Canadian Conference - Pacific Conference on Earthquake Engineering 2023
Vancouver, British Columbia
June 25th – June 30th, 2023

Influence of the 2020 National Seismic Hazard Model Changes on the Residential Risk; Case Study in Greater Montreal

Rosset Philippe[1*], Long Xuejiao[2], and Chouinard Luc[3]

[1] Associate Researcher, Department of Civil Engineering, McGill University, Montreal, Canada
[2] Former Master student, Department of Civil Engineering, McGill University, Montreal, Canada
[3] Professor, Department of Civil Engineering, McGill University, Montreal, Canada
[*] philippe.rosset@affiliate.mcgill.ca (Corresponding Author)

ABSTRACT

This study highlights the impact on expected losses for residential buildings in the Greater Montreal area induced by changes in seismic hazard estimates in the updated 2020 Canadian seismic hazard model. Loss estimates for the residential building stock correspond to 1.9% of the total property values based on 2015 hazards for a probability level of 2% in 50 years. The 2020 hazards for the same probability level are significantly higher (+18% for PGA and +39% in average for other spectral periods for soil type C). The scale of the exposure model used in this comparative study is the census dissemination areas (6100 in total). It concerns residential building counted and classified as a function of building type, year of construction and occupancy. Property values are based on the 2018 property assessment roles and the content value is derived from the CatIQ database. Calculations are performed using FEMA's Hazus software, which provides capacity and fragility curves to estimate the probability of damage states, and estimates of structural and non-structural repair costs for each damage state and the associated building content losses. The comparison shows a 50% increase on total residential building loss between the 2015 to the 2020 hazard models, or an increase from 1.9 to 3.0% of the total value of building stock.

Keywords: risk analysis, residential buildings, Greater Montreal, seismic hazard, building code

INTRODUCTION

The seismic hazard is essential to perform risk analysis and is often calculated using the classical probabilistic seismic hazard approach (PSHA) at global or national scales [1]. In many countries, the estimate of the level of ground motion one could expect in a given site for a certain probability of occurrence follows this approach and new seismic related data and research help to update it. In Canada, this work has been released five times since the first probabilistic map presented in 1970 as the basis for seismic design in the National Building Code of Canada (NBCC). Since 2005, the seismic hazard model (SHM) is updated every five years with new considerations on seismic sources, ground motion attenuation relationships, site conditions. In 2020, the 6th generation of the SHM has been released after the 2015 model (SHM5) by incorporating a multiple-ground-motion model (GMM) logic tree approach and sampling sigma model (standard deviation around the mean) published within each GMMs [2]. SHM6 also proposes site amplification functions embedded within each GMM (or added if not inherently included) to calculate the ground shaking directly for a range of site conditions rather than provision of hazard values on a reference class C site and then applying amplification factors F(T) [2]. Finally, SHM6 has an improved understanding for median ground motion models, aleatory uncertainty and site term leading to distinct changes in hazard values compared to SHM5. In general SHM6 increases the hazard compared to SHM5 and for instance, in Eastern Canada, it increases the value of Sa(0.2s) of 70 % and Sa(2.0s) of 45% due to changes in the GMMs and site term [2].

The multi-hazard and risk tool, Hazus MH has been regularly released since 1997 [3] and has been applied for seismic loss estimation at various spatial scales in the USA. Thus, Tantala et al. [4] for the New York City Metropolitan region, Field et al. [5] for scenario earthquake in Los Angeles, Moffatt and Cova [6] for the Salt Lake County, Utah, and Chen et al. [7] analyzing the sensitivity of seismic losses in California due to soil amplification. It has been also used in many regions around the world as Bendito et al. [8] who evaluated the influence of two potential large earthquakes in Mérida State in Venezuela. Similarly, Levi et al. [9] performed seismic loss estimate for Israel and Ansal et al. [10] in Turkey. Damage assessments for individual buildings were obtained in Northern Israel [11] and in Iran [12]. In Canada, a version HazCan [13], has been applied for risk assessment and loss estimation in urban areas first by Ploeger et al. [14] in Ottawa.

In the region of Montreal, Yu et al. [15] investigated damage and human losses for a set of 38 earthquakes scenarios based on the deaggregation of the seismic hazard (for an exceedance probability of 2% in 50 years) and for three different Ground Motion Prediction Equations (GMPEs) developed for Eastern North America. In 2018, Rosset et al. [16] completed the analysis considering an updated residential building inventory for Montreal and six earthquake scenarios including the repetition of the M5.8 1732 Montreal earthquake hypothetically centered in Montreal. The deterministic analysis has been extended to other municipalities in Greater Montreal for the latter scenario [17] and for the other ones. Furthermore, the annualized earthquake loss from residential building damage has been calculated in Greater Montreal, which is the estimated long-term value of earthquake losses for the building stock in a given year, considering the SHM5 (2015) for return periods from 100 to 2,500 years [18].

This paper estimates the changes in residential losses when using SHM6 instead of SHM5 for a return period of 2745 years in Greater Montreal. The changes between the two seismic models are first discussed and the input data including residential building inventory, exposure, and site conditions presented. The results of the seismic losses calculated using HAZUS is presented in the Greater Montreal region.

METHOD

The SHM6 versus SHM5

In Canada, the Geological Survey of Canada (GSC) is in charge for assessing regional seismic hazard for the National Building Code (NBC). Seismic zones are mapped by the GCS based on statistical analysis of past earthquakes and knowledge of the tectonic and geological structures in Canada. On the maps, earthquake hazard is represented as the strongest ground motion that is likely to occur in an area with a given probability. The contours delineate the areas where shaking is expected to be of equal intensity. This work has been repeated 6 times, every 5 years since 2005 and for longer periods before that. Kolaj et al. [19] describe the 6th generation seismic hazard model for Canada. There are two major changes at SHM6. The first one is the adoption of new Ground Motion Models (GMMs) included in a logic tree. Compared to SHM5, which used the same aleatory model for GMMs in all regions, SHM6 used aleatory model for each GMM to better consider the epistemic variability. The second change is the selection of the site amplification model. SHM6 proposes a new approach that account for the site conditions as a function of continuous Vs30 values instead of discretized Vs30 per site classes. This new approach avoids the discrete jump from one site class to another as in the SHM5 model.

The graph in Figure 1 shows the spectral acceleration values for different periods calculated for the center of Montreal (City Hall site) and a Class C site by the 2005, 2010, 2015 and 2020 seismic hazard models for a return period of 2475 years. One can note the progressive increase of acceleration values for periods greater than 0.2s (which correspond to periods of vibration of buildings of two floors and more) except for the 2015 model, which has the lowest values below 0.5s. For periods below 0.2s, this progressiveness is no longer observed. The 2020 model provides the highest acceleration values for all periods.

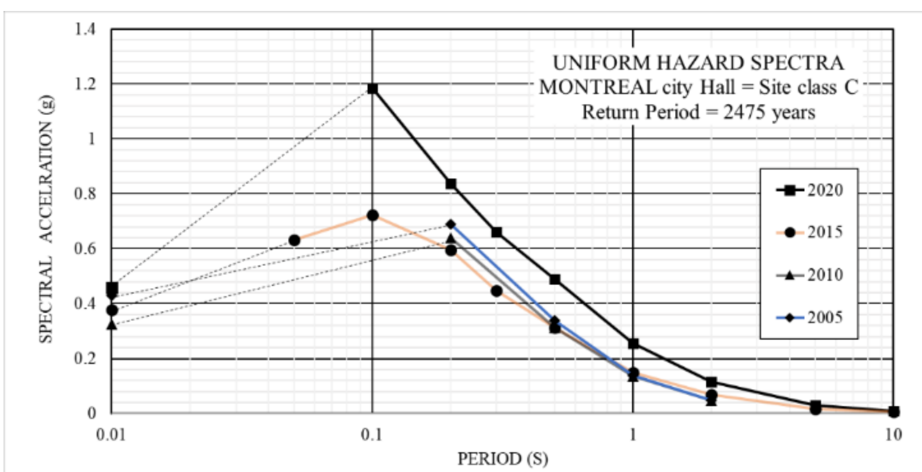


Figure 1. Uniform hazard spectra from the 2005, 2010, 2015 and 2020 seismic hazard models. The spectra presented are for a return period of 2475 years, for a class C site located in the center of Montreal (city hall).

Value of PGA for a type C soil increases by 18% between the 2015 and 2020 seismic hazard models regardless of the calculated return periods. This increase is around 29% for Sa(0.2s) values and around 42% for Sa(1.0s) values. The differences between the 2015 and 2020 values are primarily due to the use of a new attenuation law model for eastern Canada [20].

Input Data in Hazus

The tool Hazus developed by FEMA [3] is used to calculate the residential building loss. Buildings inventory uses the property assessment role (as in 2018) that provides with data on the geographical location, the built year, the number of floors and dwelling as well as the tax value of individual buildings. These primary information are interpreted to define each building in terms of construction and occupancy types (following the Hazus taxonomy) and level of design code. The table 1 lists the number of buildings by construction types counted in Montreal and in municipalities outside Montreal [17]. The building count by construction type is then aggregated at the level of the census dissemination areas. In terms of occupancy types, single-family houses (RES1) represent 74.3 % of the total (56.1% in Montreal and 86.4% outside Montreal) as the multiplex with two (RES3A), 3-4 (RES3B) and 5-11 (RES3C) dwellings count for 13.1%, 6.6% and 4.1%, respectively. The remaining percentages are distributed into multiplex with more than 11 dwellings (RES3D-F) and mobile houses.

Table 1. Distribution of buildings by construction types for Montreal and municipalities outside Montreal (From Rosset et al., 2022).

Building types	**Structural frame**	**Number of buildings (percentage)**		**Total**	**Total (%)**
		In Montreal	Outside Montreal		
W	Wood	295,602 (84.6)	501,363 (96.0)	796,965	91.4
C	Concrete	448 (0.1)	14,051 (2.7)	14,499	1.7
URM	Unreinforced masonry	47,562 (13.6)	2,023 (0.4)	49,585	5.7
S	Steel	5,743 (1.6)	-	5,743	0.7
MH	Mobile home	3	4,879 (0.9)	4,882	0.6
	Total	349,358	522,316	871,674	100

The building types are split into three levels of design code (pre, low and moderate codes) corresponding to three periods of construction related to the editions of the NBCC, namely before 1970, 1970-1990 and after 1990, where the year 1990 marks the introduction of new seismic requirements in several design standards. Wood frame houses (W1) are distributed equally between the code levels as steel and unreinforced masonry buildings mainly belong to pre-code. Concrete frame buildings are 18%, 44% and 38% in pre-, low- and moderate code, respectively. For mobile houses, the distribution is estimated around 11%, 69% and 20%.

The property roll provides the property value assigned to the buildings included in the assessment unit. In practice, all buildings in the database have an assessed value by roll and it is this assessment that is used directly to document total property values by dissemination area and occupancy type. An analysis of the data showed that the calculated total value from the roll differs by less than 1% from that calculated using the total floor area, and by 10% from that calculated using the number of buildings and the median value by area. The total building value of the residential built-up area is estimated to be around Can$196.5 billion. Hazus considers by default that the value of the contents of the buildings is on average 50% of its property value. The ICLR (Institute for Catastrophic Loss Reduction) provided us with the relevant information for Quebec available in the CatIQ database. The information concerns the ratio of the content value of residential buildings to their property value for the years 2016 to 2019 by forward sortation areas. The data within Greater Montreal boundaries provide an average ratio for 2018 (the year of the property roll data) of 54 ± 7%. The value of the building content is estimated at Can$99 billion for a total building value of Can$196.5 billion, which gives a total residential portfolio of Can$295.5 billion. Single-family houses represent more than 65% of this total, with duplexes and triplexes accounting for 13.7 and 8.4%, respectively. The mean value for the 6,116 DAs is about Can$48 million with a standard deviation of the same order of magnitude. The first quartile is 29 million and the third quartile is 51 million.

The compiled data are adapted to the format required in Hazus in order to apply the seismic hazard in terms of PGA, Sa(0.3s) and Sa(1.0s) calculated for the CMM using both SHM5 and SHM6 and taking into account the site condition model described in Rosset et al. [18] and shown in Figure 2. The map was derived from a combination of seismic measurements, borehole profiles and geological data and used in seismic hazard models. It characterizes soil conditions in terms of average shear wave velocity for the first 30 m of soil (V_{s30}). NBCC2015 uses the NEHRP classification system to classify site conditions into five classes (A to E as shown in the legend of Figure 2), each class corresponding to a range of V_{s30} values. Most of the regions in central Montreal Island, Laval and Longueil are in class B. The northeastern part is mainly in classes D and E, which is related to a thickness of soft soil (mainly clay) with a thickness up to 50m. These soils may amplify seismic waves at certain frequencies.

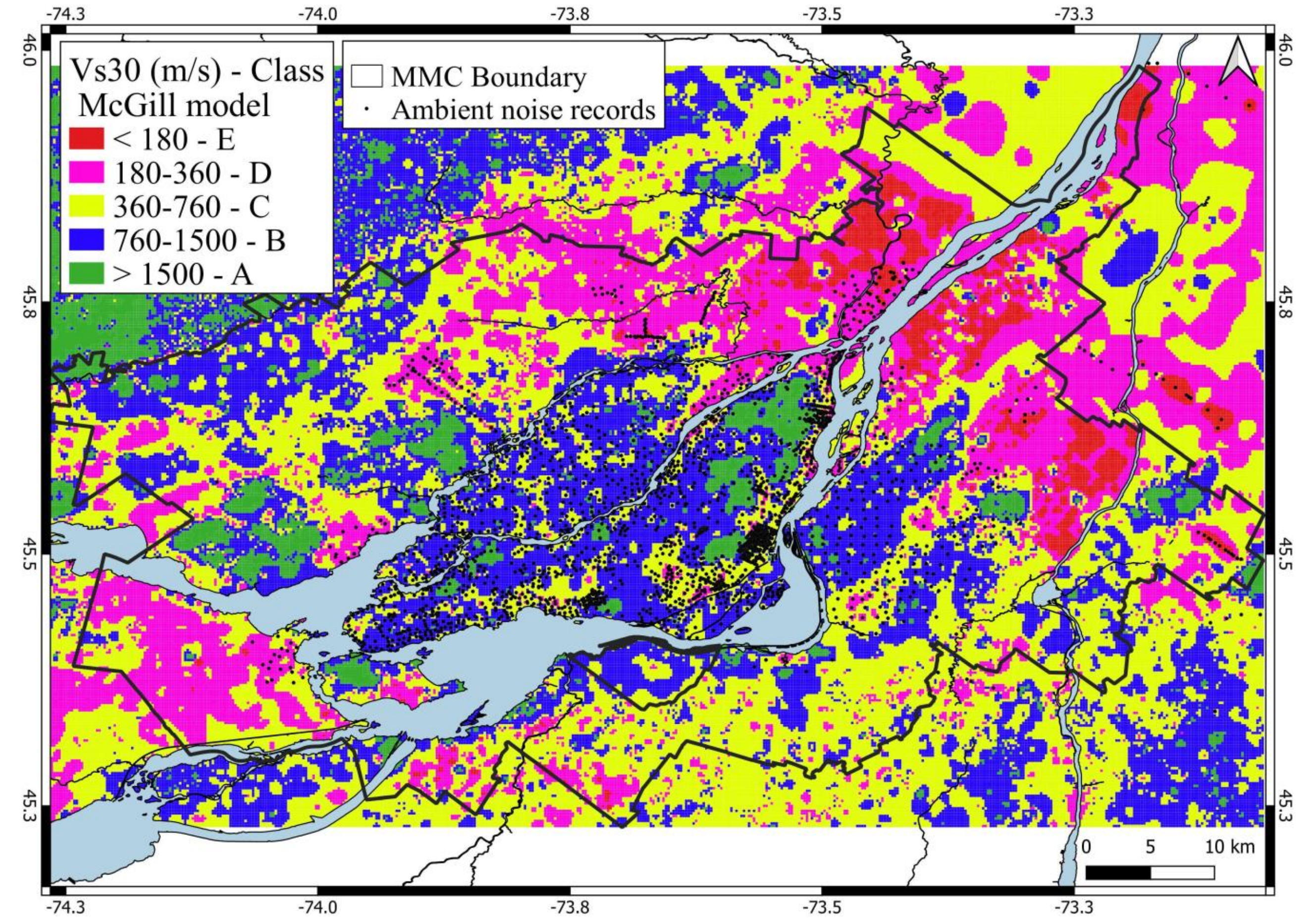


Figure 2. Distribution of V_{s30} grouped into site classes following the NBCC (From Rosset et al., 2023). Black dots locate the sites with ambient noise records.

RESULTS

Variation of PGA, Sa(0.3s) and Sa(1.0s) using SHM5 and SHM6

The PGA, Sa(0.3s) and Sa(1.0s) are calculated by DAs for both SHM5 and SHM6 hazard models. Figure 3 shows the PGA distribution in the Greater Montreal region obtained from SHM5 (left) and SHM6 (right). A notable increase in the hazard values from SHM5 to SHM6 is observed. The PGA ranges from 0.28g to 0.4g with SHM5 as the range is 0.28g to 0.48g for SHM6. The maximum PGA by DA increases of 20%. In both PSHA models, the PGA values are higher in the DAs in southwestern part of Greater Montreal region, which reflects the influence of the M5.8 earthquake (September 16, 1732) in Southern Montreal, a major earthquake occurred in the Western Quebec seismic zone [21].

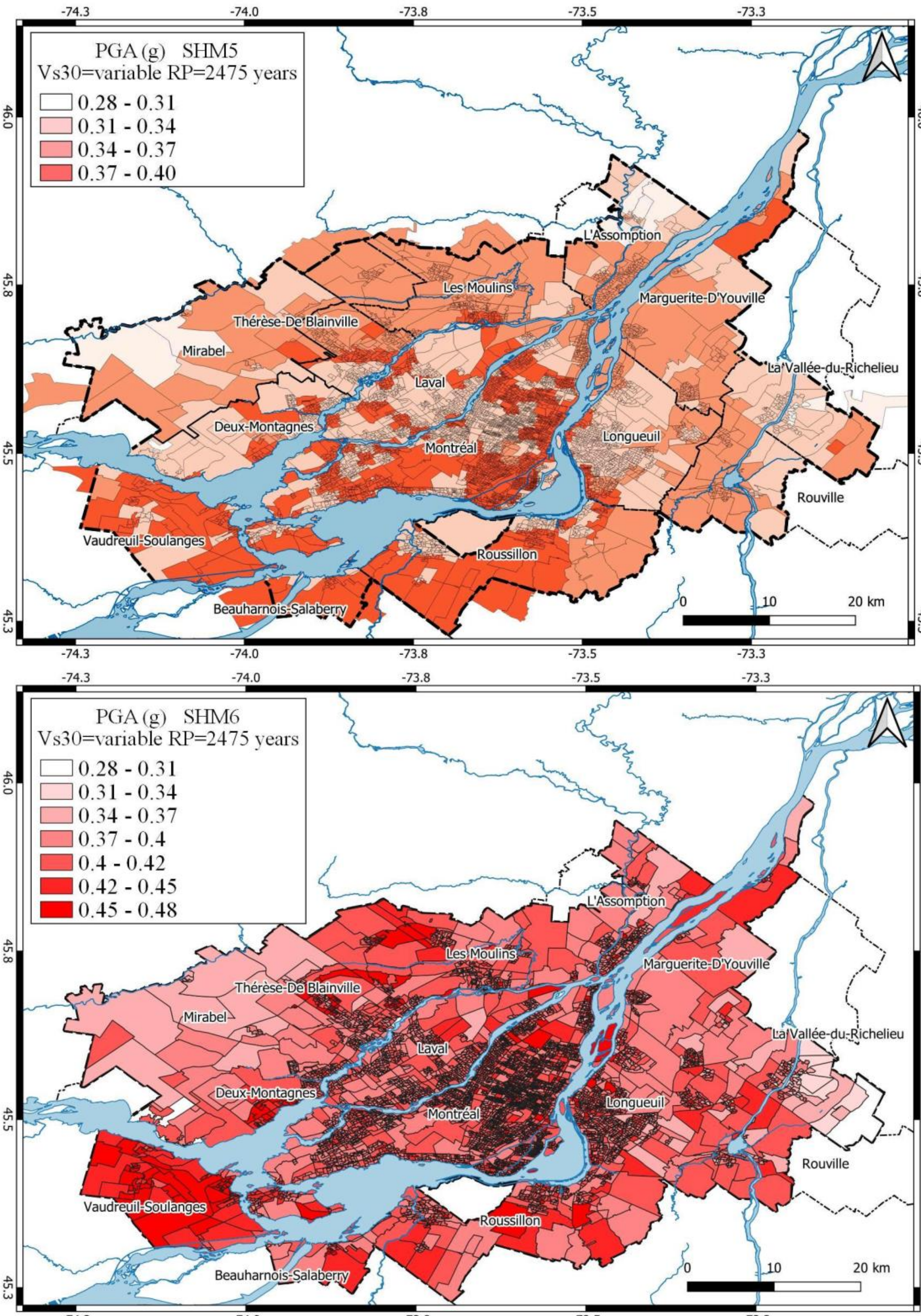
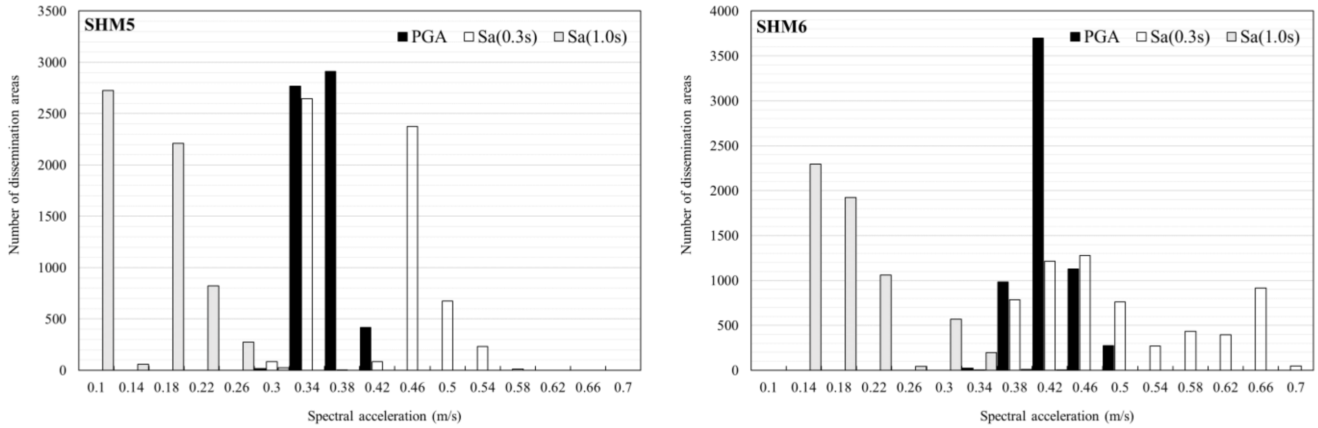


Figure 3. PGA by DA calculated using (a) SHM5 and (b) SHM6 for the return period of 2475 years (probability of exceedance of 2% in 50 years).

The graphs in Figure 3 distribute by bins the PGA, Sa(0.3s) and Sa(1.0s) averaged by DAs for both SHM5 (Left) and SHM6 (right) hazard models. The median values with the latter model are 0.4g, 0.45g and 0.14g for PGA, Sa(0.3s) and Sa(1.0s), respectively, since they are slightly lower with the SHM5 (0.36g, 0.43g and 0.15g, respectively).



(a) *(b)*

Figure 4. Distribution of calculated spectral acceleration by DA using (a) SHM5 and (b) SHM6 for the return period of 2475 years (probability of exceedance of 2% in 50 years).

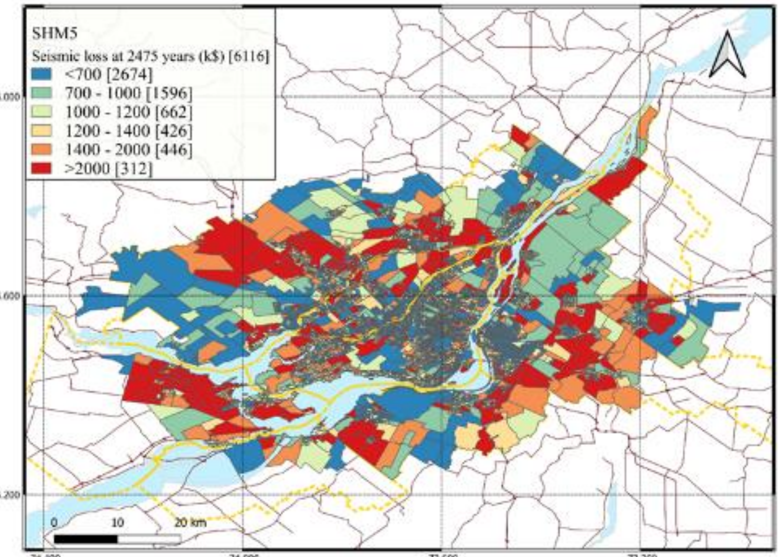
Changes in the loss

The table 2 summarized the calculated residential building loss using both seismic hazard models, from structural, non-structural and content damage. The SHM6 induces an increase of 50% of the total loss compared to the one calculated with SHM5. Loss from structural damage have the largest increase with a factor of 2.2 but play a minor role in the total loss since they represent only 5% of the total in SHM5.In contrary, loss from non-structural and content are predominant representing 61% and 34% of the total in SHM5, respectively. The total loss increases from 1.9% to 3.0% of the total residential asset value when moving from SHM5 to SHM6 (i.e. an increase of 57%).

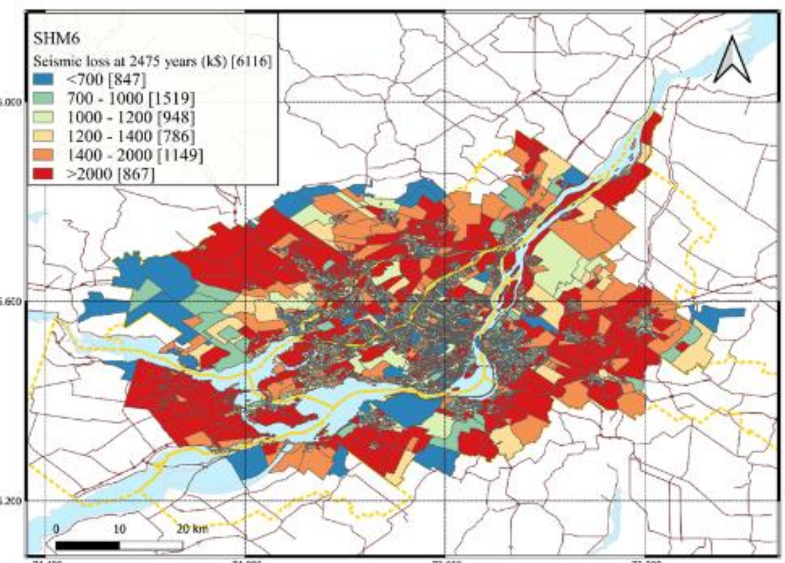
Table 2. Residential building loss using SHM5 and SHM6 at a 2% probability of exceedance in 50 years.

Types of loss	**Residential building loss (in million Can$)**		**Total building value (in million Can$)**	**Increase rate**
	SHM5	SHM6		
Structural	298	667	28,551	2.2
Non-Structural	3,508	5,386	167,953	1.5
Content	1,925	2,695	99,030	1.4
Total	5,731	8,748	295,534	1.5

The residential buildings loss maps in Figure 5 using the 5th and 6th generations of the seismic hazard show an increase of DAs with high values in the latter one. A total of 312 DAs have losses greater than 2 million when using SHM5 while there are 867 with SHM6. The seismic loss in the northeastern region where the ground shaking is largely increased move from the range of Can$700-1000 to 1400-2000 thousands. This observation is consistent with the increase of maximum hazard values in certain part of the region.



(a)



(b)

Figure 5. Total residential loss by DA calculated for a probability of exceedance of 2% in 50 years using (a) SHM5 and (b) using SHM6. The V_{s30} model in Figure 2 is used to consider site condition in the hazard model.

CONCLUSIONS

In 2020, the released Canadian SHM adopted a new ground motion models with updated logic tree and a continuous function of V_{s30} to account for site conditions. Hazards from SHM6 at a probability level of 2% in 50 years are significantly higher (+18% for PGA and +39% in average for spectral acceleration at other periods for soil type C) than the hazards from 2015 (SHM5).

The scale of the exposure model used in this comparative study is the census dissemination areas (6116 in total). It concerns residential building counted and classified as a function of building and occupancy types as well as year of construction. Property values are based on the 2018 property assessment roles and the content value is derived from the CatIQ database. The software, Hazus, provides capacity and fragility curves to estimate the probability at different damage states and structural and non-structural repair costs for each damage state and the associated building content losses.

The expected seismic losses for residential buildings in the Greater Montreal area increased by changes in seismic hazard estimates in the 2020 Canadian seismic hazard model. Loss estimates for the residential building stock correspond to 1.9% of the total property values based on SHM5 for a probability level of 2% in 50 years. There is a 50% increase on total residential building loss between the 2015 to the 2020 hazard models.

A further study of annualized earthquake loss using SHM6 will account for the long-term average losses. In addition, a study for a larger region in the province of Quebec will bring a more comprehensive understanding on the impact of hazard on seismic loss in this seismic zone.

ACKNOWLEDGMENTS

This analysis was made possible by a financial contribution in the context of the *programme cadre pour la prévention de sinistres du gouvernement du Québec* [CPS 20-21-09]. The authors thank Johanna Pollet, Adil Takahashi and Huanru Zhu who contributed to part of complementary research.

REFERENCES

[1] Parvez, I. A., and Rosset, P. (2014). “The role of microzonation in estimating earthquake risk”. In *Earthquake hazard, risk and disasters*, Elsevier, 273–308. https://doi.org/10.1016/B978-0-12-394848-9.00011-0

[2] Kolaj, M., Allen, T., Mayfield, R., Adams, J. and Halchuk, S. (2019). “Ground-motion models for the 6th Generation Seismic Hazard Model of Canada”. Proceeding of the *12th Canadian Conference on Earthquake Engineering*, Quebec City, Canada.

[3] FEMA (2022). Hazus Earthquake Model Technical Manual: Hazus 5.1. Federal Emergency Management Agency, https://www.fema.gov/sites/default/files/documents/fema_hazus-earthquake-model-technical-manual-5-1.pdf

[4] Tantala, M.W., Nordenson, G.J.P., Deodatis, G., and Jacob, K. (2008). « Earthquake loss estimation for the new york city metropolitan region”. *Soil Dynamics and Earthquake Engineering*, 28(10-11), 812–835. https://doi.org/10.1016/j.soildyn.2007.10.012

[5] Field, E.H., Seligson, H.A., Gupta, N., Gupta, V., Jordan, T.H., and Campbell, K. W. (2005). “Loss estimates for a Puente Hills blind-thrust earthquake in Los Angeles, California”. *Earthquake Spectra*, 21(2), 329–338.

[6] Moffatt, S.F., and Cova, T.J. (2010). “Parcel-scale earthquake loss estimation with HAZUS: A case study in salt Lake County, Utah”. *Cartography and Geographic Information Science*, 37(1), 17–29.

[7] Chen, R., Jaiswal, K.S., Bausch, D., Seligson, H., and Wills, C. J. (2016). “Annualized earthquake loss estimates for California and their sensitivity to site amplification”. *Seismological Research Letters*, 87(6), 1363–1372. https://doi.org/10.1785/0220160099

[8] Bendito, A., Rozelle, J., and Bausch, D. (2014). “Assessing Potential Earthquake Loss in Mérida State, Venezuela Using Hazus”. *International Journal of Disaster Risk Science*, 5(3), 176–191. https://doi.org/10.1007/s13753-014-0027-0

[9] Levi, T., Bausch, D., Katz, O., Rozelle, J., and Salamon, A. (2015). “Insights from Hazus loss estimations in Israel for Dead Sea Transform earthquakes”. *Natural Hazards*, 75(1), 365–388. https://doi.org/10.1007/s11069-014-1325-y

[10] Ansal, A., Akinci, A., Cultrera, G., Erdik, M., Pessina et al. (2009). “Loss estimation in Istanbul based on deterministic earthquake scenarios of the Marmara Sea region (Turkey)”. *Soil Dynamics and Earthquake Engineering*, 29(4), 699–709.

[11] Felsenstein, D., Elbaum, E., Levi, T., and Calvo, R. (2021). “Post-processing HAZUS earthquake damage and loss assessments for individual buildings”. *Natural Hazards*, 105(1), 21–45. https://doi.org/10.1007/s11069-020-04293-1

[12] Firuzi, E., Ansari, A., Amini Hosseini, K., and Rashidabadi, M. (2019). Probabilistic earthquake loss model for residential buildings in Tehran, Iran to quantify annualized earthquake loss. *Bulletin of Earthquake Engineering*, 17(5), 2383–2406. https://doi.org/10.1007/s10518-019-00561-z

[13] Ulmi, M., Wagner, C.L., Wojtarowicz, M., and Bancroft, J.L. (2014). “Hazus-MH 2.1 Canada, User and Technical Manual: Earthquake Module”. Natural Resources Canada. 245 pages. https://publications.gc.ca/collections/collection_2016/rncan-nrcan/M183-2-7474-eng.pdf

[14] Ploeger, S.K., Atkinson, G.M., and Samson, C. (2010). “Applying the HAZUS-MH software tool to assess seismic risk in downtown Ottawa, Canada”. *Natural Hazards*, 53(1), 1–20. https://doi.org/10.1007/s11069-009-9408-x

[15] Yu, K., Rosset, P. and Chouinard, L. (2016). “Seismic Vulnerability Assessment for Montreal”. *Georisk*, 10(2), 164-178. https://doi.org/10.1080/17499518.2015.1106562

[16] Rosset, P., Kert, M., Youance, S., Nollet, M-J., and Chouinard L. (2019). “Could Montreal residential buildings suffer important losses in case of major earthquakes?” In Proceeding of the *12th Canadian Conference on Earthquake Engineering*, Quebec, Canada, June 17-20. 7 pages.

[17] Rosset, P., Chouinard, L., and Nollet, MJ. (2021). “Consequences on Residential Buildings in Greater Montreal for a Repeat of the 1732 M5.8 Montreal Earthquake”. In Proceedings of the *Canadian Society of Civil Engineering Annual Conference 2021*. CSCE 2021. Lecture Notes in Civil Engineering, vol 240. Springer, Singapore. https://doi.org/10.1007/978-981-19-0507-0_58

[18] Rosset, P., Xuejiao, L., Chouinard, L. and Nollet, MJ. (2023). “Annualized Residential Earthquake Losses in the Greater Montreal Area”. In Proceedings of the *13th Canadian Conference on Earthquake Engineering*, Vancouver, 2023, Paper 228.
[19] Kolaj, M., Halchuk, S., Adams, J., and Allen, T. (2020). “Sixth Generation Seismic Hazard Model of Canada: input files to produce values proposed for the 2020 National Building Code of Canada”. *Geological Survey of Canada, Open File 8630*, 15. https://doi.org/10.4095/327322
[20] Adams, J., Allen, T., Halchuk, S., and Kolaj, M. (2019). “Canada’s 6th generation seismic hazard model, as prepared for the 2020 National Building Code of Canada”. In Proceeding of the *The 12th Canadian Conference on Earthquake Engineering*, Quebec, Canada, June 17-20.
[21] Leblanc, G. (1981). “A closer look at the September 16, 1732, Montreal earthquake”. *Canadian Journal of Earth Sciences* 18(3), 539–550. https://doi.org/10.1139/e81-047