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Seismic vulnerability in Southwestern BC - impact of long duration subduction ground motions on wood typologies

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ABSTRACT

Fragility curves generated based on site specific seismic hazard are essential to get an accurate assessment of seismic risk for buildings in each region. The seismicity in Southwestern British Columbia (BC) 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. This scenario poses significant seismic risk since Southwestern BC is densely populated, with compact building stock, most which are aging. With most of the building stock being light frame wood structures, low rise masonry and pre-code constructions, it is necessary to accurately estimate damages.

The most recent Canadian National Risk Model utilizes the fragility curves developed by Global Earthquake Model (GEM), which are used to run seismic risk models in OpenQuake. These fragility curves are developed for building typologies adopted from HAZUS and using FEMAP695 ground motions. But, the FEMA P695 ground motions are moderate duration ground motions and are imprecise for the seismic hazard in Southwestern British Columbia. This study investigates how these fragility curves change when accounting for longer ground motion duration and higher intensities typically seen in long duration subduction ground motions expected in regions of Southwestern BC. This study is carried out for the most prevalent building typologies in Southwestern BC, as noted in an extensive building survey carried out by UBC. This study also considers only damage probabilities; however, damage is directly related to expected loss.

Keywords: Seismic risk Assessment, Site Specific Seismic Hazard, Global Earthquake Model, Southwestern British Columbia, Long Duration Earthquakes

INTRODUCTION

The increasing possibility of natural hazards necessitates the assessment and management of risk that plays a vital role in deciding emergency preparedness, appropriate retrofits and legislating public policy. Understanding risk profiles, expanding from local to regional and national scale is its basic requirement, and more so for Western Canada, where the possibility of a mega-thrust earthquake in the Cascadia region is significant. With most of the building stock being light frame wood structures, low rise concrete, masonry and pre-code constructions, it is necessary to estimate the probability of expected damages and losses due to seismic hazards for appropriate action, emphasizing development of a realistic risk profile for the Canadian provinces and at the national level

The objective of this paper is to investigate how fragility curves change when accounting for longer ground motion duration and higher intensities typically seen in long duration subduction ground motions expected in South-Western British Columbia. This study is carried out for the most prevalent building typologies in Vancouver, as noted in an extensive building survey carried out by UBC. The presence of a building population dominated by wood construction built before 1972 has motivated the study of their behavior under potential earthquake conditions. The subduction assessment was performed for subduction events corresponding to a probability of roughly 2% in 50 years.

The city of Vancouver, located in British Columbia, Canada is used as an example study region. Vancouver is in the Cascadia subduction earthquake zone where both large magnitude subduction rupture events are expected at the interface of the Juan de Fuca and north American plates and smaller crustal rupture events are seen. It has an area of 114.97 km^2 and is the most populous city in BC, with a recorded population of 631,486 people in the city as per the 2016 census and has the highest population density in Canada with over 5,400 people per square km. A building inventory that comprises about 96,000 buildings, put together by UBC (University of British Columbia), was considered. Most of the buildings in the city are constructed from wood and built before 1972, when modern building codes were introduced. The mid- and high-rise concrete, steel and masonry construction, dominates the building stock in downtown Vancouver. Of its total building stock, more that 50% are built before 1972. This combination of a high population density, high building population density and an aging building stock makes it very important for proper damage assessment in the event of an earthquake.

Seismic Hazard

To evaluate seismic risk for a region, it is required to assess the seismic hazard and identify the events of interest. The seismicity of the City of Vancouver is dominated by the Cascadia Subduction Zone.

The deaggregation plots for Vancouver at 0.5 and 1.0 seconds at the total 2% in 50-year hazard using data acquired from the GSC 2015 seismic hazard model implementation in EZFrisk is shown in Figure 1. The Deaggregation results of Southwest BC demonstrates that crustal events occur at smaller magnitudes of 5.5 to 7.5, near the surface at a depth less than 30km, in the upper crust of the continental plate and at distances less than 80km. The sub-crustal or inslab events occur with magnitudes of 6 to 7.5, at a depth of 30-90km, deep in the subducting Juan de Fuca tectonic plate and at distances of 30-150km. Possible large magnitude subduction earthquakes at the interface of the Juan de Fuca and North American Plate [1] can occur at depths of 0-50km, at the plate boundary and distances from about 50-250km depending on the site location [2].

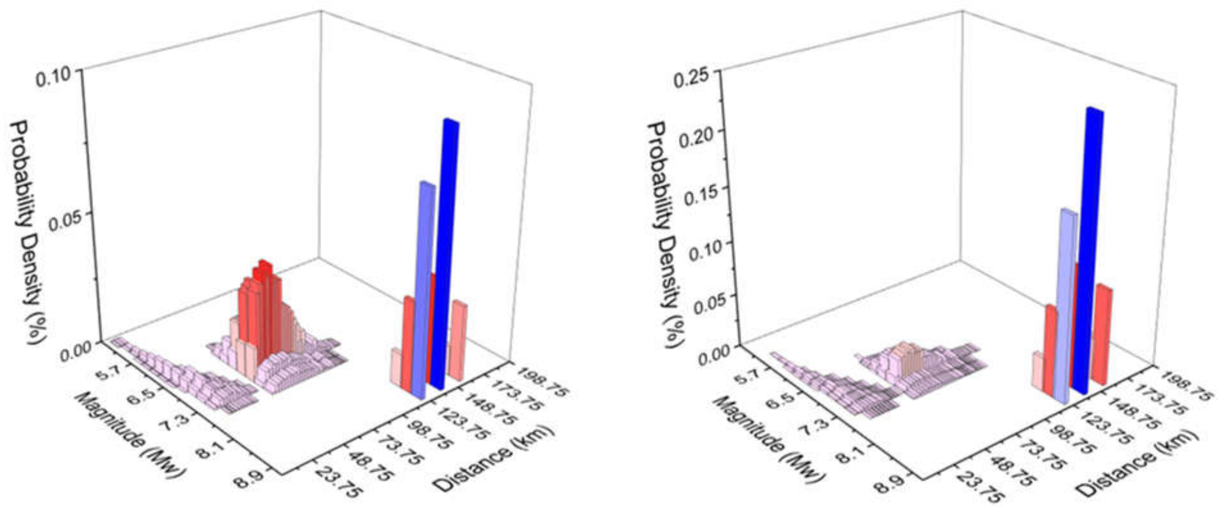

Figure 1. Deaggregation plots for Vancouver [2]: (a) Vancouver Total Deaggregation for Sa(0.5sec) = 0.751g (b) Vancouver Total Deaggregation for Sa(1.0sec) = 0.425g

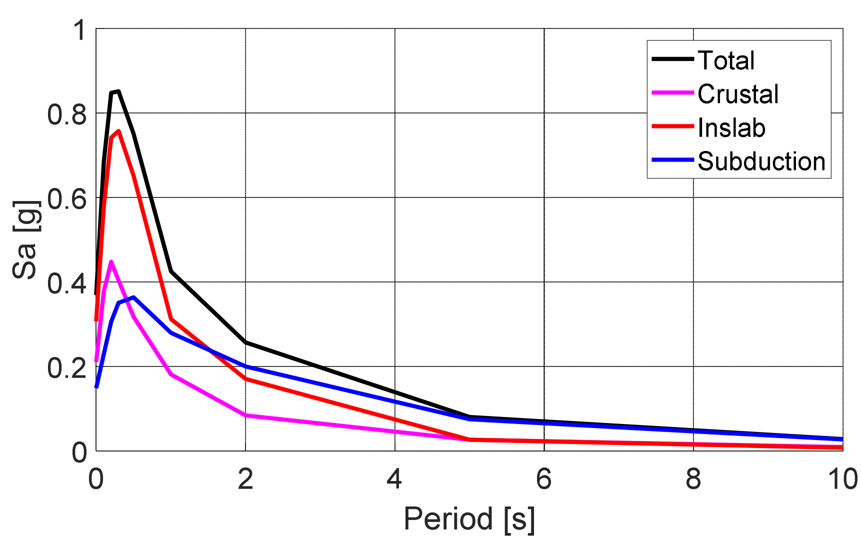

Figure 2. Vancouver Uniform Hazard Spectrum deaggregated

These deaggregation results suggest that seismic hazard values for longer vibration periods (>1.0 s) are affected more significantly by the large subduction events. The subduction events are seen to be comprised of richer long period spectral content as compared to crustal and sub-crustal events. Thus, the subduction event becomes important as the dominant scenario for longer period structures and is therefore very important to be considered for seismic performance evaluations. It must be considered when selecting ground motion records for non-linear dynamic analysis, for the development of fragility curves for buildings in Vancouver for regional damage assessment.

Ground motion Selection

The ground motions used for the study are those developed for the SRG3 (School Retrofit Guidelines) of the University of British Columbia, Canada. The SRG3 implements the 2015 Western Canada hazard values, provided by the Geological survey of Canada [3].

The seismic hazard in British Columbia is dominated by three types of earthquakes: crustal, subcrustal, and subduction. Two Conditional Spectra are developed for each of the three sources, conditioned at 0.5 and 1.0 sec, and twenty records are selected from a comprehensive database to match the mean and variance of each CS. The records are selected to match geophysical parameters (distance, depth, magnitude, and site conditions) for each source based on seismic hazard deaggregation results. The ground motions were selected to represent each of these three types of earthquakes and were also chosen from regions like Southwestern BC, tectonically, to account for spectral shape effects and local site conditions.

For record selection and scaling, the conditional spectra (CS) is implemented because, since their shape bears a better likeness to the spectral shape of realistic ground motions, as compared to a UHS, the CS provides a more realistic target spectrum which enables easier ground motion selection and scaling [4]. Also, since both mean spectral values and their variance is matched during CS procedure, appropriate record-to-record variability is accounted for, making the methodology more probabilistically robust. A suite of individually scaled ground motion records with a mean close to the conditional mean spectral (CMS) values are selected and a required variance about that mean is incorporated to match records to a target Conditional Spectra. The CMS are "anchored" to a UHS (2% in 50-year probability of exceedance for the study) at a "conditioning period" (T_c). The standard deviations associated with the ground motion prediction equations (GMPEs) used to derive the CMS are used to calculate the required variance about the mean [5].

Figure 3 shows the 20 scaled subduction records selected to match the CS (mean and variance) for subduction sources with conditioning period at 1.0 sec and Figure 4 shows the 25 scaled FEMA p695 ground motions used by GEM to derive its fragility curves, at 1.0 s. Figure 5 compares the 100% mean spectra of subduction ground motions used in the study to develop fragility curves to the mean spectra of the 25 FEMA p695 ground motions scaled down to match Sa (1.0) for Vancouver subduction spectra. A very visible difference in spectral shape is seen in the comparison, with a richer spectral content in the long periods for subduction ground motions, after 1.0s. This difference should have manifested in the fragility curve result, driving damage especially for the W2-PC higher. However, such an expected marked difference is not visible, and needs further study.

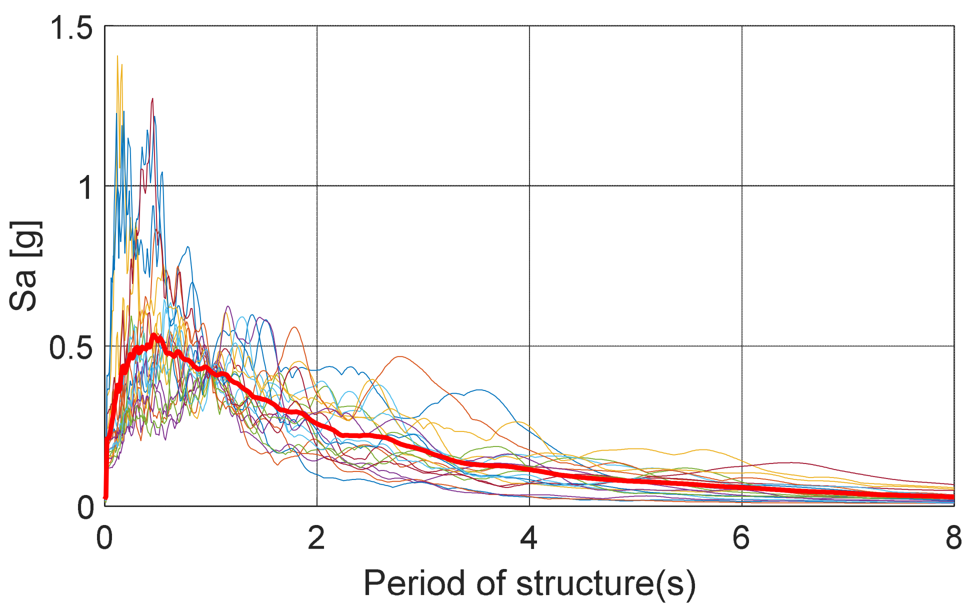

Figure 3. Subduction records for Vancouver with T_C = 1.0s. Mean spectra is shown in red

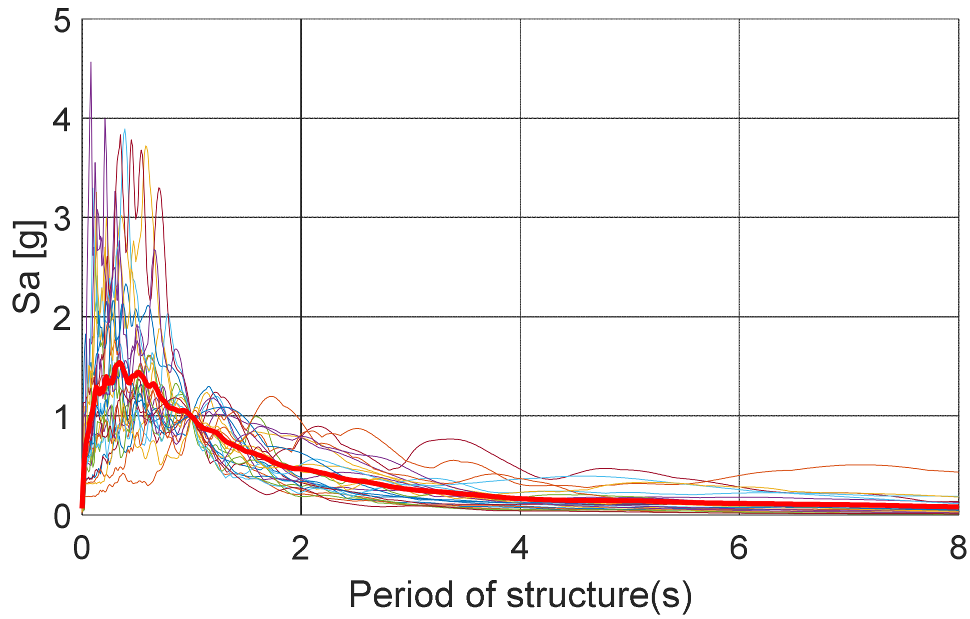

Figure 4. FEMA p695 records used, matched and scaled at 1.0s. Mean spectra is shown in red

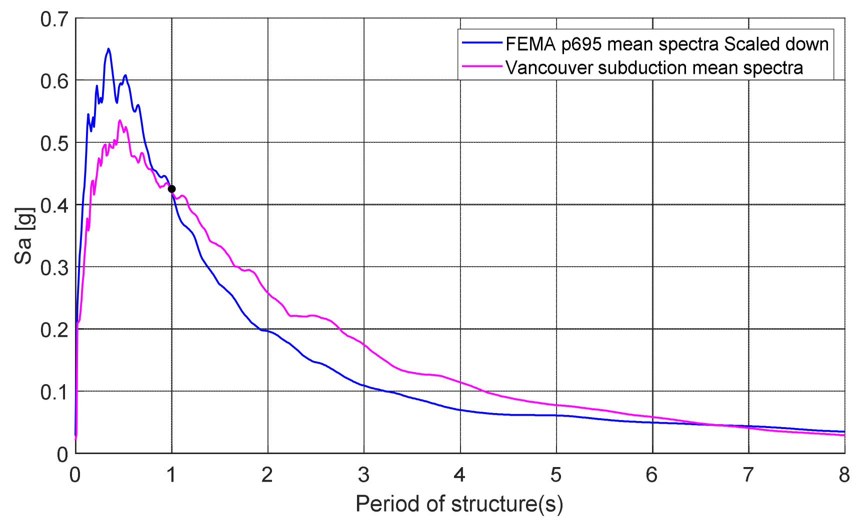

Figure 5. Comparison of 100% mean spectra of subduction ground motions used in the study to mean spectra of FEMA p695 ground motions scaled down to Sa (1.0) for Vancouver spectra (0.425 g)

Vancouver building stock

Wood construction is the most prevalent construction material in the City of Vancouver– approximately 95% of the buildings surveyed in Vancouver are constructed using wood. Concrete is the second most common construction material followed by masonry (reinforced and unreinforced) and then steel.

A total of 95642 buildings a were surveyed and classified based on their material type, height, age (used as a proxy for design level referring to building code evolution and hazard estimation), archetype, occupancy, number of stories, area of the building and such. Of these, 90,000 were mostly wood and concrete. 80,000 were single family dwellings. About 50,000 were built before 1972, of which 27,000 were single family pre-code wood construction.

The major typologies are found to be: W1 -Single family wood housing followed by W2 –Wood, Commercial and Industrial, URML- Unreinforced Masonry Bearing Walls Low-Rise, C2L- Concrete Shear Walls Low-Rise, C2H- Concrete Shear Walls High-Rise, C2M- Concrete Shear Walls Mid-Rise, URMM- Unreinforced Masonry Bearing Walls Mid-Rise and RM1L-

Reinforced Masonry Shear Wall Low Rise. As the wood typologies alone make up 95% of the building stock, for this study, we will concentrate on the wood typologies, namely W1 and W2, built before 1972.

Methodology to create fragility curves

The capacity curves provided by GEM Pavia are developed from Hazus initially, following the Ryu et al methodology for converting Hazus capacity curves for use in non-linear time history analysis [6]. Then, these are back calibrated from loss ratios obtained from scenario analysis. These capacity curves are used to build single degree of freedom systems (SDOFs). In order to consider building to building variability, a Monte Carlo sampling is applied to the capacity curves, considering the initial capacity curve as the median capacity curve. Thus, instead of a single SDOF system, a collection of 150 SDOFs, each representing different buildings of the same typology, are used when deriving the fragility curves for that typology. 150 capacity curves are chosen based off previous sensitivity studies conducted by GEM Pavia to capture at which number of SDOFs, there is a convergence of expected building to building variability within a 5% tolerance. The hysteresis and degradation are also introduced within these models.

For each building typology, 150 SDOF oscillators are created and they are subjected with a select suite of 240 subduction ground motion records. The derivation of fragility functions for the building typologies were carried out using the GEM Risk Modeler's Toolkit (RMTK) [9]. The RMTK uses OpenSEES to perform the non-linear time history analysis of the SDOF systems. The damage states are taken as Slight, Moderate, extensive and Collapse, following HAZUS definitions [7]. The damage state criteria used to allocate buildings into a damage state are set to correlate 100% with the capacity curve [10]. The ultimate displacement (Sdu) is taken as the Complete damage, Slight damage is associated with the yielding displacement point as 0.75*Sdy. Another two notable points between the yielding and ultimate displacement on the capacity curves are taken to represent moderate and extensive damage states. Figure 6 shows the damage state definitions for W1-PC.

With these damage criteria, the results of the 36,000 dynamic analyses is recorded into a damage probability matrix (DPM), defining the fraction of buildings in each damage state per ground motion record. For different intensity measure levels (IM), a damage distribution is obtained. With this DPM, a simple regression analysis is carried out to calculate the mean and standard deviation of the cumulative log-normal distribution. The GEM Canada currently uses the FEMA 695 ground motions (shallow crustal) to create the fragility curves. These fragility curves are then used in the Canadian National Risk Model [8] [9].

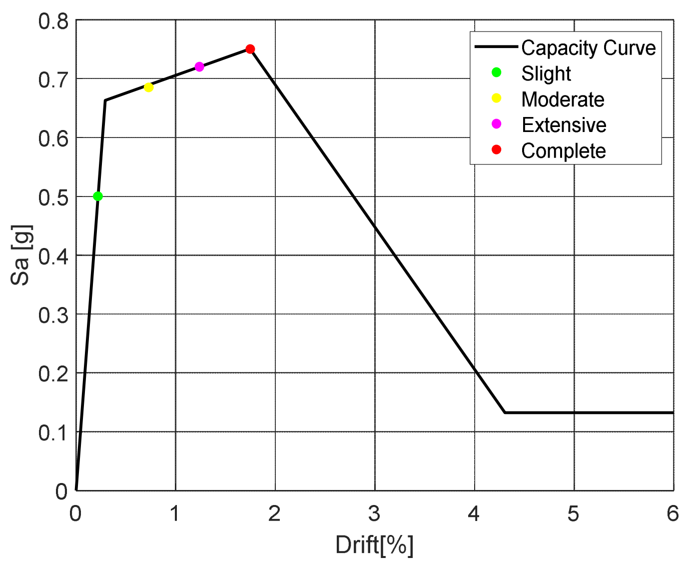

Figure 6. Damage state definitions for W1-PC.

Comparison of GEM fragility curves and fragility curves developed using Subduction ground motions

This section discusses the damage results predicted by GEM using the FEMA p695 ground motions, as compared to damage results predicted by fragility curves developed using subduction ground motions for the most prominent building typologies in Vancouver, W1 and W2, pre-code. Four discrete damage states are considered: Slight, Moderate, Extensive, and Complete. The duration of shaking impacts the energy dissipation capacity of the structure. The level of shaking is computed by the spectral acceleration at the effective period of the structure [9].

Figures 7 and 8 compares the fragility curves for two pre-code typologies: single family wood houses (W1) and multi-storey wood apartments (W2). The GEM fragility curves seem to predict lower damage than the fragility curves that were developed using subduction ground motions. The former predicts a lower probability of Extensive and Complete damage compared to the latter at higher intensity levels. For lower intensity levels, the damage predicted is comparable, with no Extensive and Complete damage predicted for W1-PC. However, there is a large portion of W1-PC predicted to be in Slight damage state by the fragility curves developed for subduction ground motions.

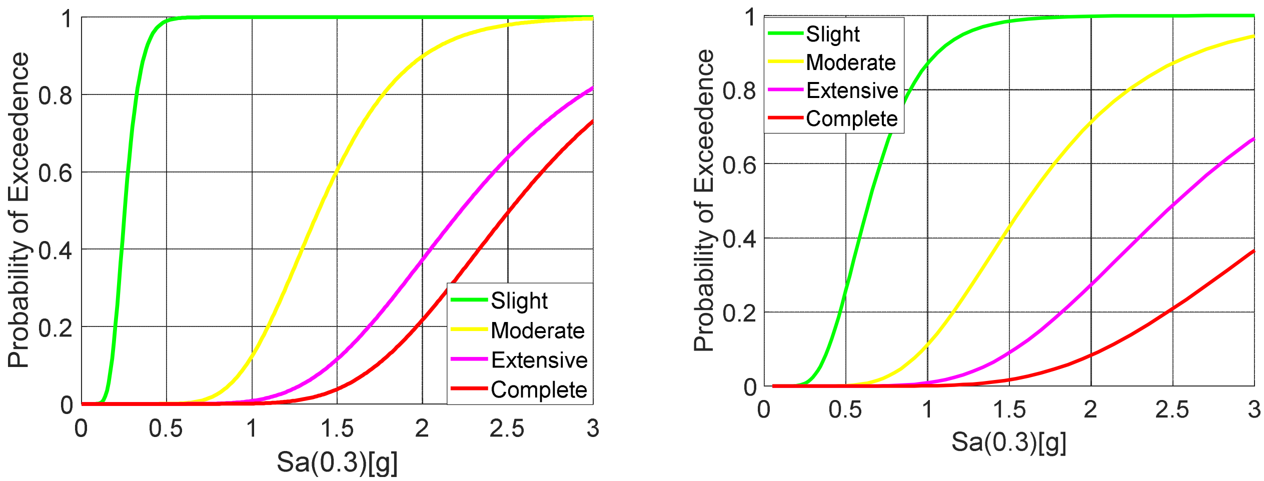

Figure 7. Comparison of W1-PC fragility curves: (a) developed using subduction ground motion, (b) developed using FEMA p695 ground motions by GEM Pavia.

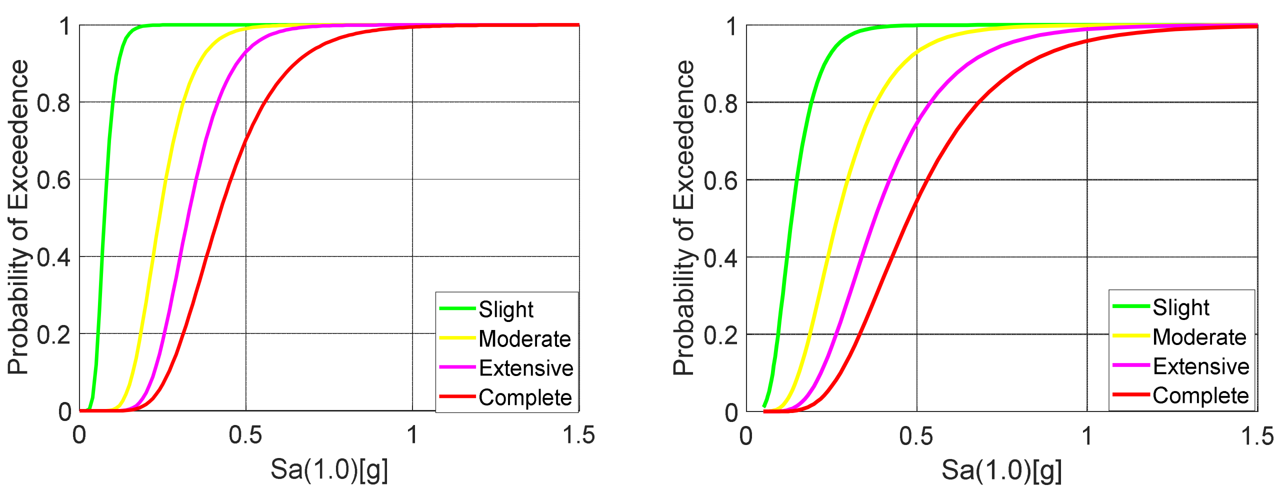

Figure 8. Comparison of W2-PC fragility curves: (a) developed using subduction ground motion, (b) developed using FEMA p695 ground motions by GEM Pavia

Figure 7 shows that the median of Complete and Extensive damage for the pre-code single family wood houses (W1- PC) is higher than 2g in both versions of the W1 Pre-code fragility curves. This may not be accurate, since pre-1972 single family wood houses with short-storey deficiencies due to presence of cripple walls are more vulnerable to damage at higher intensity of ground shaking.

For pre-1972 three to four storey wood apartments (W2-PC) as shown in Figure 8, it is observed that the GEM is more conservative towards estimation of seismic damage at lower shaking levels. However, for the fragility curves created using subduction ground motions, which is not seen. This could be because degradation has not been fully incorporated into the SDOF models and needs further study. These curves also imply that a lot more damage can be expected for buildings with higher time periods at lower intensity of shaking, and in softer soils. Figures 7(a) and 8 also shows that the median of the Extensive and Complete damage fragility curves in most cases are close, which makes the damage prediction very sensitive to the level of shaking.

CONCLUSIONS

This paper presents the comparison between the damage predicted during an earthquake for the City of Vancouver, using fragility curves developed by GEM Pavia using FEMA p695 ground motions vs fragility curves developed using subduction ground motions predicted in Vancouver. The increased seismic demand potential for the subduction records is related to the rich long period spectral content and the long duration excitation. The long duration effects are seen to have an influence on the fragility curves, as the SDOFs oscillate within the elastic region for a longer time. Thus, the collapse potential due to subduction events is greater than crustal and sub-crustal events.

All pre-code wood typologies on stiffer soils are predicted to perform better under all scenarios, while those on softer soils are predicted to perform worse. It is also observed that the median of the fragility curves for Extensive and Complete damage for most of the wood typologies and design code levels are close, which makes the damage prediction highly sensitive to the level of ground shaking. The results obtained point out that more attention should be paid to the results from pre-code single family wood homes that are a large portion of the Vancouver building stock. These homes may have structural deficiencies that can cause short-storey effects under strong shaking, which can make it vulnerable to damage. Since the fragility curves obtained W1-PC seems to show no damage at intensities even up to 2.0g, better SDOF models which can represent the W1 typologies with cripple walls have to be considered. This is also true for many 3-4 storey wood apartment buildings due to tuck-under parking underneath the second level.

Owing to the marked difference in spectral shapes of the mean of the FEMA p695 ground motions and mean of the subduction ground motions, a more visible difference was expected in the fragility curves, especially of the W2 typologies, which seemed to be absent. It could be because the degradation properties have not been properly captured within the SDOF models. This needs further investigation. From the subduction motions, a difference was also expected in the fragility curves due to long durations of ground shaking. However, this effect of ground motion duration, though present, was also not as strong. This needs further investigation as well. It is also important that the fragility curves be redeveloped using capacity curves that are more representative of the as-built building typologies in Canada, reflecting the lower resistance levels especially for pre-code and low-code constructions.

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