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Characterizing Seismic Risk Across Canada

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ABSTRACT

The Geological Survey of Canada recently published a national seismic risk model, quantifying seismic risk at the neighborhood level across Canada. A newly accepted Earthquake Spectra article documents the scientific basis and methodology of this assessment, whereas this article will present summary results of the model, including loss exceedance curves at the national and provincial levels, neighborhood level risk indicators, and expected 500-year economic losses. We find that national 500-year economic losses have the potential to exceed capacities of the insurance sector to absorb expected financial consequences, based on recent reporting from within that industry. We also present results of the Seismic Risk Index, a compound measure of seismic risk which factors in both physical and social dimensions of vulnerability. The Seismic Risk Index identifies communities most at risk from earthquakes in Canada, many of which are large municipalities in British Columbia, Ontario and Quebec. Through a normalized Seismic Risk Index, we find that small communities in Western Canada are also at great risk from earthquakes, including communities which are primarily made up of Indigenous people.

We will also demonstrate a custom web application, RiskProfiler.ca, designed to allow stakeholders to visualize and explore the results of the national seismic risk assessment in a user-friendly way. It includes maps and charts, as well as a toggle that allows users to consider the impact of retrofit measures on some or all building types. We anticipate that this model will be of use to those in the planning, insurance, and emergency management sectors, and of interest to those engaged in seismic retrofit and earthquake engineering in Canada.

Keywords: seismic risk, retrofit, loss exceedance, seismic hazard.

INTRODUCTION

The Sendai Framework, released by the United Nations in 2015 [1], requires signatory nations to develop risk assessment capacities in order to measure their progress toward stated risk reduction targets. Canada signed onto the Sendai Framework in 2015, with commitments extending until 2030. As part of its commitment, Canada completed a national scale seismic risk assessment [2,3]: the first generation Canadian Seismic Risk Model (CanSRM1). The goals were to assess the potential consequences from select earthquake scenarios that could occur in Canada (e.g. a deterministic earthquake risk assessment), and the consequences expected to occur over long time scales as a result of earthquakes, such as the average annual economic cost to Canadians (e.g. probabilistic seismic risk assessment). This model builds upon years of work in partnership with the Global Earthquake Model Foundation [e.g. 4], ensuring that practices in Canada are consistent with international best practice.

The earthquake risk assessment approach is described in detail in [2,3], and summarized here. CanSRM1 uses the OpenQuake Engine [5] for stochastic damage and loss calculations within the probabilistic portion of the model. For the deterministic catalogue, OpenQuake's scenario calculators are used. The hazard model input (Figure 1), composed of a seismic source model and ground motion model, is based on the Sixth Generation Canadian Seismic Hazard Model [6,7]. This is the seismic hazard model used for calculating seismic design values in the National Building Code of Canada. The exposure model is a representative inventory of buildings for all of Canada, and is reported at the scale of 'Settled Areas' (SA), which approximately delineate clusters of buildings within Census Disseminations Areas [8]. The fragility and vulnerability functions used in

CanSRM1 are originally developed by the Global Earthquake Model Foundation [9] and subsequently updated for Canada [2,3]. The site model uses the time averaged shear wave velocity in the upper 30 m of the earth's surface (v_{s30}), based on the global slope proxy v_{s30} model of [10,11].

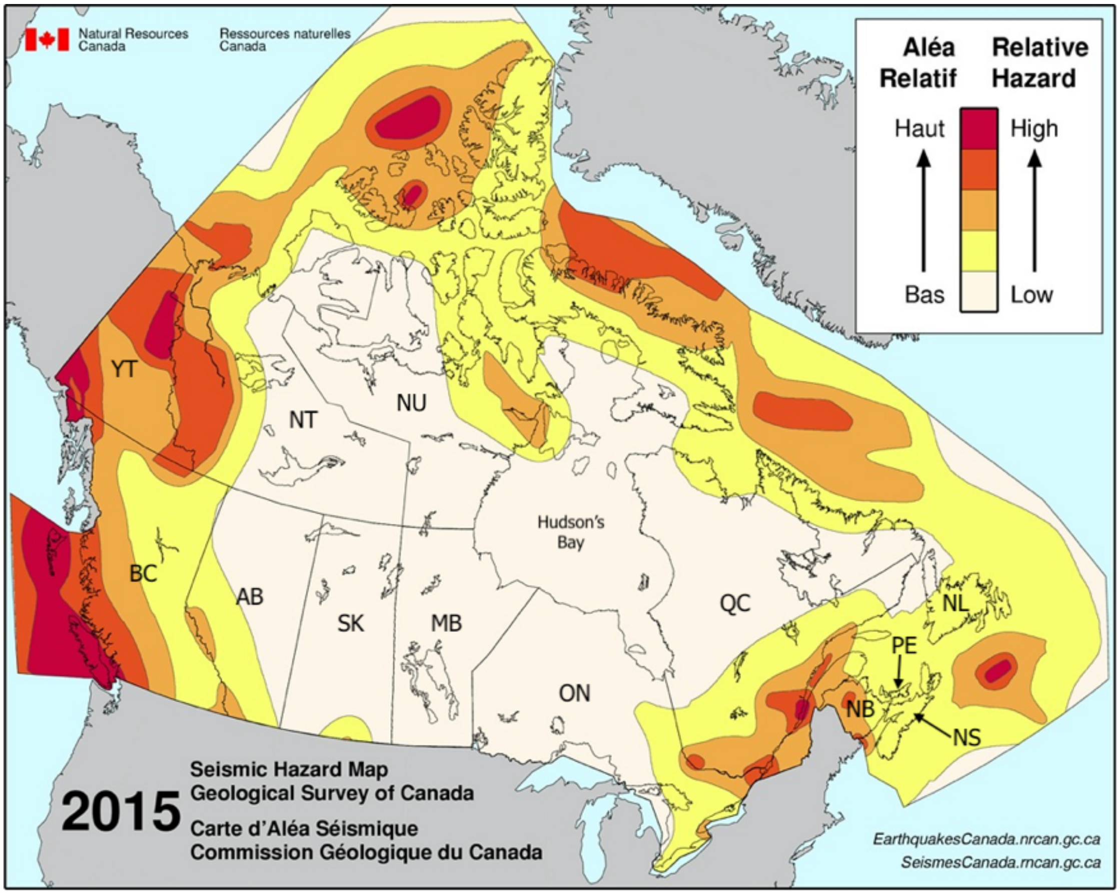


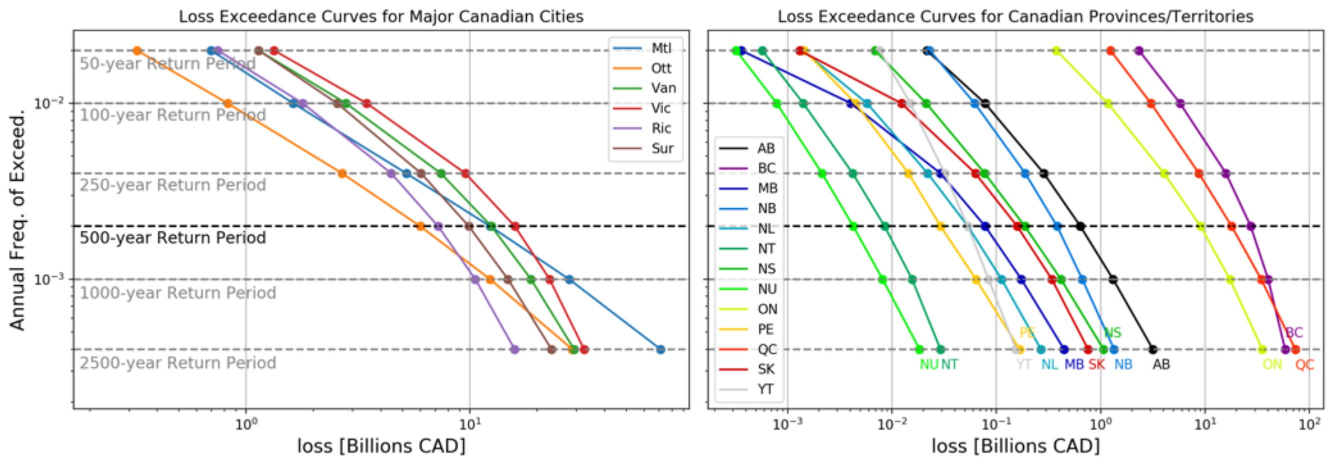
Figure 1. A simplified seismic hazard map of Canada, modified from https://www.seismescanada.rncan.gc.ca/hazard-alea/simphaz-en.php. Provinces and territories are marked by their abbreviations: AB is Alberta, BC is British Columbia, MB is Manitoba, NB is New Brunswick, NL is Newfoundland, NS is Nova Scotia, NT is Northwest Territories, NU is Nunavut, ON is Ontario, PE is Prince Edward Island, QC is Quebec, SK is Saskatchewan, and YT is Yukon Territory. Note that this map is based on the Fifth Generation Seismic Hazard Model (CanadaSHM5), which has been superceded by CanadaSHM6. This figure is for illustrative purposes.

CanSRM1 results include return period economic losses at the national, provincial/territorial, and regional levels; average annual economic losses and fatalities at the SA and provincial/territorial level; and 50-year average damages to buildings at the SA level. Return periods considered are 50, 100, 250, 500, 1000, and 2500 years. Average values, as well as the 5th and 95th percentile results are available for each risk metric. Herein we present key metrics and results.

ECONOMIC RISK

Loss Exceedance Curves

Figure 2 shows loss exceedance curves for all Canadian provinces and territories, and for select major cities in Canada. Generally, the cities in the west (e.g. Vancouver, Victoria, Richmond, Surrey, all in BC) have a more steeply sloping curve, which suggests higher economic losses at lower return periods. Cities in the east (e.g. Ottawa, ON and Montreal, QC) have more shallow curves, which means that economic losses continue to climb at a greater rate as the return period increases. This is very likely due to the long return periods of crustal faults in the stable craton surrounding Hudson's Bay in Eastern Canada. For provinces and territories, it is unsurprising to see that BC, ON, and QC have the greatest losses at all return periods. These provinces have the highest exposure and seismic hazard.

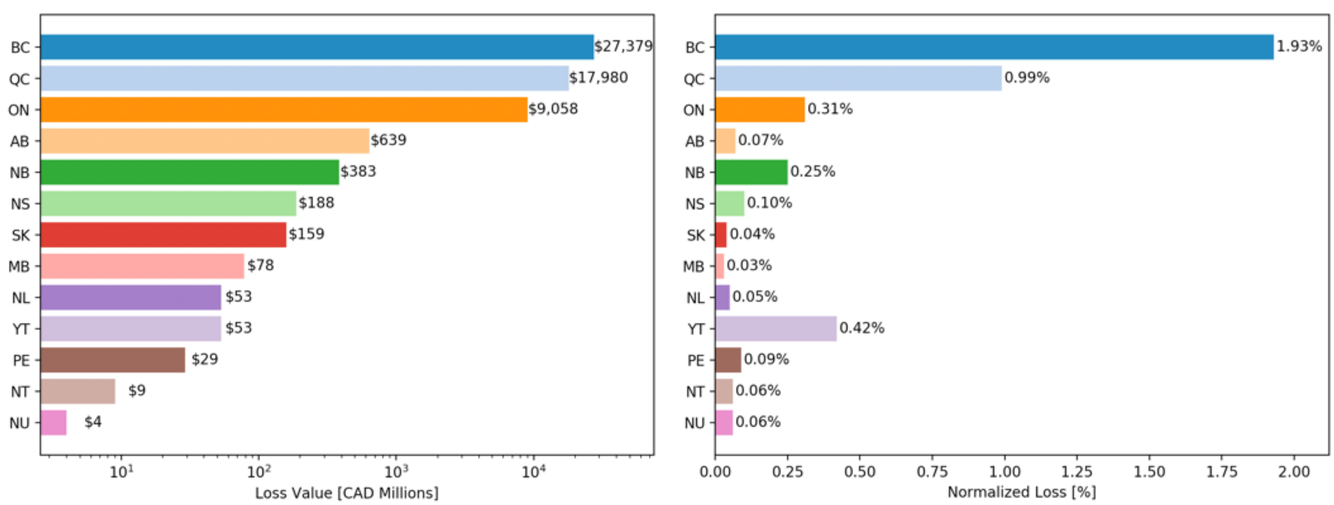


(a) *(b)*

Figure 2. Loss exceedance curves for (a) major cities in Canada and (b) all provinces and territories, by their common abbreviations. Mtl is Montreal, QC; Ott is Ottawa, ON; Van is Vancouver, BC; Vic is Victoria, BC; Ric is Richmond, BC; and Sur is Surrey, BC. Dashed lines are the indicated return periods.

500 Year Expected Economic Loss

Figure 3 shows the 500-year economic loss for each province and territory in Canada, grouped by absolute economic loss and normalized economic loss. The absolute economic loss represents the total losses expected in the province, while the normalized economic loss represents the total losses expected in the province divided by the total value of assets. The 500-year economic loss is significant because regulations in Canada require property and casualty insurers to maintain sufficient capital to cover a 500-year loss [12].



(a) *(b)*

Figure 3. The mean 500 year return period expected loss, per province and territory, for (a) absolute economic losses and (b) economic loss ratios.

The results show that the provinces/territories with the highest 500-year expected economic losses are British Columbia and Quebec, followed by either Ontario or the Yukon, depending on whether you consider absolute loss or normalized loss ratios. This is important as many risk mitigation efforts tend to be focused on cities with large populations. In the Yukon, the largest city has a population of under 35,000 people [13]. However, the Denali Fault runs very close to the Alaska Highway, along which much of the population of YT is focused. Clearly, strategies must be developed that will be pertinent to more rural settlements in Canada's north, with a particular focus on Indigenous communities that may be relatively isolated.

For Canada as a whole, the 500-year return period average expected loss is $45.9B. Depending on insurance penetration in the location that such a large event occurs, this may exceed the tolerable limit to avoid collapse of the insurance sector [14,15]. This limit is currently around $30-35B in insured losses. Although commercial insurance penetration is high across the country, if this magnitude of loss were to occur in Eastern Canada, where residential insurance penetration is around 3-4% [16], then the insurance sector would likely be able to withstand the several billion in claims. However, if it occurred in British Columbia where residential insurance penetration is roughly 10-70% [16] then claims from this magnitude of loss could be in excess of $32.1B, extending slightly above the threshold, if losses are at least 70% of the $45.9B economic loss.

We also note that the 500-year economic losses reported here are low estimates. This is because our model currently does not account for losses to vehicles or linear infrastructure, losses caused by secondary perils like tsunami or fire following, or claims related to business interruption or temporary shelter.

Average Annual Losses

Figure 4 shows the contribution to Average Annual Loss (AAL) from buildings with differing construction materials and seismic code levels. Wood buildings make up the majority of exposed assets in Canada, and also represent the largest contributor to AAL. However, wood construction tends to be relatively seismically resilient, compared to building typologies like unreinforced masonry. This construction material makes up 9% of the exposed assets in Canada, but contributes to 16% of the AAL --- a disproportionately high loss. Figure 5 demonstrates that the amount of damage in unreinforced masonry buildings is likely to be higher than damage from the same level of shaking in wood buildings, resulting in higher repair and replacement costs and longer housing/business disruption for occupants. Although retrofit, replacement and other mitigation measures can also be costly and disruptive, these measures can at least be spaced out over time to alleviate the impact [17]. Waiting for a large earthquake to render these buildings uninhabitable will also result in higher costs due to surge pricing and labor or goods shortages.

Mitigation of wood buildings, however, is comparatively simple. Many single family wood frame houses can be retrofitted without displacing residents [18], and for much less than the cost of an earthquake deductible [19], which in BC and QC are 12.5% and 4% of the home value, on average [16]. Education and voluntary wood retrofit programs in California have seen high take up, bolstered by state programs to offset costs [20, and references therein], and evidence suggests that retrofitted homes may fetch a higher resale price as a result [21].

In terms of the AAL by municipality (Table 1), the majority of top-ranking cities are found in British Columbia. Exceptions are Montreal, Ottawa, and Toronto. It is worth noting that Montreal and Vancouver have very high AAL, with more than double the AAL of the 4th ranked city (Richmond). This is useful knowledge when it comes to mitigation, as efforts can be concentrated on a very small number of cities while having an oversized impact on risk. It's also worth noting that Vancouver, Richmond, Surrey, and Burnaby are all part of Metro Vancouver, clustering almost 19% of the country's AAL in a relatively small geographical region. This, unsurprisingly, makes Metro Vancouver an important target for risk mitigation.

LIFE SAFETY

Annual Probable Life Loss

The Annual Probable Life Loss (APLL) equals the average number of fatalities from earthquakes each year in a given area, when considered over a very long time period. It indicates jurisdictions where earthquake-related fatalities might be the largest, and it can be compared to PLL from other hazards.

Table 1 lists the municipalities with the highest APLL in Canada. Ranked from highest to lowest APLL, the top five municipalities include: Montreal, QC; Vancouver, BC; Ottawa, ON; Surrey, BC; and Toronto, ON. We note that Montreal, Ottawa, and Toronto are in Eastern Canada, where the seismic hazard (Fig. 1) is generally not as extreme as it is in parts of western Canada [6]. The high seismic risk is mainly because these municipalities have a high population, and a higher proportion of buildings vulnerable to earthquakes than in Western Canada [8].

Figure 4 shows the proportion of fatalities expected in different building types across Canada, when considering the total national APLL. This shows that approximately 77% of the expected fatalities occur in pre-code buildings, and approximately 50% are expected to occur in concrete and unreinforced masonry buildings. We note that pre-code concrete and unreinforced masonry buildings make up only 8% of all buildings in Canada, suggesting there may be an opportunity to retrofit or replace a relatively small fraction of buildings and drastically reduce the life safety risk from earthquakes. If this were limited to buildings in British Columbia, Ontario, and Quebec, it would represent only 6% of buildings in Canada, and if it were further constrained to only pre-code concrete and unreinforced masonry in Montreal, Vancouver, Ottawa, Surrey, and Toronto it would represent just 1% of buildings in Canada.

In total, we estimate that earthquakes are expected to kill about 9 people per year on average in Canada (Table 1). For comparison, on average since 1950, landslides have killed about 3 people per year [22], floods have killed about 1 person per year [23], and wildfires have killed at least 2 people per year [23,24]. This means that earthquakes have the potential to cause higher loss of life than many natural hazards Canadians face, despite that only two deaths have been directly attributed to earthquakes in Canada since the arrival of European settlers in the 16th Century [25]. This likely because of Canada has been relatively undeveloped for much of this time and because large and potentially deadly earthquakes are relatively rare [ex. 26].

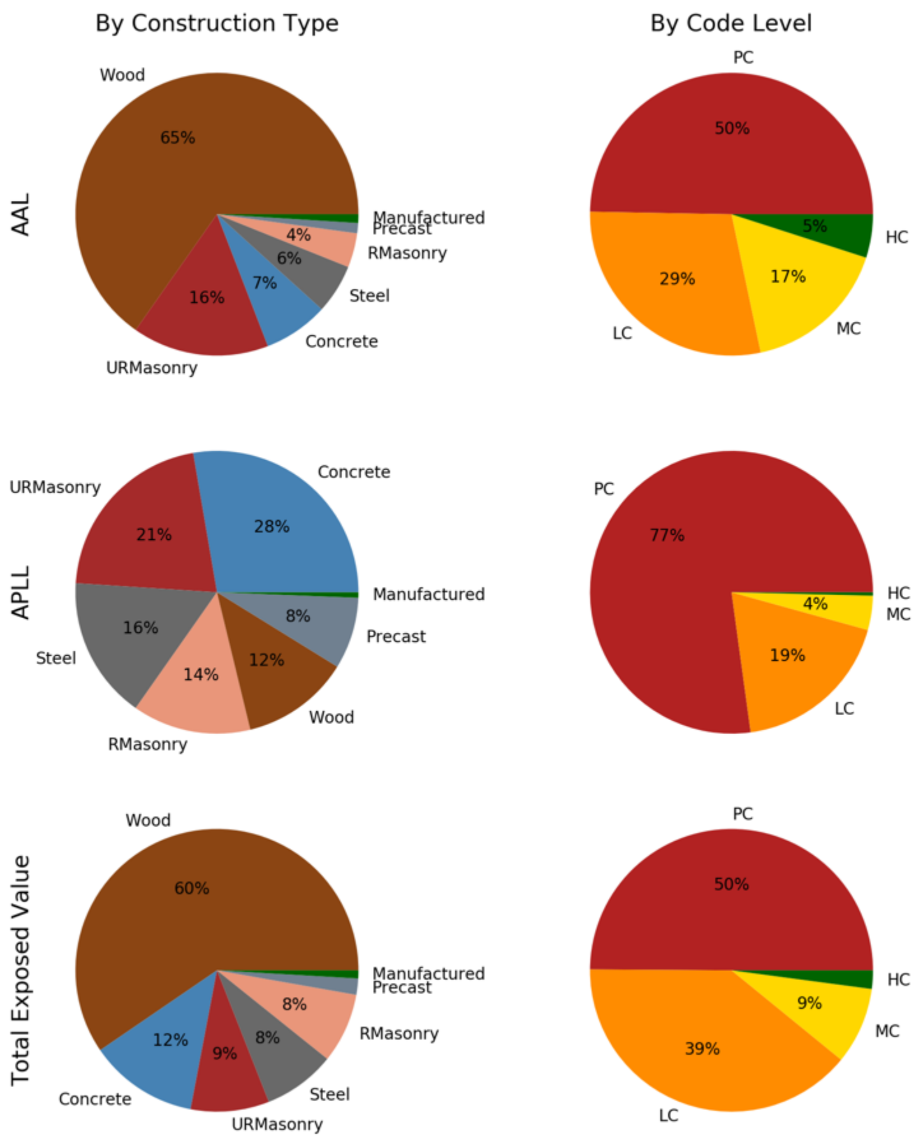


Figure 4. Average Annual Losses (AAL, top row) and Annual Probable Life Loss (APLL, middle row), disaggregated by construction material (left column) and seismic code level (right column), compared against the proportions of each in the exposure dataset (Total Exposed Value, bottom row). Seismic Code Levels are Pre-Code (PC), Low Code (LC), Moderate Code (MC) and High Code (HC) [2].

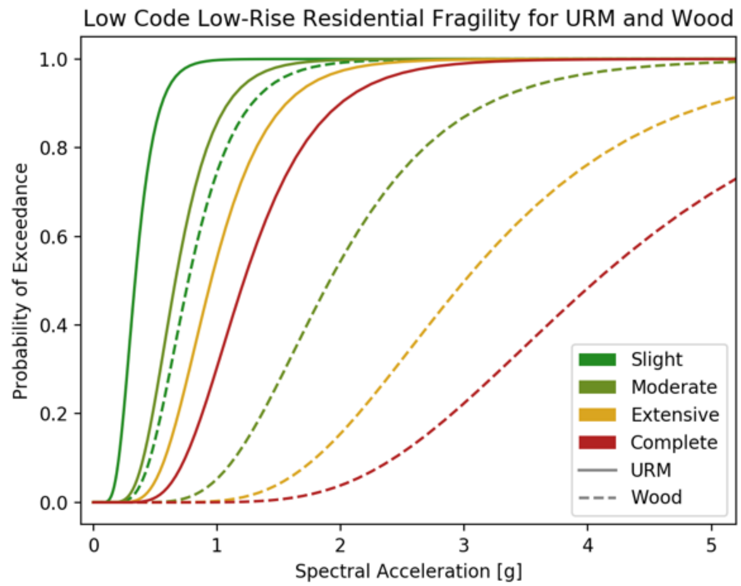


Figure 5. Fragility functions for low code (LC), low-rise, residential buildings of light-frame wood and unreinforced masonry (URM) construction. Colors denote damage states: slight, moderate, extensive, and complete. Note that the wood fragility function is conditioned on a period of 0.3s and the URM is on 0.6s.

Individual Risk

Individual risk, which can also be referred to as the Probability of Death of an Individual (PDI), is the probability of a death from earthquakes resulting from building damage. For a given settled area, it equals the fraction people killed in buildings of the same occupancy, construction, and seismic code level, divided by the total population within those buildings. PDI was calculated for all buildings across Canada, and the distribution of PDI in select Canadian cities is plotted in Figure 6. Other individual risks Canadians face are also plotted for reference. These results show that the probability of an individual being killed by an earthquake across all of Canada is lower than that of being killed in a motor accident (i.e. approximately 1:10,000), and in many buildings it's lower than the risk of drowning. We also note that local governments in Western Canada commonly use an annual probability of death of 1:10,000 as a threshold to evaluate if landslide risk is acceptable or not [27]. By this metric, the individual risk from earthquakes would be considered tolerable in many western Canadian jurisdictions.

Table 1. Average Annual Losses (AAL) and Annual Probable Life Loss (APLL), by Census Subdivision (city). Top 10 AAL cities are shown here, as well as the total for all of Canada.

City	AAL (Absolute)	AAL (Fraction of Total)	APLL (Absolute)	APLL (Fraction of Total)
Montreal, QC	$73.0M	8.4%	0.90	10.4%
Vancouver, BC	$72.4M	8.3%	0.62	7.1%
Surrey, BC	$45.1M	5.2%	0.34	3.9%
Richmond, BC	$27.4M	3.1%	0.26	3.0%
Ottawa, ON	$27.0M	3.1%	0.38	4.4%
Victoria, BC	$22.0M	2.5%	0.18	2.1%
Saanich, BC	$21.4M	2.5%	0.22	2.6%
Toronto, ON	$20.2M	2.3%	0.30	3.5%
Burnaby, BC	$19.3M	2.2%	0.16	1.9%
Abbotsford, BC	$16.8M	1.9%	0.13	1.4%
National Total	$871M	--	8.65	**--**

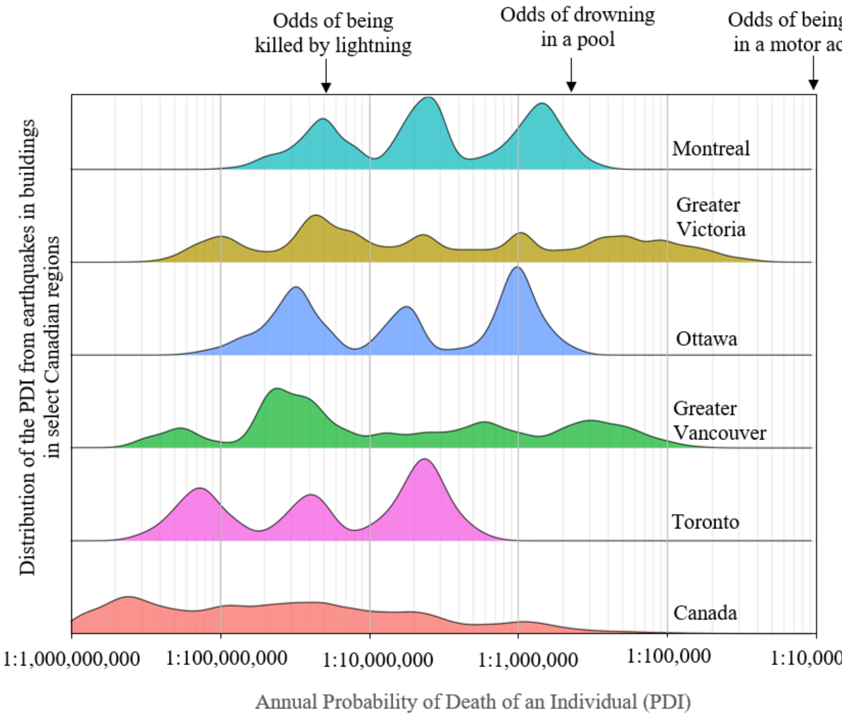


Figure 6. Distribution of individual risk from earthquakes in buildings in select Canadian cities and for all of Canada. Other individual risks are plotted for reference. The individual risk is represented as a histogram of the probabilities of dying in individual buildings.

Group Risk

Group risk is the probability that a given number of people, or more, will be killed by an earthquake in a year. It is calculated in much the same way as loss exceedance curves for financial losses, but considering the expected number of fatalities over a return period or annual probability of exceedance, rather than the financial loss. Group risk can be used to evaluate societies tolerance for multi-fatality events [28,29], and is a useful companion metric to individual risk.

Figure 7 plots the group risk from earthquakes in Montreal, Vancouver, Ottawa, Surrey, and Toronto. The results show that Montreal has the highest group risk of any Canadian municipality, largely because the expected fatalities from low probability events are higher than other municipalities in Canada. When considering more frequent events, Vancouver and Surrey (i.e. communities in Western Canada) have higher group risk.

For comparison to international thresholds of safety, APLL = 0.01 is plotted on Figure 7 for reference. This line is consistent with the Hong Kong group risk tolerance threshold for landslides, and the reference lines used by dam agencies in the USA, Canada, and Australia to evaluate dam safety risk [27]. We note that the group risk from earthquakes in Montreal, Vancouver, Ottawa, Surrey, and Toronto plot above this line.

RISK PRIORITIZATION

The Seismic Risk Index (SRI) was developed to identify communities most at risk from earthquakes in Canada. It can be used to support strategic disaster risk reduction decision making such as resource allocation and prioritization. Two versions of the SRI are estimated in this assessment, and they are based on the United States Federal Emergency Management Agencies (FEMA) National Risk Index [30]. The Absolute Loss SRI, SRI_{abs}, helps to identify the Canadian communities expected to experience the largest absolute loss (e.g. those with high exposure within active seismic zones); and the Normalized Loss SRI, SRI_{norm}, helps to identify the Canadian communities expected to experience the largest losses relative to their population and value of assets.

Municipalities with the highest SRI_{abs} include major urban areas in western and central Canadian seismic hazard zones. The five highest scoring communities (ranked by absolute risk score) include Montreal, QC; Vancouver, BC; Surrey, BC; Richmond, BC; and Victoria, BC (Figure 8). Municipalities expected to suffer the highest normalized loss include small communities along Canada's west coast where earthquake frequency and magnitude are higher and where communities may be more vulnerable to earthquake disruption [8]. The five highest scoring communities ranked by normalized risk score include Skidegate, BC; Zeballos, BC; Duncan, BC; Burwash Landing, YT; and Tsussie 6, BC (Figure 8). These include rural and remote communities with limited access to lifeline services and Indigenous communities who bear a disproportionate burden of risk, sometimes in more isolated geographic settings.

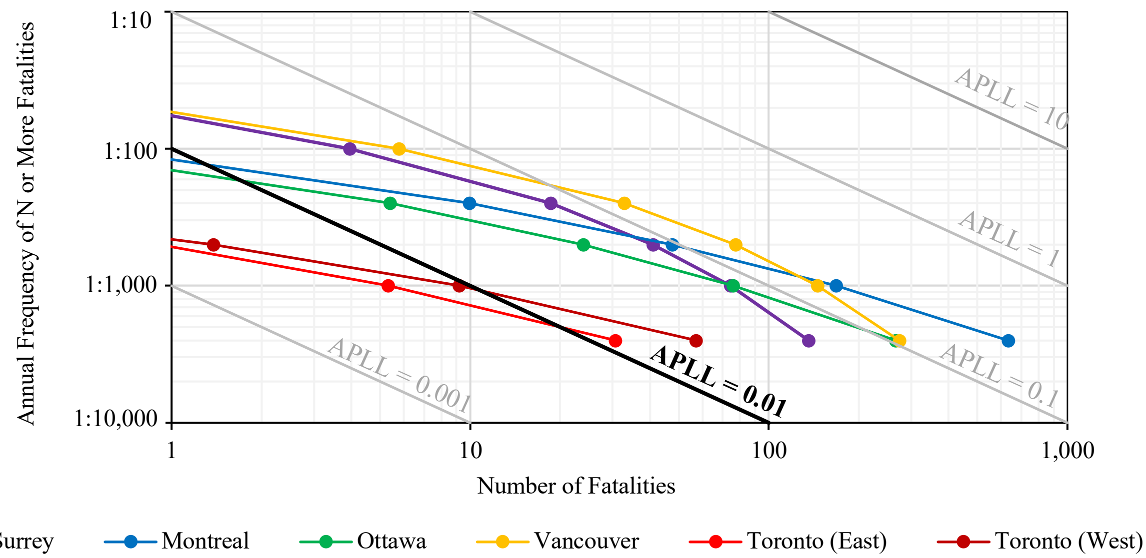


Figure 7. Group risk from earthquakes in select Canadian cities.

Figure 9 shows the distribution of SRI values for census subdivisions in Canada, ranked from lowest to highest, for absolute and normalized cases. These results show that seismic risk is extremely unevenly distributed in Canada, with only a small number of communities rated as very high risk. For example, when considering economic risk, about 28% of the total average annual economic loss is distributed between the cities of Montreal, Vancouver, Surrey, Richmond, and Ottawa (Table 1), even though these municipalities make up only 11% of the national building asset value. These results highlight the potential efficiency of prioritizing earthquake risk reduction efforts in the highest risk communities, rather than enacting broad risk reduction efforts.

COMMUNICATION

There are several relevant stakeholders for seismic risk information in Canada, including the [re]insurance industry, financial planners, community planners, emergency managers, policy makers, and the general public. Making technical material available and comprehendible to these stakeholders can be a significant roadblock to sharing an understanding of risk. Therefore, NRCan has developed a custom-built web application, called RiskProfiler (www.RiskProfiler.ca), that allows users to access, visualize, and explore the earthquake assessment results at a variety of spatial scales. RiskProfiler has deterministic and probabilistic information delivered via maps, charts, and tables. The user can select an individual SA, or inspect results at a higher level of aggregation such as by municipality. At this time, NRCan has focused its communication efforts on community planners and emergency managers, although in the future we hope to extend to additional users.

Scenarios are listed next to a map of their distribution, and users can filter by magnitude, deaths, damage, or dollars lost. Once a scenario is selected (Figure 10), the user can visualize the shaking, damage, debris generation, casualties, or financial impacts. They can also disaggregate those results by building construction material, occupancy, or seismic design level. Finally, a user can toggle on or off a retrofitted simulation, wherein all buildings are assumed to have been retrofitted. These features combined allow the user to investigate the impact to any of the metrics of retrofitting particular building constructions or code levels.

For the probabilistic side of RiskProfiler, a user can select a region of interest to explore the AAL, APLL, SRI, and probable damage to buildings over a 50-year period. Loss exceedance curves are also generated at the Forward Sortation Area.

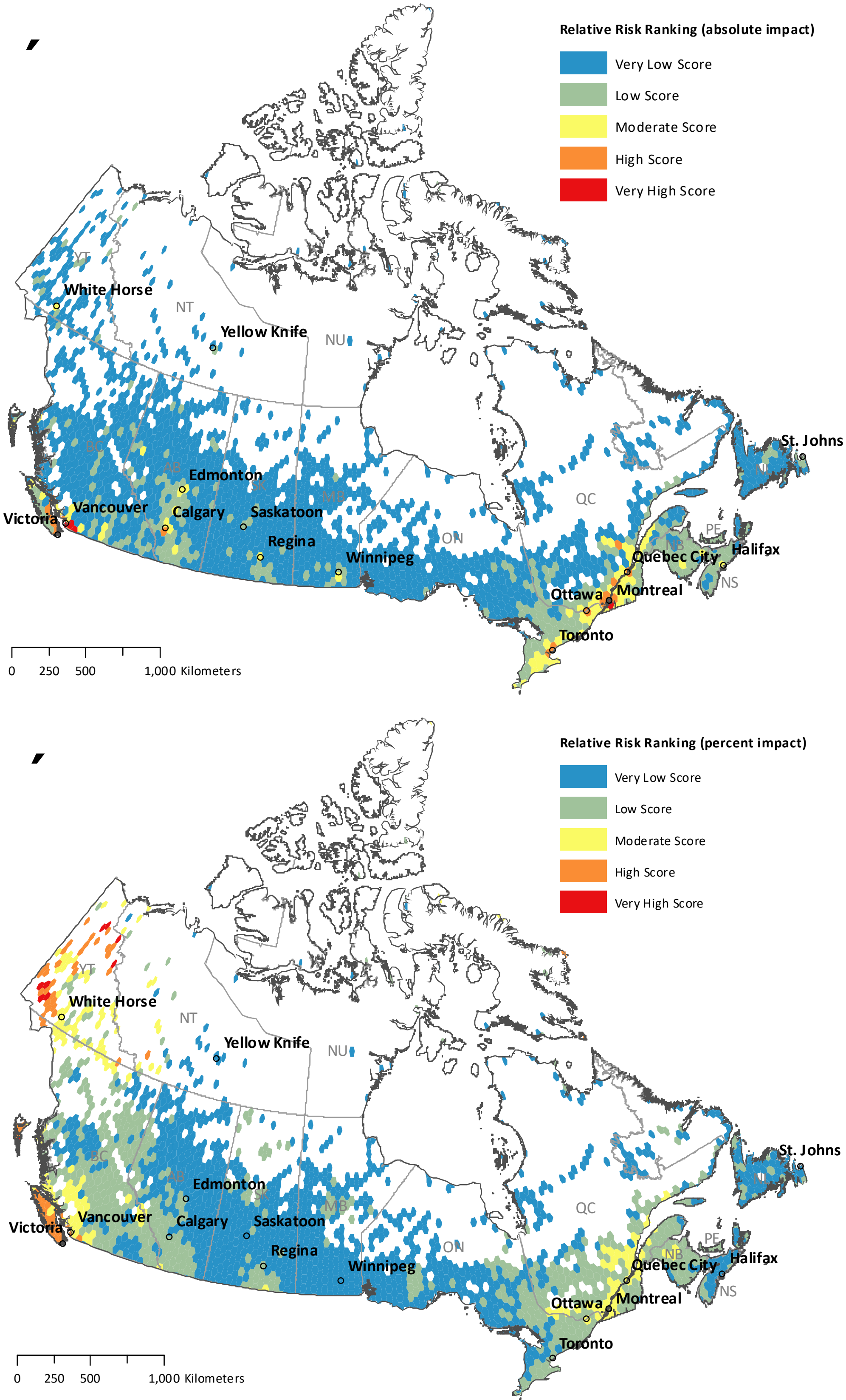


Figure 8. Relative seismic risk across Canada. a) absolute seismic risk rating. b) normalized seismic risk rating. Note that seismic risk ratings are displayed at the scale of a 50 km hexagonal grid across Canada. Hexagonal grid ratings are calculated using the method summarized in [2].

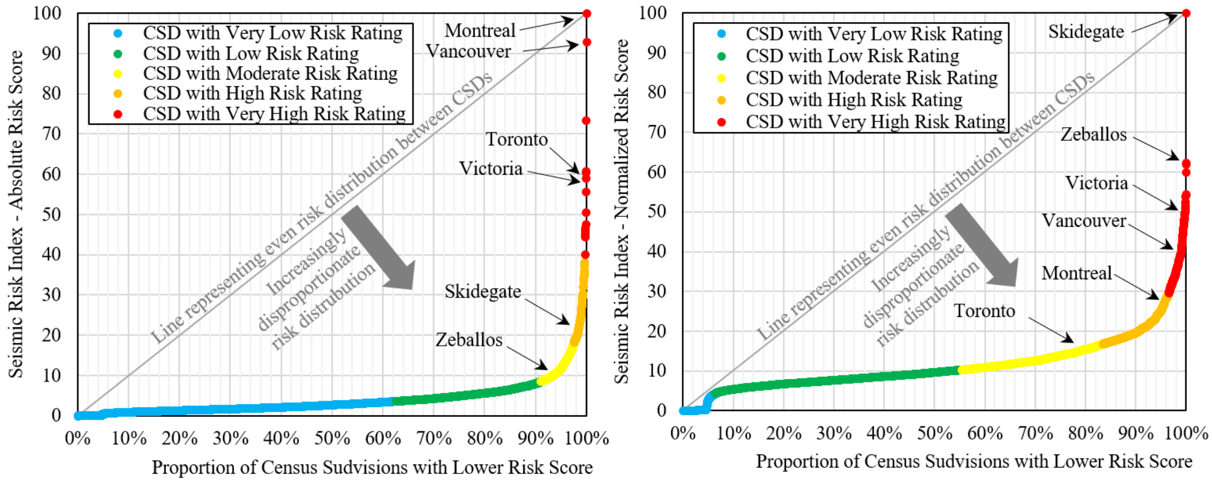


Figure 9. Distribution of the Normalized and Absolute Seismic Risk Index Scores for all census subdivisions in Canada. Each census subdivision is colored by its associated risk rating. A selection of municipalities is labelled for illustrative purposes.

CONCLUSIONS

This work highlights some key results of Canada's first generation national seismic risk assessment, which was carried out in pursuance of the Sendai Framework targets. Results indicate that seismic risk is very unevenly distributed across the country, with only a small handful of cities holding an oversized share of the Average Annual Loss and Annual Probable Life Loss. These same cities, which include Montreal, Vancouver, Surrey, Richmond, Victoria, Ottawa, and Toronto, also tend to hold the highest Seismic Risk Index scores, which take into account physical and social elements of earthquake risk. This may come as a surprise to residents of eastern Canadian cities like Ottawa, Montreal, and Toronto, where risk perception is relatively low [16]. Risk here is largely driven by high exposure of older, more vulnerable building stock than found in the more seismically active western Canada.

Although the highest losses are expected from cities, results also warn of high loss ratios in more rural parts of British Columbia and the Yukon. Through the Seismic Risk Index, individual municipalities with higher vulnerability can be effectively prioritized for risk reduction.

This analysis shows that a small fraction of buildings make up the majority of the seismic risk in Canada. In particular, pre-code buildings constructed before the early 1970's are responsible for 77% of the Annual Probable Life Loss, while making up 50% of the total exposed assets in Canada. In terms of construction materials, wood frame housing represents the highest contribution to Average Annual Losses, due to the preponderance of wood construction throughout Canada. Concrete and unreinforced masonry, however, are responsible for almost 50% of the Annual Probable Life Loss, far outpacing their share of exposure. These findings may help in creating a mitigation strategy for existing buildings.

These results should be considered a lower bound to the seismic risk, because there are many factors not considered at this time. These include secondary perils, disruption costs, and loss to linear or vehicular assets. Many of these features are in development for the second generation seismic risk model for Canada.

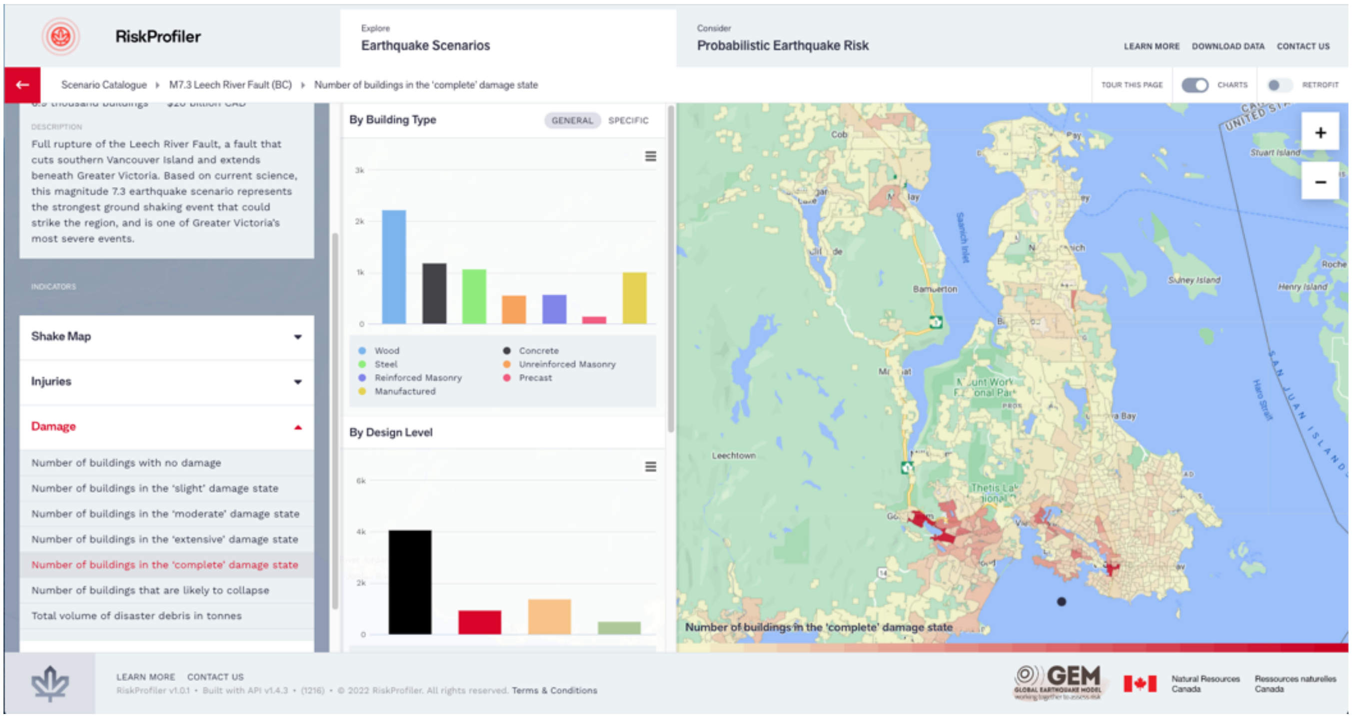


Figure 10. Screenshot showing the RiskProfiler web application, for a magnitude 7.3 scenario event along the Leech River Fault.

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