Seismic Vulnerability of Victoria, British Columbia, Canada

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ABSTRACT

The City of Victoria, British Columbia, is located on the southern tip of Vancouver Island off Canada's Pacific coast. The City of Victoria is one of the oldest cities in Western Canada with a population of 85,000 people in just 19.5 km^2. The seismicity in Southwestern BC, which is where the City of Victoria located, is dominated by the subduction of the oceanic Juan de Fuca plate beneath the continental North America plate occurring about 100km west of Southern Vancouver Island – also called the Cascadia Subduction Zone. Large mega-thrust earthquakes have occurred at the interface of these two plates reaching moment magnitudes as high as 9.0 in the past. Smaller and more frequent earthquakes can also occur in the Cascadia Subduction zone. Both of these events pose a constant threat to the infrastructure and population of the city. The combination of a large, dense urban population, an aging building stock, and its location put Victoria at a high seismic risk. This study summarizes the citywide vulnerability assessment study done for the City of Victoria in order to identify the city's most at-risk buildings and infrastructure; and to facilitate the development of a seismic resiliency plan. As part of this study an extensive citywide building by building database including over 13,000 buildings was developed. Damage distribution in City of Victoria due to a major subduction megathrust event and smaller, more frequent earthquakes are presented in this paper. The major differences in damage results using both HAZUS and OpenQuake methodologies are discussed. The risk assessment for buildings is also presented considering the aggregation of all hazard types and possible levels of shaking in order to rank the city's building stock. Finally, damage estimation assessment to supporting infrastructure including water and sewer pipelines is presented for different earthquake scenarios.

Keywords: Seismic Risk Assessment, Seismic Resiliency, Cascadia Subduction Zone, Risk Management, Societal impacts.

INTRODUCTION

This paper provides a complete citywide seismic hazard, vulnerability and risk assessment for the City of Victoria. This involves the prediction of seismic hazard(s), the consideration of site soil conditions and their potential effect on ground shaking, the classification of buildings and infrastructure including their seismic vulnerability, and ultimately, the estimation of seismic risk. This paper also compares the damage predicted from the HAZUS [1] and OpenQuake [2] earthquake damage estimation frameworks.

Several existing building databases for the city were compared, updated and combined to create an extensive citywide building database. Both virtual and physical surveys were conducted in order to update the database where there was missing or outdated data. The building database used for this study includes over 13,000 buildings. The majority of the buildings in the city are constructed from wood and built before 1972, when modern building codes were introduced. The downtown core of the city comprises mainly mid- and high-rise concrete, steel and masonry construction, also built prior to 1972. Buildings were classified based on their material type and height as well as age (which was used as a surrogate for design level due to the evolution of building standards and hazard estimation). The level of damage (Complete, Extensive, Moderate, Slight, or None) was estimated and compared for each building for each scenario using the two frameworks.

This paper is only concerned with the damage and vulnerability of buildings and infrastructure; other loss metrics, such as monetary losses and casualties were not considered. This aim of this study is a high level overview of damage due to building class and construction date. It does not take into account the mitigation of specific buildings.

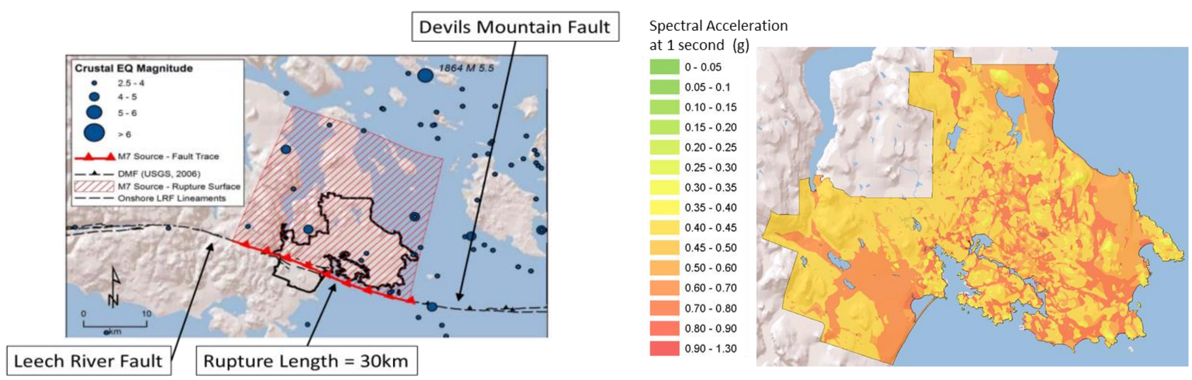
SEISMIC HAZARD

Seismic Hazard Potential

The seismicity of the City of Victoria and surrounding areas is dominated by the interface of the oceanic Juan de Fuca plate beneath the continental North America plate occurring about 100km west of Southern Vancouver Island – also called the Cascadia Subduction Zone. In this paper three potentially damaging seismic scenarios are considered: a magnitude 9.0 rupture of the Cascadia Subduction fault, a deep inslab (magnitude 7.0) under the Strait of Georgia, and a large (magnitude 7.0) rupture of the Leech River crustal fault beneath the city Geophysical parameters and structural response can vary substantially between these types of earthquakes. These events represent possible seismic scenarios from two of the seismic hazards that could cause significant damage in the City of Victoria. Deep earthquakes in the subducting Juan de Fuca plate are also possible, but due to their depth and distance would not likely be as damaging as the two considered scenarios.

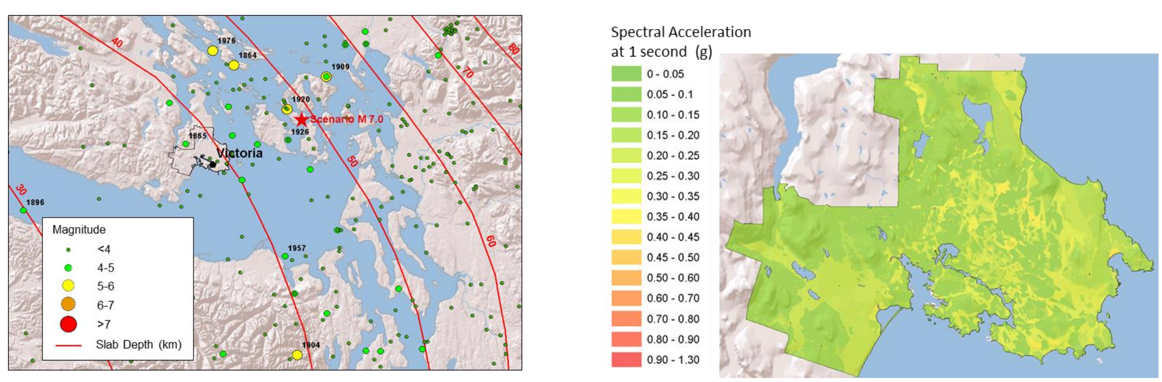
Crustal Scenario: M = 7 on the Leech River Fault

Shallow crustal earthquakes, which are caused by the slipping of faults in the Earth's crust, typically less than 20km deep, are frequently recorded in the North American plate, around 200-300 per year. The vast majority of these events are very small; however larger magnitude events are also possible: in the past 70 years, more than 100 magnitude 5 or greater earthquakes have been recorded in Western Canada. For the shallow crustal earthquake scenario, a partial rupture of the Leech River fault beneath the City of Victoria was considered. A 30km rupture between the mapped Leech River Fault and Devils Mountain fault, which could produce up to a magnitude 7 event [3,4] was selected as illustrated in Figure 1(a). The level of shaking across the City of Victoria from this event is illustrated in Figure 1(b). In this figure the 1 second spectral acceleration is used as a surrogate for shaking intensity, as this parameter is closely related to damage potential. The Ground Motion Prediction Equation (GMPE) by [5] was used to predict shaking levels from the assumed rupture.



(a) (b)

Figure 1: (a) Leech River Fault M = 7.0 Scenario Map (Modified from [4]) (b) Ground Motion Intensity (1 Second Spectral Acceleration) Expected from the M = 7 Crustal Earthquake



(a) (b)

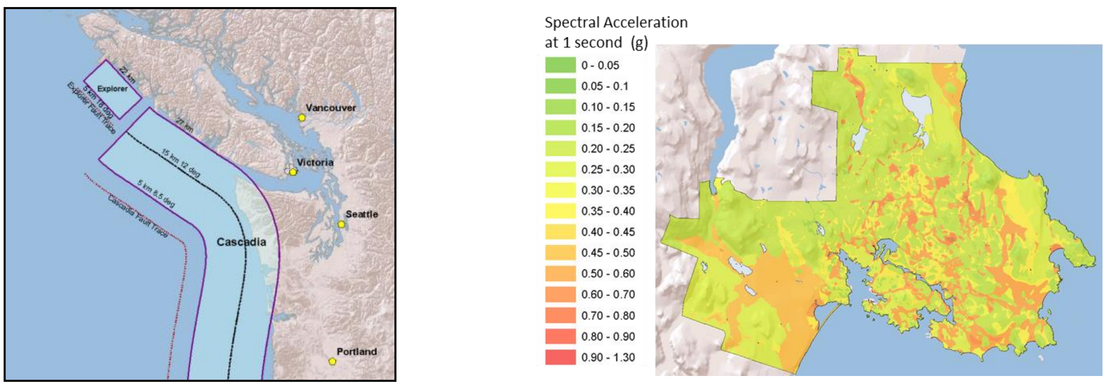
Figure 2: (a) Inslab Scenario Map with Historic Seismicity from [7] and. Slab contours from [8,9] (b) Ground Motion Intensity (1 Second Spectral Acceleration) Expected from the M = 7 Inslab Inslabl Earthquake

Inslab Scenario: M = 7 under the Strait of Georgia

Although inslab events are caused by fault ruptures deep in the Juan de Fuca plate (from 30-100km deep), shaking from these events can still have significant effects on the ground above them. There have been several recordings of deep inslab events in the Pacific Northwest – including the costly 2001 Nisqually (M = 6.8) event. Accordingly, it is necessary to define and analyze a possible inslab earthquake event that could cause damage to infrastructure in the City of Victoria. For the inslab event scenario, a magnitude 7.0 rupture 50km deep underneath the Strait of Georgia was considered (Figure 2). The location of this event was based on the work by [6], who proposed that inslab earthquakes are concentrated in two zones which are controlled by changes in slab orientation.

Interface Scenario: M = 9 Cascadia Rupture

The Cascadia subduction fault runs from Northern California all the way to the middle of Vancouver Island and has the potential to slip and cause very large earthquakes. These earthquakes could cause devastating levels of shaking along the west coasts of Oregon, Washington, and British Columbia. These events happen on average once every 500 years (+/- 200-300 years), and the last event occurred approximately 300 years ago [10]. A full rupture of the Cascadia Subduction Zone (CSZ) would be about 1025km long and 125km wide and could slip 25m [11]. An equally weighted combination of three GMPEs from [12-14] were used to predict shaking levels given the assumed rupture shown in Figure 3(b).



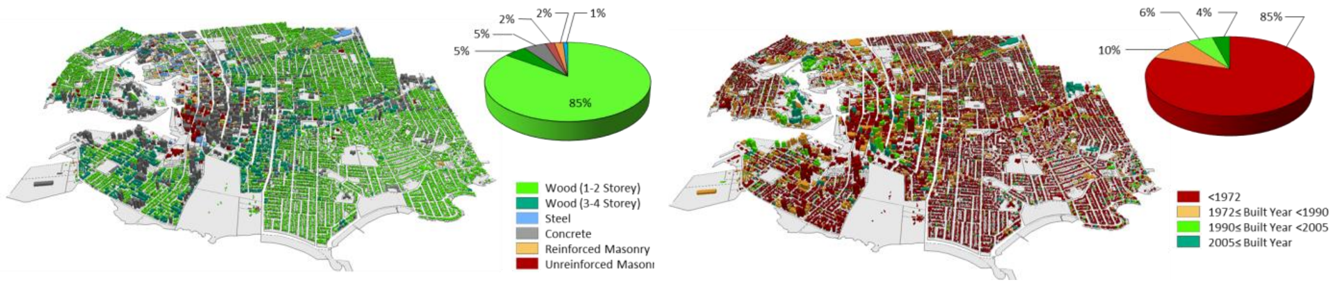
(a) (b)

Figure 3: (a) *Cascadia Subduction Zone including fault surface traces, fault depths and dips, (data from [7])* (b) *Ground Motion Intensity (1 Second Spectral Acceleration) Expected from the M = 9 Subduction Earthquake Scenario*

GENERAL BUILDING STOCK

In the mid-1990's, a 3-year study of seismic risk of Vancouver, New Westminster, and Victoria was conducted by [14] and it was updated in 2010. As part of this study a database of the buildings inventory in the City of Victoria was compiled. This inventory is merged with the BC Assessment's 2016 Building Inventory Report (BIR) to create the basis of the new building inventory database used for this study. Each listing was checked, and particular attention was paid to the building's structural systems and use. Buildings with inaccurate or missing information were investigated through a virtual survey using Google Maps® and other online resources. The virtual survey was conducted from May 18 to August 20, 2016. Through the virtual survey, the majority of the database information was confirmed or updated. From August 21 through August 24, 2016, a team of several undergraduate students travelled to Victoria to conduct a "sidewalk survey" in order to update any missing or unreliable information in the database.

Wood construction is the prevalent construction material in the City of Victoria – approximately 90% of the buildings surveyed in Victoria are constructed using wood (85% are 1-2 stories and another 5% are 3-4 stories). Concrete is the second most common construction material followed by masonry (reinforced and unreinforced), then steel, which is the rarest. Concrete is the primary construction material of taller (more than 6 stories) buildings in the downtown core. Many of the older buildings downtown are masonry, and about half of these are unreinforced masonry (URM). Due to the age of the city, many of the buildings are older – about 80% were built before 1972, which is when seismic design became much more stringent in the National Building Code of Canada (NBCC). Many of these older buildings are weak and brittle compared to modern construction which makes them much more vulnerable to damage when subjected to significant ground shaking. Figure 4 (a) and (b) illustrate the distribution of buildings in the City of Victoria based on construction type and year constructed, respectively. These figures show a high density of modern and old concrete and masonry construction in the downtown core and a large amount of pre-1972 wood residential buildings in the surrounding area.



(a) (b)

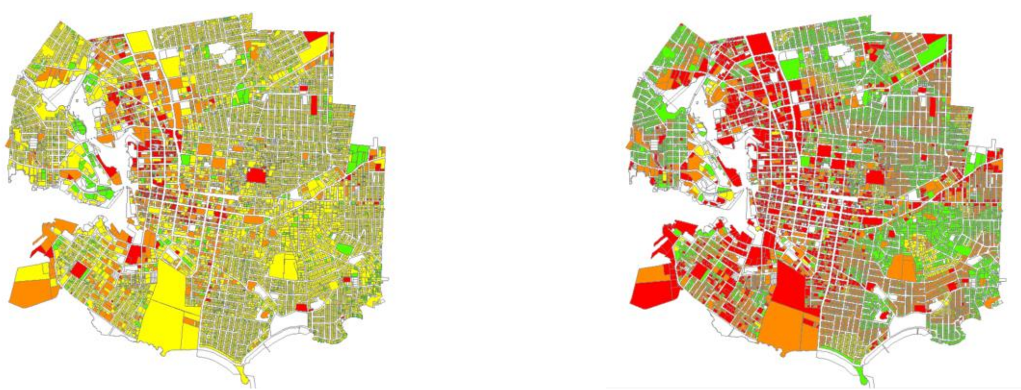
Figure 4: Distribution of City of Victoria Buildings Based on

DAMAGE TO BUILDING STOCK: SCENARIO – BASED

This section presents and discusses the damage results predicted for each of the earthquake scenarios when using both HAZUS [1] and OpenQuake [2]. Five discrete damage states are considered in both methods: None, Slight, Moderate, Extensive, and Complete. HAZUS damage probability functions describe the probability of reaching, or exceeding, structural and non-structural damage states, given estimates of ground shaking and structural response. These curves take into account the variability and uncertainty associated with structural properties, damage states and ground shaking. Structural response is calculated explicitly through nonlinear static analysis based on structural fragility curves, the level of shaking, and the energy dissipation capacity of the structure [1]. Shaking level is quantified by an acceleration response spectrum and duration of shaking. The duration of shaking impacts the energy dissipation capacity of the structure. OpenQuake [2] is an open platform that allows users to integrate their own damage fragility curves. For this study, the 2017 Canadian OpenQuake Fragility Model developed by GEM [2] Pavia, for the various HAZUS typologies were employed. These were developed based on the work by [15] and predict probability of reaching damage states based directly on the level of shaking expected. The level of shaking is quantified by the spectral acceleration at the effective period of the structure. From this point on, we refer to these fragility curves as the OpenQuake fragility curves.

Crustal Scenario: M = 7 on the Leech River Fault

Due to its close proximity to the City of Victoria and shallow depth, the simulated magnitude 7 rupture of the Leech River fault is an extremely damaging event. Figure 5(a) and Figure 5(b) present the damage distribution expected for this event using HAZUS and OpenQuake. Five damage states are considered: complete (red), extensive (orange), moderate (yellow), slight (green), and none (white). From the HAZUS results Complete damage is mostly localized to the concrete and masonry buildings in the downtown core. There are also large areas of moderate and extensive damage in the older wood frame structures surrounding the downtown core. OpenQuake predicts much more Complete and Extensive damage, especially to the concrete and masonry buildings in the downtown core and South/South-West of the city. However, the low-rise wood frame buildings, which make up a large portion of the building stock, were predicted to perform better in OpenQuake: most of these were labeled as Slight damage – compared to Moderate damage in HAZUS. In general, the buildings on softer soils were also predicted to sustain higher levels of damage.



(a) (b)

Figure 5: Damage Distribution for the Magnitude = 7 Crustal Scenario from: (a) HAZUS (b) OpenQuake

Subduction Scenario: M = 9 Cascadia Rupture

The damage results from the magnitude 9 Cascadia rupture using HAZUS and OpenQuake are illustrated in Figure 6. HAZUS predicts a similar amount of complete damage compared to the crustal event – mostly localized to the downtown core – however damage in the surrounding areas is slightly less than in the crustal event. Again, large areas of light frame wood buildings are predicted to be moderately damaged. The OpenQuake results show much lower levels of damage. There are still significant amounts of Complete and Extensive damage in the downtown core, however very little damage predicted in other areas. Most of the old wood buildings are classified as None or Slight damage, depending on soil conditions. The drastic difference compared to HAZUS is attributed in the way HAZUS account for the duration of shaking. In HAZUS, the energy dissipation capacity of buildings is reduced during longer duration events, which increases the predicted displacements and corresponding damage levels.

(a) (b)

Figure 6: Damage Distribution for the Probable Magnitude = 9 Subduction Scenario (a) HAZUS (b) OpenQuake

Damage Scenario Summary

A summary of the number and percent of the total building stock expected in each damage state for the five scenarios is presented in Table 1 using HAZUS. This table also includes the risk level of each scenario, calculated as the probability of exceeding the specified level of shaking over a 50 year period.

Table 1: Damage State Results from the Five Earthquake Scenarios

	None	Slight	Moderate	Extensive	Complete	Risk (% in 50 years)
M7 Crustal	0 (0%)	641 (5%)	3742 (28%)	8503 (64%)	444 (3%)	1
M7 Inslab	2426 (18%)	5906 (44%)	4987 (37%)	11 (0%)	0 (0%)	5
M7 (+1std) Inslab	7 (0%)	2678 (20%)	6634 (50%)	3993 (30%)	18 (0%)	2
M9 Subduction	307 (2%)	2265 (17%)	5612 (42%)	4706 (35%)	440 (3%)	5
M9 (+1std) Subduction	0 (0%)	928 (7%)	3502 (26%)	8059 (60%)	841 (6%)	2

From these results it can be seen that the magnitude 7 rupture of the crustal Leech River fault beneath the City of Victoria is expected to be a very damaging scenario, with a large amount (64%) of buildings reaching extensive levels of damage. However, this level of shaking from a crustal event would be very rare, as indicated in Table 1.The probable Cascadia rupture scenario is also expected to be very damaging, with similar levels of complete damage as compared with the crustal event, however, lower levels of extensive damage. Because this event is much less rare then the crustal event (5% vs. 1% probability of occurrence in the next 50 years) it poses a much greater risk to the city and its infrastructure. When considering the maximum credible Cascadia event (a very rare level of shaking) the damage results predicted become very large: 6% of the building stick would reach complete damage with 60% reaching extensive damage. This means that approximately 65% of the entire building stock could be "red-tagged" after this event - this can be considered the worst case event for the city.

DAMAGE TO BUILDING STOCK: RISK – BASED

The results presented in the previous sections are valuable because they provide a reasonable estimate of the damage that might be expected from a credible shaking scenario; however, they cannot be used to determine the risk or ranking of the city's building stock. This is because only one single shaking event is considered in isolation. For a proper evaluation of seismic risk, all possible shaking levels, from low levels to very rare levels of shaking must be considered. For example, two buildings might suffer similar levels of damage at a certain level of shaking – yet if one of the structures is much more likely to become severely damaged at a lower level of shaking, then it clearly has a higher overall seismic risk. First, a wide range of shaking levels for each seismic source (crustal, inslab, and interface) were run using the building models from the previous sections (from a probability of exceedance of 0.005% to 99.3% in 50 years. The damage results from each level of shaking were combined (integrated) with the corresponding rate of exceedance of that level of shaking and source to calculate a rate of damage exceedance for each damage state. The contributions of the three seismic sources (which are assumed to be independent) were added together. Structures in the City of Victoria were ranked based on their damage risk, as calculated in the previous section. Each building was assigned one of four ranking categories, as summarized in Table 2, based on their probability of complete damage (PDE) in a 50 year period. This approach was adopted from BC Schools 3rd-Edition Seismic Retrofit Guidelines (SRG3, [17])

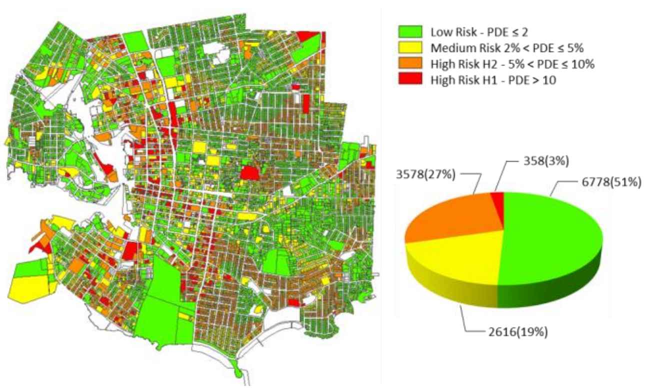


Figure 7: Probability of Complete Damage (PDE) Results for Buildings in the City of Victoria

Table 2: Priority Ranking (SRG3, [17])

Priority Ranking	Probability of Complete Damage (PDE) in 50 years
H1 – High Level 1	> 10%
H2 – High Level 2	5-10%
M – Medium	2-5%
L – Low	< 2%

The probability of complete damage was used as the indicator for risk because this damage state poses the greatest risk to the safety of building occupants. Figure 7 shows the distribution of buildings in each priority ranking category. There are several trends that should be observed in Figure 7. The light frame wood structures in the Southeast corner of the city are at high levels of risk (H1 or H2). This is due to the combination of the age of these buildings (Figure 4) and the soft soil that they were constructed on. Also, the older concrete and masonry structure in the downtown core, especially the areas where the soil is softer, have a very high seismic risk. The unreinforced masonry structures are at a particularly high risk. The Southwest corner of the city, with many tall concrete buildings and residential and commercial wood buildings is at a medium to high risk. Again, soil conditions and building age are the two largest contributing factors to this risk.

DAMAGE TO INFRASTRUCTURE

In addition to building performance, it is also necessary to estimate the damage and vulnerability associated with other urban infrastructure, such as water and sewage pipeline systems and facilities. These systems play a huge role in the recovery and resilience of an earthquake effected community. Even with safe buildings, if a community has no access to fresh water or a wastewater system, it will not be functional after the event and will not be able to recover efficiently. The infrastructure considered in this study include water pipelines and gravity and force sewer pipelines. The damage to other infrastructure such as utility facilities and transportation systems have not been considered in this study. Figure 8 illustrates the distribution of water and sewer pipelines in the City of Victoria based on material type, which is related to their ductility (ability to deform beyond yielding without rupturing). A large amount of sewer pipelines (95%) were built using brittle material such as asbestos concrete, brick, cast iron, reinforced concrete, and vitrified clay. Brittle material and pre-1935 construction make the sewer pipelines especially vulnerable to damage during an earthquake.

Figure 8: (a) Water and (b) Gravity and Force Sewer Pipeline Distribution Map Based on Material Type

Similar to buildings, five scenario earthquakes were considered to obtain the vulnerability of pipelines. HAZUS [1] was used to estimate the damage including leaking and breaking of the pipelines. The performance of the pipelines is usually described in terms of serviceability, system reliability, and connectivity indices for a post-earthquake evaluation. A rough estimation of a pipeline functionality (i.e. the percentage of users served immediately after the event) can be based on serviceability index for the entire system, through the identification of rate of breaks per kilometer [1]. A summary of the serviceability index (percentage) for each pipeline systems in each event is presented in Table 3.

Table 3: Summary of Pipeline Serviceability Index (percentage) for the Five Earthquake Scenarios

	Risk (% in 50 years)	Water Pipeline (~345 km)	Sewer Pipeline (~260 km)
M7 Crustal	1	25%	10%
M7 Inslab	5	90%	70%
M7 (+1std) Inslab	2	50%	35%
M9 Subduction	5	60%	40%
M9 (+1std) Subduction	2	15%	5%

Table 3 illustrates the poor post-earthquake serviceability of sewer pipelines. In a low intensity inslab event this system loses 30% serviceability. In a probable subduction event, only 40% of sewer pipelines are in service. And in a maximum credible subduction event it is only 5% in service. The poor serviceability of sewer system is because the pipelines are 90% pre-1935 construction and 95% made of brittle material. The performance of sewer pipelines is classified as very poor. The water pipeline system performs well and remains about 90% in service in a low intensity inslab event. In a probable subduction event, water pipelines are only 60% in service. In the maximum credible subduction event, they perform poorly and only remain 15% in service, respectively.

CONCLUSIONS

From this study it was concluded that pre-1972 construction including low-rise buildings (concrete, steel, and reinforced masonry), unreinforced masonry (of all heights), and 3-4 storey wood apartment buildings; and pre-1960 single family wood homes are at a high seismic risk. Soft soil and structural deficiencies, such as cripple walls in older single family homes or tuck-under parking in 3-4 storey wood apartment buildings, make these buildings even more vulnerable. Additionally, pre-1972 mid- and high-rise buildings; post 1972 unreinforced masonry; and concrete/steel/masonry low-rise and 3-4 storey wood apartment buildings constructed from 1972-1990 on soft soil are also at a high seismic risk. The most at-risk buildings identified in this study should be further investigated to determine if they have any structural deficiencies. This paper also presents the comparison between the earthquake damage predicted from the HAZUS and OpenQuake for the City of Victoria. In this study we refer to the current recommended damage fragility curves developed by GEM for use in Canada. It is observed that a large portion of the building stock constructed of steel, concrete and masonry show comparable levels of damage under both HAZUS and OpenQuake for the considered earthquake scenarios. OpenQuake shows more severe damage levels in downtown Victoria, due to the greater damage estimated for 1-3 storey concrete buildings and 3-4 storey wood apartment buildings. Single family wood houses on stiffer soils are predicted to perform better under OpenQuake, while those on softer soils are predicted to perform worse. In regards to the water and sewer pipeline systems, the most vulnerable is the sewage system. This is due to its age and construction type. An adequate and functioning post-event sewage system is a necessity to prevent disease spread and improve the resilience of the effected communities. A solution to this would be to replace the vulnerable sections of the existing sewage pipeline system with newer, more ductile pipes such as ductile iron or HDPE along with ductile joint types. Critical lengths of the water pipeline system could also be remediated in this way to improve the resilience of this system which is equally necessary post-event.

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