

**EXECUTIVE SUMMARY**  
**Citywide Seismic Vulnerability Assessment of**  
**The City of Victoria**

**Prepared for:**  
**The Corporation of the City of Victoria**  
Victoria, British Columbia, Canada

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The building models used for this study use average, or typical, properties of buildings based on their construction type/year/height/etc. Accordingly, any results presented in the report are high level results and are expected to be reasonably accurate over a large area/community/region of buildings. These results cannot be used to assess the vulnerability of an individual building – this would require a specific study for the building which utilizes a much more refined analysis and modelling procedure. A similar approach was adopted for the infrastructure study including water and sewer pipelines. Neither VC Structural Dynamics nor the City makes any representations of accuracy of this report in relation to any specific property or group of properties.

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## SYNOPSIS

This document summarizes the citywide vulnerability assessment study done for the City of Victoria by VC Structural Dynamics Ltd. The scope of this study was to provide a complete citywide seismic hazard, vulnerability and risk assessment for the City of Victoria. This report provides a summary of the work conducted and discusses the key results of the study. A companion report includes all the technical information that supports the findings, results and recommendations presented in this report.

The first objective of the study was to identify the seismic hazard setting of the City of Victoria using the latest scientific information available. This comprised a review of the tectonic background and historical seismicity of Southwestern British Columbia, along with probabilistic seismic hazard analysis to determine the earthquake sources and characteristics that govern the seismic hazard of the City. Three plausible earthquake scenarios were then selected in order to conduct scenario-specific evaluations of infrastructure damage in the City of Victoria: a magnitude 7 rupture of the shallow, crustal Leech River fault beneath the city; a deep magnitude 7 earthquake in the Strait of Georgia; and a magnitude 9 full rupture of the Cascadia subduction fault.

Ground vibration tests were carried out at 65 locations in order to map the soil stratigraphy in certain areas of the city. This data was used to update existing soil hazard maps, which in turn were used to estimate the amplification or deamplification of ground motion shaking due to local soil conditions. Soil classification plays a large role in predicting shaking intensity due to a possible seismic event.

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 three scenarios were run using the HAZUS loss estimation methodology to predict the damage distribution in Victoria. Both the Leech river fault and Cascadia fault ruptures were shown to be extremely damaging, especially to older buildings on soft soil. The Leech River rupture, however is a very rare event that has a probability of occurrence much lower than those earthquakes that the current building code designs for. Because the Cascadia rupture has a much higher probability of occurrence compared to the crustal event, it poses a much greater risk to the city and its infrastructure. The Cascadia event was also run at a rarer “maximum credible” level of shaking, with a similar intensity of shaking as specified in the building code for the design of new buildings. This event was extremely damaging and can be considered as a worst case event for the city for seismic risk mitigation purposes.

The deep rupture in the Georgia Strait produced much lower ground motion intensities and considerably lower levels of damage than the other two events. However, the cost associated with the damage caused by this type of event is still expected to be high. A maximum credible Georgia Strait rupture, with a hazard similar to that considered by the building code, was also considered. This event was more damaging, but still less critical than the Leech River or Cascadia scenarios.

A risk assessment for buildings was also carried out considering the aggregation of all hazard types and possible levels of shaking. From this analysis 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 vulnerabilities such as cripple walls and sub-floors in single family wood homes, and tuck-under parking in wood apartment buildings make these buildings even more vulnerable to severe levels of ground shaking. 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.

Finally, damage estimation assessment to supporting infrastructure including water and sewer pipelines was carried out for three scenarios. The numbers of leaks and breaks for each pipeline were calculated using HAZUS. The percentage of pipelines in service immediately after each event, denoted as the serviceability index, was calculated. In a low intensity ground shaking caused by an earthquake produced by a deep rupture in the Georgia Strait, the sewer pipeline system is expected to lose 30% of its normal serviceability. About 90% of water pipelines would be in service after this event. In the much larger events due to the Leech River or Cascadia fault rupture, the serviceability of the water pipelines may be reduced to about 20% of its normal serviceability. In those events, the sewer pipelines may be lost completely. The poor performance of the sewer pipelines is due to the existing old (pre-1935) and brittle pipeline system. Replacing the older and brittle lengths of these pipes with more ductile materials is recommended to improve the performance of these systems, which are essential for the post-event resilience of any of the affected communities.

## MAIN FINDINGS AND RECOMMENDATIONS

The main findings of this study include:

1. The seismic vulnerability of buildings depends greatly on local soil conditions.
2. The most probable damaging scenario for The City of Victoria is due to the rupture of the Cascadia Subduction Zone.
3. Older (pre-1972) construction is particularly vulnerable to ground motion shaking in Victoria. Soft soil conditions amplify their seismic vulnerability.
4. Structural deficiencies, such as cripple walls in older single family homes or tuck-under parking in 3-4 storey wood apartment buildings, increase the seismic risk of buildings.
5. Unreinforced masonry at all heights and ages pose a high seismic risk.
6. The sewage system in The City of Victoria is particularly vulnerable to ground motion shaking due to its age and construction type.

Based on the findings from this study, the following recommendations are made:

1. Due to the importance that local soil conditions play on the vulnerability of buildings, priority should be made for the refinement of the soil maps for the City. This will permit a more refined assessment of the areas of the City where ground shaking could be more severe due to the presence of soft soils.
2. The most at-risk buildings should be further investigated to determine in detail what their structural deficiencies are. Special studies using detailed assessment methodologies employed by structural engineers will be required for these buildings.
3. Replace the vulnerable sections of the existing sewage system with more ductile pipes and joints.
4. For critical facilities, such as bridges, treatment plants, power substations, etc., special studies should be conducted in order to assess their vulnerabilities and determine their seismic risk.
5. The Risk Maps provided by this study should be used to develop risk mitigation strategies and for decision making purposes. The earthquake scenarios considered are valuable to better understand the potential consequences of the severe earthquakes in the region, however these are not recommended for developing mitigation strategies.
6. A Technical Advisory Board should be established to assist in the development and implementation of a seismic risk mitigation plan.



## **PART A. INTRODUCTION**

The City of Victoria is one of the oldest cities in Western Canada, with British settlement beginning in 1843. Currently, the city has a population of just over 80,000 people, while the metropolitan area of Greater Victoria has a population in exceedance of 344,000 people. The City of Victoria is located on the southern tip of Vancouver Island off Canada's Pacific coast. This happens to be in the Cascadia Subduction earthquake zone in which both major megathrust earthquakes and smaller, more frequent earthquakes pose a constant threat to infrastructure and the population. Due to the combination of a large, dense urban population, an aging building stock, and a high seismic risk, it is essential that the City of Victoria be prepared for a potential major earthquake event and that its city planners and decision makers are aware of the seismic vulnerability of its building stock and other infrastructure. This study aims to address these points and provide city planners in Victoria with the information they need to develop a seismic resiliency plan and a possible seismic retrofit strategy.

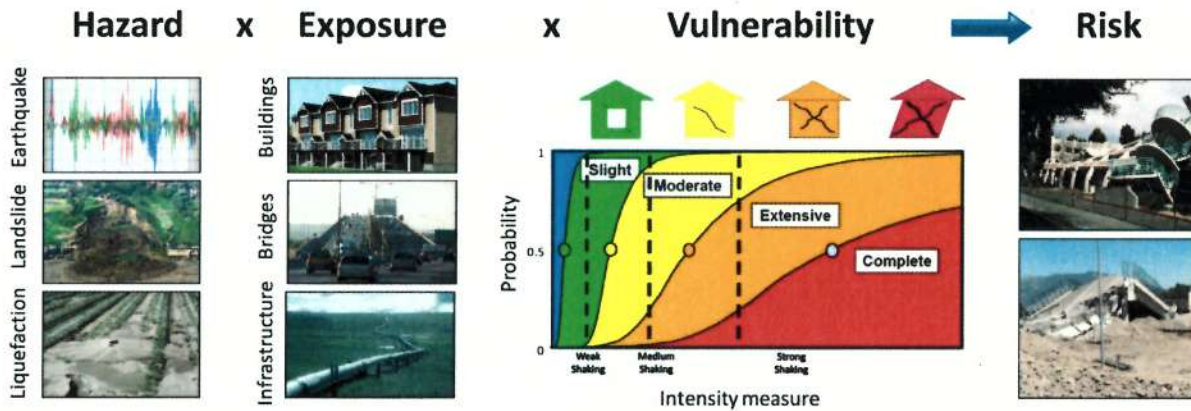
### **A.1. PROJECT SCOPE**

The scope of this project is to provide 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.

The degree of risk (potential losses) depends, not only on the level of hazard, but also on the elements exposed to the hazard, including their value and their vulnerability to the type of hazard (Figure 1). The level of risk is increased when a higher concentration of assets is exposed to the hazard. Accordingly, risk analysis and management must include consideration of all relevant factors contributing to the level of risk including the hazard, exposure, and building and infrastructure vulnerability. An explanation of each factor and their relevant impact to seismic risk assessment of City of Victoria is presented in the following sections.

For this project a "building-by-building" approach was considered, in which hazard, vulnerability, and risk is determined at the building level (as opposed to lumping buildings into blocks or regions). This project 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.



**Figure 1: Relevant Factors Contributing to Risk**

### A.2. GENERAL METHODOLOGY

The first step in any damage or risk study is to quantify the hazard that poses a threat to the study region (Figure 1). This was done using the latest Geological Survey of Canada (GSC) seismic hazard model which was developed for generating seismic hazard maps for the 2015 National Building Code of Canada (NBCC). This model was carefully studied to ensure that it is applicable for the specific region of the City of Victoria, and modified in cases where it was not.

For this study, exposure is defined as the building stock and other infrastructure in the City of Victoria that could experience ground movement due to an earthquake. A comprehensive database was compiled over several months which comprised building-by-building information for all structures in the City of Victoria. This was achieved by considering two previously developed databases as well as virtual and physical surveys to ensure the accuracy of the information.

Next, the HAZUS framework, developed by FEMA (2003), was employed to compute the seismic vulnerability and damage predicted in City of Victoria on a building-by-building scale. Several earthquake scenarios were chosen to illustrate the levels of damage that might be expected for different types and levels of shaking intensity.

Finally, seismic risk was calculated by considering all earthquake scenarios and possible levels of shaking by combining the amount of damage expected for each shaking level and the likelihood of observing that level of shaking. This information is valuable for ranking and retrofit priority.

## **PART B. SEISMIC HAZARD**

### **B.1. SEISMIC HAZARD POTENTIAL**

Seismic Hazard is defined as the study of expected earthquake ground motions at any point on Earth. The expected level of shaking at the site or region of interest is calculated based on the characteristics of the areas seismic sources, the attenuation (decay) or amplification of seismic waves from the epicenter to the site, and the local site conditions (i.e. soil characteristics) which may amplify or deamplify the motions.

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 (Ristau, 2004) – also called the Cascadia Subduction Zone, as shown in Figure 2. Large interface earthquakes have occurred at the interface of these two plates reaching moment magnitudes as high as 9.0 in the past (Goldfinger et al., 2012). The last large interface event in the Cascadia subduction zone was approximately 300 years ago. Other, more recent worldwide interface events, such as the 2010 magnitude 8.8 El Maule earthquake in Chile and the 2011 magnitude 9.0 Tohoku earthquake in Japan, have been extremely devastating and caused severe amounts of damage over very large areas.

Inslab earthquakes can occur deep below the surface in faults along the subducting Juan de Fuca plate at depths of 30 to 100 km. The most recent major inslab event in the Cascadia region was the 2001 Nisqually earthquake, which was a magnitude 6.8 event that occurred 50km beneath Seattle, Washington. The earthquake caused significant damage to Seattle and the surrounding area – it is estimated that up to \$2 billion worth of damage was caused by this event in the state of Washington. Other historic inslab events in the Pacific Northwest include the 1949 Puget Sound event (M = 7.1), and the 1965 Olympia, Washington (M = 6.9) earthquake.

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 (earthquakescanada.nrcan.gc.ca). 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. The largest recorded event has been the magnitude 8.1 Queen Charlotte Island Earthquake in 1949. Several large events (magnitude 7.3 in 1946 and magnitude 7.0 in 1918) have been recorded on or near Vancouver Island, and one magnitude 7.4 event was observed near the Washington border in 1872. These events have the possibility of occurring very close to large population centers which could cause significant amounts of damage. Figure 3 illustrates the historic earthquake events that have occurred in or near Canada in the past ~390 years.

Geophysical parameters and structural response can vary substantially between these three types of earthquakes. Therefore, the definition of seismic hazards for each type of earthquake is an important step for the seismic risk assessment of Victoria. For the seismic risk assessment of the City of Victoria, prediction of building and infrastructure response to each of these possible sources was considered.

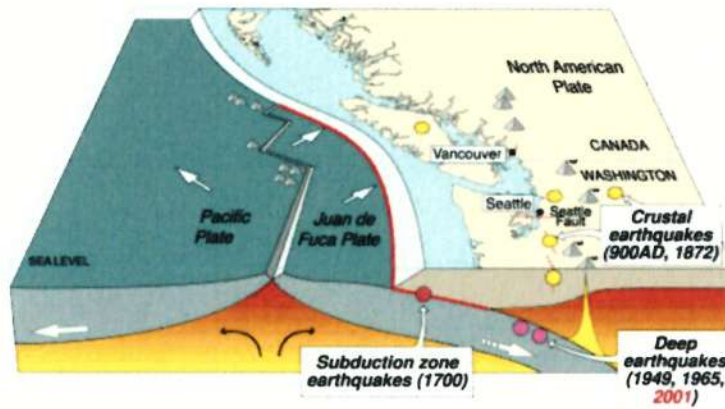


Figure 2: Cascadia Earthquake Sources Affecting BC (Source: United States Geological Survey)

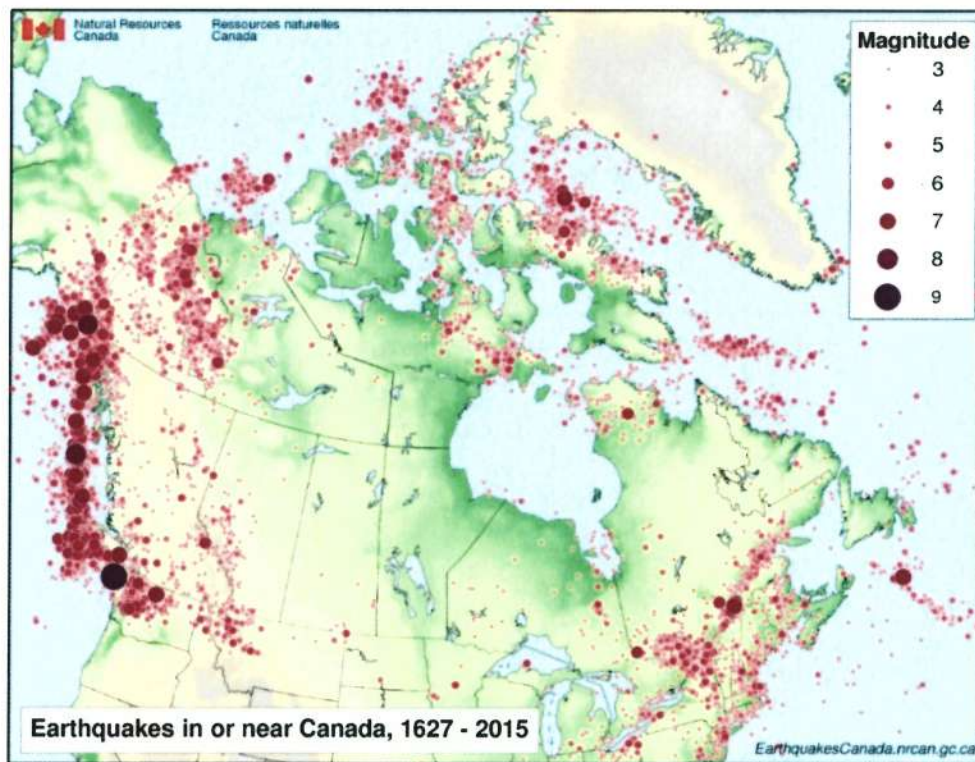


Figure 3: Historic Earthquakes in or Near Canada (Source: Natural Resources Canada)

## B.2. GROUND MOTION SCENARIOS

For the seismic vulnerability study of the City of Victoria three potential seismic scenarios are considered: a magnitude 9.0 rupture of the Cascadia Subduction fault; a large (magnitude 7.0) rupture in the Leech River crustal fault beneath Victoria, and a large (magnitude 7.0) rupture of the Juan de Fuca plate beneath the Strait of Georgia. These three events represent possible seismic scenarios from the three seismic hazards that could cause significant damage in the City of Victoria.

### ***a) Crustal Scenario: $M = 7$ on the Leech River Fault***

As mentioned in the previous section, small shallow crustal events occur frequently in Southwestern BC, and while large magnitude events are rarer, they are still possible and have been recorded near Queen Charlotte Island, Vancouver Island and the Washington border. There are several mapped crustal faults near Victoria – the two closest to the city are the Leech River Fault and the Devils Mountain Fault. There is evidence that both of these faults are active, or have been active in the past (Morell et al. 2016).

For the shallow crustal earthquake scenario, a partial rupture of the Leech River fault was considered beneath the City of Victoria. A 30km rupture between the mapped Leech River Fault and Devils Mountain fault, which could produce up to a magnitude 7 event, was selected as illustrated in Figure 4. Although the link between the Leech River and Devils Mountain faults has not been conclusively established, there is evidence that these faults are joined (Morell et al. 2016). Personal communication with Kristen Morell has also established that this is a possible scenario.

Using the assumptions made in the Geological Survey of Canada's (GSC) 2015 seismic hazard model for Southwestern Canada, there is about a 1% chance that shaking from this event would be exceeded in Victoria in a 50 year period from crustal earthquakes alone. This is a much rarer event than considered for the design of new buildings in the National Building Code of Canada (NBCC), which considers an event with a 2% in 50 year probability of exceedance.

The level of shaking across the City of Victoria from this event is illustrated in Figure 5. 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 amplification or deamplification of motions due to local soil conditions is considered in this figure. More information on the effect of site soil conditions is described in following sections.

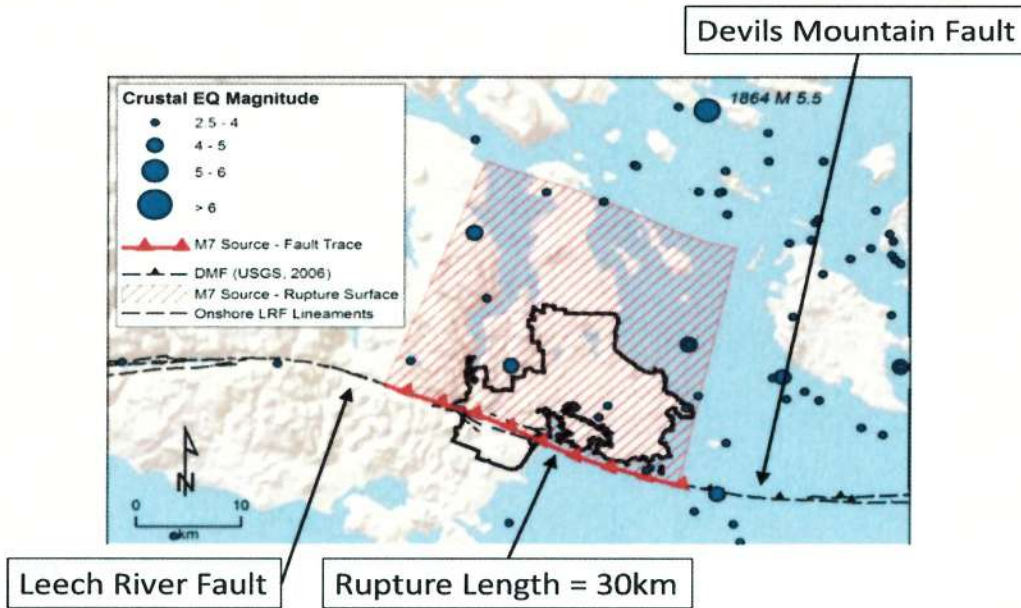


Figure 4: Leech River Fault M = 7.0 Scenario Map (Modified from Zaleski, 2014)

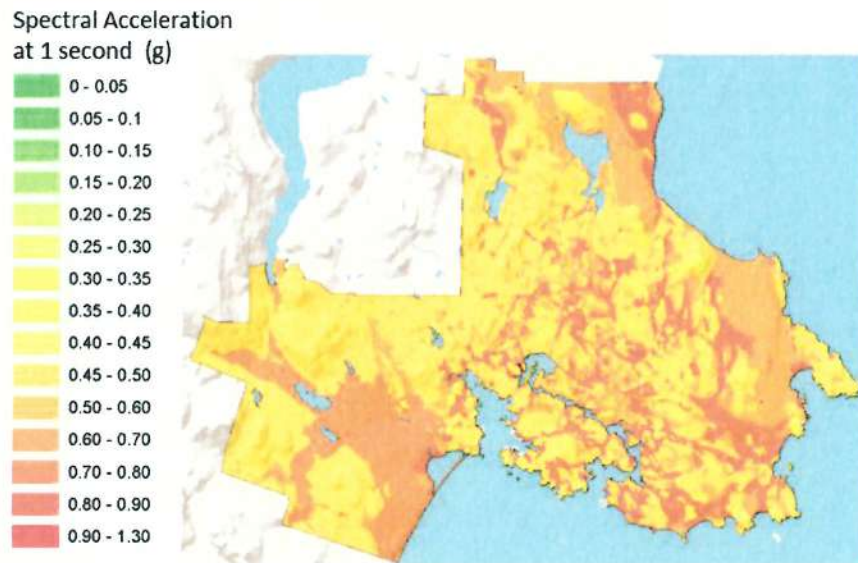
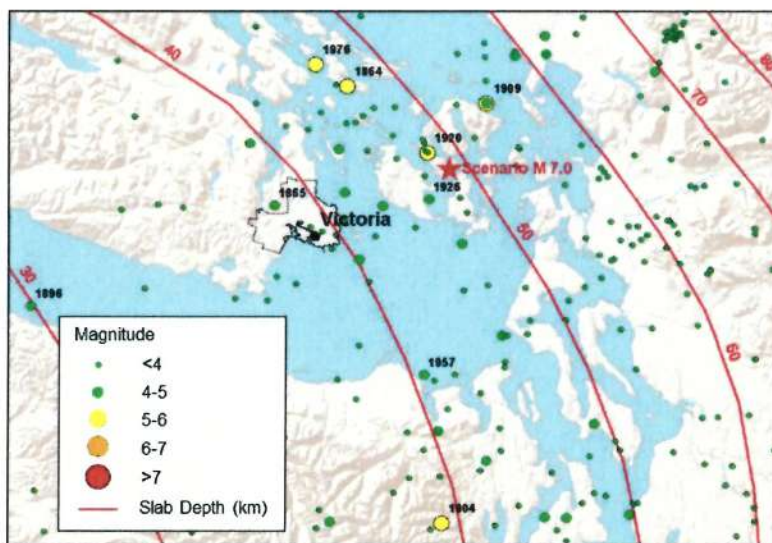


Figure 5: Ground Motion Intensity (1 Second Spectral Acceleration) Expected from the M = 7 Crustal Earthquake Scenario

**b) 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. The location of this event was based on the work by Rogers (1996), who proposed that inslab earthquakes are concentrated in two zones which are controlled by changes in slab orientation. One zone is near the west coast of Vancouver Island, about 30km deep, where the subducting Juan de Fuca plate changes from nearly flat to a dip of 15 degrees. The other zone is beneath the Georgia Strait and Puget Sound, about 50km deep where the dip of the plate steepens to about 30 degrees. These zones can be seen in the historical record of large inslab events in the Cascadia region. Because of this, it was considered unlikely that a large inslab event will occur directly beneath Victoria, which is in the middle of these two zones. It was found that, between the two zones, the governing scenario was an event under the Strait of Georgia, at the 50km slab depth contour line as shown in Figure 6. A magnitude = 7.0 event was selected based on the recommendations from Zaleski (2014) – it is also the approximate magnitude of several historic inslab events in the Cascadia region including the 2001 Nisqually event (M = 6.8), the 1949 Puget Sound event (M = 7.1), and the 1965 Olympia, Washington (M = 6.9) earthquake. Figure 7 presents the shaking intensity from this event (accounting for local soil conditions).



**Figure 6: M = 7.0 Inslab Scenario Map with Historic Seismicity (from: Halchuk, 2009 and Earthquake Canada, 2016). Slab contours from McCrory et al. (2012) and Blair et al. (2013)**



**Figure 7: Ground Motion Intensity (1 Second Spectral Acceleration) Expected from the M = 7 Inslab Earthquake Scenario**

***c) 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. When people in these areas think of earthquakes, this is the event that comes to mind, and as such, it is colloquially referred to as “The Big One”.

These events happen on average once every 500 years (+/- 200-300 years), and the last event occurred approximately 300 years ago (Goldfinger et al., 2012). Assuming a return period of 500 years, this event has approximately a 10% probability of occurring in the next 50 years, which makes it a crucial scenario to analyze and prepare for.

A full rupture of the Cascadia Subduction Zone (CSZ) would be about 1025km long and 125km wide and could slip 25m (Adams and Rogers, 2012). This could generate an earthquake of magnitude 9 or greater. An important factor in this event would be how far it occurs from Victoria. We assumed that the rupture limit of this event would be constrained by the 450 degree isotherm, after which temperatures are too high for a significant rupture to occur as the plates begin to melt (Adams and Rogers, 2012). Figure 8 illustrates the proximity of the City of Victoria to the predicted rupture area. The best estimate of the 450 degree isotherm is the 27km deep contour in this figure. Figure 9 presents the shaking intensity predicted from this event.



One unique problem that has been associated with large magnitude subduction events, is the duration of shaking. In the 2011 Tohoku earthquake, because of the huge rupture area, strong shaking was observed which lasted for several (up to and exceeding three) minutes. This long duration motion has the potential to be very damaging to structures due to the large amount of load reversal cycles it puts them through (Hancock and Bommer, 2006; Raghunandan and Leil, 2013). The methodology adopted to estimate damage from this event does account for ground motion duration – and as such, this event is expected to be quite damaging.

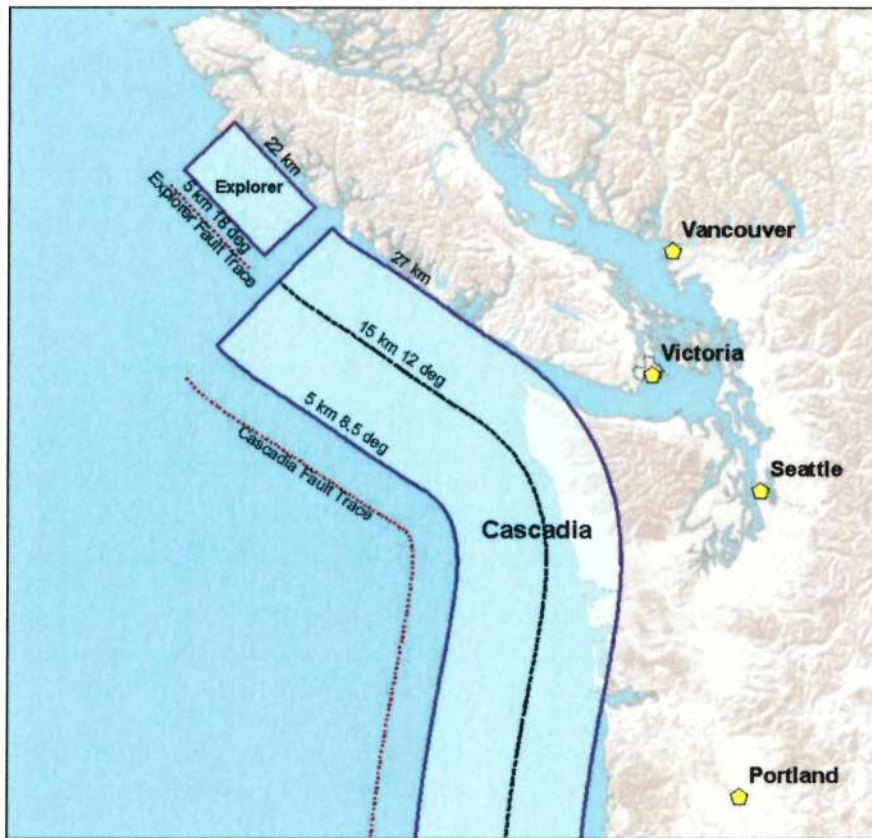
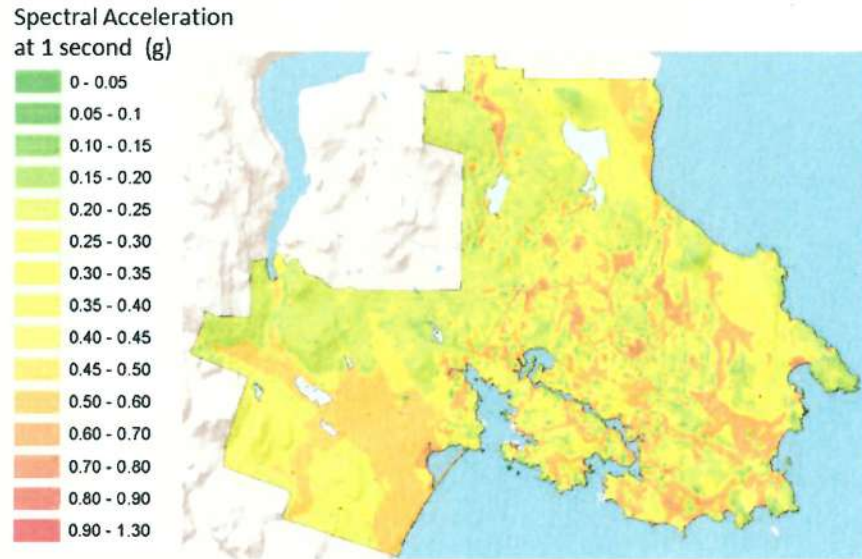


Figure 8: Cascadia Subduction Zone Including the Fault Surface Traces, Fault Depths and Dips, and Best Estimate of Landward Rupture Extent (data from Halchuk et al., 2014)



**Figure 9: Ground Motion Intensity (1 Second Spectral Acceleration) Expected from the M = 9 Subduction Earthquake Scenario**

### B.3. IMPACT OF SOIL CONDITIONS

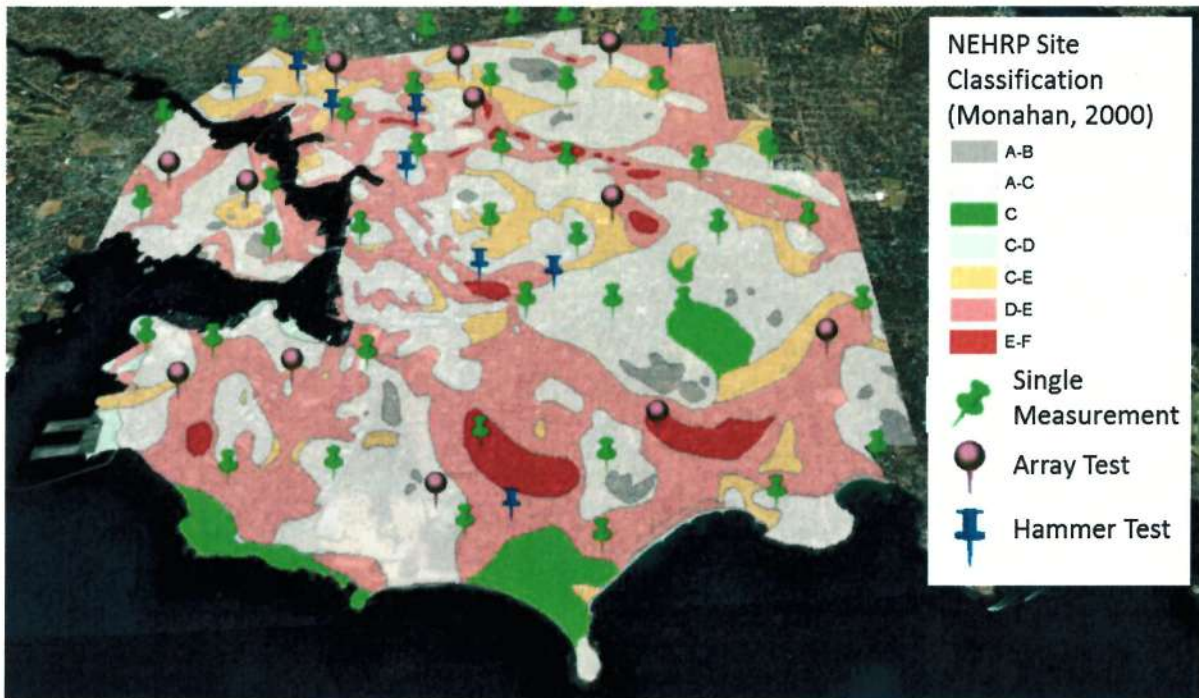
Soil conditions can also have a considerable effect on the vulnerability to damage the buildings and infrastructure. It is well known from previous earthquakes that soft soil can amplify certain types of ground motion shaking. In the 1985 Mexico City Earthquake (magnitude = 8.0), the city suffered extensive damage, not only due to the large magnitude of the event, but also the fact that Mexico City resides on an ancient lake bed comprising very soft soils. The soft soils significantly amplified certain parts of the ground shaking which made it very damaging, particularly to taller buildings. In total, 412 buildings collapsed in the event and another 3,124 were seriously damaged. At least 5,000 people were killed and approximately \$3-4 billion USD was lost due to the damage.

To account for the impact of soil conditions, modern building codes amplify (or deamplify in the case of stiff soils and rock) seismic demand requirements on structures based on the shear wave velocity (defined as site class) measured or predicted at the site. An important part of this study was to identify the areas in Victoria in which the earthquake hazard is potentially amplified due to the local soil conditions.

To begin, the site classification maps prepared by Monahan et al. (2000) were considered. In order to further constrain the site classes mapped by Monahan et al., a series of microtremor array tests were performed at different locations in the City of Victoria. These tests involved placing an array of instruments on the ground surface and recording vibrations in the ground, either naturally occurring (from traffic, pedestrians, wind, tides, etc.), or forced (i.e. through a hammer impact). By analyzing the velocity at which these vibrations travel through the soil,

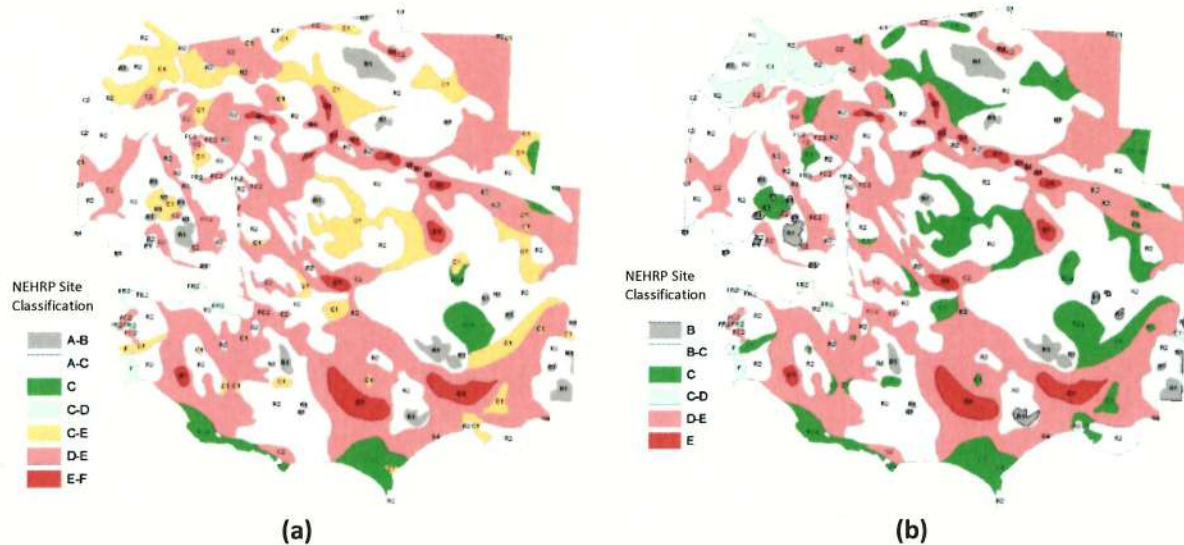
accurate estimates can be drawn about the mechanical properties of the subsurface geology including the shear wave velocity profile which is used for classification of the site. Single station tests can also be done in order to estimate the fundamental period of the site, which is related to its stiffness; however, complete soil profiles cannot be drawn from only single station tests.

In total, 25 multi-station tests (15 array-based and 10 hammer impact tests) were performed and 40 single station tests were performed in the City of Victoria between April 10 and May 10, 2016. The locations of these tests are shown in Figure 10.



**Figure 10: Locations of Single Instrument, Array, and Hammer Tests Performed in the City of Victoria Combined with the Original NEHRP Site Amplification from Monahan (2000)**

The resulting soil profiles and site classifications predicted from the test data agreed well with the original maps prepared by Monahan et al. (2000); however, in some areas the vibration tests indicated slightly stiffer soils than mapped. This is in part due to the lack of data that was available for the preparation of the original maps, which forced its creators to make several judgements and estimations, usually on the conservative (softer) side. The test results were reviewed by Patrick Monahan (the lead developer of the original 2000 map) who gave guidance on updating the soil maps based on this new data. The original and updated soil map used for this study are shown in Figure 11. In this figure, soil hazard is mapped in terms of the NEHRP Site Classification (Table 1), in which soil is given a classification (A-F) based on the shear wave velocity measured in its top 30m ( $V_{s30}$ ).



**Figure 11: (a) Soil Hazard Map for the City of Victoria (Monahan et al., 2000) and (b) Updated Soil Hazard Map for the City of Victoria**

**Table 1: Site Classification using  $V_{s30}$  as an Indicator of Site Response (NEHRP)**

NEHRP Site Classification	Profile Type	$V_{s30}$ (m/s)
A	Hard rock	> 1500
B	Rock	760-1500
C	Very dense soil/soft rock	360-760
D	Stiff soil	180-360
E	Soft Soil	< 180
F	Special soils requiring site-specific evaluation	-

It must be noted that this soils map does not take liquefaction into account, which may be an issue to the limited amount of buildings that were constructed on fill. Neither does it does address 3-D effects, resonance due to soils, or amplification due to topography. It does not reflect where seismic considerations or mediations have been taken into account in building construction, particularly for newer buildings. It is stressed that these are regional maps and that polygon boundaries are inherently uncertain.

## **PART C. BUILDING DAMAGE, RISK, AND RANKING**

Exposure is defined as the valuables that could suffer losses as the result of earthquake shaking. These valuables can be either economic or social and include human lives, infrastructure and business revenue. Risk assessments for large areas require a comprehensive inventory to store exposure data and classify structures into groups according to their use, structural characteristics and importance. This section is concerned with the building stock exposure in Victoria.

### **C.1. GENERAL BUILDING STOCK**

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). The vast majority of single- and multi-family homes are of wood construction. 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 12 and Figure 13 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.

In the mid-1990's Ventura and Finn conducted a 3-year study of seismic risk of Vancouver, New Westminster, and Victoria, which was updated in 2010. As part of this study a database of the buildings inventory in the City of Victoria was compiled. This inventory was 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.

After merging these two databases, each building was classified based on the accuracy of its information. Buildings with inaccurate or missing information (either outdated information or with discrepancies in building information between the two databases) were investigated through a virtual survey using Google Maps® and other online resources (i.e. satellite images or realtors websites). This 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; however, there were still a handful of structures that could not be accurately classified through online tools alone. Accordingly, 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.



Figure 12: Distribution of City of Victoria Buildings Based on Construction Type



Figure 13: Distribution of City of Victoria Buildings Based on Year Built

Through the combination of two separate databases, a comprehensive virtual survey, and finally, the sidewalk survey, we are confident that our final database is both complete and highly accurate. In total, the database comprises over 13,000 individual buildings and includes information including construction type, year built, number of stories, presence of any subfloors, footprint area, and others.

Because different construction types and structural systems respond differently to ground shaking, it was necessary to classify the buildings into different prototypes based on their material, construction type, and height. Table 2 presents the 32 considered prototype's name and short hand code from Ventura et al. (2005). Buildings were also classified based on their year of construction. Due to evolving construction practices and seismic design codes, even buildings of the same material and construction type are expected to behave differently based on their year of construction.

**Table 2: Prototype Classification (Ventura et al., 2005)**





Number	Code	Description
1	WLFR	Wood Light Frame, Residential
2	WLFCI	Wood Light Frame, Commercial/Inst.
3	WLFLR	Wood Light Frame, Low Rise
4	WPB	Wood Post and Beam
5	LMF	Light Metal Frame
6	SMFLR	Steel Moment Frame, Low Rise
7	SMFMR	Steel Moment Frame, Mid Rise
8	SMFHR	Steel Moment Frame, High Rise
9	SBFLR	Steel Braced Frame, Low Rise
10	SBFMR	Steel Braced Frame, Mid Rise
11	SBFHR	Steel Braced Frame, High Rise
12	SFCWLR	Steel Frame Concrete Walls, Low Rise
13	SFCWM	Steel Frame Concrete Walls, Mid Rise
14	SFCWHR	Steel Frame Concrete Walls, High Rise
15	SFCI	Steel Frame with Concrete Infill Walls
16	SFMI	Steel Frame with Masonry Infill Walls
17	CFLR	Concrete Frame with Concrete Walls, Low Rise
18	CFMR	Concrete Frame with Concrete Walls, Mid Rise
19	CFHR	Concrete Frame with Concrete Walls, High Rise
20	RCMFLR	Reinforced Concrete Moment Frame, Low Rise
21	RCMFMR	Reinforced Concrete Moment Frame, Mid Rise
22	RCMFHR	Reinforced Concrete Moment Frame, High Rise
23	RCFIW	Reinforced Concrete Frame with Infill Walls
24	RMLR	Reinforced Masonry Shear Wall, Low Rise
25	RMMR	Reinforced Masonry Shear Wall, Mid Rise
26	URMLR	Unreinforced Masonry Bearing Walls, Low Rise
27	URMMR	Unreinforced Masonry Bearing Walls, Mid Rise
28	TU	Tilt Up
29	PCLR	Precast Concrete, Low Rise
30	PCMR	Precast Concrete, Mid Rise
31	MH	Mobile Homes
32	WLFCR	Wood Light Frame, Commercial/Residential

## C.2. VULNERABILITY OF BUILDINGS IN VICTORIA

The primary tool for establishing building damage and vulnerability for this assessment is HAZUS (FEMA, 2003) damage probability functions. These 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. HAZUS defines four discrete damage states for each type of building: Slight, Moderate, Extensive, and Complete. For example, Table 3 provides example HAZUS damage states for light-frame wood buildings.

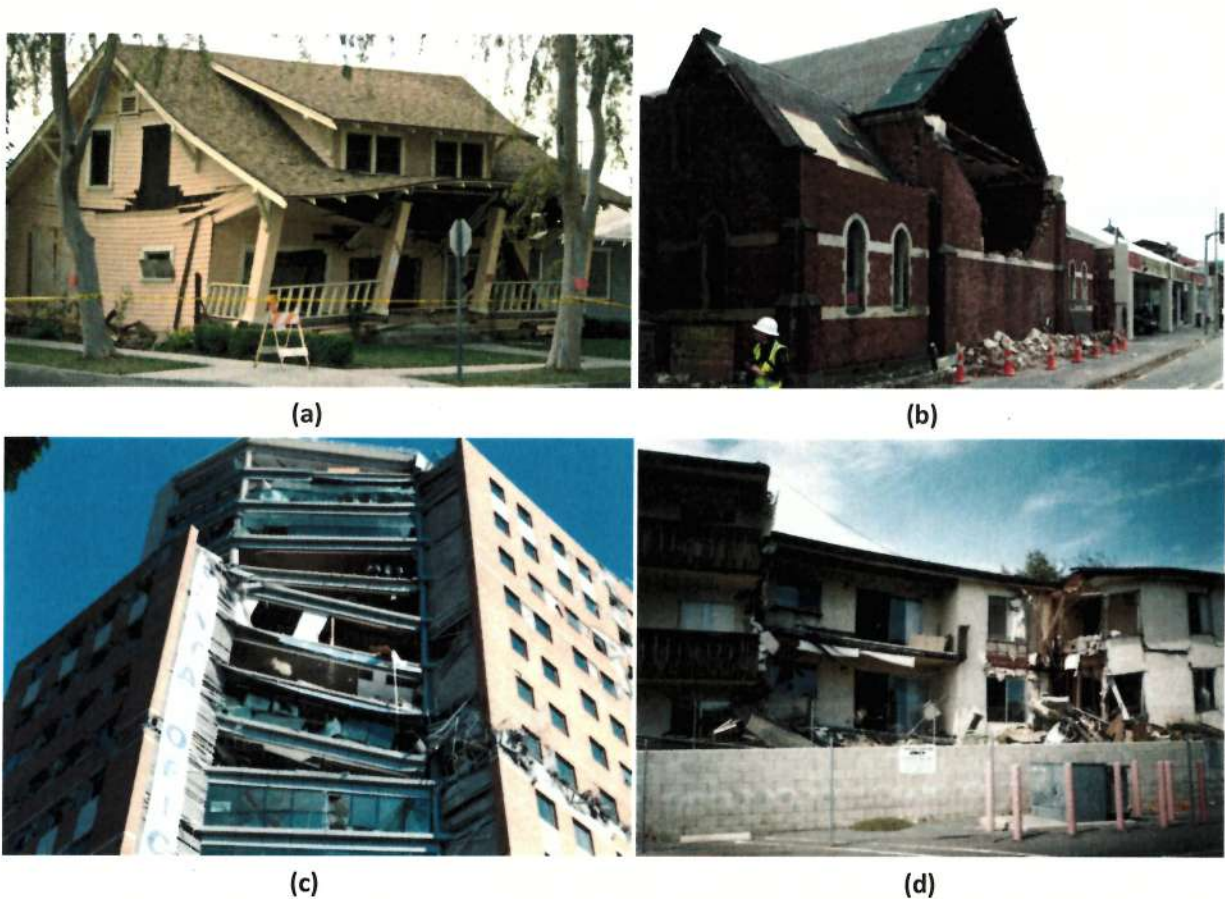
The default HAZUS structural types and damage probability curves were originally prepared for US building types and construction methods. Where applicable, this data, including structural systems and damage functions, was updated to reflect typical BC construction types.

**Table 3: HAZUS Damage States – Light-Frame Wood Buildings**

Damage State		Description
	<b>Slight</b>	Small plaster cracks at corners of door and window openings and wall-ceiling intersections; small cracks in masonry chimneys and masonry veneers. Small cracks are assumed to be visible with a maximum width of less than 1/8 inch (cracks wider than 1/8 inch are referred to as “large” cracks).
	<b>Moderate</b>	Large plaster or gypsum-board cracks at corners of door and window openings; small diagonal cracks across shear wall panels exhibited by small cracks in stucco and gypsum wall panels; large cracks in brick chimneys; toppling of tall masonry chimneys.
	<b>Extensive</b>	Large diagonal cracks across shear wall panels or large cracks at plywood joints; permanent lateral movement of floors and roof; toppling of most brick chimneys; cracks in foundations; splitting of wood sill plates and/or slippage of structure over foundations.
	<b>Complete</b>	Structure may have large permanent lateral displacement or be in imminent danger of collapse due to cripple wall failure or failure of the lateral load resisting system; some structures may slip and fall off the foundation; large foundation cracks. Three percent of the total area of buildings with Complete damage is expected to be collapsed, on average.



Complete damage is the main damage state used in this study to assess risk. Complete damage includes large residual displacements (the building will not be safe to enter after the event and will almost always require demolition), excessive damage to structural and non-structural components, and full or partial collapse. Figure 14 presents four completely damaged buildings with construction types similar to that found in many Victoria buildings: unreinforced masonry, high-rise concrete, and single- and multi-family light frame wood construction.



**Figure 14: Examples of Complete Damage: (a) Single-family Residential Wood Light Frame Building after the 1994 Northridge, California, Earthquake (from: FEMA); (b) Unreinforced Masonry Building after the 2011 Christchurch, New Zealand, Earthquake (reidmiddleton.wordpress.com); (c) High-rise Concrete Shearwall Buildings after the 2010 El Maule, Chile, Earthquake (reidmiddleton.wordpress.com); and (d) Multiple-family Wood Light Frame Building after the 1994 Northridge, California, Earthquake (bayarearetrofit.com).**

An example of a cripple wall failure in a light wood frame structure is presented in Figure 15, which would be classified extensive damage. Although it does not threaten the life safety of building occupants, it does require significant and costly repairs. This type of deficiency is common in single-family residences in the City of Victoria.



Figure 15: Cripple Wall Failure Due to an Earthquake (homerepair.com)

### C.3. DAMAGE TO BUILDING STOCK

To predict the intensity of shaking and damage over the City of Victoria, first a scenario earthquake is defined. Three scenario earthquakes were considered based on the three sources of seismic activity in the Pacific Northwest region: a shallow crustal event, a deep slab event, and a large magnitude subduction event (see Section: B.2. GROUND MOTION SCENARIOS).

The attenuation (decay) of shaking from the source to the City of Victoria was predicted using the relationships developed for the 2015 Geological Survey of Canada (GSC) seismic hazard model which is a state-of-the-art model which and used for developing seismic hazard maps for Canada for the 2015 National Building Code of Canada (Halchuk et al. 2014). These relationships were first modified to make them more accurate for the site conditions specific to the Victoria region. Soil conditions are considered in these relationships to account for amplification or deamplification of shaking based on the stiffness of the soil at a site.

We implemented HAZUS, developed by FEMA, as the primary software for damage assessment (FEMA, 2003). HAZUS is a standardized methodology that contains modules for estimating damage and potential losses from earthquakes and other natural hazards. HAZUS uses Geographic Information Systems (GIS) technology to estimate physical, economic and social impacts of disasters such as earthquakes. HAZUS has been modified to reflect the seismicity and construction practices of BC by Natural Resource Canada (NRCan).

This section presents and discusses the damage results predicted for each of the earthquake scenarios.

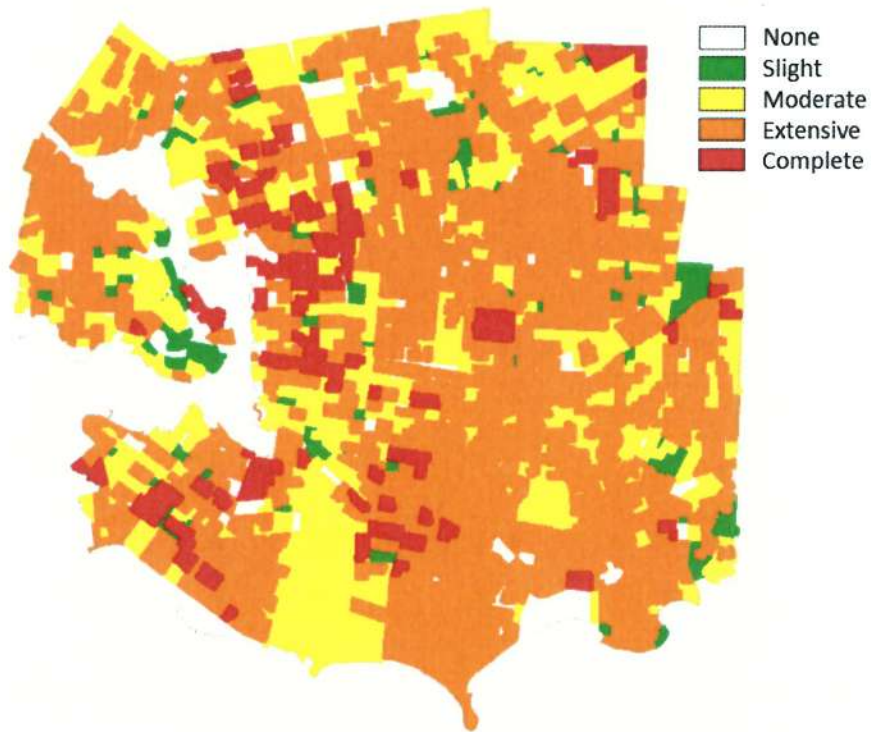
#### ***a) Crustal Scenario: $M = 7$ on the Leech River Fault***

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 16 presents the damage

distribution expected for this event. Four damage states are considered as described previously: complete, extensive, moderate, and slight.

Complete damage is mostly localized to the concrete and masonry buildings in the downtown core. Due to this it is likely that downtown would have to be completely restricted to public access, halting any business, and leaving many people homeless. Many of these buildings will ultimately have to be demolished and replaced. Christchurch, New Zealand faced a similar situation in 2011 and the following years when it was struck by a large earthquake occurring beneath the city – in the end most of its downtown core buildings were demolished and replaced.

There are also large areas of moderate and extensive damage in the older wood frame structures surrounding the downtown core. While collapse of these buildings would be rare, the amount of damage to these buildings poses a significant monetary loss. Additionally, many families may be left without homes, as many of these mostly residential buildings, especially the extensively damaged ones, would be “red-tagged” (too dangerous for anyone to enter).



**Figure 16: Damage Distribution for the Magnitude = 7 Crustal Scenario**

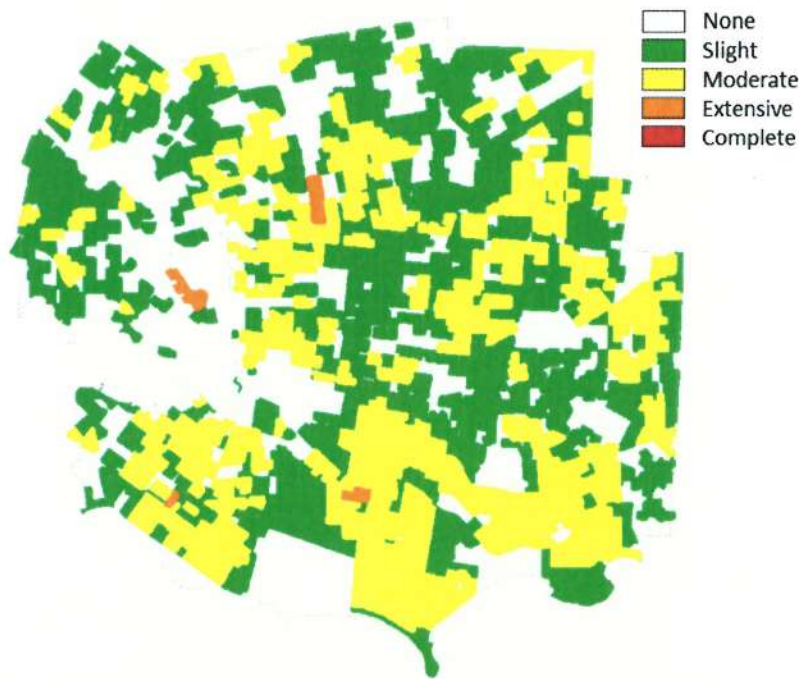
***b) Inslab Scenario: M = 7 under the Strait of Georgia***

Because the inslab event was simulated at a 50km depth and ~25km from the City of Victoria, this magnitude 7 rupture is less damaging than the much closer crustal event considered in the

previous section. The distribution of expected damage for this event is summarized in Figure 17.

Figure 17 shows that the majority of the buildings have slight to no damage – there are however, large areas where moderate damage is likely to occur. These areas include the downtown core and the buildings in the Southeast and Southwest corners of the city. From Figure 11 it can be seen that the Southeast and Southwest corners of the city have very soft soils (Cites Classes D and D-E), which is the cause of the damage that is observed here.

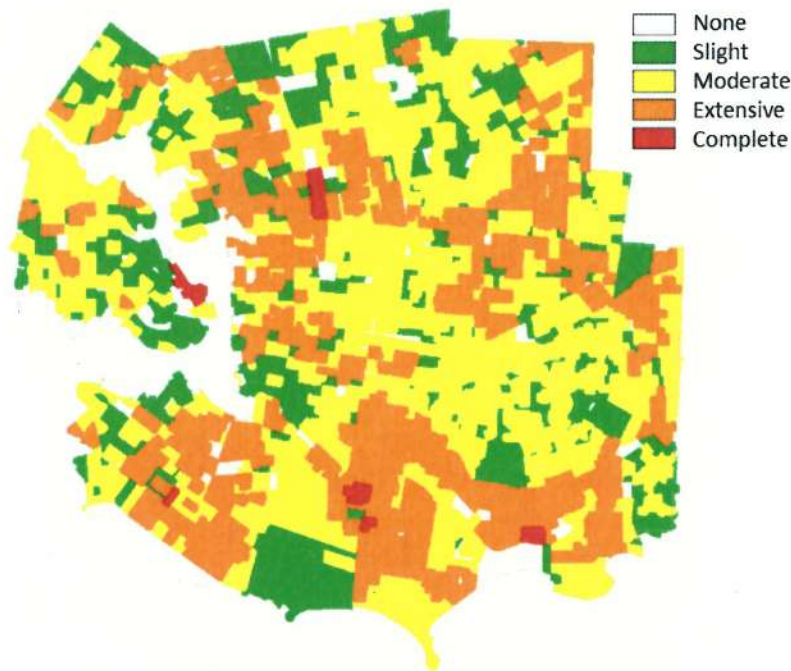
While moderately and slightly damaged buildings are still safe and usable in most cases, they will still require repair after the event. Due to this, despite the lack of collapse or complete damage predicted from this scenario, the number of moderately damaged buildings may make it a very costly event. This is similar to the inslab Nisqually earthquake which shook Seattle and the surrounding area in 2001. Despite a lack of collapse or casualties, this event caused up to \$2 billion USD in repair costs and was declared a national emergency.



**Figure 17: Damage Distribution for the Probable Magnitude = 7 Inslab Scenario**

Next, this scenario was rerun, but with median plus one standard deviation ground motion accelerations. This was done to decrease the probability of exceedance of this event and bring it closer to 2% in 50 years, which is the hazard level designed for in the NBCC (designated as the maximum credible earthquake).

Results for this maximum credible inslab scenario are presented in Figure 18. Comparing this to the previous results for the probable scenario (Figure 17), it can be seen that many of the slightly damaged areas have shifted to moderately damaged, and that many of the previous moderately damaged areas have shifted to extensively damaged. There are also now a few small localized areas with complete damage.



**Figure 18: Damage Distribution for the Maximum Credible Magnitude = 7 Inslab Scenario (+1 Standard Deviation)**

***c) Subduction Scenario: M = 9 Cascadia Rupture***

The damage result from the magnitude 9 Cascadia rupture are illustrated in Figure 19. This is another very damaging potential event – similar to the crustal scenario. A similar amount of complete damage is expected – 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, which will have significant economic and social impacts.

Results for the maximum credible Cascadia rupture (median plus one standard deviation ground shaking level) are presented in Figure 20. This is a very extreme and rare scenario that causes huge amounts of damage to the city. There is a large area of completely damaged buildings in the downtown core. The surrounding areas are extensively or moderately damaged. Very few areas receive only slight damage.

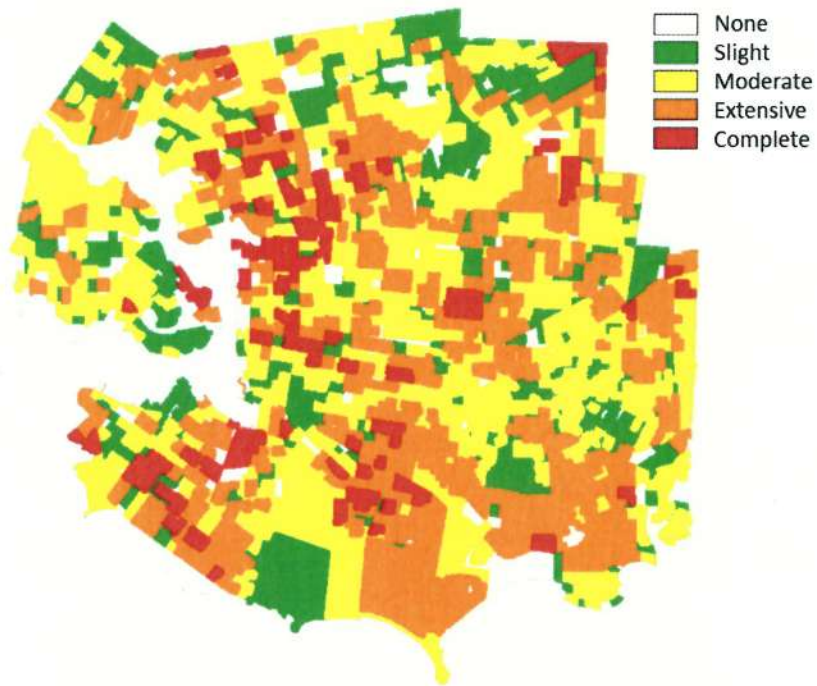


Figure 19: Damage Distribution for the Probable Magnitude = 9 Subduction Scenario

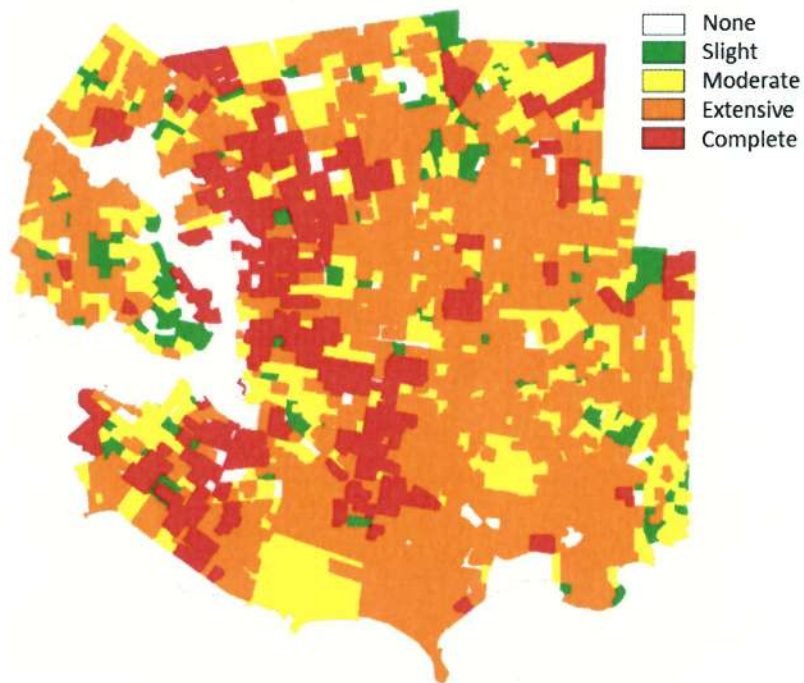


Figure 20: Damage Distribution for the Maximum Credible Magnitude = 9 Subduction Scenario (+1 Standard Deviation)

**d) 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 4 and illustrated in Figure 21. 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 4: Damage State Results from the Five Earthquake Scenarios**

	None	Slight	Moderate	Extensive	Complete	Risk (% in 50 years)
<b>M7 Crustal</b>	0 (0%)	641 (5%)	3742 (28%)	8503 (64%)	444 (3%)	1
<b>M7 Inslab</b>	2426 (18%)	5906 (44%)	4987 (37%)	11 (0%)	0 (0%)	5
<b>M7 (+1std) Inslab</b>	7 (0%)	2678 (20%)	6634 (50%)	3993 (30%)	18 (0%)	2
<b>M9 Subduction</b>	307 (2%)	2265 (17%)	5612 (42%)	4706 (35%)	440 (3%)	5
<b>M9 (+1std) Subduction</b>	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 4.

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 than 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 stock 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.

The inslab event produces the lowest levels of shaking with the city, and consequently produces the lowest amount of damage. However, large amount of moderate and slight damage may still be observed, which may not pose a threat to life safety in the city, but will almost certainly impose large monetary demands. These events are quite common in the area (three events equal to or greater than magnitude 6.8 have occurred in the last ~70 years), and as such, the City of Victoria should be well prepared for this level of shaking. The maximum credible inslab

event creates large amounts of damage, but because these levels of shaking from an inslab event are very unlikely, these results from this event are not critical.

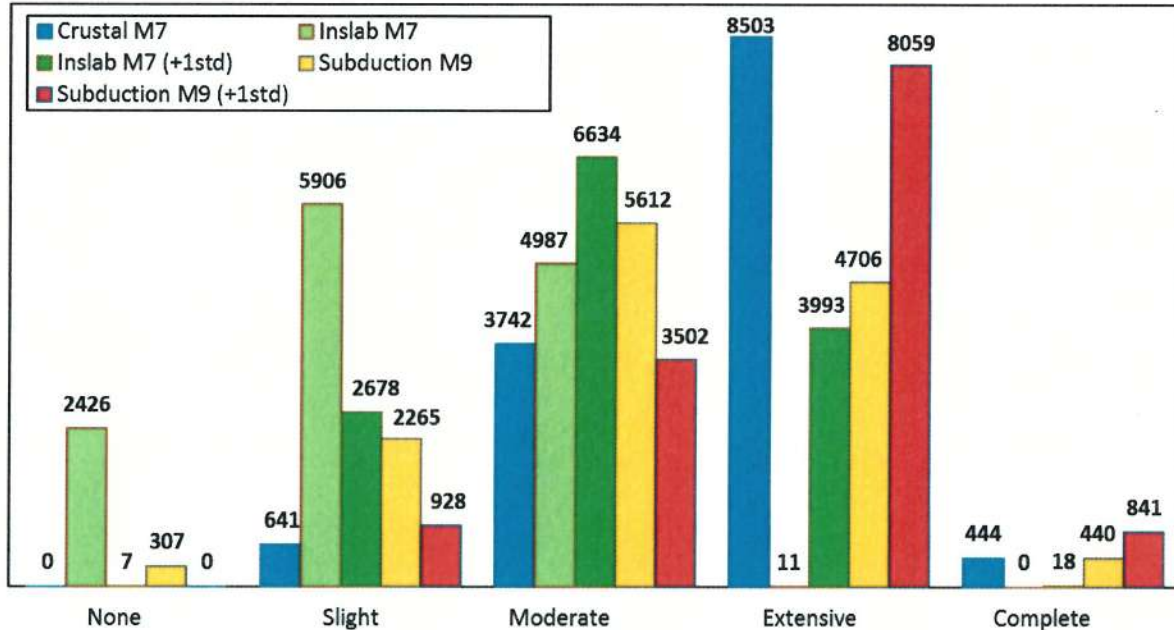


Figure 21: Number of Buildings at each Damage State for the Five Earthquake Scenarios

#### C.4. SEISMIC RISK

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.

The simple example from above effectively illustrates the concept that was employed to determine the seismic risk of buildings in the City of Victoria. 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 – calculated using EZFrisk, McGuire, 1995). 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.

Using these rates, a time-independent Poisson probability model was employed to calculate the probability of exceeding each damage state over a 50 year period. Because this probability includes contributions from all possible levels of shaking and all three seismic sources, it is an accurate measure of the total seismic risk of the buildings and can be used to classify and rank the different buildings.

### C.5. RANKING AND PRIORITIZATION

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 5, based on their probability of complete damage (PDE) in a 50 year period.

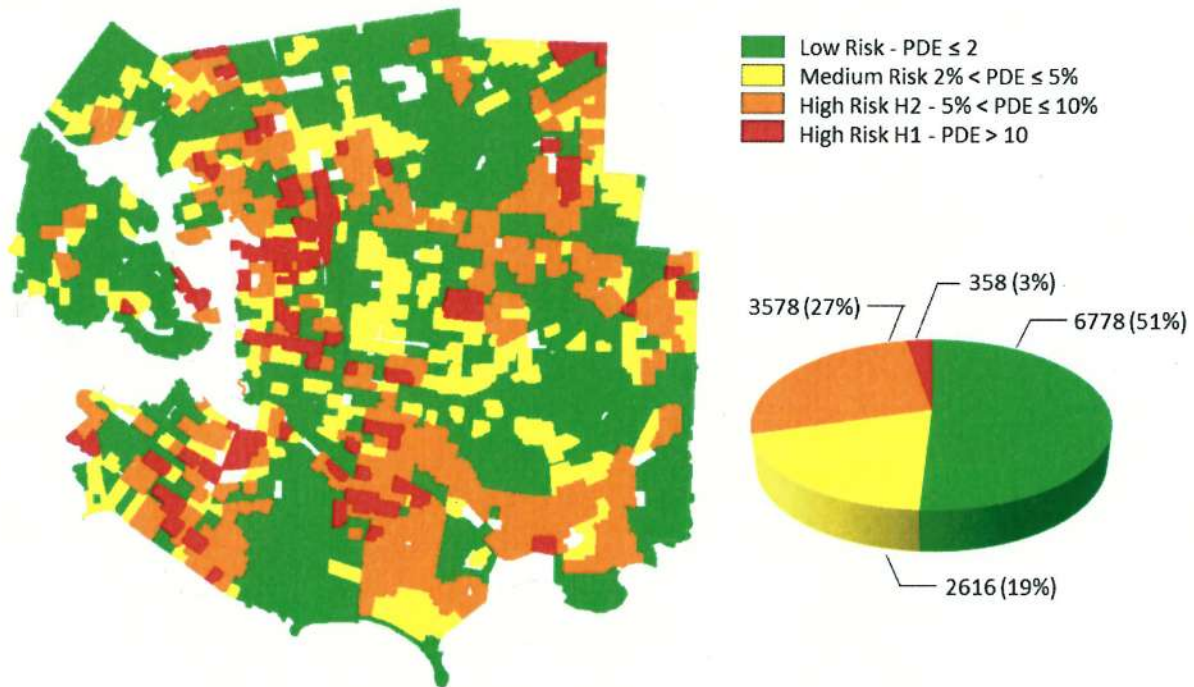
**Table 5: Priority Ranking**

<b>Priority Ranking</b>	<b>Probability of Complete Damage (PDE) in 50 years</b>
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 22 shows the distribution of buildings in each priority ranking category.

There are several trends that should be observed in Figure 22. 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 13) and the soft soil that they were constructed on (Figure 11).

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.



**Figure 22: Probability of Complete Damage (PDE) Results for Buildings in the City of Victoria**

From the previous figures: Figure 22 (risk), Figure 11 (soil hazard), Figure 12 (construction type), and Figure 13 (year built); several trends can be observed as summarized in Table 6.

From Table 6 the following prioritization strategies are recommended:

Pre-1972 low-rise concrete, steel, and reinforced masonry buildings are classified as high risk – priority should be given to these buildings on softer soils (Site Class DE or E).

Unreinforced masonry buildings (URM) are classified as high risk buildings no matter the height, construction date, or soil type. However, such buildings on soft soils are especially hazardous and should be prioritized.

Three to four storey wood apartment buildings constructed pre-1990 on soft soil or pre-1972 on stiffer soil (BC/C/CD) are high risk. Many of these buildings have obvious structural deficiencies, including soft-stories from tuck-under parking, and should be prioritized.

Low-rise pre-1960 single family dwellings with structural deficiencies such as cripple walls or sub-floors on soft soils are high risk no matter what type of soil they are on (very high risk if they are on soft soil). Newer construction (post-1960) is only high risk on very soft soil.

Mid- and high-rise buildings constructed pre-1972 on soft soil are also deemed to pose a high seismic risk. Such buildings constructed from 1972-1990 with soft stories would also fall into this risk category.

**Table 6: Building Ranking and Prioritization Summary**

Soil Type	High Risk (H2): 5% ≤ PDE <10%	High Risk (H1): PDE ≥10%
<b>BC/C/CD</b>	Pre-1972 construction Including: <ul style="list-style-type: none"> <li>• Concrete /Steel/RM low-rise (1-3 stories)</li> <li>• URM (all heights)</li> <li>• 3-4 storey wood apartment buildings</li> </ul> Pre-1960 single family wood construction with cripple walls or sub-floors	
<b>DE/E</b>	1972-1990 construction Including: <ul style="list-style-type: none"> <li>• Concrete/Steel/RM low-rise (1-3 stories)</li> <li>• 3-4 storey wood apartment buildings</li> </ul> Post-1960 Single family wood construction with cripple walls or sub-floors Pre-1972 Mid- and high-rise buildings on Site Class DE 1972-1990 Mid- and high-rise buildings on Site Class E URM (all heights) post-1972	Pre-1972 construction Including: <ul style="list-style-type: none"> <li>• Concrete/Steel/RM low-rise (1-3 stories)</li> <li>• URM (all heights)</li> <li>• 3-4 storey wood apartment buildings</li> </ul> Pre-1960 single family wood construction with cripple walls or sub-floors

## **PART D. 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.

In the major 2010 Chile earthquake, underground infrastructure experienced extensive damage including burst water and sewer pipes. There was heavy damage to sewage systems and some cases of discharge of sewage into rivers. This damage took significant time to repair. Significant pipeline damage was also observed in the recent 2011 Tohoku, Chile earthquake and the 2011 Christchurch, New Zealand earthquakes - especially in older pipes constructed with brittle materials. In all three of these cases, this damage severely impeded recovery and caused a large amount of monetary losses.

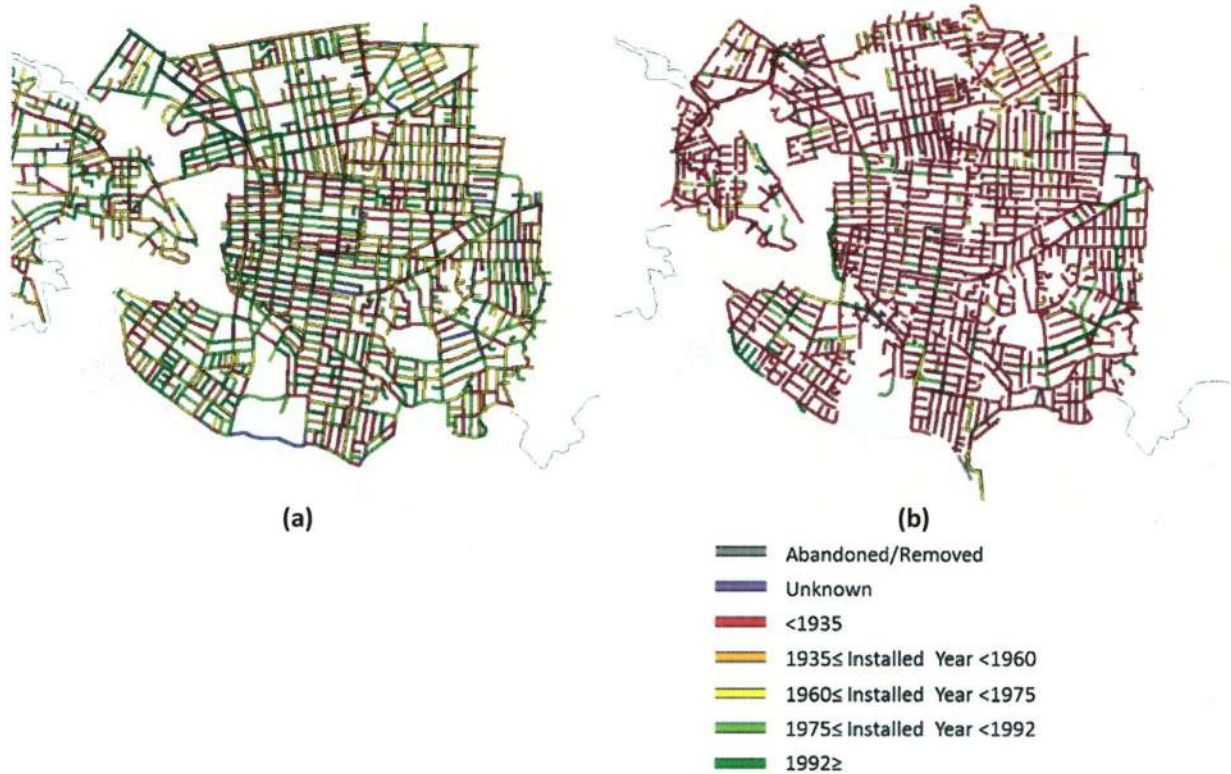
Due to the significant effect of water and sewage pipeline system serviceability on the recovery and resilience of a community, the expected damage to these systems is an important consideration in the seismic vulnerability assessment of a city or community.

This part of the report describes the general infrastructure stock in the City of Victoria, particularly the age and construction type of underground pipelines. It then presents damage results on these systems from the three considered earthquake scenarios to give a realistic perspective on the amount of damage that may be incurred to these systems in a possible earthquake event.

### **D.1. GENERAL INFRASTRUCTURE STOCK**

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 23 illustrates the distribution of water and sewer pipelines in the City of Victoria based on year installed. Figure 23(b) shows that a large amount of sewer pipelines (85%) was installed pre-1935 which makes these pipelines vulnerable to an earthquake damage. About 30% of water pipelines were installed pre-1935; therefore this distribution system is less vulnerable compared to sewer pipelines.



**Figure 23: (a) Water and (b) Gravity and Force Sewer Pipeline Distribution Map Based on Installation Date**

Figure 24 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.

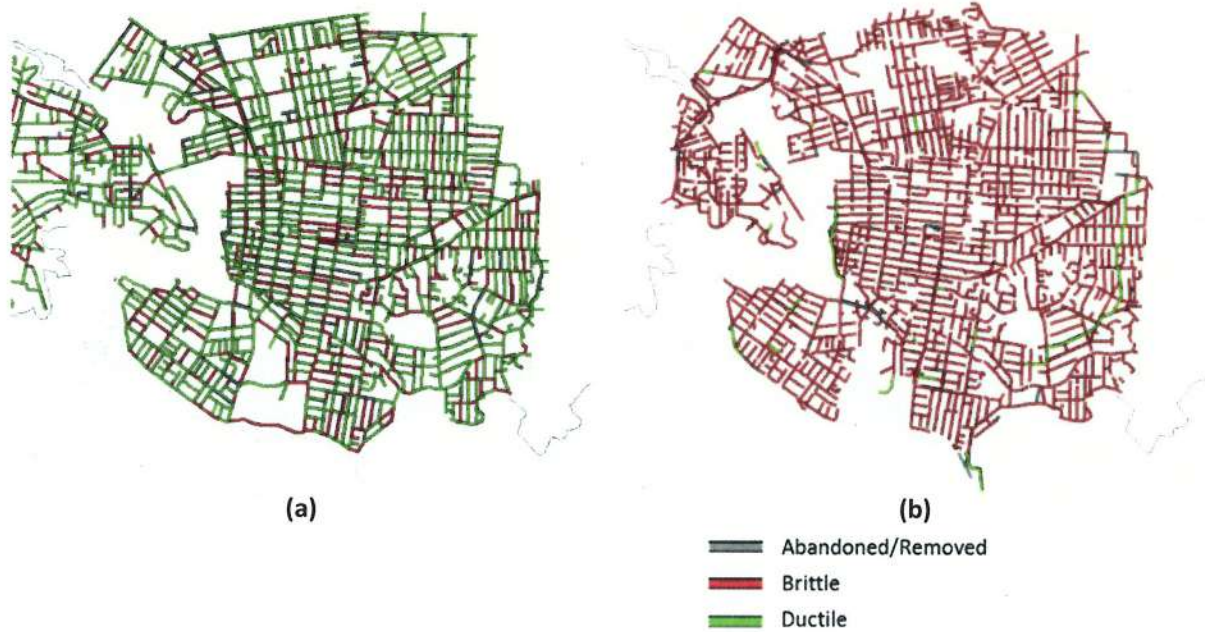


Figure 24: (a) Water and (b) Gravity and Force Sewer Pipeline Distribution Map Based on Material Type

## D.2. DAMAGE TO PIPELINES

Similar to buildings, five scenario earthquakes were considered to obtain the vulnerability of pipelines. HAZUS was used to estimate the damage including leaking and breaking of the pipelines. A summary of the number of leaks and breaks for each pipeline systems in each event is presented in Table 7.

Table 7: Summary of Pipeline Damage for the Five Earthquake Scenarios

	Risk (% in 50 years)	Water Pipeline (~345 km)		Sewer Pipeline (~260 km)	
		Leaks	Breaks	Leaks	Breaks
<b>M7 Crustal</b>	1	240	60	280	70
<b>M7 Inslab</b>	5	40	10	60	15
<b>M7 (+1std) Inslab</b>	2	120	30	140	35
<b>M9 Subduction</b>	5	100	25	120	30
<b>M9 (+1std) Subduction</b>	2	300	75	340	85

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 (FEMA, 2003). A summary of the serviceability index (percentage) for each pipeline systems in each event is presented in Table 8.

Table 8 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.

In the 2011 Christchurch, New Zealand earthquake many wastewater pipe sections completely collapsed, particularly older earthenware pipes. Wastewater pipes were observed to suffer more collapse than fresh water pipes due to their higher proportion of old construction materials. Many wastewater pipes had to be diverted before repairs could commence which significantly impacted and decelerated the recovery process. A similar situation may arise in Victoria in the event of a significant earthquake.

**Table 8: Summary of Pipeline Serviceability Index (percentage) for the Five Earthquake Scenarios**

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

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. Figure 25 and Figure 26 illustrate the post-earthquake serviceability of water pipelines for a probable and maximum credible subduction event.

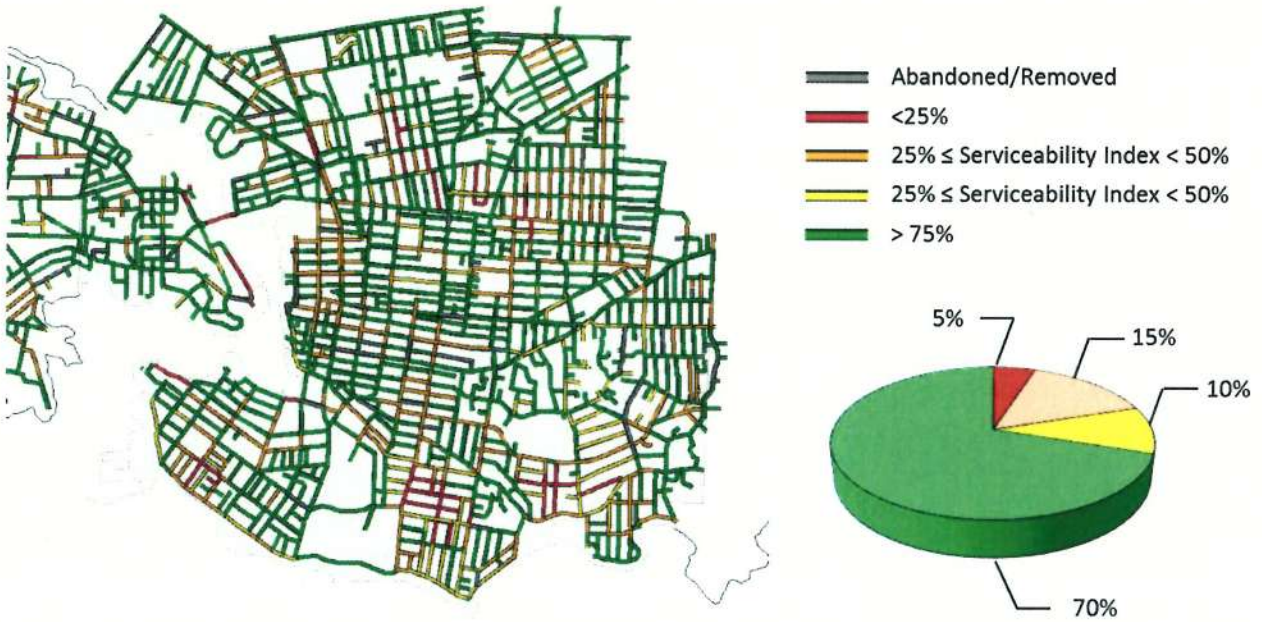


Figure 25: Serviceability Index for Water Pipeline for the Probable Magnitude = 9 Subduction Scenario

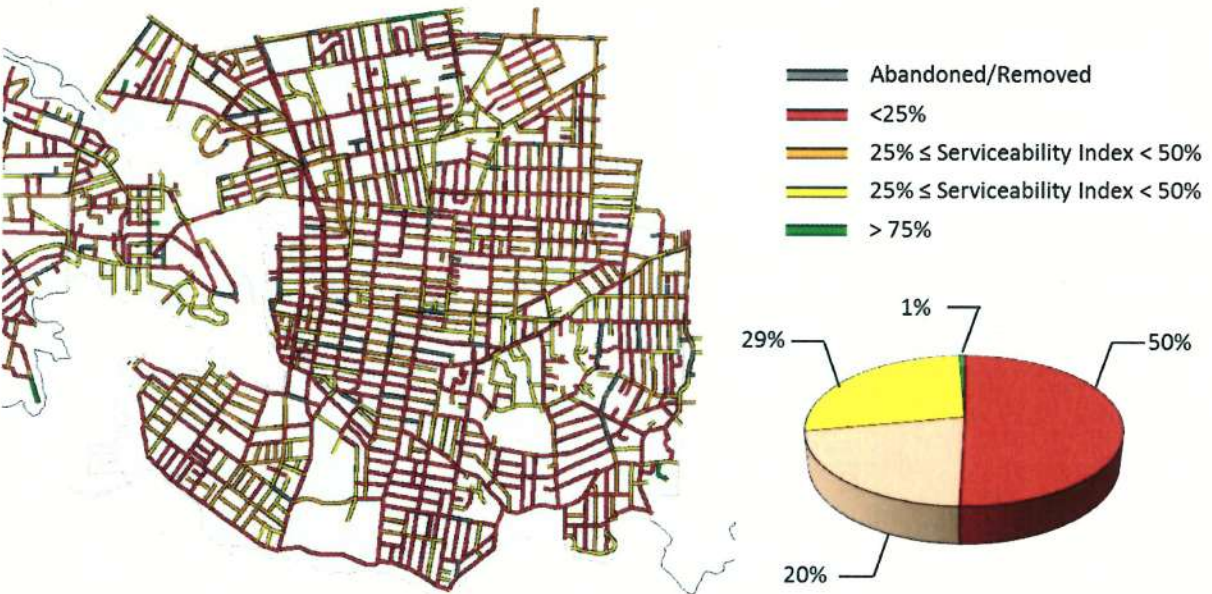


Figure 26: Serviceability Index for Water Pipeline for the Maximum Credible Magnitude = 9 Subduction Scenario (+1 Standard Deviation)



## **PART E. CONCLUSIONS AND RECOMMENDATIONS**

### **E.1. MITIGATION STRATEGIES**

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. Individual evaluation reports should be generated on a building-by-building level to determine a retrofit priority scheme. This would be a significant undertaking, but is necessary for any future seismic mitigation planning and implementation. A retrofit scheme targeted at the most at-risk buildings identified by these reports may then be launched.

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.

### **E.2. FUTURE STUDIES**

From the results presented previously, it can be seen that local soil conditions play a large factor when determining the seismic vulnerability of a building. Despite the improvements made to the existing soil maps, there are still many uncertainties due to lack of data and measurements. Soil conditions vary significantly and rapidly in Victoria - for example: two neighboring buildings might be on completely different Site Classes, and thus, would be expected to be at two completely different risk levels. Accordingly, a highly accurate and well-defined soil hazard map should be the first priority when discussing future studies. Although the modified soil map used for this study represents the best current knowledge of soil conditions, refining this map would improve future studies and would help to classify at-risk buildings. A building-by-building seismic evaluation study as mentioned in the previous section would be the second recommended study.

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