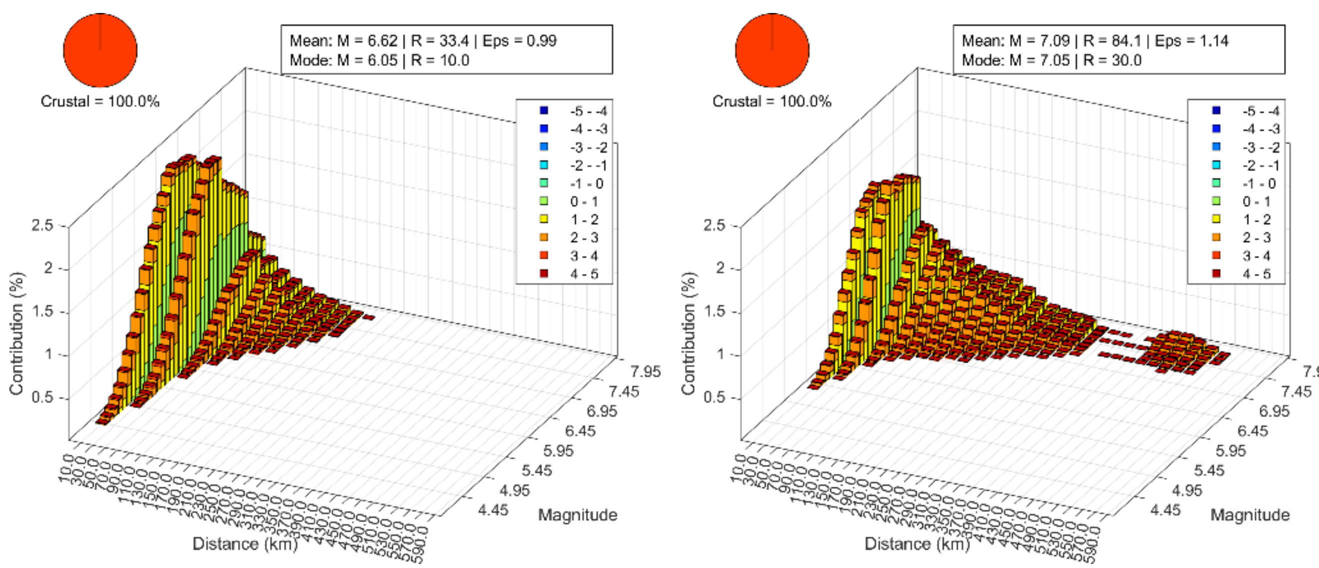
Table 2: UHS and ratios for Ottawa from the modified (NGA-East GMMs) SHM6 with the two M_{min}.

POE	SA(0.1)	SA(0.2)	SA(0.3)	SA(0.5)	SA(1.0)	SA(2.0)	SA(5.0)	SA(10.0)	PGA
SHM6_NGAe485									
2	0.7152	0.4390	0.3325	0.2319	0.1234	0.0579	0.0163	0.0061	0.3824
5	0.3983	0.2491	0.1903	0.1341	0.0696	0.0317	0.0085	0.0031	0.2051
10	0.2428	0.1548	0.1195	0.0848	0.0428	0.0189	0.0048	0.0017	0.1211
20	0.1383	0.0902	0.0705	0.0502	0.0244	0.0102	0.0024	0.0008	0.0667
40	0.0694	0.0465	0.0367	0.0260	0.0119	0.0046	0.0010	0.0003	0.0321
SHM6_NGAe405									
2	0.8043	0.4841	0.3633	0.2514	0.1315	0.0605	0.0167	0.0062	0.4432
5	0.4577	0.2782	0.2102	0.1462	0.0748	0.0335	0.0089	0.0032	0.2488
10	0.2868	0.1757	0.1335	0.0933	0.0466	0.0202	0.0051	0.0018	0.1540
20	0.1699	0.1048	0.0800	0.0561	0.0270	0.0112	0.0027	0.0009	0.0897
40	0.0898	0.0561	0.0429	0.0298	0.0135	0.0053	0.0012	0.0004	0.0464
Ratio									
2	1.12	1.10	1.09	1.08	1.07	1.04	1.03	1.02	1.16
5	1.15	1.12	1.10	1.09	1.07	1.06	1.04	1.03	1.21
10	1.18	1.13	1.12	1.10	1.09	1.07	1.06	1.05	1.27
20	1.23	1.16	1.13	1.12	1.10	1.10	1.10	1.09	1.35
40	1.30	1.21	1.17	1.14	1.13	1.14	1.15	1.15	1.45



(a) *(b)*

Figure 6: Seismic hazard disaggregation for Ottawa for a 40%/50 year POE obtained from the SHM6_NGAe405 for: a) SA(0.2 s), and b) SA(2.0 s).



(a) *(b)*

Figure 7: Seismic hazard disaggregation for Ottawa for a 2%/50 year POE obtained from the SHM6_NGAe405 for: a) SA(0.2 s), and b) SA(2.0 s).

To account for the effect of lower magnitude events (M = 4.05-4.8) on the seismic hazard at the site of interest, the UHS generated by the SHM6 was factored by the period- and POE-dependent ratios from Table 2. Although these ratios were generated by a modified version of the model (which only used the NGA-East GMMs), the original model also showed an increase in the hazard by lowering the M-R lower limit – however, due to limits in the GMMs it used, could not be used to include contributions below magnitude 4.5. The resulting UHS (SHM6_405) are presented in Table 3. An example adjustment for POE = 40% in 50 years is illustrated in Figure 8.

Table 3: UHS for Ottawa (modified for lower M_{min}) for different return periods.

POE	SA(0.1)	SA(0.2)	SA(0.3)	SA(0.5)	SA(1.0)	SA(2.0)	SA(5.0)	SA(10.0)	PGA
2	0.6467	0.4003	0.2917	0.1994	0.1023	0.0473	0.0130	0.0049	0.3697
5	0.3688	0.2301	0.1679	0.1144	0.0575	0.0260	0.0068	0.0026	0.2135
10	0.2327	0.1464	0.1065	0.0722	0.0358	0.0158	0.0040	0.0015	0.1361
20	0.1400	0.0885	0.0642	0.0434	0.0210	0.0090	0.0021	0.0008	0.0821
40	0.0754	0.0484	0.0350	0.0232	0.0108	0.0044	0.0009	0.0004	0.0444

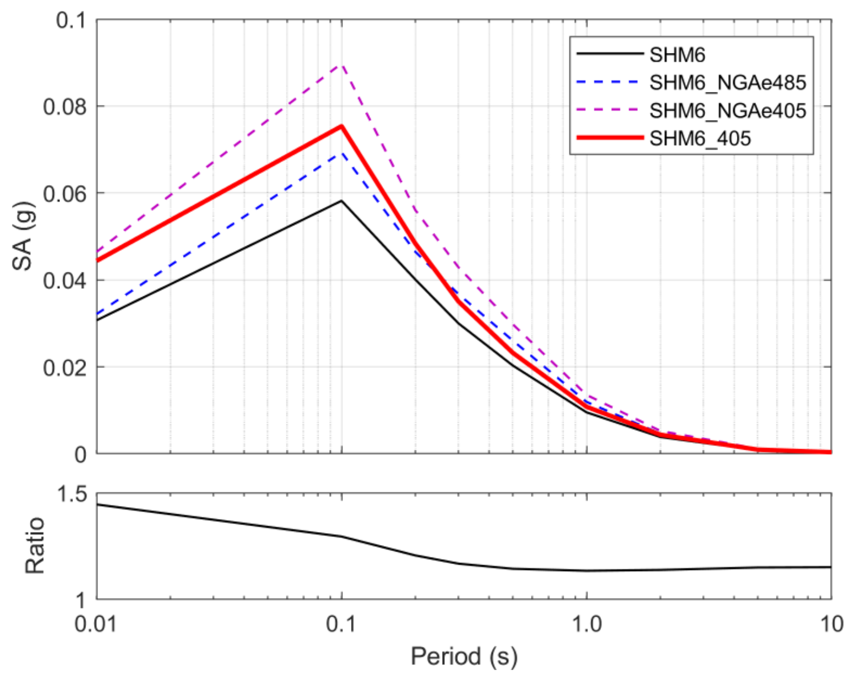


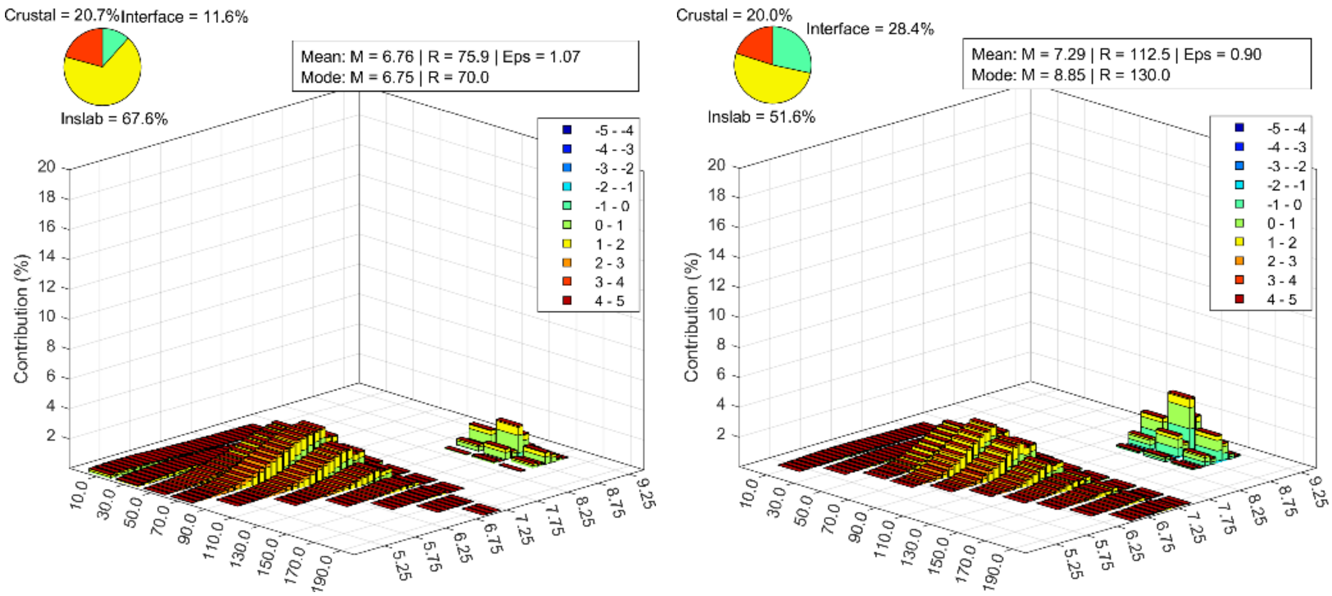
Figure 8: 40%/50-year UHS and ratio for the different seismic hazard model iterations.

M-R LOWER LIMIT IN WESTERN CANADA

For Western Canada, the UHS were obtained from the SHM6 for downtown Vancouver and Victoria for a V_{S30} = 450 m/s site, as summarized in Table 4 and Table 5. The seismic hazard for Vancouver was disaggregated for several periods at different POEs in 50 years in order to determine the scenarios (magnitudes/distances) that contribute to the total seismic hazard. Sample figures are shown for periods of 0.2 and 2.0 s in Figure 9 for a 40% in 50-year POE, and Figure 10 for a 2% in 50-year POE.

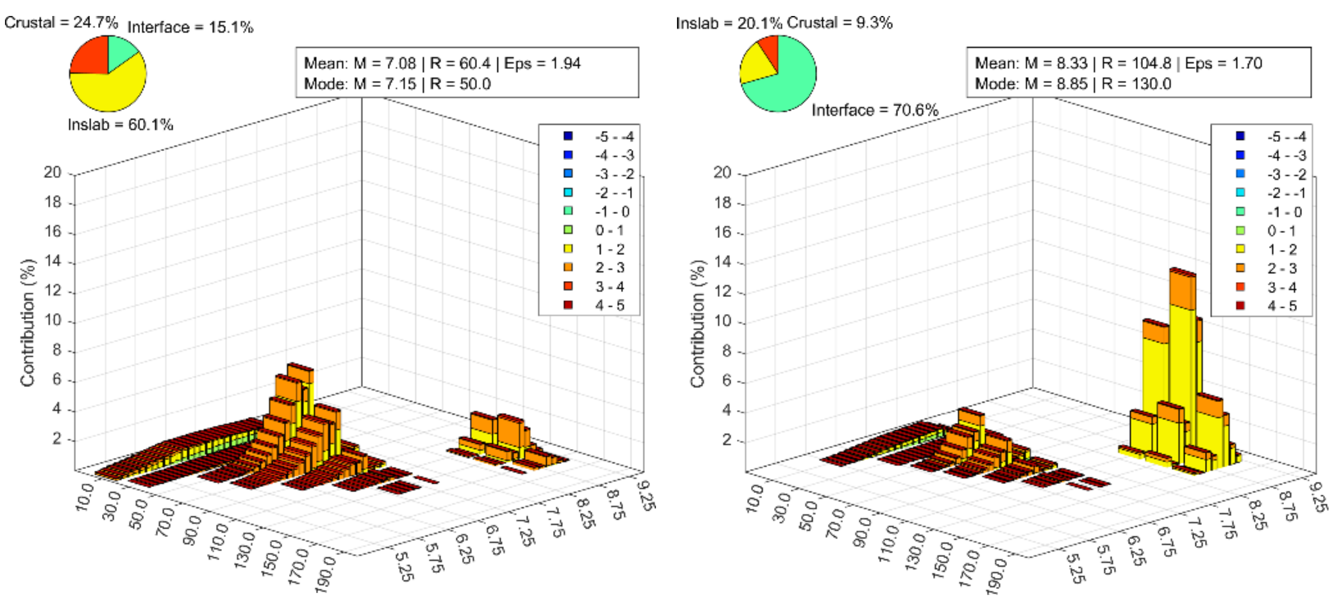
Next, the SHM6 was modified by reducing the magnitude lower limit to 4.05 for all crustal sources. The inslab and interface sources were not modified. The resulting UHS from this model (SHM6_405) are presented in Table 4 and Table 5, for Vancouver and Victoria, respectively. As seen in Table 4, the seismic hazard for Vancouver – which is governed by larger magnitude subduction inslab and interface sources – is not significantly affected by the magnitude lower limit used in the crustal source models. Additionally, the contributions at M_{min} = 4.85 approach 0 at all periods and POEs (see: Figure 9 and Figure 10), suggesting that including lower magnitude events will not significantly affect even the source-specific crustal earthquake hazard (if the subduction source hazard contributions were removed).

Victoria has more hazard contribution from the nearby Leech River fault source [12] (however, also has more hazard contribution from the subduction interface source), and thus is slightly more affected by the lower M_{min} – but still, not more than a 4% increase in hazard was observed at any period.



(a) *(b)*

Figure 9: Seismic hazard disaggregation for Vancouver for a 40%/50 year POE obtained from the SHM6 for: a) SA(0.2 s), and b) SA(2.0 s).



(a) *(b)*

Figure 10: Seismic hazard disaggregation for Vancouver for a 2%/50 year POE obtained from the SHM6 for: a) SA(0.2 s), and b) SA(2.0 s).

CONCLUSIONS

It was shown that the seismic hazard in Eastern Canada, particularly for low hazard levels (high POEs) and short periods, can be significantly increased by events with magnitudes lower than the range considered in the 2020 6^{th} generation SHM6 (magnitudes ≥ 4.85). These low magnitude events may be able to induce structural damage to very low resistance structures. Accordingly, for the seismic hazard assessment such structures, it may be important to consider the effect of these low magnitude events on the seismic hazard [6].

To account for these low magnitude events, the SHM6 was modified and run using the 13 NGA-East GMMs (which are valid from magnitudes 4-8.2) with M-R lower limits of 4.85 (reference) and 4.05 (lower limit of the NGA-East GMMs). The UHS ratio between these two iterations is recommended to adjust SHM6 UHS to account for the influence of magnitude 4.05-4.8 events on the seismic hazard. This will increase the seismic hazard anywhere from 45% (40% in 50-year POE for PGA) to ~0% (2-5% in 50-year POE for periods > 2.0 s).

In Western Canada, the seismic hazard at all return periods analyzed (from 2-40% in 50 years POE) was not sensitive to lowering the M-R lower limit from 4.85 to 4.05 for the crustal seismic sources. This is because the hazard in Western Canada is governed by larger magnitude subduction inslab and interface earthquakes. Thus, there is no need to modify SHM6 results for Western Canada to account for the effect of lower magnitude earthquakes.

Table 4: UHS and ratios for Vancouver from the SHM6 with the two M_{min}.

POE	SA(0.1)	SA(0.2)	SA(0.3)	SA(0.5)	SA(1.0)	SA(2.0)	SA(5.0)	SA(10.0)	PGA
					SHM6				
2	0.9717	1.0773	1.0327	0.7722	0.4414	0.2724	0.0743	0.0315	0.4596
5	0.6711	0.7500	0.7127	0.5302	0.2947	0.1674	0.0412	0.0159	0.3223
10	0.4837	0.5457	0.5163	0.3784	0.2045	0.1064	0.0252	0.0096	0.2347
20	0.3276	0.3726	0.3486	0.2520	0.1307	0.0621	0.0145	0.0054	0.1607
40	0.1945	0.2263	0.2093	0.1472	0.0734	0.0328	0.0075	0.0026	0.0970
					SHM6_405				
2	0.9739	1.0786	1.0331	0.7722	0.4415	0.2724	0.0743	0.0315	0.4604
5	0.6733	0.7515	0.7132	0.5303	0.2947	0.1675	0.0412	0.0159	0.3232
10	0.4862	0.5472	0.5168	0.3785	0.2045	0.1064	0.0252	0.0096	0.2356
20	0.3304	0.3744	0.3493	0.2522	0.1307	0.0621	0.0145	0.0054	0.1617
40	0.1974	0.2282	0.2104	0.1475	0.0735	0.0328	0.0075	0.0026	0.0980
					Ratio				
2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
10	1.01	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
20	1.01	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.01
40	1.02	1.01	1.01	1.00	1.00	1.00	1.00	1.00	1.01

Table 5: UHS and ratios for Victoria from the SHM6 with the two M_{min}.

POE	SA(0.1)	SA(0.2)	SA(0.3)	SA(0.5)	SA(1.0)	SA(2.0)	SA(5.0)	SA(10.0)	PGA
					SHM6				
2	1.6364	1.9073	1.9119	1.4866	0.8472	0.4997	0.1233	0.0466	0.7953
5	1.1656	1.3493	1.3231	1.0130	0.5577	0.3044	0.0696	0.0237	0.5705
10	0.8632	0.9952	0.9533	0.7103	0.3778	0.1890	0.0411	0.0140	0.4254
20	0.6001	0.6865	0.6440	0.4612	0.2320	0.1049	0.0219	0.0075	0.2961
40	0.3684	0.4225	0.3826	0.2635	0.1244	0.0516	0.0106	0.0035	0.1824
					SHM6_405				
2	1.6496	1.9202	1.9190	1.4892	0.8473	0.4991	0.1231	0.0466	0.8005
5	1.1799	1.3632	1.3327	1.0180	0.5595	0.3042	0.0695	0.0237	0.5763
10	0.8772	1.0103	0.9645	0.7168	0.3806	0.1894	0.0411	0.0140	0.4313
20	0.6147	0.6999	0.6539	0.4677	0.2348	0.1058	0.0220	0.0075	0.3024
40	0.3822	0.4339	0.3917	0.2683	0.1264	0.0523	0.0107	0.0035	0.1882
					Ratio				
2	1.01	1.01	1.00	1.00	1.00	1.00	1.00	1.00	1.01
5	1.01	1.01	1.01	1.01	1.00	1.00	1.00	1.00	1.01
10	1.02	1.02	1.01	1.01	1.01	1.00	1.00	1.00	1.01
20	1.02	1.02	1.02	1.01	1.01	1.01	1.01	1.00	1.02
40	1.04	1.03	1.02	1.02	1.02	1.01	1.01	1.01	1.03

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