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Assessing the Financial Impact of an Earthquake in Greater Vancouver

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Executive Summary

This study examines the financial impact of the shaking damage from an earthquake on buildings located in the Greater Vancouver region. Specifically, this study considers how such damage would be distributed across the insurance industry, building owners, and other stakeholders, and whether they have the financial capacity to handle these losses. The scenarios considered are a hypothetical earthquake centered 10 kilometers under Vancouver City Hall, and this study will mainly focus on catastrophic magnitude 6.5 and magnitude 7.0 scenarios. According to the OpenQuake model, a magnitude 6.5 earthquake would cause $30 billion in shake damage to buildings in the Greater Vancouver region and a magnitude 7.0 earthquake would cause $65 billion in shake damage. Assuming a 10% deductible, total insured losses from shaking would reach $6.1 billion for a magnitude 6.5 earthquake and $18.8 billion for a magnitude 7.0 earthquake. The insurance industry, private owners, lenders, and the government have the financial capacity to handle these losses in isolation. With standard assumptions on liquefaction, fire following earthquake, and indirect damage, a magnitude 7.0 earthquake may result in failure of some insurance companies and may approach the threshold to threaten systemic failure in the insurance industry.

This study also examines the value of seismic retrofits of unreinforced masonry buildings. Unreinforced masonry buildings are extremely vulnerable to shake damage and will be damaged at disproportionate rates, especially for smaller earthquakes. Retrofitting all unreinforced masonry buildings would generate avoided losses from shaking of $0.8 billion for a magnitude 6.0 earthquake, $1.3 for a magnitude 6.5 earthquake, and $1.6 billion for a magnitude 7.0 earthquake. However, estimates of the total cost to retrofit all unreinforced masonry buildings in Greater Vancouver range from $2.3 billion to $11.4 billion. Shaking damage alone would likely not justify a seismic retrofit of all unreinforced masonry buildings in the Greater Vancouver region.

Section 1: Losses from earthquakes in Vancouver

It is inevitable that a major earthquake will strike in the Vancouver area, likely resulting in extensive losses if mitigation efforts are not undertaken. While studies have examined the overall damage caused by such an earthquake, the impact of the distribution of these losses across the financial sector have not been examined as closely. A study by PACICC (Kelly, 2016) found that Canada's insurers can fully respond to an earthquake resulting in up to $25 billion in insurance claims, including those resulting from shaking, fire following earthquake, tsunami, liquefaction, landslide, and business interruption and additional living expenses. Some insurance companies may fail if total claims fall between $25 billion and $35 billion, and claims exceeding $35 billion would exceed the capacity of the insurance industry. The PACICC study focuses on the impact of total insurance claims and does not consider the intensity of earthquake required to generate such claims. Insurance regulations require Canadian insurance companies to model and demonstrate they have the financial capacity to handle the impact of a 1-in-500 year earthquake. Public discussion about the financial capacity of the insurance industry typically focuses on extreme or catastrophic earthquakes that may result in damages beyond current requirements. Extreme earthquakes could result in damage that will require financial support from the insurance industry, governments, lending institutions and property owners.

This section examines how the losses of earthquakes of various magnitudes in the Greater Vancouver region would affect the financial industry. The main focus is on whether insurance companies have the capacity to pay for the insurance claims. This section will also briefly examine the financial impact on banks, businesses, and individual asset owners.

Scenarios and Estimated Shake Damage

This section examines the total direct damage caused by earthquakes in Vancouver. The scenario considered is a shallow crustal earthquake centered 10 kilometers under Vancouver city hall. Intensities are varied from magnitude 4.5 to 9.0. This section focuses on the damages caused by shaking from the earthquake, but will reference previous studies' estimates on damage due to liquefaction and fire following earthquake. The OpenQuake model is used to generate mean losses for each scenario with a different earthquake intensity. For each scenario, 1000 realizations of the ground motion fields are generated using the same random seed, with random ground motion outcomes are truncated at 3.0 standard deviations. [1] For comparison, losses implied by the median ground motion fields are also generated for each scenario.

The exposure file used was compiled by the Geologic Survey of Canada (GSC) for the region of Greater Vancouver for 2016. A full list of the 3-digit forward sortation area (FSA) codes included in this region are listed in Appendix A. In total, there are $717 billion dollars of buildings and contents in this region in the database. Each asset is listed by construction type at a given location. Multiple assets of the same occupancy type and construction type at the same location are consolidated into the same entry. For each entry, the database contains information on the GPS coordinates of the building, construction type of building (e.g., HAZUS taxonomy), occupancy type of building (e.g., commercial, industrial, or residential), number of assets, total dollar value of structural and non-structural building components, total dollar value of contents, and total occupancy by time of day.

Table 1 shows the mean damages (the average damages implied by the random ground motion fields) and median damages (the damage implied by the median ground motion field) generated by the OpenQuake engine for each scenario. The mean direct shaking damage in the Greater Vancouver region exceeds $2.4 billion with a magnitude 5.5 earthquake and increases dramatically for stronger earthquakes. Mean shake damages approach $30 billion with a magnitude 6.5 earthquake and $65 billion with a magnitude 7.0 earthquake. While the outcomes of individual scenarios aren't directly comparable to exceedance curves produced by a probabilistic assessment, these figures are especially interesting because the magnitude 6.5 and magnitude 7.0 earthquakes produce maximum shaking intensities which are roughly comparable to the 1-in-500 year shaking under the 2015 and 2020 standards, respectively.

[1] These results were validated for the magnitude 4.5 and magnitude 5.0 earthquakes by running the same scenarios with 5000 realizations and a different random seed. While some individual assets experienced slightly different losses, the aggregate damage to structural components, nonstructural components, and contents were similar.

Table 1: Direct Damage in Greater Vancouver Region by Magnitude by Billions of Dollars and Percent of Total Asset Values

	M4.5	M5.0	M5.5	M6.0	M6.5	M7.0	M7.5	M8.0	M8.5	M9.0
Mean ($B)	$0.2	$0.7	$2.4	$8.3	$29.7	$64.8	$102	$130	$142	$155
Median ($B)	$0.1	$0.4	$1.1	$3.7	$15.9	$41.7	$70.8	$97.9	$110	$123
Mean (%)	0.0%	0.1%	0.3%	1.2%	4.1%	9.0%	14.2%	18.2%	19.8%	21.6%
Median (%)	0.0%	0.1%	0.2%	0.5%	2.2%	5.8%	9.9%	13.7%	15.3%	17.2%

The OpenQuake model generates mean damages from random ground motion fields which are much larger than damages from the median ground motion field. For the magnitude 6.5 and magnitude 7.0 earthquakes, the mean loss is 87% and 55% larger than the median, respectively. The magnitude 5.5 earthquake has the largest percent difference with a mean loss 118% larger than the median. This difference between mean and median damages may occur because the slope of damages increases with the intensity of ground motion and/or because the distribution of damages is right-skewed for a given intensity of ground motion. Overall, these results show it's important to examine the mean damage instead of the median damage when considering the financial impact of earthquakes.

Other Sources of Earthquake Damage

While the OpenQuake model only generates losses due to shaking, it's important to consider other ways in which an earthquake can cause damages. The IBC/AIR earthquake study (2013) examined losses in British Columbia for a magnitude 9.0 Cascadia subduction zone earthquake. This study estimates fire following damages of 1% of shake damages, tsunami damages are 9%, and liquefaction and landslide damages that are 11% of shake damages. Additionally, the study finds indirect losses which are 20% of the total shake damage. In total, the IBC/AIR study suggests it may be appropriate to add roughly 40% of shake damages as additional losses for a Cascadia earthquake. Tsunami risk is less applicable for the scenarios considered in this study, so a 30% figure will be used as the additional non-shaking losses.

Estimates of the effects of fire following an earthquake varies significantly across studies. Fire following an earthquake is especially important for insured losses because fire insurance policies are much more prevalent than earthquake policies, and fire policies also have lower deductibles. A study by EQE International and the Institute for Catastrophic Loss Reduction (2001) found a magnitude 6.5 earthquake in New Westminster would cause $8.5 billion in fire damage in 1999 dollars ($11.2 billion in 2016 dollars), which represented 3.1% of the $260 billion of assets at risk in the region.[2] This assessment did not include an assessment of the shaking damage caused by such an earthquake. Similarly, a Montreal study (Scawthorn, 2019) finds fire following an earthquake would represent between 0.8% and 2.5% of assets at risk. Using the NRC exposure database and the OpenQuake output, 3.12% of the assets at risk would represent $22.4 billion, which is 75% of the shake damage to buildings of a magnitude 6.5 earthquake. The ratio of damage from fire following an earthquake to shake damage should also change with the intensity of the earthquake. A weak earthquake is not likely to start fires or

[2] An updated study on fire following an earthquake in Vancouver conducted by the Institute for Catastrophic Loss Reduction will be released later in 2020. The updated study will likely find a similarly high level of losses for fire following an earthquake in Vancouver.

affect fire-fighting capabilities, while a strong earthquake would start more fires and cause more damage to fire-fighting capabilities.

Finally, post-event inflation in construction costs may occur after an extreme earthquake. Shortages of materials and workers may increase recovery costs. For example, insurance companies paid 25% to 35% more to rebuild homes destroyed following the Fort McMurray wildfire than the typical cost of rebuilding homes destroyed by fire. This was also evident in the recovery after the 2011 Christchurch earthquake and after the 2005 Hurricane Katrina in New Orleans. A catastrophic earthquake in the Vancouver area will result in higher costs of reconstruction and extensive delays in the recovery time. The amount of post-event inflation is also expected to increase with the size of the earthquake.

Insured and Uninsured Losses

To consider the effects of the financial impact of a Vancouver earthquake on the financial sector, the earthquake shake damage generated by the OpenQuake engine are divided into insured and uninsured losses. Information from the CatIQ database is used to approximate the earthquake insurance penetration for commercial and personal policies for each 3-digit FSA. For each asset, earthquake damages are divided into insured and uninsured losses using the earthquake insurance penetration of that FSA and policy type.

The CatIQ database surveys insurance companies to collect information on insurance policies. It reports aggregate values for the replacement value of covered buildings and contents, deductibles, coverage limits, and business interruption/additional living expenses. These values are reported by 3-digit FSA, type of peril, and policy type (commercial, personal, and automobile). Values are imputed for non-responders to arrive at an estimate for the entire insurance market. While the CatIQ database provides data starting in 2016, 2017 is the first year for which earthquake insurance policies are reported in detail.

An approximation for the total value of assets in each FSA is needed to approximate the earthquake insurance penetration for each FSA and policy type. Unfortunately, the GSC exposure database cannot be used for this purpose because asset values across these two databases are not directly comparable (see Appendix B for a comparison of asset values across these two databases). As such, the values of fire insurance policies in CatIQ are used as a proxy for the total asset value in the region under the assumption that most commercially and individually owned buildings are insured for fire damage. The ratio between the total dollar values covered for earthquake damage and the total dollar values covered for fire damage is used as the earthquake insurance penetration rate. This ratio is calculated separately for each combination of FSA, policy type (commercial vs. personal), and building value or content value.

Table 3: Average Earthquake Penetration by Value of Policy

	Commercial	Personal	Combined
Greater Vancouver	94%	51%	73%
Montreal	87%	4%	81%
Victoria	95%	67%	42%

Earthquake insurance penetration in British Columbia is relatively high. In the Greater Vancouver region, almost all commercial buildings have earthquake insurance and about half of personal buildings also have earthquake insurance. Victoria has some of the highest earthquake insurance penetration rates in Canada, with two-thirds of their personal buildings being insured for earthquake risk. For other regions in Canada, earthquake insurance penetration rates still tend to be high for commercial policies but are extremely low for personal policies. Less than 5% of homes owners located outside of British Columbia purchase earthquake shake insurance. Notably, damage from fire following an earthquake is covered by fire insurance, which most property-owners have. Because of the focus on shake damage, this study does not separately consider fire insurance.

These insurance penetration rates are then applied to the earthquake damages from the OpenQuake engine to estimate insured losses from shaking, as the model does not yet include a capacity to estimate losses from fire, liquefaction, tsunami and business interruption. The earthquake insurance penetration used is based on the asset's FSA and HAZUS occupancy type. For some occupancy types, the asset's building components and contents are covered under different types of insurance policies. For example, multi-family dwellings of 5 or more units are assumed to be covered by a commercial policy for the building while their contents are covered under personal policies. Most governmental buildings do not have insurance, so occupancy types that are usually owned by governments are assumed not to have earthquake insurance. Tables 3 and 4 list the coverage type assumptions of the building and contents, respectively, for each HAZUS occupancy code.

Most earthquake insurance policies have deductibles, and deductibles can have a significant effect on the distribution of losses. A higher deductible results in a lower expected payment if a loss occurs but lowers the premium and thus makes the coverage more affordable. There is no standard deductible shared across earthquake insurance policies, but deductibles for earthquake insurance tend to be a percent of the asset's value rather than a flat amount. Deductibles differ between companies, and some insurance companies allow the consumer to select the deductible they prefer. For this study, a 10% deductible is used. A 10% deductible has been used as a baseline in past studies (e.g., IBC/AIR 2013 study), and is close to the average ratio of deductibles to building values on earthquake policies in the CatIQ database.

Table 4: Insurance Coverage Type for Building (Structural and Nonstructural) Components by Occupancy Type

Occupancy Type	Occupancy Codes	Building Coverage Type
Agriculture, Commercial, Industrial	All AGR, COM, IND codes	Commercial
Colleges/Universities, Church/Non-Profits	EDU2, REL1	Commercial
Temporary Lodging and Nursing Homes	RES4, RES6	Commercial
Dwellings of 4 or fewer units	RES1, RES2, RES3A, RES3B	Personal
Dwellings of 5 or more units	RES3C, RES3D, RES3E, RES3F	Commercial
Grade Schools	EDU1	None
Government Buildings	All GOV codes	None

Table 5: Insurance Coverage Type for Contents by Occupancy Type

Occupancy Type	Occupancy Codes	Contents Coverage Type
Agriculture, Commercial, Industrial	All AGR, COM, IND codes	Commercial
Colleges/Universities, Church/Non-Profits	EDU2, REL1	Commercial
Temporary Lodging and Nursing Homes	RES4, RES6	Commercial
Dwellings of 4 or fewer units	RES1, RES2, RES3A, RES3B	Personal
Dwellings of 5 or more units	RES3C, RES3D, RES3E, RES3F	Personal
Grade Schools	EDU1	None
Government Buildings	All GOV codes	None

The distribution of losses must be modeled to calculate the effect of deductibles on insured losses. OpenQuake provides information on the mean and standard deviation of losses for structural components, nonstructural components, and contents. The distribution of losses are modeled as a beta distribution (Lallemant & Kiremidjian, 2014) using the method of moments. See Appendix C for a detailed explanation of how insured losses are calculated in this analysis.

Three simplifying assumptions are used when modeling the distribution of losses. First, since structural and non-structural components share the same deductible, the analysis applies the distribution of losses for structural components to the distribution of losses for nonstructural components when calculating the effect of the deductible. Second, a separate deductible is assumed to apply for building components and contents. Third, GSC's exposure model groups multiple assets with the same location, construction type, and occupancy type into one entry. This analysis aggregates damages and deductibles for each entry. Effectively, this assumes assets in the same entry are assumed to suffer damage equally and have the same dollar amount as their deductibles.

Table 6 shows the insured and uninsured losses in the Greater Vancouver region under the base case with a 10% deductible. Insured losses for earthquakes of magnitude 5.0 are small and below $50 million. Insured losses quickly increase and exceed $6 billion for a magnitude 6.5 earthquake and approach $19 billion for a magnitude 7.0 earthquake. Uninsured losses are much higher than insured losses for all earthquake scenarios considered. The analysis finds 21% of losses are insured for a magnitude 6.0 earthquake and 29% are insured for a magnitude 7.0 earthquake. These are similar to the findings of the IBC/AIR study (2013) which find 21% of losses from a magnitude 9.0 Cascadia subduction zone earthquake would be insured.

Table 6: Insured and Uninsured Losses with 10% Deductible by Magnitude (in billions of dollars)

	M4.5	M5.0	M5.5	M6.0	M6.5	M7.0	M7.5	M8.0	M8.5	M9.0
Insured Loss	$0.01	$0.04	$0.2	$1.0	$6.1	$18.8	$31.9	$44.3	$50.4	$57.1
Uninsured Loss	$0.21	$0.68	$2.3	$7.4	$23.6	$46.0	$69.6	$85.9	$91.5	$97.5
Percent of Loss Insured	6.0%	5.7%	6.4%	11.4%	20.6%	29.0%	31.5%	34.1%	35.5%	36.9%

Tables 7 and Table 8 show how the insured and uninsured losses, respectively, change with the deductible. The deductible has a significant effect on insured losses. For small earthquakes, moving from no deductible to a 5% deductible reduces insured losses by roughly 90%. This is expected since most damage caused by these earthquakes would be small. The decrease in insured losses is not as dramatic for larger earthquakes but is still large. The 5% deductible reduces insured losses by almost 50% for a magnitude 6.5 earthquake and by 37% for a magnitude 7.0 earthquake. These results show the deductible is an important tool for the affordability of earthquake insurance as it has a significant effect on expected insured losses.

Table 7: Insured Losses by Deductible and Magnitude (in billions of dollars)

Deductible	M4.5	M5.0	M5.5	M6.0	M6.5	M7.0	M7.5	M8.0	M8.5	M9.0
15%	$0.01	$0.04	$0.1	$0.6	$4.0	$12.2	$20.8	$30.0	$35.1	$41.0
12%	$0.01	$0.04	$0.1	$0.8	$5.1	$15.7	$27.0	$38.3	$44.0	$50.3
10%	$0.01	$0.04	$0.2	$1.0	$6.1	$18.8	$31.9	$44.3	$50.4	$57.1
8%	$0.01	$0.04	$0.2	$1.2	$7.6	$22.4	$37.3	$50.8	$57.2	$64.4
5%	$0.01	$0.05	$0.3	$1.8	$10.8	$28.7	$46.7	$62.0	$69.2	$77.1
0%	$0.16	$0.52	$1.8	$6.1	$21.5	$45.7	$68.5	$86.1	$94.1	$102.7

Table 8: Uninsured Losses by Deductible and Magnitude (in billions of dollars)

Deductible	M4.5	M5.0	M5.5	M6.0	M6.5	M7.0	M7.5	M8.0	M8.5	M9.0
15%	$0.21	$0.68	$2.3	$7.7	$25.7	$52.6	$80.7	$100.1	$106.8	$113.6
12%	$0.21	$0.68	$2.3	$7.5	$24.6	$49.1	$74.5	$91.9	$97.9	$104.3
10%	$0.21	$0.68	$2.3	$7.4	$23.6	$46.0	$69.6	$85.9	$91.5	$97.5
8%	$0.21	$0.67	$2.2	$7.1	$22.1	$42.5	$64.2	$79.4	$84.7	$90.2
5%	$0.21	$0.67	$2.1	$6.5	$18.9	$36.1	$54.9	$68.2	$72.7	$77.4
0%	$0.06	$0.20	$0.7	$2.2	$8.2	$19.1	$33.0	$44.1	$47.8	$51.9

Changes in the deductible around the 10% level also have a significant effect for larger earthquakes. For magnitude 6.5 and magnitude 7.0 earthquakes, a 2% change in deductibles around 10% changes insured losses by roughly 15% - 20%. While these represent changes of roughly $1 - $1.5 billion for a magnitude 6.5 earthquake, these changes are in the $3 - $3.5 billion range for a magnitude 7.0 earthquake. These differences have significant implications for the reinsurance required to support earthquake insurance policies and thus the affordability of earthquake insurance premiums.

Financial Capacity

Insurance companies actively manage their exposure to severe earthquakes and have put in place considerable capacity to respond to such events. Insurance companies purchase roughly $25 billion in reinsurance coverage that would be available to support their response to a catastrophic earthquake. Insurance regulators require insurance companies to report annually with an estimate of the expected financial impact of a severe earthquake and prove that reinsurance and other financial capacity is in place to pay claims. This process, however, has limits. The PACICC study (Kelly, 2016) found the insurance industry can absorb losses of $25 billion without bankruptcies, but some companies may fail if the earthquake results in $25 billion to $35 billion in claims and losses greater than $35 billion may cause systemic insurance failure. This includes insurance claims resulting from shake, fire, liquefaction, tsunami, business interruption, post event inflation and any other sources.

This study projects the insurance industry would likely have the capacity to absorb insured losses generated by a magnitude 6.5 earthquake but may face some difficulties when faced with a magnitude 7.0 earthquake. A magnitude 6.5 earthquake is projected to cause $6.1 billion of insured shake losses. Even if insured losses are increased by 30% of insured shake losses to account for non-shake losses (reflecting the IBC/AIR (2013) study), the resulting $7.9 billion of insured losses should be within the financial capacity of the insurance industry. A magnitude 7.0 earthquake would result in $18.8 billion in insurance claims related to shake damage. When losses due to liquefaction, fire following, and indirect losses are considered, projected total insurance claims approach $25 billion and some companies may be at risk of failing. As such, there's a strong chance the insurance industry may experience a small number of bankruptcies.

Assumptions around the extent of fire following an earthquake has a strong effect on these conclusions. If the higher estimate of fire following an earthquake from the EQE/ICLR study (2001) are used, total losses increase by $22.3 billion for a magnitude 6.5 earthquake and by $48.6 billion for a magnitude 7.0 earthquake. These losses would almost entirely be insured due to the lower deductibles on fire insurance policies. These higher fire following earthquake losses would push insured losses to $28.4 billion for a magnitude 6.5 earthquake, which is over the threshold where a small number of insurance companies would go bankrupt. The magnitude 7.0 earthquake would almost certainly suffer from systemic failure with almost $75 billion in insured losses. These results show the importance of improved modeling and mitigation of fire following earthquakes.

The effects of losses which fall on entities besides insurance companies require less precise estimates due to a lack of better data. Table 9 shows how the uninsured losses would be distributed across personal, commercial, and government asset owners. Despite having similar total asset values ($367 billion owned personally, $346 billion owned commercially), personal asset owners would suffer greater uninsured losses because they are less likely to have earthquake insurance. Government buildings represent only 0.4% of total asset values in the GSC exposure model and as such suffer small losses. However, this figure does not include government-owned critical infrastructure such as roads, sewers, and other non-building assets, which are likely to be significant contributors to losses in an earthquake.

Table 9: Uninsured Losses by Asset Owners with 10% Deductible (in billions of dollars)

	M4.5	M5.0	M5.5	M6.0	M6.5	M7.0	M7.5	M8.0	M8.5	M9.0
Personal	$0.128	$0.397	$1.26	$3.94	$13.0	$27.6	$45.4	$58.5	$62.7	$67.2
Commercial	$0.082	$0.275	$1.00	$3.37	$10.4	$18.0	$23.6	$26.6	$28.0	$29.4
Government	$0.002	$0.005	$0.02	$0.05	$0.2	$0.4	$0.6	$0.8	$0.8	$0.9

These losses can be absorbed by different entities. If the solvency of the asset owners is not a concern, then the losses will fall entirely on the asset owners. If solvency is a concern, then part of these losses will fall onto their lenders. The federal and provincial governments may also backstop some of these losses. The financial capacity of each of these entities are assessed.

Statistics Canada (2020) provides annual information on household economic accounts by province. The fraction of real estate assets can be used as a rough proxy of the fraction of the total British Columbia numbers that the Greater Vancouver region represents. In 2016, there were $1,227 billion of real estate assets in British Columbia. In the Exposure Database, the Greater Vancouver area had $181 billion in personal building assets and $288 in commercial building assets. Since some households may privately own commercial property, this analysis will use an estimate of $200 billion of real estate assets in the Greater Vancouver area, which implies the Greater Vancouver area makes up roughly 1/6 of the household economic accounts.

The total net worth of B.C. in 2018 was $1,868 billion. If the Greater Vancouver region represents 1/6 of B.C., personal net worth in the Greater Vancouver region would be $311 billion. Personal uninsured losses due to shake damage from a magnitude 7.0 earthquake would represent 9% of net worth. Even with 30% higher losses[3] due to non-shaking direct and indirect damage, total uninsured losses would be a small fraction of net worth. Uneven distributions of losses and net worth across asset owners may mean the direct shaking damage of such an earthquake could still cause bankruptcies, but overall, the total net worth in the region could be large enough to absorb the losses from a magnitude 7.0 earthquake.

Next, the possible effect on mortgage lenders is considered. From 2014-2018, mortgage liabilities averaged 21.8% of real estate assets in the household economic accounts. Assuming these mortgage liabilities are distributed evenly across assets affected by an earthquake, there would be $6 billion of uninsured damages to personal property with mortgages in a magnitude 7.0 earthquake. This estimate should be high. For example, the owner of a home that suffers minor damage with a mostly-paid mortgage is unlikely to default on the mortgage. Similarly, this assumes mortgaged homes are equally likely to be covered by earthquake insurance as non-mortgaged homes.

To put these mortgage losses in perspective, the financial information of the five largest commercial banks in Canada (Royal Bank of Canada, Toronto-Dominion Bank, Bank of Nova Scotia, Bank of Montreal, Canadian Imperial Bank of Commerce) can be considered. In 2019, these banks combined for a total equity of $331.2 billion and net income of $44.9 billion. Some of the losses will fall onto smaller banks and credit unions, and these financial institutions may be less capable of absorbing additional losses. Overall, however, the Canadian financial sector is large enough to absorb the direct mortgage losses from a Vancouver earthquake.

Finally, the financial positions of British Columbia and the Government of Canada are considered. In its 2020 budget, British Columbia forecast revenues of $59.3 billion, expenses of $58.8 billion, and an after-allowance surplus of $0.2 billion for the 2019-2020 fiscal year. A magnitude 7.0 earthquake cause damages to government buildings and contents that is $0.2 billion more than this after-allowance surplus. Additional damages due to liquefaction and fire following using the IBC/AIR (2013) estimates would have little effect on this outcome. Overall, the damage to buildings in such an earthquake should be manageable for the province. Damage to other government-owned critical infrastructure, which is not considered in this study, could potentially be a greater concern.

The Government of Canada has greater financial resources and more flexibility to run a deficit. In its 2019 budget, the Government of Canada showed revenues of $311.2 billion and total expenses of $330.2 billion for the 2017-2018 fiscal year, for a deficit of $19 billion. This deficit represented 0.9% of the country’s 2018 GDP. If the federal government covered the entirety of the $46 billion uninsured

[3] This overestimates uninsured losses, since a greater fraction of losses would be insured.

direct damage of a magnitude 7.0 earthquake, it would increase the federal debt by 2.1% of 2018's GDP. This figure would increase to 2.7% of 2018 GDP if liquefaction, fire following, and indirect damages are added. The fiscal burden of these damages would be higher since an earthquake could significantly reduce GDP and these damage figures don't include damage to critical infrastructure and indirect losses caused by the earthquake. However, these losses should still be small relative to the government's fiscal capacity.

Section 2: Unreinforced Masonry

Unreinforced masonry buildings are especially vulnerable to earthquake damage. Overall, there is widespread agreement that unreinforced masonry buildings are not safe in seismically-active areas. For example, the City of San Francisco has mandated the seismic retrofit of all unreinforced masonry buildings. Construction of unreinforced masonry buildings have been prohibited in Canada since the 1930's. This section considers the costs and benefits of retrofitting unreinforced masonry buildings in the Greater Vancouver region.

In the GSC exposure database, there are 13,917 unreinforced masonry buildings worth $12.3 billion in the Greater Vancouver region, and an additional $11.1 billion of contents inside these buildings. In total, they represent 3% of the total buildings and contents in the Greater Vancouver region by value. These unreinforced masonry buildings are divided into 10,767 low-rise buildings worth $7.3 billion with $6.5 billion of contents, and 2,427 mid-rise buildings worth $5 billion with $4.5 billion of contents.

Retrofitting unreinforced masonry prevents a large fraction of losses for small earthquakes but reduces a smaller share of losses from a large earthquake. Table 10 shows total earthquake damage under the different scenarios if all unreinforced masonry buildings in the Greater Vancouver region were retrofit to be classified as reinforced masonry. Unreinforced masonry buildings are disproportionately more vulnerable to small earthquakes compared to other buildings. Retrofitting all unreinforced masonry buildings can avoid roughly 20% of damage inflicted by earthquakes of magnitude 5.5 and under. The percentage of avoided losses falls under 10% for a magnitude 6.5 earthquake and under 5% for a magnitude 7.0 earthquake. In absolute terms, the avoided damages are relatively small. Avoided losses are under $1 billion for earthquakes of magnitude 6.0 and under, and only approaches $2 billion with a magnitude 7.5 earthquake.

Table 10: Direct Damage after Retrofit of All Unreinforced Masonry Buildings (in billions of dollars)

	M4.5	M5.0	M5.5	M6.0	M6.5	M7.0	M7.5	M8.0	M8.5	M9.0
Base Case	$0.23	$0.7	$2.4	$8.3	$29.7	$64.8	$102	$130	$142	$155
Retrofit	$0.18	$0.6	$2.0	$7.5	$28.4	$63.2	$99.7	$128	$140	$153
Avoided Losses $	$0.05	$0.1	$0.4	$0.8	$1.3	$1.6	$1.8	$1.9	$1.9	$2.0
Avoided Losses %	22.2%	20.9%	15.5%	9.5%	4.4%	2.5%	1.8%	1.5%	1.3%	1.3%

The total cost of retrofitting these unreinforced masonry buildings retrofit costs depends heavily on the methodology, but these retrofits tend to be expensive no matter which estimate is used. A study based on San Francisco retrofit records found it would cost roughly $11.88 USD or $16.38 CAD per square foot to retrofit an unreinforced masonry building, which averages to $131,000 CAD to retrofit a low-rise unreinforced masonry building and $366,000 CAD to retrofit a mid-rise unreinforced masonry building. These costs imply a cost of $2.3 billion to retrofit all unreinforced masonry buildings in the Greater Vancouver area.

On the high side, a Seattle study of seismic retrofits considers hard construction costs, soft costs (e.g., permits, inspections, insurance, testing) and relocation expenses incurred during a retrofit. This study found a seismic retrofit would cost an average of $59 USD or $81 CAD per square foot (National Development Council, 2019). When applied to the average square-footage of buildings in the San Francisco study, it implies a seismic retrofit cost of $653,000 CAD and $1,817,000 CAD for low-rise and mid-rise buildings, respectively. With this higher estimate, retrofitting all unreinforced masonry buildings in the Greater Vancouver area would cost $11.4 billion.

The model finds that the costs of the seismic retrofits would be greater than avoided shaking damages. The benefits are still relatively small when adjusted by 30% to account for liquefaction, fire following earthquake, and indirect damages. When using the lower San Francisco estimate of retrofit costs, the benefits of avoided losses in an earthquake would never exceed the costs. Additionally, an earthquake is not guaranteed to happen, and this does not discount the avoided losses. A justification for the seismic retrofit of buildings in Vancouver may need to consider alternative factors like loss of life and other cultural and social benefits.

Conclusion

This study examines the financial impact of a Vancouver earthquake. Overall, it finds the insurance industry, private building owners, lenders, and the government have extensive capacity to handle the shaking damage from a large earthquake. However, the financial capacity of several stakeholders may struggle with absorbing the losses of catastrophic earthquakes. The model also finds that a seismic retrofit of all unreinforced masonry buildings would generate relatively small avoided losses due to shake damage to buildings, and the costs would almost certainly exceed these benefits. While the shaking damage to buildings of a Vancouver earthquake is manageable, additional damage done to non-building assets like roads and utilities, indirect damage from business interruption and additional living expenses, and non-pecuniary damages such as loss of life are important considerations that need additional investigation. Several risks could not be fully explored until the model moves beyond assessing shake damage to also include a rigorous assessment of fire following earthquake, liquefaction, tsunami, business interruption and post event inflation.

One methodological finding of this study is the difference in estimated losses by the OpenQuake model between using the median ground motion fields and averaging the losses from random ground motion fields. Averaging the losses from random ground motion fields generate damage significantly larger than the losses implied by the median ground motion field. Using the median ground motion field to estimate damages could severely underestimate the expected damage that would be suffered with an earthquake.

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Appendix A: FSAs used in analysis

The 3-digit FSA codes associated with the Greater Vancouver region are listed below. These codes are labeled with the Greater Vancouver region in the OpenQuake database.

V0N
V1M
V2V, V2W, V2X, V2Y, V2Z
V3A, V3B, V3C, V3E, V3H, V3J, V3K, V3L, V3M, V3N, V3R, V3S, V3T, V3V, V3W, V3X, V3Y, V3Z
V4A, V4B, V4C, V4E, V4G, V4K, V4L, V4M, V4N, V4P, V4R, V4W, V4X
V5A, V5B, V5C, V5E, V5G, V5H, V5J, V5K, V5L, V5M, V5N, V5P, V5R, V5S, V5T, V5V, V5W, V5X, V5Y, V5Z
V6A, V6B, V6C, V6E, V6G, V6H, V6J, V6K, V6L, V6M, V6N, V6P, V6R, V6S, V6T, V6V, V6W, V6X, V6Y, V6Z
V7A, V7B, V7C, V7E, V7G, V7H, V7J, V7K, V7L, V7M, V7N, V7P, V7R, V7S, V7T, V7V, V7W

Appendix B: Comparison Between GSC and CatIQ Exposure Values (in billions of dollars)

The GSC and CatIQ databases differ in their estimates of total building assets in the Greater Vancouver region. Table B1 compares the total exposure in these databases for this region, where fire policies are used as a proxy for total exposure for the CatIQ database. Despite uninsured assets not being covered by the CatIQ database, its total exposure values are higher than the total asset values in the GSC database. This difference is significant and averages 29% across the total assets. Possible explanations for this could include differences in valuation, differences in imputing the total building stock, and/or the consideration of post-event construction cost inflation.

Table B1: Total Exposure Values in Database ($ billions)

	Personal Buildings	Personal Contents	Personal Total	Commercial Buildings	Commercial Contents	Commercial Total	Total
GSC	$181	$186	$367	$288	$59	$347	$717
CatIQ	$288	$206	$494	$408	$101	$509	$1,004
%Diff	37%	10%	26%	29%	42%	32%	29%

Table B2: Adjusted Insured and Uninsured Losses with 10% Deductible by Magnitude (in billions of dollars)

	M4.5	M5.0	M5.5	M6.0	M6.5	M7.0	M7.5	M8.0	M8.5	M9.0
Insured Loss	$0.02	$0.05	$0.2	$1.2	$8.0	$24.5	$41.5	$57.6	$65.5	$74.2
Uninsured Loss	$0.28	$0.88	$3.0	$9.6	$30.7	$59.8	$90.5	$111.6	$119.0	$126.8

These differences do not qualitatively affect the conclusions of this paper, but they do increase concerns for the insurance industry's ability to absorb the losses of a magnitude 7.0 earthquake. The insurance industry should still suffer no bankruptcies following a magnitude 6.5 earthquake, but some insurance companies may go insolvent following a magnitude 7.0 earthquake (see Table B2). This is especially concerning if non-shaking damage is considered. Adjusting for 30% additional non-shaking losses, the magnitude 7.0 earthquake would cause roughly $32 billion in insured losses, which is close to the $35 billion threshold for when the insurance industry would suffer systemic failure.

Appendix C: Modeling the Deductible

The distribution of total losses must be modeled to estimate the effects of the deductible on insured losses. Importantly, information about the fraction of damages which exceed the deductible and the expected value of damages that do not exceed the deductible are required.

The OpenQuake model provides the mean and standard deviation of losses for structural components, nonstructural components, and contents. This information is sufficient to model total losses as a beta distribution. The beta distribution has a support between 0 (no damage) and 1 (total loss) and is an appropriate approximation of earthquake damage (Lallemant & Kiremidjian, 2014).

One complication is the losses from structural and nonstructural building components would be combined for insurance purposes, but OpenQuake reports them separately. While their means and standard deviations on structural and nonstructural losses are similar, they do differ. These losses are likely to be correlated so it is difficult to model the distribution of these losses combined. A simplifying assumption is used where the distribution of structural losses is used for the distribution of total building component losses. The deductible on content losses are considered separately.

The method of moments is used to estimate the distribution of the losses. The mean and standard deviation of losses are normalized by dividing by the total asset values. The parameters of the beta distribution α and β are modeled using the following equations, where $\bar{x}$ is the normalized mean and s is the normalized standard deviation of losses:

$$\alpha = \bar{x}\left(\frac{\bar{x}(1-\bar{x})}{s^2} - 1\right)$$

$$\beta = (1-\bar{x})\left(\frac{\bar{x}(1-\bar{x})}{s^2} - 1\right)$$

The fraction of damage which exceeds the deductible is simply the compliment of the CDF of the beta distribution for the deductible. The expected value of damages which do not exceed the distribution can be modeled as a truncated beta distribution, where F is the CDF of the beta distribution and k is the deductible:

$$E[X|X<k] = \frac{\alpha}{\alpha+\beta}\frac{F(k,\alpha+1,\beta)}{F(k,\alpha,\beta)}$$

Total insured losses can be calculated as:

$$L = P * D\left(1-\left(1-F(k,\alpha,\beta)\right) * k - F(k,\alpha,\beta) * E[X|X<k]\right)$$

Where L is insured losses, P is the insurance penetration for the FSA and type of policy, and D is total damage.

Appendix D: OpenQuake Settings

job.ini:

```
[general]
description = M4.5 Random Greater Vancouver
calculation_mode = scenario_risk
random_seed = 113

[Rupture information]
rupture_model_file = M4.5 earthquake_rupture_model.xml
rupture_mesh_spacing = 2

[Hazard sites]

[Exposure model]
exposure_file = MetroVancouver.xml
taxonomy_mapping_csv = CAN_UBC2hzTaxon_s0.csv

[Vulnerability model]
structural_vulnerability_file = vulnerability_structural.xml
nonstructural_vulnerability_file = vulnerability_nonstructural.xml
contents_vulnerability_file = vulnerability_contents.xml
occupants_vulnerability_file = vulnerability_occupants.xml

[Site conditions]
reference_vs30_value = 760
reference_vs30_type = inferred
reference_depth_to_2pt5km_per_sec = 2.0
reference_depth_to_1pt0km_per_sec = 100.0

[Calculation parameters]
gsim_logic_tree_file = gmpe.xml
ground_motion_correlation_model =
truncation_level = 3.0
maximum_distance = 100.0
number_of_ground_motion_fields = 1000
```

gmpe.xml:

```
<?xml version='1.0' encoding='utf-8'?>
<nrml xmlns:gml='http://www.opengis.net/gml'
      xmlns='http://openquake.org/xmlns/nrml/0.5'>

<logicTree logicTreeID='lt1'>
  <logicTreeBranchingLevel branchingLevelID='bl1'>
    <logicTreeBranchSet uncertaintyType='gmpeModel'
                        branchSetID='bs1'
                        applyToTectonicRegionType='Active Shallow Crust'>
      <logicTreeBranch branchID='b0'>

<uncertaintyModel>NBCC2015_AA13_activecrust_central</uncertaintyModel>
        <uncertaintyWeight>1.000</uncertaintyWeight>
      </logicTreeBranch>
    </logicTreeBranchSet>
  </logicTreeBranchingLevel>
</logicTree>
</nrml>
```

M4.5 earthquake_rupture_model.xml:

```
<?xml version="1.0" encoding="utf-8"?>
<nrml xmlns:gml="http://www.opengis.net/gml"
xmlns="http://openquake.org/xmlns/nrml/0.4">
    <singlePlaneRupture>
        <magnitude>4.5</magnitude>
        <rake>0</rake>
        <hypocenter lat="49.2446229" lon="-123.1710832" depth="10"/>
        <planarSurface strike="180" dip="45">
            <topLeft lon="-123.13575" lat="49.30813" depth="7.43873"/>
            <topRight lon="-123.13585" lat="49.18110" depth="7.43873"/>
            <bottomLeft lon="-123.20641" lat="49.30813" depth="12.56127"/>
            <bottomRight lon="-123.20632" lat="49.18110" depth="12.56127"/>
        </planarSurface>
    </singlePlaneRupture>
</nrml>
```