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**GEOLOGICAL SURVEY OF CANADA
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seismic risk model**

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Scientific Basis of Canada's First Public National Seismic Risk Model

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Abstract

Natural Resources Canada, in partnership with the Global Earthquake Model Foundation, has prepared a public Canadian Seismic Risk Model to support disaster risk reduction efforts across industry and all levels of government, and to aid in Canada's adoption of the Sendai Framework for Disaster Risk Reduction. Developing this model has involved the creation of a national exposure inventory, Canadian specific fragility and vulnerability curves, and adjustment of the Canadian Seismic Hazard Model which forms the basis for the seismic provisions of the National Building Code of Canada. Using the Global Earthquake Model Foundation's OpenQuake Engine (OQ), risk modelling is completed using both deterministic and probabilistic risk calculations, under baseline and simulated retrofit conditions. Output results are available in all settled regions of Canada, at the scale of a neighbourhood or smaller. We report on expected shaking damage to buildings, financial losses, fatalities, and other impacts such as housing disruption and the generation of debris. This paper documents the technical details of the modelling approach including a description of novel datasets in use, as well as preliminary results for a magnitude 9.0 earthquake on the Cascadia megathrust and nation-wide 500 year expected probabilistic losses. These kinds of results, such as earthquake scenario impacts, loss exceedance curves, and annual average losses, provide a quantitative base of evidence for decision making at local, regional, and national levels.

1 Introduction

Globally, it is estimated that 1 in 3 people are exposed to earthquakes (Corban et al., 2017). In Canada, a similar proportion of inhabitants are exposed to ground shaking intensities at the 1-in-2475 return period that are capable of causing structural damage, with that number being closer to 1 in 2 for high hazard areas in British Columbia (BC) and Quebec. While many in Canada have not experienced damaging earthquakes, destructive earthquakes have occurred in the past (Cassidy et al., 2010; Lamontagne et al., 2018) and are sure to occur again in the future. This is particularly alarming as our population grows and development extends further into high hazard areas.

For decades, Natural Resources Canada (NRCan) has been developing seismic hazard models, with the most recent edition being the 6th Generation Seismic Hazard Model of Canada (CanSHM6) (Kolaj et al., 2020a,b). Canada has also adopted the Sendai Framework for Disaster Risk Reduction (United Nations Office for Disaster Risk Reduction, 2015), which outlines achievable goals and prioritizes the quantification of risk. To support implementation of this framework alongside international agencies, NRCan has partnered with the Global Earthquake Model Foundation (GEM) to implement national-scale assessments of seismic hazard (Kolaj et al., 2020b; Pagani et al., 2020) and risk (Silva et al., 2020) into GEM's global mosaic. The initial version of the risk model (Silva et al., 2020) was based on the CanSHM5 hazard model (Adams et al., 2015) and supporting framework datasets, and was intended to establish a baseline for refinements leading up to release of the current model: the 1st Generation public Canadian Seismic Risk Model (CanSRM1). Using updated models for hazard, site conditions, exposure, vulnerability, and fragility information this new risk model reports the physical risk to Canadian buildings and their occupants. It considers both deterministic (scenario) and probabilistic risks. These models will provide a base of evidence for policy development and planning across multiple end users including: community planners, emergency managers, policymakers, financial analysts, citizen groups, academics, and governmental agencies at the municipal, provincial/territorial, and federal level.

Herein, we report upon the scientific basis of the risk assessment and some preliminary results. We provide a technical description of CanSRM1, reserving an in depth discussion of the motivation and outcomes for future work. The latter will be more suited to a broad and nontechnical audience, whereas the current document will go into detail as to the modelling approach and input datasets used. It will describe the existing datasets that were considered, and outline modifications that were made for this assessment. It will also provide sample initialization scripts, with the goal of providing all information required to reproduce CanSRM1 using the OQ Engine. All values are reported in Canadian Dollars (CAD) unless otherwise noted. Secondary hazards such as fire-following, liquefaction, earthquake triggered landslides, and tsunami are not considered in this version as they either cannot be computed routinely in GEM's OpenQuake software or the requisite information to do so is not currently available at a national scale in Canada. That said, given the challenges of analyzing seismic risk at a detailed level for geographically large regions like Canada, this

work will likely be of interest to other countries conducting similar national-level assessments.

2 Modelling Approach

Physical seismic risk is the combination of hazard, exposure, and fragility — each of which is outlined below.

2.1 Seismic Hazard Model

Seismic hazard describes the hazard posed by earthquakes to a specific location and is typically quantified as the expected amplitude of ground shaking with an associated probability of being exceeded during a given time period. A seismic hazard model is composed of seismic sources which describe the spatial distribution, magnitude and rate of earthquakes, and Ground Motion Models (GMMs) that provide values of ground motion intensity parameters (ex. Peak Ground Acceleration) as a function of the earthquake source, path, and site characteristics. An equally important aspect of seismic hazard analysis is the careful characterization and inclusion of uncertainty. Aleatoric uncertainty, related to the random aspect of seismic phenomena, is incorporated directly into the source and ground motion characterization (e.g., standard deviation about median ground motions). Epistemic uncertainty, which is related to gaps in our knowledge and data, is incorporated through the use of a logic tree (ex. Kulkarni et al., 1984; Bommer and Scherbaum, 2008).

The CanSHM6 (Kolaj et al. 2020a,b) is the latest seismic hazard model produced by NRCan and represents our best national estimate of natural seismic hazard in Canada. CanSHM6 was also adopted as the basis for seismic hazard values for the 2020 edition of the National Building Code of Canada (NBCC) such that earthquake-resistant engineering can be appropriately utilized across Canada. CanSHM6 includes recent advancements in understanding of the recurrence of great subduction earthquakes; revisions in the geometry of deep, in-slab earthquake sources; the adoption of new ground motion models; and the addition of newly-discovered potentially-active faults. The model has now also directly incorporated site-effects into the hazard calculation, providing fully probabilistic hazard values for a range of V_{s30} (time-averaged shear wave velocity of the upper 30 m) values and Site Classes. Model implementation has also transitioned from legacy earthquake hazard software to the OpenQuake engine (Pagani et al., 2014). A brief overview of the main model components is described below; interested readers are referred to Kolaj et al. (2020a,b) for more complete details.

2.1.1 Seismic Sources

The CanSHM6 source model consists of areal and fault sources within three sets of regionalized seismic source models: southeast, east-arctic and west. For the majority of sources within the three geographic zones, three separate activity rates (representing the high, central and low values), estimated from the catalogue of Halchuk et al. (2014, 2015), are used in the logic tree to represent the epistemic uncertainty in the magnitude-recurrence parameters.

For the southeastern model, three alternative source models are considered based on different interpretations of long-term seismicity rates in stable intra-plate settings, considering historical seismicity, observed seismicity along seismotectonic structures, or a hybrid between the two (Adams, 2011; Adams et al., 2015). Similarly, the eastern-arctic Canada model includes two source models to account for different interpretations of long-term rates from historical data and structures. The southeastern and eastern-arctic models use only areal sources. In contrast, for western Canada, a single source model is used, which includes both areal and fault sources. This model includes epistemic uncertainty in the geometry and activity rates of fault sources. The western model includes faults for the Cascadia Subduction Zone, including the Juan de Fuca, Explorer and Winona segments; faults in the Alaska-Yukon-BC region; and along the boundary between the Pacific and North American plates. In contrast with the other two regional models, there is no splitting into historical and seismotectonic models as the historical activity is expected to be representative of long-term rates.

2.1.2 Ground Motion Models

The GMMs used in CanadaSHM6 are described in Kolaj et al. (2020a) and summarized in Table 1. All GMMs include a site term characterized by V_{s30} : the time-averaged shear wave velocity of the upper 30m of subsurface that indicates whether the site conditions are likely to amplify (or reduce) reference-condition ground motions. In contrast to the hazard model which provides hazard maps for specific reference V_{s30} values, the risk model considers variable V_{s30} values across Canada. For CanSRM1, the values for V_{s30} are obtained from the global United States Geological Survey (USGS) database, which uses topographic slope as a proxy for V_{s30} (Wald and Allen, 2007; Allen and Wald, 2009). The V_{s30} is calculated at every asset location and at a 10 km background grid spacing where there are no buildings. While this is a useful model in that it allows us to consider the effect of site conditions on risk at a national level, the slope proxy for V_{s30} does not perform well in regions that have undergone previous glaciation (ex. Cannon and Dutta, 2015; Wu et al., 2020) or volcanic environments. Because the former refers to large portions of Canada, this model could be greatly improved by using regional models or by including terrain-based corrections to V_{s30} proxies (ex. Wald et al., 2011; Ahdi et al., 2017).

2.1.3 The Simplified National Model

The CanSHM6 was simplified to be computationally tractable for risk calculations. In the full version of CanSHM6, each source in each source model includes 9 branches for the magnitude recurrence parameters (the product of three activity rates and three maximum magnitudes). These 9 branches were collapsed to a single “collapsed” branch by finding the weighted sum of the resultant magnitude frequency distributions. Collapsing the branches in this manner preserves the mean hazard but will underestimate the full epistemic uncertainty. Although the simplification was intended for mean-hazard estimates for the National Building Code of Canada, this simplification process was augmented for CanSRM1, as follows. CanSHM6 is regionalized into three subregions: west, east and east-arctic (Kolaj

et al., 2020b). Hazard was computed independently for each region, with the larger hazard being adopted for overlap areas (this is referred to as a “robust” hazard value). However, for the CanSRM1 implementation in OpenQuake, a single national model was required. The development of the national model is described in Halchuk et al., 2022 (in preparation). In short, the three regional models, and their epistemic variations, were combined to form a national source model composed of 6 epistemic branches, which encompass each unique combination of source models for the three regions. Opportunity was also taken to correct several sources in northwestern Canada, specifically the Alaska Interface Source (Halchuk et al., 2022). Elsewhere, the national model, in general, reproduces the mean hazard values of the original CanSHM6 regional model.

One other modification of CanSHM6 is in the weights assigned to the stable crust GMMs. The NGA-East GMMs (Goulet et al., 2017, 2021) recommend the use of period-dependent weights for the logic tree (i.e., the branch weights in the logic tree change as a function of the ground motion period). Sample calculations testing the proposed weights for each period found a negligible impact on mean hazard estimates for probabilities relevant to the building code. As this type of weighting is not possible for risk calculations in the OpenQuake Engine (and thus for CanSRM1), a single weighting scheme was implemented based on the weights for the spectral acceleration of 0.3 seconds — the most common spectral acceleration used in CanSRM1 for Canadian building stock.

2.2 Exposure

A detailed summary of the exposure model, how it was developed, and key findings about the current state of Canada’s building stock are summarized in Journeay et al. (2022a). A brief summary of the dataset and how it was generated is provided below.

The exposure model includes a representative national inventory of buildings, building occupants, and replacement value of buildings generated at the scale of a Settled Area (SA). SAs approximately delineate areas of building development in Canada, and are the smallest geometry used for calculating seismic risk in CanSRM1. In urban areas, a SA boundary generally corresponds to a Census Dissemination Area (DA), which is often less than one square kilometer. In rural areas, DAs, which are contiguous across the entire land mass of Canada, can span more than thousands of square kilometers, so SA boundaries, which are not required to be contiguous, approximately correspond to areas where building clusters are actually situated. This is crucial for hazards that vary in intensity across spatial scales less than a single rural DA.

The representative building inventory includes a collection of points with locations at the centroids of SAs. Each point represents buildings with identical occupancy, construction type, and seismic design level, defined here as ‘building archetypes’, and summarizes the number of occupants in those buildings at different times of day, and the replacement value of those buildings and their contents. Taxonomies used for building occupancy and construction type are based on standard HAZUS classifications (FEMA, 2021), with some adjustments to account for Canadian building conditions (Tables 2-4). Seismic design levels are based on the approximate building code requirements at the time of construction, and

are assigned to buildings using the criteria in Table 4. This approach assumes that all buildings met existing seismic standards at the time of their construction. The inventory of buildings of different occupancies is derived from residential population and dwelling statistics from the national census provided at the census dissemination area level (Statistics Canada, 2016), and from georeferenced business listings that describe non-residential buildings based on the North American Industrial Classification Standard (Dun & Bradstreet, 2011). The portfolio of distinct building archetypes within each settled area is based on mapping schemes that relate detailed characteristics of land use to the corresponding mix of specific building occupancies and associated construction types of a particular time period that are likely to be present at a given location. Mapping schemes are calibrated using surveyed building inventories for metropolitan regions in southwest BC and the St. Lawrence Lowland region of southern Quebec where the relationships between building occupancy and construction type for a given land use class have been established at the parcel level through direct observation (Onur, 2002; Journeay et al., 2015; Ploeger et al., 2018). Regional adjustment factors are used to account for variations in construction practices based on general building type information compiled by Statistics Canada (1991) and broad patterns established as part of the FEMA HAZUS model (FEMA, 2012, 2006). The number of occupants in buildings are estimated for daytime, nighttime, and transit hours (9am-5pm; 7pm-7am; and 7am-9am plus 5pm-7pm, respectively). Occupants in residential buildings are estimated based on national housing statistics that report the average number of dwellings of a given building occupancy class for each census dissemination area in Canada (Statistics Canada, 2016), as well as approximations of the proportion of nighttime occupants in residential buildings at different times of day (FEMA, 2012). Occupants in non-residential buildings are estimated based on approximations of the average number of people per 1,000 square feet by the total finished building area for each building occupancy classification (Hamburger et al., 2012). Replacement values are provided for structural, non-structural, and contents components of buildings. These are estimated based on industry standard construction costs (CAN\$/ft²) for building construction types (Moselle, 2015; Turner & Townsend, 2017; Altus Group, 2020), and on regional variations in price estimated using the Canadian Consumer Price Index (Chiru et al., 2015).

In total, the model characterizes 35.2 million people in 9.7 million buildings with a total approximate replacement value of \$8.2 trillion (2019 equivalent). Most buildings are single-family wood-frame structures (75%, 7.17 million buildings). Unreinforced masonry buildings, which can be highly vulnerable to seismic shaking relative to other building types in Canada (Fathi-Fazl et al., 2019), make up approximately 8% of the building stock, with the majority being located in Ontario and Quebec (61% and 16%, respectively, of the total stock of unreinforced masonry buildings).

2.3 Fragility and Vulnerability

Fragility and vulnerability functions, which relate seismic intensity to damage states and economic loss ratios, respectively, were developed specifically for Canada starting from the capacity curves listed in HAZUS (FEMA, 2014). The original HAZUS fragility curves are

conditioned on spectral displacement rather than spectral acceleration, making them inconvenient to use directly in risk analysis where the hazard curves or ground motion fields are in terms of spectral accelerations. Instead, as described in Rao et al. (2017) and Martins and Silva (2020), the bilinear capacity curves provided by HAZUS are adapted for use in nonlinear time-history analysis following the general methodology outlined in Karaca and Luco (2008) and Ryu et al. (2008) and are described below. Through a collaboration with the University of BC, further adaptations were made to wood and unreinforced masonry building classes by altering their yield and ultimate drift to be in line with Canadian construction practices.

Several Single Degree of Freedom (SDoF) models are generated for each building class using these adapted capacity curves and a pinching hysteretic model (ex: Ibarra et al., 2005), and non-linear time-history analysis is performed for each of the models using the FEMA P695 set of far-field records (Applied Technology Council and United States. Federal Emergency Management Agency, 2009). For these analyses, scaling of ground motions from FEMA P-695 is performed for 3 Intensity Measure (IM) levels: spectral accelerations of 0.3, 0.6, and 1.0 seconds. Pertinent IMs are then selected for each typology based on the natural period of vibration or resonance for structures of a given building area and height. Each set of records contains scaled ground motions for IM levels of 0.05 to 2.5 g, with the maximum scaling factor constrained to 2.0. Per HAZUS recommendations, the variability in the capacity within each building class is modeled by assuming a dispersion $\beta = 0.25$ for High-Code, Moderate-Code, and Low-Code buildings, and $\beta = 0.30$ for Pre-Code buildings. Then, for each iteration of a Monte-Carlo simulation for a particular building class, a capacity curve is sampled to build the SDoF structural model (assuming the capacity parameters to be lognormally distributed), and a set of limit-state thresholds is sampled as well. For each building class, a set of fifty Monte-Carlo iterations are used in order to propagate the building-to-building variability. To capture the record-to-record variability in the structural response, the SDoF model in each iteration is subjected to a suite of 44 ground motion records from the FEMA P-695 far-field set. The median values of the spectral displacements at the threshold of the different damage states are taken from HAZUS, and a lognormal distribution is assumed for the damage state threshold. The uncertainty in the damage-state threshold of the structure is modeled by assuming a dispersion $\beta = 0.40$ for all structural damage states and building types, as recommended by HAZUS. The results of time-history analyses are used to estimate, through regression, the probability distribution of a set of engineering demand parameters conditional on IM values.. Using those engineering demand parameter values obtained from the time-history analyses and the median and dispersion of damage state thresholds from HAZUS, the current set of fragility functions are obtained and expressed as a probability of falling into each of the damage states (Figure 1).

To derive the vulnerability functions from the fragility functions, the HAZUS building repair costs ratio tables for each damage state (expressed as a percentage of the replacement cost of the building) are employed, and for each IM level, a sum-product of the probabilities of occurrence of each damage state and the corresponding repair cost ratios yields the mean loss ratio for that IM level. These repair cost ratios are assumed to be mainly dependent on the occupancy class rather than the building type, and default values are provided in HAZUS

for each of the four damage states and the three building components – i.e. structural, nonstructural drift-sensitive and nonstructural acceleration-sensitive. Thus, the vulnerability model files have separate functions for every combination of the 33 occupancy classes and the 220 building types, for a total of 7,260 vulnerability functions for the structural components, non-structural components, and building contents.

Vulnerability functions for the building occupants are derived from the structural fragility functions, using the fatality rates for each damage state for each building and occupancy class (FEMA, 2012). The complete damage state is split into two fractions for this purpose, i.e., complete damage without collapse of the structure, and complete damage with collapse, since the fatality rates for collapsed buildings are expected to be significantly higher than for buildings that are classified as a complete write-off in terms of economic loss but where the structure may not have suffered collapse. For each IM level, a sum-product of the probabilities of occurrence of each damage state and the corresponding fatality ratios yields the mean fatality ratio for that IM level.

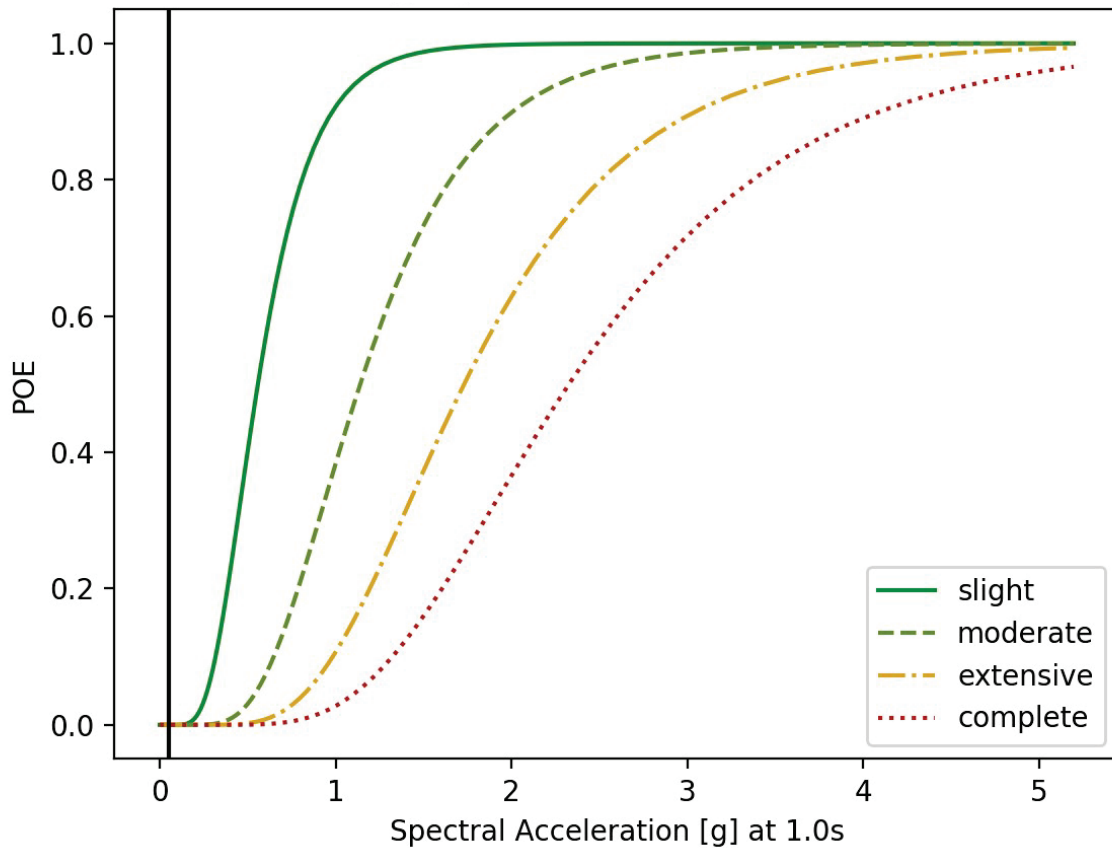


Figure 1: Example fragility function for a high rise, concrete shear wall, residential building, showing the probability of exceedance for each of 4 damage states. These functions are based on spectral acceleration, expressed in units of g , conditioned on 1.0 second. The vertical black line at a spectral acceleration of $0.05 g$ represents the minimum intensity threshold used for probabilistic risk calculations, described in Section 3.3

Although HAZUS used only two wood building classes, the exposure dataset for Canada contains four wood building classes to better represent the variability of timber construction in Canada: light frame wood, light frame wood with cripple wall or subfloor, heavy frame wood industrial/commercial, and heavy frame wood residential. Work is ongoing to develop fragility and vulnerability functions for these new building classes, but currently there are only fragility and vulnerability functions for the original set of HAZUS building classes. Therefore, a taxonomy mapping file is used to assign the Canadian wood building types back to the original HAZUS options (Table 5).

2.3.1 Retrofit

The retrofitting of buildings, whereby the structural or nonstructural components of an existing building are upgraded to improve building performance to seismic shaking, is an important tool in reducing risk. Based on a comprehensive review of over 4,000 federal mitigation programs commissioned by the US National Institute of Building Sciences (Multihazard Mitigation Council, 2005, 2019), researchers found that one dollar in mitigation investments by federal agencies in the US results in four dollars of accrued benefits. Complementary studies of global disaster risk reduction efforts have shown that the benefits of proactive investments in mitigation and adaptation can outweigh the costs by a factor of approximately 5:1 for damaging earthquakes (Shreve and Kelman, 2014). While the rationale and evidence for substantial returns on disaster risk reduction investments are clear, there remain significant barriers in transforming this knowledge into actions that are needed to build disaster resilience at the community level in Canada.

CanSRM1 provides a base of evidence for evaluating the outcomes of different policies for management or retrofit of existing buildings, by considering what the impact would be of raising the seismic design level of the current building stock. This is simulated by reassigning, to higher values, the fragility and vulnerability functions, applied to building typologies within the exposure file within OQ. The assignment strategy was developed through consultation with Canadian engineers and subject matter experts, to better understand what kinds of retrofits are actually occurring and what kinds of precedents exist for retrofitting policy, as documented by Hobbs et al. (2021a). In general, most buildings that get retrofitted are modified with the intent to bring the structure to 60-80% of the current building code, which is roughly equivalent to a moderate code level in the exposure file. Therefore, the baseline retrofit assumption is that anything below moderate code would be brought to that level. Exceptions are made for buildings with intended post-earthquake functionality and those with unreinforced masonry elements. The former, hospitals and government emergency facilities (COM6 and GOV2 in Table 2), are assumed to be retrofitted to a high code level in order to retain functionality. The latter are limited to a low code level, due to the impractical nature of modifications to these building types (S5, C3, and URM in Table 3).

CanSRM1 models retrofit scenarios by assuming that every eligible building undergoes a retrofit, for computational simplicity, but it is up to the user to select relevant portfolios when calculating the benefits of retrofit. For example, one might wish to understand the benefit of a retrofit program for concrete high rises in their municipality. To do this, they

would compare the baseline conditions against the retrofitted results for those buildings only. When developed strategically, targeted retrofit programs like these, wherein only a small fraction of the building stock is modified, can produce considerable financial savings in the events of a major earthquake, as well as reduced damage to buildings, fewer injuries, and less down time.

This retrofit modelling approach, while useful, assumes that retrofitted performance is equivalent to the performance of newer versions of the same building typology rather than accounting for the observed performance of specific retrofit interventions used, such as tie-downs or diagonal bracing between stories. This renders it slightly less accurate and less specific, although broadly informative.

3 Risk Analysis

3.1 The OpenQuake Engine

Analyses are performed using the OQ engine (Pagani et al., 2014; Silva et al., 2014; GEM, 2020), a seismic risk assessment software built by the GEM Foundation. The Geological Survey of Canada (GSC) deploys OQ version 3.11.0 on an Amazon Web Services (AWS) EC2 Instance to meet the processing demands of the national model and large scale scenarios. Hazard, damage, and risk calculations are run directly in OQ to calculate the shaking, damage to buildings, and the financial and human losses, respectively. For all calculations, we utilize a default 3 sigma uncertainty (the Gaussian ‘truncation level’ parameter in OQ). Notably, this is slightly lower than in CanSHM6 where sigma is set to a value of 5. This simplification is not expected to have a large impact on national-level results but was required for computational efficiency.

3.2 Deterministic Assessment

The deterministic, also known as scenario, portion of the CanSRM1 model considers the impact of individual earthquake scenarios. This is useful because scenarios are often used for emergency management planning, and because we are able to model greater detail at the scenario level than we can using a probabilistic approach (Section 3.3).

For the deterministic portion of the model we use the scenario hazard, damage, and risk calculators native to the OQ Engine (GEM, 2020). ‘Consequences’, such as building disruption times, injuries, generation of debris, and impacted residents or employees, are calculated using a separate python script (Appendix 11.3) to implement the heuristics introduced in HAZUS (FEMA, 2012). Some further generation of indicators is completed in post-processing, described in Section 3.4. Sample initialization files are provided in 11.1.

Scenario outputs are described in detail in Hobbs et al. (2021b), and outlined here. Hazard outputs are available at SA centroids, superimposed on a background grid with 10 kilometre point spacing for unpopulated regions. Hazard indicators include peak ground acceleration (PGA) and spectral acceleration at various periods of engineering interest (0.1,

0.2, 0.3, 0.5, 0.6, 1.0 and 2.0 seconds). Damage, risk, and consequence results are available at the asset level (tied to SA centroids) only, and report upon

- the expected (average) damage state of buildings,
- the ratio of damaged to total buildings,
- the required time to complete various stages of recovery,
- the volume of debris generated,
- the number of people in various casualty states at various times of day,
- the number of affected residents and employees through time,
- the number of households who will be displaced,
- the number of individuals who may seek mass shelter,
- the financial losses expected from assets and their components (excluding indirect losses), and
- the associated loss ratios.

All of these indicators, totalling over 50, are available for the baseline condition as well as the simulated retrofit condition.

The scenario model aims to establish a uniform procedure for assessing deterministic seismic risk in Canada, and to provide a catalogue of vetted scenarios for practitioners and researchers. In keeping with this objective, scenarios are selected generally based on historic events, paleoseismic earthquakes or known faults without well-characterized rupture geometries. Where possible, geometries and magnitudes are pulled directly from CanSHM6.

The first set of scenarios in the deterministic catalogue were selected to meet the needs of practitioners such as emergency managers and policy makers. These users are typically asked to report on scenarios which are already in the public discourse, such as a large megathrust event on the Cascadia subduction zone or shallow crustal events near urban centres on the West Coast. For these users we aim to select earthquake scenarios which are based on historical precedent, so-called ‘worst case’ planning, or responding to a well-documented threat (ex: Cascadia, Leech River). Therefore, the initial round of earthquakes in the scenario catalogue should equip planners to conduct their work in regions of concern across Canada, including: Vancouver Island, Metro Vancouver, Whitehorse, Ottawa-Gatineau, Montreal, and the St. Lawrence-Charlevoix region.

3.3 Probabilistic Assessment

The probabilistic portion of CanSRM1 considers the likelihood of all earthquakes in a given time period to produce an estimate of the probable impact from all sources of seismicity. It provides information about expected building damage, financial loss, and fatalities from long term seismicity in Canada.

For the probabilistic portion of the model we primarily use the stochastic damage and risk calculators of OQ (GEM, 2020). The benefit of the stochastic calculations is that we are able to aggregate results for multiple assets, whereas classical calculations produce probabilities for each asset which cannot mathematically be aggregated. To reduce the memory burden for calculations, we set the minimum intensity, minimum magnitude, maximum distance, and, in the case of the nationwide stochastic risk runs, minimum asset loss as outlined in Table 7 to reduce the number of moot calculations that the engine needs

to perform and save. The thresholds used are selected to ensure that the impact on the risk will be negligible, such as from small and/or distant earthquakes and from spectral accelerations that are too small to produce damage (Figure 1). Sample initialization files are provided in 11.2.

The probabilistic portion of the model contains information about damage and risk, available at several scales. Damage results report on the probability and number of buildings expected for various damage states, over a 50 year horizon. Those results are available at the asset level (tied to SA centroids). Risk results include average annual losses/ratios and fatalities at the asset level, and expected losses for various return periods from 50 to 2,500 years at the Forward Sortation Area (FSA), provincial/territorial level, or national level. Expected losses are reported in terms of their mean value as well as the 5 and 95% quantiles. Together, this set of results allows one to investigate the probabilistic financial losses, casualties, and building damages expected over time periods of interest, at spatial scales relevant to end-users such as community planners, insurance sector, and financial regulators.

To make computations tractable, the national exposure dataset is subdivided into files with up to 81,000 assets — the upper limit that can be handled with available memory based on test runs with various sizes of exposure files. However, files needed to be kept as large as possible to limit the total number of runs. As aggregate stochastic risk outputs involve ranking observed annual losses for a given set of rupture events (Silva, 2018), outputs from one run cannot be combined with results from other runs. Therefore, the goal becomes to combine assets that are relevant to one another into exposure files that are close to but not more than about 81,000 assets. ‘Relevancy’ is determined as regions which are likely to be grouped by practitioners.

To achieve the exposure subdivision as outlined in the preceding paragraph, the national exposure file was first subdivided along provincial and territorial boundaries. Where a province or territory has more than 81,000 assets, it must be further subdivided. We manually created groups of Census Divisions (Statistics Canada, 2016) that were geographically and/or regionally connected to one another (Table 6). Where an individual Census Division was greater than the asset threshold, as is the case for Toronto, Vancouver, Calgary, and Edmonton, they were further broken down, by Census Subdivision (CSD), between urban and suburban areas or geographically by cardinal directions. The algorithm for splitting exposures is available on <https://opendrr.github.io>.

3.4 Post Processing in SQL

After calculations are completed, the results are imported into a PostgreSQL database and a series of SQL scripts are used to compute shelter needs, displacement, seismic risk index, and a selection of other standardized indicators. We then push the data into an Elasticsearch database for easy access through API calls, and prepare versions of the results for cataloguing in a public federal scientific data repository. The details of this post-processing workflow will be made available in van Ulden et al., 2022 (in preparation), but the relevant portions that underlie the scientific results are reported herein.

3.4.1 Displaced Households

Per Section 13.2 of the HAZUS Technical Manual (FEMA, 2020), the number of displaced households is calculated based on the probable damage state a building is in and the type of housing affected. Single family households are more likely to stay in their home, either inside or in a tent in the backyard. Therefore, the threshold for being displaced is lower in multi family homes.

The form of the displaced households equations, modified from FEMA (2020) equations 13-1 to 13-3, are:

$$D = (w_M * M) + (w_E * E) + (w_C * C) \quad (1)$$

and

$$DH = U * D \quad (2)$$

where

D = the weighted probability of displacing damage

w_M, w_E, w_C = weight factors for damage states, described in Table 8

M = the probability of moderate structural damage

E = the probability of extensive structural damage

C = the probability of complete structural damage

DH = the number of displaced households

U = the number of units

The notation used here does not split the calculation into single family (SF) or multifamily (MF) components, as was done in FEMA (2020), because the calculation is performed at the asset level. In this case, an asset cannot simultaneously be both a single family and multifamily asset. The weights, however, are specific to the number of families per building, as shown in Table 8.

3.4.2 Public Shelter Needs

In Section 13.3 of the HAZUS Technical Manual (FEMA, 2020), the number of people requiring shelter after an earthquake is dependent upon multiple factors relating to the physical damage to their dwelling and socioeconomic considerations. Although a clear oversimplification of the nuanced response of individuals to a disaster event, we follow the methodology of HAZUS to attempt to estimate how these factors contribute to the total number of individuals who may seek shelter in mass shelter facilities. This methodology incorporates research findings from previous disasters to estimate the proportion of people belonging to certain groups who will seek mass care, relating specifically to income and ethnicity. There is space in the calculation for factors such as age and ownership, but the weighting of those was set to zero due to a lack of reliable data on how they affect mass care (described in section 13.4.1 and Table 13-2 in FEMA, 2020).

The formulas used in this calculation are reproduced from Equation 13-4 and 13-5 in FEMA (2020), eliminating age and ownership factors as they are unweighted:

$$STP = \sum_{i=1}^5 \sum_{j=1}^5 \left(\alpha_{ij} * \left[\frac{DH * POP}{HH} \right] * HI_i * HE_j \right) \quad (3)$$

$$\alpha_{ij} = (IW + IM_i) + (EW * EM_j) \quad (4)$$

where

STP = the number of people seeking mass care

DH = the number of displaced households in the SA

POP = the population in the SA

HH = the number of households in the SA

HI_i = the percentage of the population in the *i*th income class (Table 10)

HE_j = the percentage of the population in the *j*th ethnicity class (Table 10)

IW, EW = weighting factors, described in Table 9

IM_i, EM_j = modification factors, described in Table 10

Modification and weighting factors are taken directly from FEMA (2020) and references therein (Harrald, 1992; Harrald et al., 1994), and displayed in Tables 9 and 10. Values are identical to HAZUS, except for ethnicity, in which case the categories used are 'Visible Minority', 'Indigenous', and 'Neither'. The 'Indigenous' modification factor is based on the HAZUS 'Native American' value, and the 'Visible Minority' factor is the average of HAZUS's values for 'Asian', 'Black', and 'Hispanic'. Notably, although ownership and age are included as categories, their weighting is set to 0. This was a decision made by HAZUS, presumably due to the shortage of appropriate data with which to quantify the effect these categories have on shelter seeking. HAZUS also reports that weather is likely to have an impact on shelter seeking behaviour, as the family car and tents in the backyard were common alternate shelter locations that are less suitable in much of Canada if the earthquake does not occur during the summer.

3.4.3 Seismic Risk Index

The seismic risk index is a useful tool to identify communities most at risk from earthquakes in Canada, and can be used to support strategic disaster risk reduction decision making such as resource allocation and prioritization. It builds on physical risk outputs of the probabilistic portion of the CanSRM1 model, by including a consideration of social vulnerability that makes evident the groups who are likely to be most affected by underlying conditions that limit capacities to withstand, cope with and recover from future disaster events. It combines estimates of annual expected life loss and economic loss generated from CanSRM1 with a modifier for social vulnerability to estimate relative seismic risk at every SA and CSD across Canada. Herein, we consider a seismic risk index assessment based on absolute losses, as well as one based on normalized losses. These indices are based on work completed by the United States Federal Emergency Management Agency and the European Commissions Joint Research Council (Tsionis, 2014; Marin-Ferrer et al., 2017; FEMA, 2020).

The Absolute Loss Seismic Risk Index, SRI_{abs} , helps to identify the communities in Canada expected to experience the largest absolute loss. This will predominately include the major urban areas exposed to earthquake hazards such as Vancouver or Montreal, as areas of high exposure within active seismic zones have the potential to experience the highest losses. The SRI_{abs} is calculated for each SA using the following formula (FEMA, 2020):

$$SRI_{abs} = (AAL + (ALL * VSL)) * SOVI \quad (5)$$

where

AAL = the annual average economic loss from seismic shaking, summed over the SA, reported in Canadian dollars

ALL = the annual average life loss from seismic shaking, summed over the SA, reported in a number of persons

VSL = the value of a statistical life, reported in Canadian dollars per person, which is an estimate of willingness to pay for small reductions in mortality risks rather than how much a human life is worth (Andersson and Treich, 2011)

SOVI = an index representing the relative levels of social vulnerability for each SA in Canada (Journeay et al., 2022b).

For this study we use a VSL of \$6.11 million (2004 equivalent) adjusted for inflation (Jenkins et al., 2007). The SOVI index is a unitless integer ranging from 1 (lowest score) to 30 (highest score), and is generated as a composite score of 30 indicators of potential social vulnerability in each SA. The AAL and ALL terms estimate expected consequences from earthquakes, while the SOVI term is a consequence adjustment factor accounting for the level of loss that could be amplified as a result of social factors. It should be noted that similar models used to generate risk indexes (Tsionis, 2014; FEMA, 2020) also include a consequence reducing factor that accounts for the contributions to loss reduction from community resilience (Tsionis, 2014; FEMA, 2020). Currently, there is no national model of community resilience available in Canada, so this factor is not considered.

The SRI_{abs} for CSDs in Canada is calculated by summing over all SAs contained within. Index values for SAs and CSDs are min-max normalized so they can be presented as a value between 0 (lowest score) and 100 (highest score) to support communication and intuitive understanding. Each SA and CSD are also assigned a percentile rank indicating the percent of communities in Canada with a lower earthquake risk index, to potentially provide users of the data with a mechanism for prioritization of resources.

The Normalized Seismic Risk Index, SRI_{norm} , helps to identify the communities in Canada that are expected to experience the largest losses relative to their population and value of assets. This will predominantly include the communities exposed to the highest hazard and/or who have a highly vulnerable building stock, as this index does not scale with increasing exposure.

The SRI_{norm} is estimated for each SA using Equation 5, however normalized values (i.e. loss ratios) for AAL and ALL were used. SRI_{norm} is estimated for each CSD based on the average of values contained within.

4 Sensitivity Testing

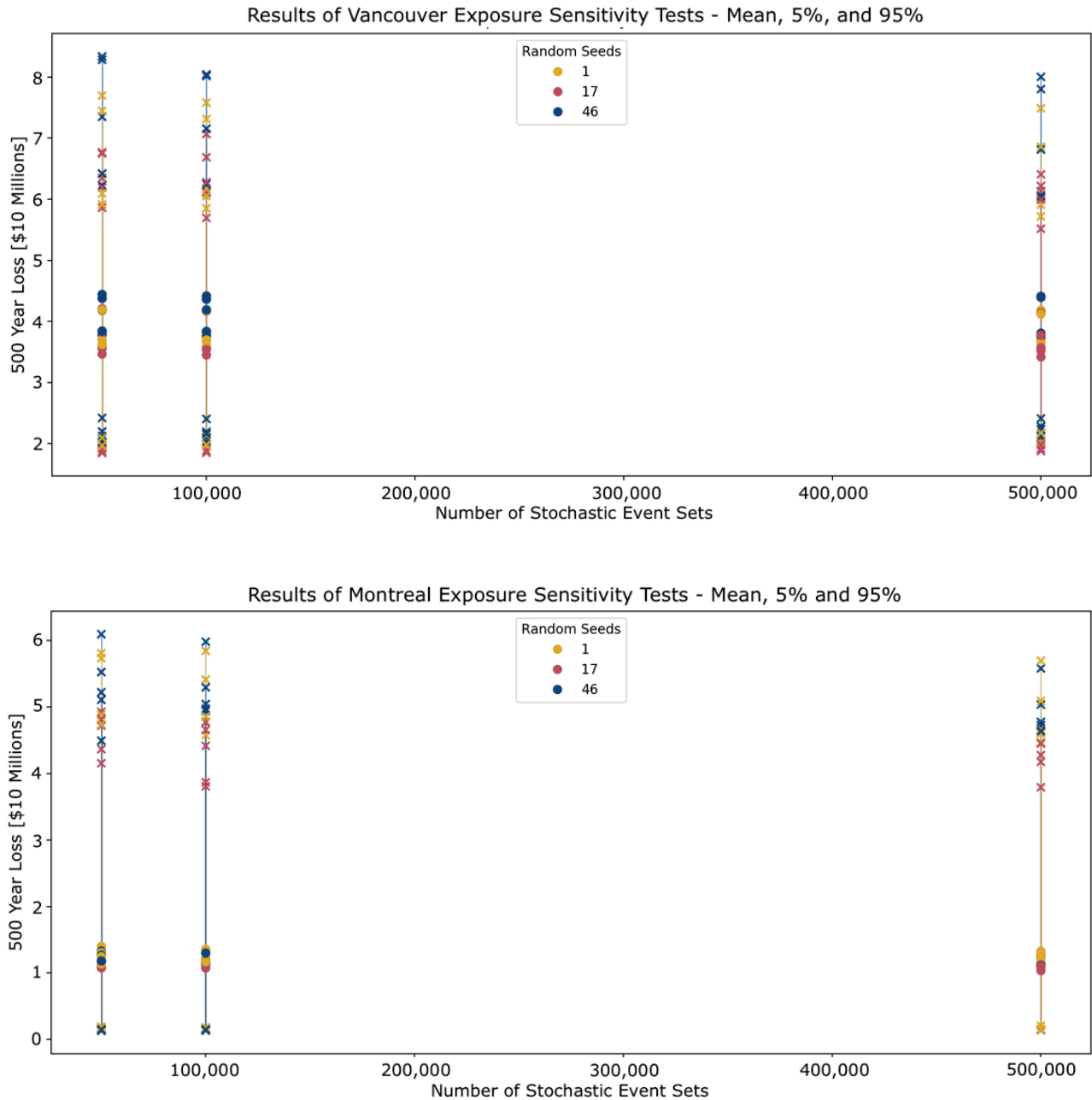


Figure 2: Results of model sensitivity test for eastern and western samples, showing that losses are insensitive to the number of stochastic event sets tested. Mean is represented by filled circles, with crosses representing the 5 and 95% quantiles. Colours are different random seeds, or different sets of selected branches, as shown in the legend. Results show the effect of different numbers of branches, isolated in Figure 3.

If computing power were unlimited, the risk model would consider every branch of the seismic hazard model. However, given computational limits and the large number of

branches (over 24,000) in the simplified Canadian hazard model, compromises are necessary. For

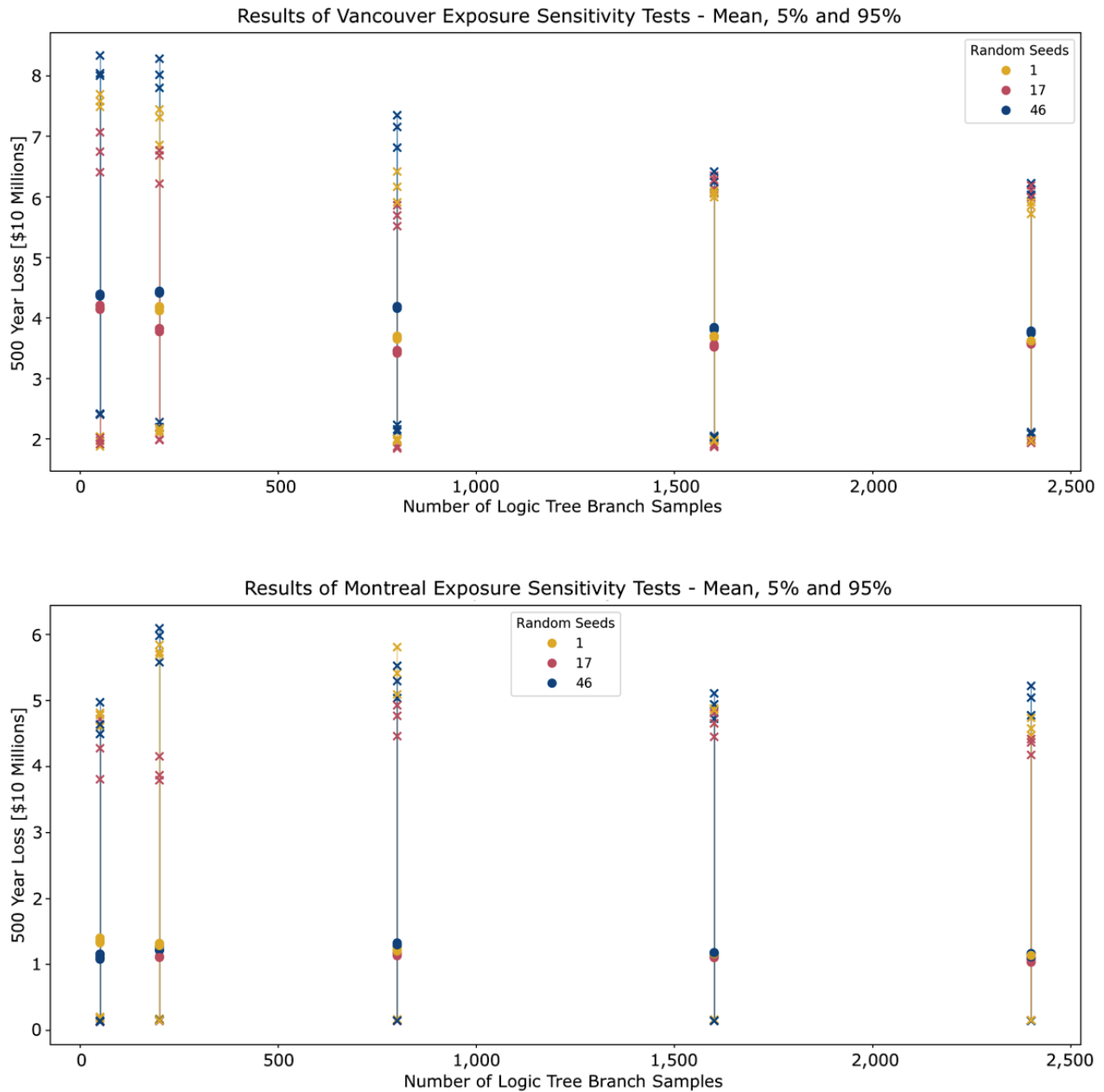


Figure 3: Results of model sensitivity test for eastern and western samples, showing that losses generally decrease with the number of logic tree branches used. Colours are different random seeds, or different sets of selected branches, as shown in the legend. Results show the effect of different numbers of stochastic event sets, isolated in Figure 2.

stochastic calculations, the OpenQuake Engine samples a finite number of branches of the source model (hazard) logic tree and then generates sets of earthquake ruptures for each selected branch (GEM, 2020). These are referred to as stochastic event sets. The product of

the number of event sets, number of branches and the length of the risk investigation time (1 year) will determine the effective length of the synthetic earthquake catalogue being considered for each branch. To ensure appropriate characterization of the sources of uncertainty in the probabilistic model, we performed a suite of sensitivity tests wherein we varied the number of logic tree branches and stochastic event sets, as well as the random seed used in the Monte Carlo sampling (Pagani et al., 2014), to see how these parameters impact our risk assessments. In this case, random seed is a parameter used to ensure there is reproducibility in the random generator of the Monte Carlo sampling. Specifically, we evaluate random seeds of [1, 17, and 46]; numbers of branches of [50, 200, 400, 800, 1600, 2400]; and numbers of stochastic event sets of [50,000, 100,000, and 500,000]. These numbers represent values up to the limits of what could conceivably be computed for the national model on an Amazon Web Services instance with 768 GiB of memory and 96 virtual CPU's. We perform these sensitivity tests on small exposure files in eastern and western Canada, each comprised of a single census aggregate dissemination area (ADA). In Vancouver we use ADA 59150312 and in Montreal ADA 24660143, selected to contain appreciable low and precode buildings as they are the most vulnerable. For all calculations, we consider the mean as well as the 5% and 95% quantiles of the 500 year total financial loss, considering how the parameterization impacts this outcome. It includes loss to buildings from structural and nonstructural elements, as well as contents.

As shown in Figure 2, we found that the mean (circles), 5% and 95% confidence interval (crosses) loss (y axis) was insensitive to the number of stochastic event sets (x axis) considered herein. We do suspect there is a lower limit on the permissible effective catalogue length (number of stochastic event sets multiplied by the risk investigation time), in that it must be sufficiently long to generate event sets that are representative of the long term hazard. For this reason, we would caution against the use of catalogue lengths less than at least double the longest recurrence interval of interest. In Canada, where faults may have recurrence intervals of thousands of years or more, we suggest a minimum catalogue length of over 20,000 years.

The number of logic tree branches, however, does slightly impact loss results (Figure 3). Generally, higher numbers of branches reduce variability of loss estimates (5-95% confidence intervals are narrower), with diminishing results as the number of branches grows. These particular results are also less dependent on the random seed (results with different random seeds are closer to one another). These results indicate that the CanSRM1 model should be run with as many branches as practical, depending on computational resources and constraints. However, the range in mean 500-year loss between all runs considered — approximately \$10 million for Vancouver — is less than one third of the tightest 5-95% confidence interval of any run: over \$36 million. This suggests that the mean values from the model are generally less sensitive to parameterization values than to its inputs such as the uncertainty in hazard and vulnerability, and can be reasonably well estimated even with limited computational resources. We do suggest caution in over-interpretation of the 5 and 95% confidence values, as results in Figure 3 (top panel) show that this may be an overestimate of risk, based on test cases with more logic tree branches.

For these reasons, this study uses 200 logic tree branches and 50,000 stochastic event sets for all calculations except the nationwide aggregate risk calculation which can be run with only 80 branches and 40,000 event sets. While this represents less than 1% of the total number of possible branches contained in the source logic tree, these parameters still push the limits of what can be feasibly calculated. Although the use of the full logic tree would be the ideal solution, the effective catalogue length (the product of the number of branches, number of stochastic event sets, and risk investigation time) for this model is 10 million years for most calculations (3.2 million for nationwide aggregate risk). Additionally, the method of selecting a subset of all branches (GMMs and source recurrence models) for large hazard models has previously been established (Rao et al., 2017) and was used for our study to obtain the best model outputs given constraints. We therefore believe that our model provides a reasonable approximation of mean risk, particularly for aggregations or portfolios containing many buildings. However, interested parties or those engaged in policy or engineering work may decide to use the datasets from this work to perform localized risk analyses which consider only branches that are relevant to their region of interest, in order to ensure that the uncertainty from their region is treated more fully.

5 Quality Control

While a full validation or verification of the model results is beyond the scope of this work, it is important to perform a quality check on the results to ensure they align with observed earthquake impacts. In Canada, there have been no very large or damaging earthquakes in the last couple of decades which could be used to validate the results, especially their effects on newer, high-code buildings. For example, the International Emergency Database (<https://www.emdat.be/>) lists only 1 Canadian earthquake in its inventory: the 1928 Grand Banks, Newfoundland earthquake. In lieu of empirical earthquake loss data in existing public databases, we use information on losses from similar earthquakes elsewhere to ensure that the probabilistic model is roughly in line with relevant real world observations. For now, we evaluate the probabilistic model in terms of meeting the following criteria:

1. Because damaging earthquakes don't occur every year in Canada, we expect that the Average Annual Loss (AAL) at each asset to be lower than the replacement value of that asset.
2. Unreinforced masonry is accepted as the construction material that is likely the most vulnerable to earthquakes in North America (Bruneau, 1994). Because of this, and the relatively good performance of wood structures, we expect that the average annual loss ratio for wood buildings must be lower than that for unreinforced masonry. This metric is computed at the census subdivision geometry, roughly equivalent to a municipality, rounded to four decimal places.

3. In the hardest hit area of the 2011 Christchurch, New Zealand earthquake, where PGA was over 0.7g (McVerry et al., 2012), 73% of unreinforced masonry buildings were red-tagged (Ingham and Griffith, 2011). This therefore makes that statistic a useful guideline for what very significant damage might look like for our most vulnerable buildings in a large and proximal earthquake. Given that the 500 year PGA shaking in Canada is generally less than the PGA observed in this Christchurch event, we expect that the 500 year losses in population centres in Canada should be less than the losses that were incurred in the most vulnerable building typologies in downtown Christchurch during that stronger event (73%).
4. As a general rule, we expect that the highest losses should come from regions with both high hazard and considerable exposure: the St. Lawrence and Charlevoix regions, Montreal, and southwest BC.

Conditions 1–3 are evaluated using a python script (Appendix 11.3) and the final condition is evaluated by visual inspection of mapped damage and loss values.

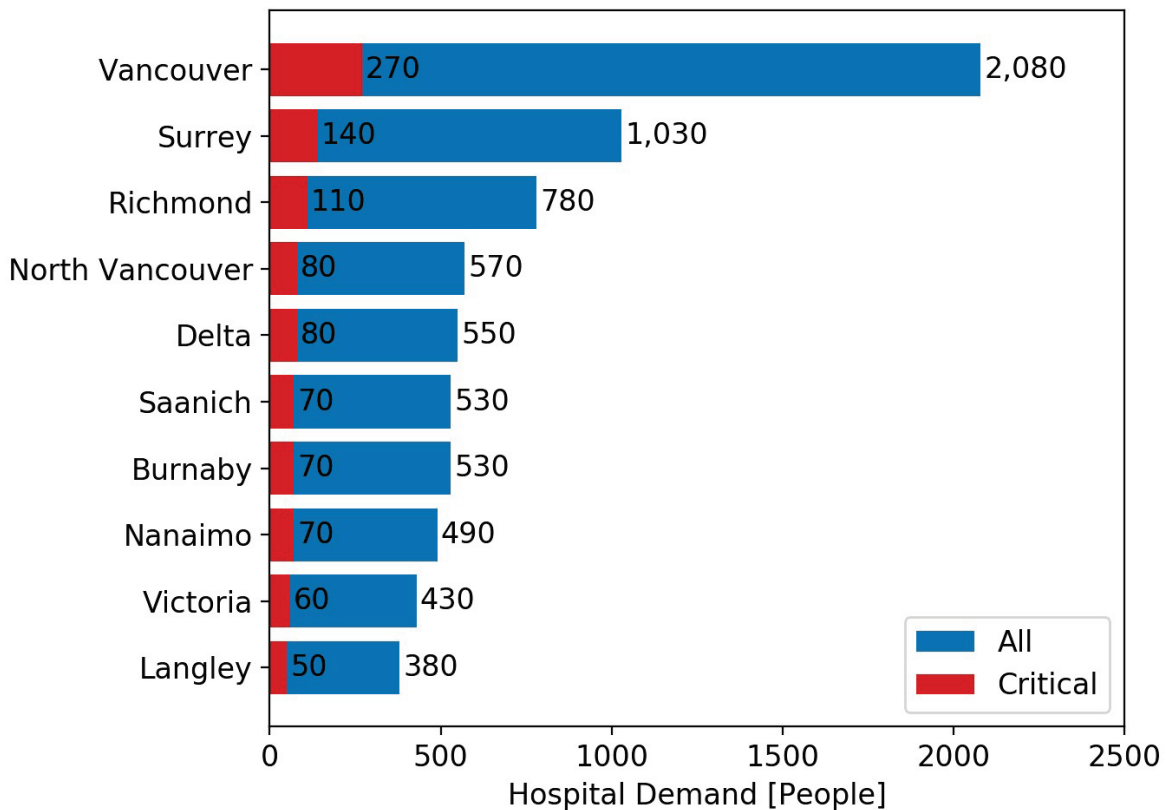


Figure 4: Stacked plot showing Canadian hospital demand, by municipality, for the M_w 9. Cascadia scenario. Intensive/critical care demand is shown in red, and the total of all hospital patients in indicated in blue.

6 Sample Results

6.1 Deterministic Example: M_w 9.0 Cascadia Earthquake

A Moment Magnitude (M_w) 9.0 Megathrust Earthquake is modelled on the Cascadia Subduction Zone interface. For our purposes, impacts are only presented for Canada even though the subduction zone extends from northern California to Vancouver Island. The geometry used is the “best” Cascadia fault geometry from CanSHM6; an event with a return period of about 430 years (Goldfinger et al., 2017). We note that the recurrence model used in CanSHM6 generally produces slightly smaller earthquakes on the Cascadia subduction zone, meaning that the 500 year loss in British Columbia is likely to be smaller than that modelled for this M_w 9.0 event. The maximum onshore PGA from this event is around 40% of gravity [g] along the west coast of Vancouver Island, and it is expected that it would be very strongly felt by 3-4 million people in southwest BC and felt into AB and SK. From shaking alone, the mean damage to buildings in BC is estimated to cost roughly \$40 billion to replace or repair. This is likely a lower bound. Total economic losses, which could be more than double our \$40 billion estimate, would include additional direct costs from infrastructure damage and secondary perils (e.g. tsunami, landslide, liquefaction, fire following, flooding), as well as the indirect losses as a result of all direct damages, such as surge pricing during recovery or business interruption. Even without these additional losses, this \$40 billion loss is equivalent to about 13% of BC’s gross domestic product (Statistics Canada, 2021).

In terms of building damage, our model indicates that this event would result in complete damage to over 18,000 buildings in BC, rendering them uninhabitable (red-tagged). Another roughly 10,000 would be in an extensive damage state (conditionally habitable or yellow-tagged). If this scenario occurred during daytime, when, at least prior to COVID-19, people are more likely to be in vulnerable pre-code commercial and industrial buildings, then the model suggests roughly 3400 lives would be lost with over 12,000 people requiring hospital care just in Canada (Figure 4). Of those, roughly 1700 would be in critical condition, requiring intensive care. Based on reported COVID-related surge capacity for intensive care beds in BC (Otto et al., 2022), this is more than double the province’s capacity as of 2022.

6.2 Probabilistic Example: National Risk Profile

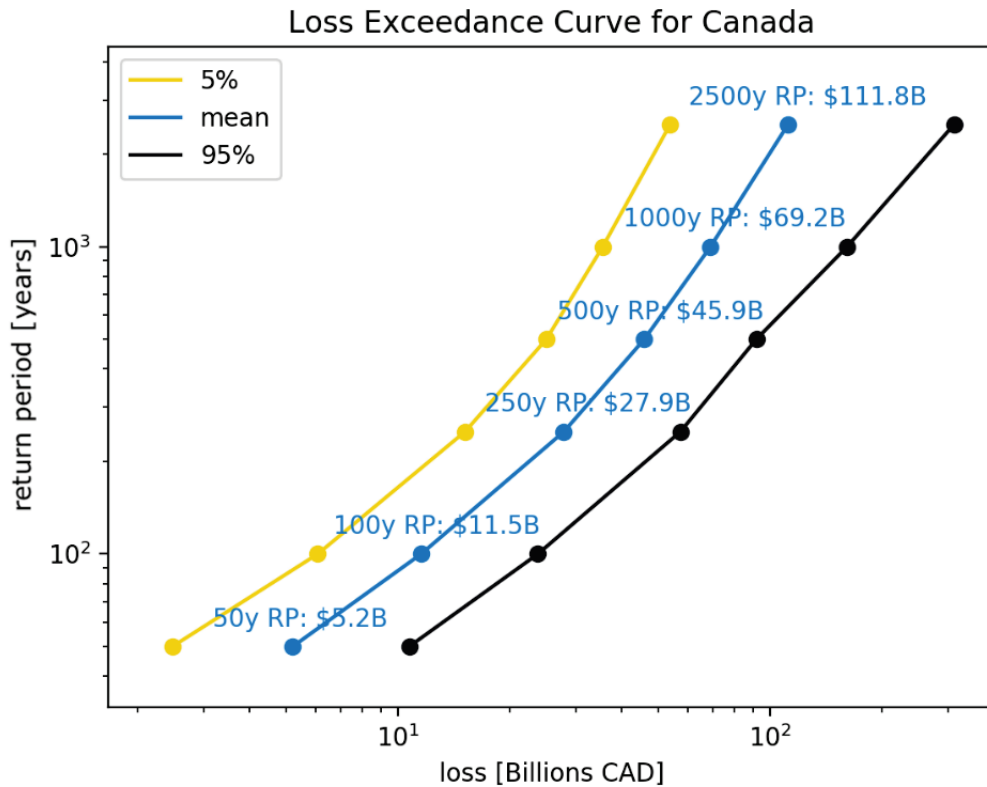


Figure 5: Loss exceedance curves for Canada at the mean as well as the 5th and 95th percentiles. Mean results are annotated in billions CAD. Note that, as described in Section 4, the model is considered to be most reliable for mean risk and the 5th and 95th percentiles should be regarded with caution.

To avoid economic collapse and insolvency, the insurance sector is federally regulated to ensure they have sufficient capital to cover an event of a scale that is expected to occur every 500 years (Office of the Superintendent of Financial Institutions Canada, 2019). The nationwide risk shows that the mean (probable) nationwide loss for a 500-year recurrence rate is roughly \$46 billion, with corresponding 5th and 95th percentile estimates of \$25 and \$92 billion, respectively (Figure 5). It should however be noted that the 5 and 95% estimates are poorly constrained due to limitations in the consideration of uncertainty (see Sections 2.1.3 and 4), so those values should be regarded with lower confidence.

The 500-year provincial/territorial risk is provided in Figure 6, showing that BC bears the largest seismic risk in the country, with a mean loss of over \$27 billion expected to occur with a 500 year return period. It should be noted that this is less than the mean loss from the M_w 9.0 scenario described in Section 6.1. This is because the scenario event chosen is near the upper magnitude limit of the Cascadia subduction zone source used in CanSHM6, meaning the average Cascadia scenario expected from the seismic source model is smaller

than what is modelled in Section 6.1. Close behind BC are Quebec and Ontario — provinces with significant seismic hazard and large populations. While the Yukon may not have a large absolute value for the 500-year mean loss, its relative loss is higher than that of Ontario when normalized by the territorial exposure value.

Each of the provincial/territorial estimates, which describe the expected 500-year loss for each province or territory individually, are below the approximately \$30 billion insurance claim threshold for complete insurance sector collapse (Kelly and Stodolak, 2013). Le Pan (2016) warns that a catastrophic earthquake of \$30-35 billion could overwhelm the ability of companies within the property and casualty insurance sector to jointly meet claims, thereby undermining the sector’s ability to satisfy their obligations to other personal and commercial policy holders across the country, and so amplifying the overall economic impact at a national level. However, the national mean 500-year loss (\$46B), which refers to the expected loss that can occur anywhere in Canada in a 500 year period, may be close to the threshold, depending on insurance penetration in the afflicted area(s). Notably, though, this estimate does not account for direct losses from secondary perils, direct losses to assets other than buildings, and indirect losses of any kind — making it a lower bound on the anticipated incurred losses.

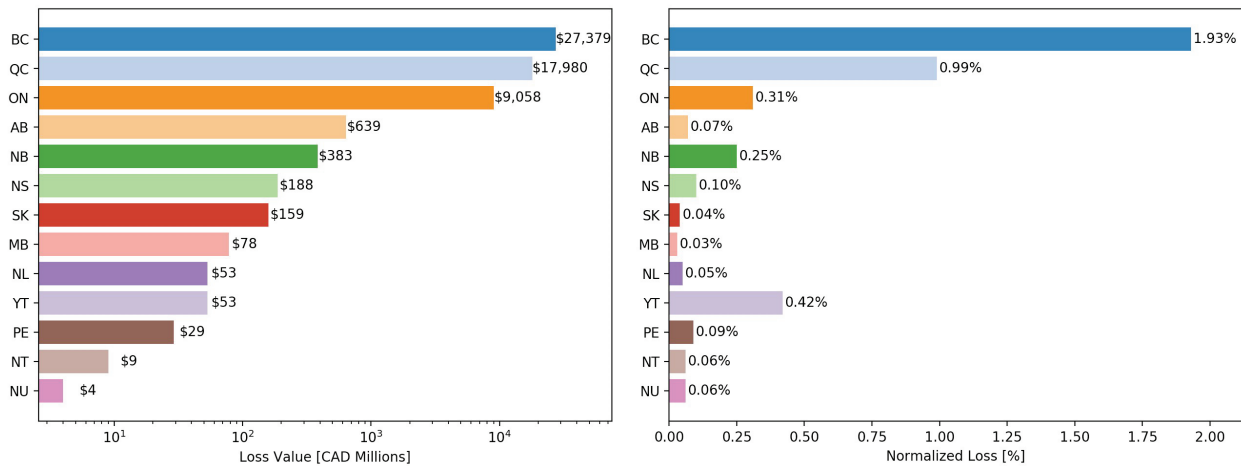


Figure 6: Mean 500-year loss for all provinces and territories in Canada. Note that these estimates need not sum to the nationwide 500-year loss, as that would mean each province/territory having its 500-year loss in the same year. Left side shows dollar values in logarithmic scale, in Millions CAD, and the right side is the same value normalized by the provincial/territorial asset value, in percent, on a linear scale.

7 Refinements and Future Work

One of the most straightforward improvements to this model will be the implementation of a systematic process for creating earthquake scenarios, to mitigate the *ad hoc* nature of the current catalogue. Work is underway to rank the seismic risk, at the community level, across Canada and, working from the top downwards, disaggregate the risk in each region to

determine which seismic source zones are contributing most. Then, representative scenarios can be generated for each zone. This is a more rigorous approach to ensuring that the catalogue can meet the needs of practitioners across the country.

For future generations of CanSRM, it would be preferred to utilize and incorporate the full epistemic variability included within CanSHM6 (e.g., using the un-simplified model and performing a full enumeration of the logic tree). If this is not feasible due to the computing overhead, alternatives are using smart-sampling of the logic tree and/or simplification of the hazard model if they can be done in a manner that preserves the desired risk metric (Rao et al., 2017). For instance, while there are thousands of logic trees possible for any given region, the number that are impactful within that region is much smaller. Therefore, the selected logic tree branches for that region could incorporate that information a priori to maximize impact. While it does not appear that the selection of a subset of branches for stochastic calculations has a major impact on mean risk (i.e., Figure 3), it is desirable to incorporate the full state of the knowledge about seismic sources in Canada. The results could also be interrogated to determine which branches are being chosen when only a subset is being used, and use those results to develop guidelines for what appropriate smart sampling of the logic tree would constitute.

In general, the vulnerability, site, and exposure models presents a significant source of uncertainty in this work. Currently, work is ongoing to develop fragility functions that better reflect building response characteristics for multi-story and older cripple wall subfloor construction practices that are common in wood frame buildings in western Canada, with input from the Canadian engineering community. We also have an interest in implementing retrofit simulations that consider fragility functions for specific retrofit interventions (ex. Paxton et al., 2015, 2017), which will further refine our quantification of how existing building policies can reduce risk. While microzonation studies have been conducted to establish high resolution maps of v_s30 for urban areas, these results have not yet been incorporated into CanSRM. In the near future we hope to include them, as available, into a mosaic v_s30 model. To improve exposure, we are interested in using up to date, commercially-available, insurance-based costing tables to calculate replacement costs for sample portfolios in different parts of the country, with and without surge pricing. This relies on opportunities to collaborate that will not undermine the competitive advantage of proprietary building portfolio assessments. However, the bigger uncertainty is in the estimation of mean finished floor area for building taxonomies in different parts of the country. Currently, this is based on a comparison of estimates based on national averages with those based on mean estimates of property-level building areas for the Greater Vancouver region. Ideally regionally specific estimates would be made available for this parameter. Alternatively, we are also working with other agencies to advocate for the development of a national building inventory. Updates to the exposure and vulnerability functions should greatly improve our confidence in the model's fidelity for baseline and retrofitted conditions.

One of the other major improvements will be to include linear infrastructure in the modelling approach. OQ considers only point sources currently, but in future may allow users to input linear exposed assets so long as relevant vulnerability functions are available.

Alternatively, linear assets could be decomposed into a string of point sources. This could allow for calculation of the probable impact to features like gas pipelines, waterways, roads, bridges, and telecommunications networks, among others. It would also allow for consideration of cascading or interconnected impacts, such as the role of road closures on the transportation of mass care goods within a disaster region. Similarly, there is ample room for improvement to both the displaced households and shelter needs calculations. This is hopefully work which will tailor the existing modification and weighting factors to the Canadian context. Clearly, this functionality would greatly improve the ability for communities to plan for resilience following a shock.

Finally, the inclusion of secondary perils would greatly improve the usefulness of this model and put it closer in line with commercially available catastrophic risk models in Canada. These perils include seismically-induced landslide and liquefaction; fire following earthquake; tsunami; disease outbreak due to sanitation issues and mass care facilities; and flooding due to dike and dam failure or coseismic subsidence. Many of these hazards are being studied in the Canadian context, and we are hopeful that future generations of CanSRM will be able to report upon some or all of them either using the OpenQuake engine or perhaps using codes from other groups that can be run using OpenQuake outputs as input. Progress has been made by NRCan in terms of implementing the ground failure module from the USGS (Allstadt et al., 2018; Wong et al., 2021), which calculates the probability of landslide and liquefaction following earthquake scenarios. In terms of the other perils, recent case studies have shown that fire following an earthquake in Montreal or Vancouver could result in billions of dollars of subsequent damage (Scawthorn, 2019, 2020), that tsunamis have the potential to impact not only the outer coast of BC but also communities on the shores of the Straits of Georgia and Juan de Fuca (Clague et al., 2000; Caston, 2021), and that seismic dike failures from aging water-control infrastructure could lead to massive flood disruption in Southwest BC following a major earthquake (Vass, 2015). Demonstrably, secondary perils must be a high priority for consideration. In addition to the inclusion of linear infrastructure and secondary perils, it would be a benefit to this model to further refine consequence functions to include elements like business interruption costs and surge pricing.

8 Conclusions

CanSRM1 computes probabilistic and deterministic seismic risk at approximately a neighbourhood scale across all of Canada. As inputs, it uses a simplified version of CanSHM6, a newly developed national exposure model (Journey et al., 2022a), and fragility/vulnerability functions that have been adapted from HAZUS (Martins and Silva, 2020) for the Canadian context. It outputs metrics of building damage, financial losses, and fatalities, as well as a score of more detailed indicators for deterministic scenarios. These results are publicly available, forming a base of evidence for policy and planning. By improving open access to uniform quantitative seismic risk data for all Canadians, this work is poised to underpin significant risk reduction work by allowing for prioritization and comparison of different risk metrics between regions. It also provides the necessary tools to

evaluate the impact of first of-their-kind existing building policies, or advocate for greater funding for more localized risk assessments by local authorities.

9 Data and Resources

All input files used in this study are available on GitHub at <https://opendrr.github.io/>, including the Canadian exposure model, Canada-specific fragility and vulnerability functions, irregularly gridded shear wave velocity data, consequence function parameters, and OQ taxonomy mapping files for baseline and retrofitted conditions. CanSRM1 model results will also be published to this site.

10 Acknowledgements

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Table 1: Ground motion prediction equations used for earthquake scenario catalogue, based on citations below and modifications (Kolaj et al., 2019) introduced for the 6th Generation Canada Seismic Hazard Map (Kolaj et al., 2020a).

Tectonic Environment	GMPE	Weight
Stable Shallow Crust	CanadaSHM6 StableCrust NGAEast 1	0.07755
	CanadaSHM6 StableCrust NGAEast 2	0.0376
	CanadaSHM6 StableCrust NGAEast 3	0.0473
	CanadaSHM6 StableCrust NGAEast 4	0.0404
	CanadaSHM6 StableCrust NGAEast 5	0.04505
	CanadaSHM6 StableCrust NGAEast 6	0.0233
	CanadaSHM6 StableCrust NGAEast 7	0.0225
	CanadaSHM6 StableCrust NGAEast 8	0.0362
	CanadaSHM6 StableCrust NGAEast 9	0.04255
	CanadaSHM6 StableCrust NGAEast 10	0.0235
	CanadaSHM6 StableCrust NGAEast 11	0.0253
	CanadaSHM6 StableCrust NGAEast 12	0.0428
	CanadaSHM6 StableCrust NGAEast 13	0.03595
	CanadaSHM6 StableCrust AA13 high	0.15
	CanadaSHM6 StableCrust AA13 med	0.25
CanadaSHM6 StableCrust AA13 low	0.10	
Active Shallow Crust	CanadaSHM6 ActiveCrust AbrahamsonEtAl2014	0.25
	CanadaSHM6 ActiveCrust BooreEtAl2014	0.25
	CanadaSHM6 ActiveCrust CampbellBozorgnia2014	0.25
	CanadaSHM6 ActiveCrust ChiouYoungs2014	0.25
Subduction Interface	CanadaSHM6 Interface AbrahamsonEtAl2015SInter	0.25
	CanadaSHM6 Interface AtkinsonMacias2009	0.25
	CanadaSHM6 Interface GhofraniAtkinson2014Cascadia	0.25
	CanadaSHM6 Interface ZhaoEtAl2006SInterCascadia	0.25
Subduction IntraSlab30	CanadaSHM6 InSlab AbrahamsonEtAl2015SSlab30	0.25
	CanadaSHM6 InSlab AtkinsonBoore2003SSlabCascadia30	0.25
	CanadaSHM6 InSlab GarciaEtAl2005SSlab30	0.25
	CanadaSHM6 InSlab ZhaoEtAl2006SSlabCascadia30	0.25
Subduction IntraSlab55	CanadaSHM6 InSlab AbrahamsonEtAl2015SSlab55	0.25
	CanadaSHM6 InSlab AtkinsonBoore2003SSlabCascadia55	0.25
	CanadaSHM6 InSlab GarciaEtAl2005SSlab55	0.25
	CanadaSHM6 InSlab ZhaoEtAl2006SSlabCascadia55	0.25

Table 2: Occupancy classes used herein, Table 3.3 from FEMA Methodology For Estimating Potential Losses From Disasters (HAZUS) (FEMA, 2012)

Label	Occupancy Class	Example Descriptions
Residential		
RES1	Single Family Dwelling	House
RES2	Mobile Home	Mobile Home
RES3	Multi Family Dwelling	Apartment/Condominium
RES3A		Duplex
RES3B		3-4 Units
RES3C		5-9 Units
RES3D		10-19 Units
RES3E		20-49 Units
RES3F		50+ Units
RES4	Temporary Lodging	Hotel/Motel
RES5	Institutional Dormitory	Group Housing (military, college), Jails
RES6	Nursing Home	
Commercial		
COM1	Retail Trade	Store
COM2	Wholesale Trade	Warehouse
COM3	Personal and Repair Services	Service Station/Shop
COM4	Professional/Technical Services	Offices
COM5	Banks	
COM6	Hospital	
COM7	MedicalOffice/Clinic	
COM8	Entertainment & Recreation	Restaurants/Bars
COM9	Theaters	Theaters
COM10	Parking	Garages
Industrial		
IND1	Heavy	Factory
IND2	Light	Factory
IND3	Food/Drugs/Chemicals	Factory
IND4	Metals/Minerals Processing	Factory
IND5	High Technology	Factory
IND6	Construction	Office
Agriculture		
AGR1	Agriculture	
Religion/Non/Profit		
REL1	Church/Non-Profit	
Government		
GOV1	General Services	Office
GOV2	Emergency Response	Police/Fire Station/EOC
Education		
EDU1	Grade Schools	
EDU2	Colleges/Universities	Does not include group housing

Table 3: *Building taxonomies used herein, Table 3.2 from HAZUS (FEMA, 2012).*

Label	Description	Name	Stories
W1	Wood, Light Frame (<5000 sq. ft.)		1-2
W2	Wood, Residential (> 5000 sq. ft.)		All
W3	Wood, Commercial & Industrial (> 5000 sq. ft.)		All
W4	Wood, Light Frame with Cripple Wall or Subfloor		1-2
S1L S1M S1H	Steel Moment Frame	Low-Rise Mid-Rise High-Rise	1-3 4-7 8+
S2L S2M S2H	Steel Braced Frame	Low-Rise Mid-Rise High-Rise	1-3 4-7 8+
S3	Steel Light Frame		All
S4L S4M S4H	Steel Frame with Cast-in-Place Concrete Shear Walls	Low-Rise Mid-Rise High-Rise	1-3 4-7 8+
S5L S5M S5H	Steel Frame with Unreinforced Masonry Infill Walls	Low-Rise Mid-Rise High-Rise	1-3 4-7 8+
C1L C1M C1H	Concrete Moment Frame	Low-Rise Mid-Rise High-Rise	1-3 4-7 8+
C2L C2M C2H	Concrete Shear Walls	Low-Rise Mid-Rise High-Rise	1-3 4-7 8+
C3L C3M C3H	Concrete Frame with Unreinforced Masonry Infill Walls	Low-Rise Mid-Rise High-Rise	1-3 4-7 8+
PC1	Precast Concrete Tilt-Up Walls		All
PC2L PC2M PC2H	Precast Concrete Frames with Concrete Shear Walls	Low-Rise Mid-Rise High-Rise	1-3 4-7 8+
RM1L RM1M	Reinforced Masonry Bearing Walls with Wood or Metal Deck Diaphragms	Low-Rise Mid-Rise	1-3 4+
RM2L RM2M RM2H	Reinforced Masonry Bearing Walls with Precast Concrete Diaphragms	Low-Rise Mid-Rise High-Rise	1-3 4-7 8+
URML URMM	Unreinforced Masonry Bearing Walls	Low-Rise Mid-Rise	1-2 3+
MH	Mobile Homes		All

Table 4: *Criteria used to assign buildings to a design code level in the exposure dataset, based on CanSHM5 hazard values and the seismic zones of the Uniform Building Code (International Conference of Building Officials, 1994).*

Seismic Zone	PGA (2%/50yr)	SA(0.2) (2%/50yr)	SA(1.0) (2%/50yr)	Construction Year			
				2005- present	1990- 2004	1973- 1989	Pre-1973
5	>0.4	≥1.15	≥0.50	High-Code	High-Code	Mod-Code	Pre-Code ¹
4	0.32-0.4	0.75-1.15	0.30-0.50	High-Code	Mod-Code	Mod-Code	Pre-Code ¹
3	0.24-0.32	0.35-0.75	0.15-0.30	Mod-Code	Mod-Code	Low-Code	Pre-Code ²
2	0.16-0.24	0.20-0.35	0.10-0.15	Mod-Code	Low-Code	Pre-Code ²	Pre-Code ²
1	0.075-0.16	0.10-0.20	0.05-0.10	Low-Code	Low-Code	Pre-Code ²	Pre-Code ²
0	0.05-0.075	≤0.10	≤0.05	Low-Code	Pre-Code ²	Pre-Code ²	Pre-Code ²

'Mod-Code' is short for Moderate-Code. ¹Assume Moderate-Code design for residential woodframe buildings.

²Assume Low-Code design for residential wood frame buildings.

Table 5: Translation between Canadian wood buildings and HAZUS taxonomies.

Canadian Taxonomy	Description	Occupancy	HAZUS Taxonomy
W1	Light wood-frame, 1-2 storeys	Residential	W1
W2	Light wood-frame, 3-6 storeys	Residential	W2
W3	Heavy wood-frame	Commercial/Industrial	W2
W4	Light wood-frame with cripple wall or subfloor	RES1, RES2, RES3A RES3B-RES6	W1 W2

Table 6: Groups of CSDs used for Exposure Division.

Province	Group Name	CSDs Included
Quebec	North West Shore Montreal	Th'eres-De Blainville, Les Moulins, L'Assomption, DeuxMontagnes, Mirabel, La Riviere-du-Nord, Montcalm, Joliette, D'Autray, Vaudreuil-Soulanges
	SouthEastShoreMTL	Longueuil, Roussillon, Marguerite-D'Youville, La Vall'eedu-Richelieu, Rouville, Le Haut-Richelieu, Les Jardins-deNapierville, Beauharnois-Salaberry, Le Haut-Saint-Laurent
	Gatineau	Les Collines-de-l'Outaouais, Gatineau
	Eastern Townships	Sherbrooke, Memphr'emagog, La Haute-Yamaska, BromeMissisquoi, Les Maskoutains, Acton, Le Val-Saint-Fran,cois, Le Haut-Saint-Fran'cois, Nicolet-Yamaska
	Quebec City	Qu'ebec, L'evs, La Jacques-Cartier, Portneuf, Lotbini`ere, La Nouvelle-Beauce, Bellechasse, L'Ile-d'Or'leans, La C`ote-deBeaupr'e, Montmagny
	Charlevoix Saguenay	Charlevoix, Charlevoix-Est, Le Saguenay-et-son-Fjord, LacSaint-Jean-Est, Le Domaine-du-Roy, Maria-Chapdelaine, L'Islet, Kamouraska, Rivi`ere-du-Loup
	Trois Rivieres West Montreal	Francheville, Nicolet-Yamaska, B'ecancour, Arthabaska, L'Erable, Les Appalaches, Robert-Cliche, Le Granit, Beauce-Sartigan, Les Etchemins Montr'eal
Ontario	Northern Ontario	Kenora, Rainy River, Thunder Bay, Cochrane, Algoma, Greater Sudbury / Grand Sudbury, Sudbury, Timiskaming, Nipissing
	Ottawa Region	Ottawa, Prescott and Russell, Stormont, Dundas and Glengarry
	Kingston Pembroke	Frontenac, Lennox and Addington, Prince Edward, Hastings, Northumberland, Renfrew, Kawartha Lakes, Haliburton
	Peel	Peel
	Hamilton Niagara	Halton, Hamilton, Niagara
	Barrie Region	Wellington, Dufferin, Simcoe
	Toronto	Toronto
	Waterloo	Waterloo, Brant, Haldimand-Norfolk
London Region	Middlesex, Oxford, Elgin	
Sarnia Windsor	Lambton, Chatham-Kent, Essex	
Manitoba	Winnipeg	Division No. 11
Saskatchewan	Regina Saskatoon	Division No. 11, Division No. 6
Alberta	Calgary	Division No. 6
	Edmonton	Division No. 11
	Northern	Division No. 18, Division No. 12, Division No. 13, Division No. 19, Division No. 17, Division No. 16
British Columbia	Vancouver	Greater Vancouver
	Coastal	Central Coast, Mount Waddington, Powell River, Sunshine Coast, Skeena-Queen Charlotte, Squamish-Lillooet

Central Island	Strathcona, Alberni-Clayoquot, Cowichan Valley, Comox Valley, Nanaimo
Okanagan Kootenay	Central Okanagan, Okanagan-Similkameen A, ThompsonNicola, North Okanagan, Kootenay Boundary, East Kootenay, Columbia-Shuswap, Central Kootenay
Fraser Valley	Fraser Valley
Capital	Capital

Table 7: Probabilistic Parameters to Reduce Computation Size.

minimum intensity	
SA(0.3)0.02 g	
SA(0.6)0.05 g	
SA(1.0)0.05 g	
SA(2.0)0.05 g	
minimum magnitude	
default	5.0
Stable Shallow Crust	4.5
Active Shallow Crust	4.5
Subduction Interface	5.0
Subduction IntraSlab30	5.0
Subduction IntraSlab55	5.0
maximum distance	
Active Shallow Crust	400 km
Stable Shallow Crust	600 km
Subduction IntraSlab30	400 km
Subduction IntraSlab55	400 km
Subduction Interface	1000 km
minimum asset loss	
structural	\$5000
nonstructural	\$5000
contents	\$1000

Table 8: *Displaced Household Damage Weighting Factors.*

Weight Factor	Single Family Value	Multi Family Value
w_M	0.0	0.0
w_E	0.0	0.9
w_C	1.0	1.0

Table 9: *Mass Shelter Weighting Factors.*

Category	Description	Value
IW	Income Weighting Factor	0.73
EW	Ethnicity Weighting Factor	0.27

Table 10: *Mass Shelter Modification Factors.*

Category	Description	Value
Income		
IM1	Household Income < \$15000	0.62
IM2	\$15000 < Household Income < \$20000	0.42
IM3	\$20000 < Household Income < \$35000	0.29
IM4	\$35000 < Household Income < \$50000	0.22
IM5	\$50000 < Household Income	0.13
Ethnicity		
EM1	Visible Minority	0.40
EM2	Indigenous	0.26
EM3	Neither	0.24

Electronic Supplement

Sample Deterministic Initialization Files

Hazard

Generated automatically with manyFaults.py on: 2021-07-01 16:32:54.160511

[general]

description = Magnitude 7.3 scenario based on complete rupture of the CanSHM6 Hazard Model implementation of the Leech River Full Fault.

calculation_mode = scenario

random_seed = 113

[site_params]

site_model_file = ../../openquake-inputs/earthquake/sites/regions/site-vgrid_BC.csv

[Rupture information]

rupture_model_file = ../ruptures/rupture_ACM7p3_LeechRiverFullFault.xml

rupture_mesh_spacing = 4

[Calculation parameters]

gsim_logic_tree_file =
../../CanadaSHM6/OpenQuake_model_files/gmms/LogicTree/OQ_classes_NGASa0p3weights_activec
rust.xml

truncation_level = 0

maximum_distance = 400

number_of_ground_motion_fields = 1

intensity_measure_types = PGA, SA(0.1), SA(0.2), SA(0.3), SA(0.5), SA(0.6), SA(1.0), SA(2.0)

Damage

Generated automatically with manyFaults.py on: 2021-07-01 16:32:54.161169

[general]

description = Magnitude 7.3 scenario based on complete rupture of the CanSHM6 Hazard Model implementation of the Leech River Full Fault.

calculation_mode = scenario_damage

random_seed = 113

[Exposure model]

exposure_file = ../../openquake-inputs/exposure/general-building-stock/oqBldgExp_BC.xml

[site_params]

site_model_file = ../../openquake-inputs/earthquake/sites/regions/site-vgrid_BC.csv

[Rupture information]

rupture_model_file = ../ruptures/rupture_ACM7p3_LeechRiverFullFault.xml

rupture_mesh_spacing = 4

[Calculation parameters]

gsim_logic_tree_file

../../CanadaSHM6/OpenQuake_model_files/gmms/LogicTree/OQ_classes_NGASa0p3weights_activec
rust.xml

truncation_level = 3.0

maximum_distance = 400

number_of_ground_motion_fields = 400

[fragility]

taxonomy_mapping_csv = ../../openquake-inputs/earthquake/vulnerability/CanSRM1_TaxMap_b0.csv

structural_fragility_file = ../../openquake-inputs/earthquake/vulnerability/structural_fragility_CAN.xml

[risk_calculation]

master_seed = 42

time_event = day

Risk

Generated automatically with manyFaults.py on: 2021-07-01 16:32:54.161989

[general]

description = Magnitude 7.3 scenario based on complete rupture of the CanSHM6 Hazard Model implementation of the Leech River Full Fault.

calculation_mode = scenario_risk

random_seed = 113

[Exposure model]

exposure_file = ../../openquake-inputs/exposure/general-building-stock/oqBldgExp_BC.xml

[site_params]

site_model_file = ../../openquake-inputs/earthquake/sites/regions/site-vgrid_BC.csv

[Rupture information]

rupture_model_file = ./ruptures/rupture_ACM7p3_LeechRiverFullFault.xml

rupture_mesh_spacing = 4

[Calculation parameters]

gsim_logic_tree_file =
../../CanadaSHM6/OpenQuake_model_files/gmms/LogicTree/OQ_classes_NGASa0p3weights_activec
rust.xml

truncation_level = 3.0

maximum_distance = 400

number_of_ground_motion_fields = 400

[Vulnerability]

taxonomy_mapping_csv = ../../openquake-inputs/earthquake/vulnerability/CanSRM1_TaxMap_b0.csv

structural_vulnerability_file =
../../openquake-
inputs/earthquake/vulnerability/vulnerability_structural_CAN.xml

nonstructural_vulnerability_file =
../../openquake-
inputs/earthquake/vulnerability/vulnerability_nonstructural_CAN.xml

contents_vulnerability_file =
../../openquake-
inputs/earthquake/vulnerability/vulnerability_contents_CAN.xml

occupants_vulnerability_file =
../../openquake-
inputs/earthquake/vulnerability/vulnerability_occupants_CAN.xml

Sample Probabilistic Initialization Files

Damage

[general]

description = eDamage-Stochastic event-based damage model for NL_A; baseline
calculation_mode = event_based_damage

[exposure]

exposure_file = ../../openquake-inputs/exposure/general-building-stock/oqBldgExp_NL_A.xml

[sites]

site_model_file = ../../openquake-inputs/earthquake/sites/regions/site-vgrid_NL.csv

[erf]

width_of_mfd_bin = 0.2
rupture_mesh_spacing = 5.0
area_source_discretization = 10.0
complex_fault_mesh_spacing = 10.0

[logic_trees]

source_model_logic_tree_file =
../../CanadaSHM6/OpenQuake_model_files/sources/nationalModel/xml/logicTree/nationalModel.xml
gsim_logic_tree_file =
../../CanadaSHM6/OpenQuake_model_files/gmms/LogicTree/OQ_classes_NGASa0p3weights.xml
number_of_logic_tree_samples = 200
ses_per_logic_tree_path = 50000

[hazard_calculation]

ses_seed = 23
random_seed = 24
truncation_level = 3
investigation_time = 1
asset_hazard_distance = 100

minimum_intensity = {"SA(0.3)": 0.02, "SA(0.6)": 0.05, "SA(1.0)": 0.05, "SA(2.0)": 0.05}
minimum_magnitude = {"default": 5.0,
"Stable Shallow Crust": 4.5,
"Active Shallow Crust": 4.5,
"Subduction Interface": 5.0,
"Subduction IntraSlab30": 5.0,
"Subduction IntraSlab55": 5.0}

maximum_distance = {"Active Shallow Crust": 400.0, "Stable Shallow Crust": 600.0, "Subduction
IntraSlab30": 400, "Subduction IntraSlab55": 400, "Subduction Interface": 1000.0}

[fragility]

taxonomy_mapping_csv = ../../openquake-inputs/earthquake/vulnerability/CanSRM1_TaxMap_b0.csv
structural_fragility_file = ../../openquake-inputs/earthquake/vulnerability/structural_fragility_CAN.xml

[risk_calculation]

master_seed = 25
risk_investigation_time = 50
quantiles = 0.05, 0.50, 0.95

Risk

[general]

description = ebRisk-Stochastic ebRisk model for NL_A; baseline
calculation_mode = ebrisk

[exposure]

exposure_file = ../../openquake-inputs/exposure/general-building-stock/oqBldgExp_NL_A.xml

[sites]

site_model_file = ../../openquake-inputs/earthquake/sites/regions/site-vgrid_NL.csv

[erf]

width_of_mfd_bin = 0.2
rupture_mesh_spacing = 5.0
area_source_discretization = 10.0
complex_fault_mesh_spacing = 10.0

[logic_trees]

source_model_logic_tree_file =
../../CanadaSHM6/OpenQuake_model_files/sources/nationalModel/xml/logicTree/nationalModel.xml
gsim_logic_tree_file =
../../CanadaSHM6/OpenQuake_model_files/gmms/LogicTree/OQ_classes_NGASa0p3weights.xml
number_of_logic_tree_samples = 200
ses_per_logic_tree_path = 50000

[hazard_calculation]

ses_seed = 23
random_seed = 24
truncation_level = 3
investigation_time = 1
asset_hazard_distance = 100

minimum_intensity = {"SA(0.3)": 0.02, "SA(0.6)": 0.05, "SA(1.0)": 0.05, "SA(2.0)": 0.05}
minimum_magnitude = {"default": 5.0,
"Stable Shallow Crust": 4.5,
"Active Shallow Crust": 4.5,
"Subduction Interface": 5.0,
"Subduction IntraSlab30": 5.0,
"Subduction IntraSlab55": 5.0}

maximum_distance = {"Active Shallow Crust": 400.0, "Stable Shallow Crust": 600.0, "Subduction
IntraSlab30": 400, "Subduction IntraSlab55": 400, "Subduction Interface": 1000.0}

[vulnerability]

taxonomy_mapping_csv = ../../openquake-inputs/earthquake/vulnerability/CanSRM1_TaxMap_b0.csv
structural_vulnerability_file = ../../openquake-
inputs/earthquake/vulnerability/vulnerability_structural_CAN.xml
nonstructural_vulnerability_file = ../../openquake-
inputs/earthquake/vulnerability/vulnerability_nonstructural_CAN.xml
contents_vulnerability_file = ../../openquake-
inputs/earthquake/vulnerability/vulnerability_contents_CAN.xml
occupants_vulnerability_file = ../../openquake-
inputs/earthquake/vulnerability/vulnerability_occupants_CAN.xml

```
[risk_calculation]
master_seed = 25
avg_losses = true
return_periods = 5, 10, 25, 50, 100, 250, 500, 1000, 2500
time_event = transit
risk_investigation_time = 1
quantiles = 0.05, 0.50, 0.95
aggregate_by = fsaid,OccType,GenType
```

Consequence Script

```
# -*- coding: utf-8 -*-
# vim: tabstop=4 shiftwidth=4 softtabstop=4
#
# Copyright (C) 2017-2020 Anirudh Rao, GEM Foundation
#
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import csv
import numpy as np
from openquake.baselib import datastore, sap
import pandas as pd
from tqdm import tqdm
import sys

params_file = "scripts/Hazus_Consequence_Parameters.xlsx" #/mnt/storage/earthquake-
scenarios/scripts/Hazus_Consequence_Parameters.xlsx"

def read_square_footage(xlsx):
    square_footage_df = pd.read_excel(xlsx, sheet_name="Square Footage", skiprows=1, index_col=0)
    return square_footage_df

def read_repair_ratio_str(xlsx):
    repair_ratio_str_df = pd.read_excel(xlsx, sheet_name="Structural Repair Ratios", skiprows=2,
index_col=0)
    repair_ratio_str_df.index.name = "Occupancy"
    repair_ratio_str_df.rename_axis("Structural Damage State", axis="columns", inplace=True)
    return repair_ratio_str_df/100

def read_repair_ratio_nsa(xlsx):
    repair_ratio_nsa_df = pd.read_excel(xlsx, sheet_name="NonstrAccel Repair Ratios", skiprows=2,
index_col=0)
    repair_ratio_nsa_df.index.name = "Occupancy"
    repair_ratio_nsa_df.rename_axis("Acceleration Sensitive Non-structural Damage State",
axis="columns", inplace=True)
    return repair_ratio_nsa_df/100

def read_repair_ratio_nsd(xlsx):
    repair_ratio_nsd_df = pd.read_excel(xlsx, sheet_name="NonstrDrift Repair Ratios", skiprows=2,
index_col=0)
    repair_ratio_nsd_df.index.name = "Occupancy"
    repair_ratio_nsd_df.rename_axis("Drift Sensitive Non-structural Damage State", axis="columns",
inplace=True)
    return repair_ratio_nsd_df/100
```

```

def read_repair_ratio_con(xlsx):
    repair_ratio_con_df = pd.read_excel(xlsx, sheet_name="Contents Damage Ratios", skiprows=2,
index_col=0)
    repair_ratio_con_df.index.name = "Occupancy"
    repair_ratio_con_df.rename_axis("Acceleration Sensitive Non-structural Damage State",
axis="columns", inplace=True)
    return repair_ratio_con_df/100

def read_collapse_rate(xlsx):
    collapse_rate_df = pd.read_excel(xlsx, sheet_name="Collapse Rates", skiprows=1, index_col=0)
    return collapse_rate_df/100

def read_casualty_rate_in(xlsx):
    casualty_rate_in_df = pd.read_excel(xlsx, sheet_name="Indoor Casualty Rates", skiprows=1,
index_col=0, header=[0,1])
    casualty_rate_in_df.index.name = "Building Type"
    casualty_rate_in_df.columns.names = ["Damage State", "Severity Level"]
    return casualty_rate_in_df/100

def read_casualty_rate_out(xlsx):
    casualty_rate_out_df = pd.read_excel(xlsx, sheet_name="Outdoor Casualty Rates", skiprows=1,
index_col=0, header=[0,1])
    casualty_rate_out_df.index.name = "Building Type"
    casualty_rate_out_df.columns.names = ["Damage State", "Severity Level"]
    return casualty_rate_out_df/100

def read_debris_weight(xlsx):
    debris_df = pd.read_excel(xlsx, sheet_name="Debris", index_col=0, header=[0,1,2])
    debris_df.index.name = "Building Type"
    debris_df.columns.names = ["Item", "Material", "Component"]
    return debris_df

def read_repair_time(xlsx):
    repair_time_df = pd.read_excel(xlsx, sheet_name="Building Repair Time", skiprows=2, index_col=0)
    repair_time_df.index.name = "Occupancy"
    repair_time_df.rename_axis("Structural Damage State", axis="columns", inplace=True)
    return repair_time_df

def read_recovery_time(xlsx):
    recovery_time_df = pd.read_excel(xlsx, sheet_name="Building Recovery Time", skiprows=2,
index_col=0)
    recovery_time_df.index.name = "Occupancy"
    recovery_time_df.rename_axis("Structural Damage State", axis="columns", inplace=True)
    return recovery_time_df

def read_interruption_time(xlsx):
    interruption_time_df = pd.read_excel(xlsx, sheet_name="Interruption Time Multipliers", skiprows=2,
index_col=0)
    interruption_time_df.index.name = "Occupancy"
    interruption_time_df.rename_axis("Structural Damage State", axis="columns", inplace=True)
    return interruption_time_df

xlsx = pd.ExcelFile(params_file)
read_params = {

```

```

"Square Footage": read_square_footage,
"Structural Repair Ratios": read_repair_ratio_str,
"NonstrAccel Repair Ratios": read_repair_ratio_nsa,
"NonstrDrift Repair Ratios": read_repair_ratio_nsd,
"Contents Damage Ratios": read_repair_ratio_con,
"Collapse Rates": read_collapse_rate,
"Indoor Casualty Rates": read_casualty_rate_in,
"Outdoor Casualty Rates": read_casualty_rate_out,
"Debris": read_debris_weight,
"Building Repair Time": read_repair_time,
"Building Recovery Time": read_recovery_time,
"Interruption Time Multipliers": read_interruption_time,
}

def calculate_consequences(job_id='-1'):
    calc_id = datastore.get_last_calc_id() if job_id=='-1' else int(job_id)
    dstore = datastore.read(calc_id)
    lt = 0 # structural damage
    stat = 0 # damage state mean values
    num_rlzs = len(dstore["weights"])
    assetcol = dstore["assetcol"]
    taxonomies = assetcol.tagcol.taxonomy

    # Read the asset damage table from the calculation datastore
    calculation_mode = dstore["oqparam"].calculation_mode
    if calculation_mode == 'scenario_damage':
        damages = dstore["damages-rlzs"]
    elif calculation_mode == 'classical_damage':
        damages = dstore["damages-stats"]
    else:
        print("Consequence calculations not supported for ", calculation_mode)
        return

    # Read the various consequences tables from the spreadsheet
    square_footage_df = read_params["Square Footage"](xlsx)
    repair_ratio_str_df = read_params["Structural Repair Ratios"](xlsx)
    repair_ratio_nsa_df = read_params["NonstrAccel Repair Ratios"](xlsx)
    repair_ratio_nsd_df = read_params["NonstrDrift Repair Ratios"](xlsx)
    repair_ratio_con_df = read_params["Contents Damage Ratios"](xlsx)
    collapse_rate_df = read_params["Collapse Rates"](xlsx)
    casualty_rate_in_df = read_params["Indoor Casualty Rates"](xlsx)
    casualty_rate_out_df = read_params["Outdoor Casualty Rates"](xlsx)
    repair_time_df = read_params["Building Repair Time"](xlsx)
    recovery_time_df = read_params["Building Recovery Time"](xlsx)
    interruption_time_df = read_params["Interruption Time Multipliers"](xlsx)
    debris_df = read_params["Debris"](xlsx)
    unit_weight_df = debris_df["Unit Weight (tons per 1,000 sqft)"]
    debris_brick_wood_pct_df = debris_df["Brick, Wood, and Other Debris Generated (in Percentage of Weight)"]
    debris_concrete_steel_pct_df = debris_df["Reinforced Concrete and Wrecked Steel Generated (in Percentage of Weight)"]

    # Initialize lists / dicts to store the asset level casualty estimates
    severity_levels = ["Severity 1", "Severity 2", "Severity 3", "Severity 4"]
    casualties_day = {"Severity 1": 0, "Severity 2": 0, "Severity 3": 0, "Severity 4": 0}
    casualties_night = {"Severity 1": 0, "Severity 2": 0, "Severity 3": 0, "Severity 4": 0}

```

```
casualties_transit = {"Severity 1": 0, "Severity 2": 0, "Severity 3": 0, "Severity 4": 0}
```

```
for rlzi in range(num_rlzs):
```

```
    print("Processing realization {} of {}".format(rlzi+1, num_rlzs))
```

```
    filename = "consequences-rlz-" + str(rlzi).zfill(3) + "_" + str(calc_id) + ".csv"
```

```
    with open(filename, 'w') as f:
```

```
        writer = csv.writer(f)
```

```
        # Write the header row to the csv file
```

```
        writer.writerow(
```

```
            ["asset_ref", "number_of_buildings",  
            "value_structural", "value_nonstructural", "value_contents",  
            "occupants_day", "occupants_night", "occupants_transit",  
            "collapse_ratio", "mean_repair_time",  
            "mean_recovery_time", "mean_interruption_time",  
            "casualties_day_severity_1", "casualties_day_severity_2",  
            "casualties_day_severity_3", "casualties_day_severity_4",  
            "casualties_night_severity_1", "casualties_night_severity_2",  
            "casualties_night_severity_3", "casualties_night_severity_4",  
            "casualties_transit_severity_1", "casualties_transit_severity_2",  
            "casualties_transit_severity_3", "casualties_transit_severity_4",  
            "sc_Displ3", "sc_Displ30", "sc_Displ90", "sc_Displ180", "sc_Displ360",  
            "sc_BusDispl30", "sc_BusDispl90", "sc_BusDispl180", "sc_BusDispl360",  
            "debris_brick_wood_tons", "debris_concrete_steel_tons"])
```

```
for asset in tqdm(assetcol):
```

```
    asset_ref = asset['id'].decode()
```

```
    asset_occ, asset_typ, code_level = taxonomies[asset['taxonomy']].split('-')
```

```
    if calculation_mode == 'scenario_damage':
```

```
        # Note: engine versions <3.10 require an additional 'stat' variable
```

```
        # as the previous output includes mean and stddev fields
```

```
        # asset_damages = damages[asset['ordinal'], rlzi, lt, stat]
```

```
        asset_damages = damages[asset['ordinal'], rlzi, lt]
```

```
    elif calculation_mode == 'classical_damage':
```

```
        asset_damages = damages[asset['ordinal'], stat, rlzi]
```

```
        asset_damages = [max(0, d) for d in asset_damages]
```

```
    asset_damage_ratios = [d/asset['number'] for d in asset_damages]
```

```
    # Repair and recovery time estimates
```

```
    # Hazus tables 15.9, 15.10, 15.11
```

```
    repair_time = np.dot(
```

```
        asset_damage_ratios, repair_time_df.loc[asset_occ])
```

```
    recovery_time = np.dot(
```

```
        asset_damage_ratios, recovery_time_df.loc[asset_occ])
```

```
    interruption_time = np.dot(
```

```
        asset_damage_ratios, recovery_time_df.loc[asset_occ] * interruption_time_df.loc[asset_occ])
```

```
    # Debris weight estimates
```

```
    # Hazus tables 12.1, 12.2, 12.3
```

```
    unit_weight = unit_weight_df.loc[asset_typ]
```

```
    weight_brick_wood = (
```

```
        unit_weight["Brick, Wood and Other"]
```

```
        * square_footage_df.loc[asset_occ].values[0] / 1000
```

```
        * asset['number'])
```

```
    weight_concrete_steel = (
```

```
        unit_weight["Reinforced Concrete and Steel"]
```

```
        * square_footage_df.loc[asset_occ].values[0] / 1000
```

```

* asset["number"])
debris_brick_wood_pct = debris_brick_wood_pct_df.loc[asset_typ]
debris_concrete_steel_pct = debris_concrete_steel_pct_df.loc[asset_typ]

debris_brick_wood_str = weight_brick_wood["Structural"] * np.dot(
    asset_damage_ratios, debris_brick_wood_pct["Structural Damage State"] / 100)
debris_brick_wood_nst = weight_brick_wood["Nonstructural"] * np.dot(
    asset_damage_ratios, debris_brick_wood_pct["Nonstructural Damage State"] / 100)
debris_concrete_steel_str = weight_concrete_steel["Structural"] * np.dot(
    asset_damage_ratios, debris_concrete_steel_pct["Structural Damage State"] / 100)
debris_concrete_steel_nst = weight_concrete_steel["Nonstructural"] * np.dot(
    asset_damage_ratios, debris_concrete_steel_pct["Nonstructural Damage State"] / 100)

debris_brick_wood = debris_brick_wood_str + debris_brick_wood_nst
debris_concrete_steel = debris_concrete_steel_str + debris_concrete_steel_nst

# Estimate number of displaced occupants based on heuristics provided by Murray
sc_Displ3 = asset["occupants_night"] if recovery_time > 3 else 0
sc_Displ30 = asset["occupants_night"] if recovery_time > 30 else 0
sc_Displ90 = asset["occupants_night"] if recovery_time > 90 else 0
sc_Displ180 = asset["occupants_night"] if recovery_time > 180 else 0
sc_Displ360 = asset["occupants_night"] if recovery_time > 360 else 0
sc_BusDispl30 = asset["occupants_day"] if recovery_time > 30 else 0
sc_BusDispl90 = asset["occupants_day"] if recovery_time > 90 else 0
sc_BusDispl180 = asset["occupants_day"] if recovery_time > 180 else 0
sc_BusDispl360 = asset["occupants_day"] if recovery_time > 360 else 0

# Split complete damage state into collapse and non-collapse
# This distinction is then used for the casualty estimates
# Collapse rates given complete damage are from Hazus table 13.8
collapse_rate = collapse_rate_df.loc[asset_typ].values[0]
dmg = {
    "Slight Damage": asset_damage_ratios[1],
    "Moderate Damage": asset_damage_ratios[2],
    "Extensive Damage": asset_damage_ratios[3],
    "Complete Damage (No Collapse)": asset_damage_ratios[4]*(1 - collapse_rate),
    "Complete Damage (With Collapse)": asset_damage_ratios[4]*collapse_rate
}
collapse_ratio = dmg["Complete Damage (With Collapse)"]
collapse_ratio_str = "{:.2e}".format(collapse_ratio) if collapse_ratio else '0'

# Estimate casualties (day/night/transit) at four severity levels
# Hazus tables 13.3, 13.4, 13.5, 13.6, 13.7
for severity_level in severity_levels:
    casualty_ratio = np.dot(
        list(dmg.values()), casualty_rate_in_df.loc[asset_typ][:, severity_level])
    casualties_day[severity_level] = (
        casualty_ratio * asset["occupants_day"])
    casualties_night[severity_level] = (
        casualty_ratio * asset["occupants_night"])
    casualties_transit[severity_level] = (
        casualty_ratio * asset["occupants_transit"])

# Write all consequence estimates for this asset to the csv file
writer.writerow(
    [asset_ref,

```



```

"{0:,.1f}".format(asset["number"]),
"{0:,.1f}".format(asset["value-structural"]),
"{0:,.1f}".format(asset["value-nonstructural"]),
"{0:,.1f}".format(asset["value-contents"]),
"{0:,.1f}".format(asset["occupants_day"]),
"{0:,.1f}".format(asset["occupants_night"]),
"{0:,.1f}".format(asset["occupants_transit"]),
collapse_ratio_str,
"{0:,.1f}".format(repair_time),
"{0:,.1f}".format(recovery_time),
"{0:,.1f}".format(interruption_time),
"{0:,.2f}".format(casualties_day["Severity 1"]),
"{0:,.2f}".format(casualties_day["Severity 2"]),
"{0:,.2f}".format(casualties_day["Severity 3"]),
"{0:,.2f}".format(casualties_day["Severity 4"]),
"{0:,.2f}".format(casualties_night["Severity 1"]),
"{0:,.2f}".format(casualties_night["Severity 2"]),
"{0:,.2f}".format(casualties_night["Severity 3"]),
"{0:,.2f}".format(casualties_night["Severity 4"]),
"{0:,.2f}".format(casualties_transit["Severity 1"]),
"{0:,.2f}".format(casualties_transit["Severity 2"]),
"{0:,.2f}".format(casualties_transit["Severity 3"]),
"{0:,.2f}".format(casualties_transit["Severity 4"]),
"{0:,.1f}".format(sc_Displ3),
"{0:,.1f}".format(sc_Displ30),
"{0:,.1f}".format(sc_Displ90),
"{0:,.1f}".format(sc_Displ180),
"{0:,.1f}".format(sc_Displ360),
"{0:,.1f}".format(sc_BusDispl30),
"{0:,.1f}".format(sc_BusDispl90),
"{0:,.1f}".format(sc_BusDispl180),
"{0:,.1f}".format(sc_BusDispl360),
"{0:,.1f}".format(debris_brick_wood),
"{0:,.1f}".format(debris_concrete_steel),
]

```

```

if __name__ == "__main__":
    calculate_consequences(sys.argv[1])

```

Quality Checking Script

```
#!/bin/python
# =====
# SPDX-License-Identifier: Open Government Licence - Canada
#
# Copyright (C) 2020-2022 Government of Canada
#
# Main authors: Tiegan Hobbs <tiegan.hobbs@nrcan-rncan.gc.ca>
# =====

import pandas as pd
import glob
import os

#####
#### STUFF YOU MIGHT WANT TO EDIT #####
#####
provs = ['AB','BC','MB','NB','NL','NS','NT','NU','ON','PE','QC','SK','YT']
#####

for prov in provs:
    print("Working on "+str(prov))
    #####
    # Read files in #####
    #####
    filelocloss = 'ebRisk/output/' #assuming it's run from canada-srm2/
    filelocdamg = 'eDamage/output/'
    filelocexpo = '../openquake-inputs/exposure/general-building-stock/'
    regions = glob.glob(str(filelocloss)+str(prov)+'/ebR_'+str(prov)+'_?*_avg_losses-stats_b0.csv')
    for region in regions:
        loss = region
        FirstChar = os.path.basename(region).split('_')[2]
        Area = os.path.basename(region).split('_')[3]
        lossdf = pd.read_csv(loss, skiprows=1)
        expo = str(filelocexpo)+'oqBldgExp_'+str(prov)+'_'+str(FirstChar)+'_'+str(Area)+'.csv'
        expodf = pd.read_csv(expo)
        lossdfE = lossdf.merge(expodf, left_on='asset_id', right_on='id', how='left', suffixes=['','_expo'])

        #####
        # AAL:Replacement Value #####
        #####
        lossdfE['AAL'] = lossdfE['structural']+lossdfE['nonstructural']+lossdfE['contents']
        lossdfE['ReplacementCost'] =
        lossdfE['structural_expo']+lossdfE['nonstructural_expo']+lossdfE['contents_expo']
        lossdfE['RCtoAAL'] = lossdfE['ReplacementCost']/lossdfE['AAL']
        #print('Are there any assets with AAL greater than Replacement Cost?
        '+str(any(lossdfE['RCtoAAL']<1))+ ' (Must be False)')
        if any(lossdfE['RCtoAAL']<1):
            print(lossdfE[lossdfE['RCtoAAL']<1])
            print('region is '+str(FirstChar)+'_'+str(Area))
```

```

#AALR < 1%?
lossdfE['LossRatio'] = lossdfE['AAL']/lossdfE['ReplacementCost']
if any(lossdfE['LossRatio']>0.005):
    print(lossdfE[lossdfE['LossRatio']>0.005])
    print('region is '+str(FirstChar)+'_'+str(Area))

#####
# URM:Wood Loss Ratios #####
#####
lossdfE['lossrat'] = lossdfE['AAL']/lossdfE['ReplacementCost']
lossdfE['wood'] = lossdfE['lossrat'][lossdfE['GenType'] == 'Wood']
lossdfE['URM'] = lossdfE['lossrat'][lossdfE['GenType'] == 'URMasonry']
#lossratios = lossdfE[['saudid','wood','URM']].groupby('saudid').mean()
lossratios = lossdfE[['csdname','wood','URM']].groupby('csdname').mean()
#print('Are there any csds with greater wood loss ratio than URM?
'+str(any(lossratios['URM']<lossratios['wood'])))
if any(round(lossratios['URM'],4)<round(lossratios['wood'],4)):
    print(lossratios[lossratios['URM']<lossratios['wood']])
    print('region is '+str(FirstChar)+'_'+str(Area))

#####
# 500 yr loss vs CHCH #####
#####
loss500 =
pd.read_csv(str(filelocloss)+str(prov)+'/ebR_'+str(prov)+'_'+str(FirstChar)+'_'+str(Area)+'_agg_curves-
stats_b0.csv', skiprows=1)
loss500df = loss500[(loss500['return_period'] == 500) & (loss500['loss_type'] != 'occupants')]
if any(loss500df['loss_ratio']>0.70):
    print(loss500df[loss500df['loss_ratio']>0.70])

```