Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 1129

SENSITIVITY OF DESIGN SPECTRUM FOR BRITISH COLUMBIA TO DIFFERENT LEVELS OF PROBABILITY OF EXCEEDANCE

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ABSTRACT

The 2005 edition of the National Building Code of Canada (NBCC) provides for each city in Canada a design response spectrum based on the corresponding Uniform Hazard Spectrum (UHS) for a probability of exceedance of 2% in 50 years. In British Columbia, the design spectrum reflects the seismicity of the region, which is affected by three different earthquake sources: crustal, subcrustal and subduction events. For Performance-Based Design (PBD) it is of interest to determine the expected behavior of structures for different levels of shaking. A possible way to characterize the various levels of demand is by using design spectra for different levels of probability of exceedance. The effect on the structural response of these levels of demand should be investigated in terms of acceleration and displacement response spectra when one considers that long period structures fall into the displacement-sensitive region of the response spectrum, while short period buildings fall into the acceleration-sensitive region of the response spectrum. In this paper the contributions to the UHS of the different source mechanisms in British Columbia are investigated for two important cities in the province (Vancouver and Victoria). This is done for three different probabilities of exceedance: 2%, 10% and 50% in 50 years. The demands at each city are then characterized by the corresponding acceleration, velocity and displacement spectra for each earthquake source and for each probability of exceedance. The results of this study provide a better insight of how the seismic hazard in each of the cities investigated contributes to the risk of different structures, and what level of performance can be expected from structures designed in accordance with the NBCC 2005 when subjected to levels of ground shaking different than those specified by the code.

Introduction

In Canada the seismic design of buildings is based on a design spectrum specified by the National Building Code of Canada (NBCC, 2005). The design spectrum provides a way to determine structural demands, and it is based on a Uniform Hazard Spectrum (UHS) for ground motions with a probability of being exceeded of 2% in 50 years. This paper evaluates the sensitivity of the design spectra to different levels of probability of exceedance in British Columbia. The seismic hazard in BC is posed mainly by three different earthquake sources:

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crustal, subcrustal and subduction, contribution from each source also is evaluated.

The input information of the seismic sources for the analyses is provided by the Geological Survey of Canada (GSC) in the Open File 4459 (Adams and Halchuk, 2003). The attenuation equations used to predict the ground motion parameter are as follows: for crustal earthquakes the equation proposed by Boore et al. (1997) and adjusted by the GSC was used, and for the subcrustal and Cascadia earthquakes the equations proposed by Youngs et al. (1997) were used. It is important to note the difference between the current GSC and the USGS approach used to estimate seismic hazard from Cascadia subduction interface, the former uses a deterministic analysis and the latter a probabilistic analysis.

The Uniform Hazard Spectra presented in this paper is obtained through a seismic hazard analysis following closely the methodology adopted in the Open File 4459. The software EZ-FRISK v 7.26 (Risk Engineering Inc., Boulder, Colorado, USA) was used for the hazard calculation, applying a probabilistic approach for the crustal and subcrustal (subduction zone intraslab) hazard computations and a deterministic approach for the Cascadia subduction interface hazard estimates. Although the results presented here do not account explicitly for the epistemic uncertainty, these are very close to the actual values recommended by the GSC which actually incorporates epistemic uncertainty.

In this paper the spectral design demands are presented for a soil site class C soil (firm soil or soft rock). According to the NBCC 2005 the ground motion amplification factors for firm soil are: Fa=Fv=1.0 (Finn et. al 2003). The NBCC 2005 design spectrum for a site on firm soil follows the same spectral demands of the UHS, but is modified for periods in the range 0sec<T<=0.2sec to be constant and equal to Sa(T=0.20sec). In the NBCC 2005 the site class C soil is characterized by having a time averaged shear wave velocity between 360 – 750 m/s in the uppermost 30 meters. The spectral values are presented in this paper as units of g for spectral acceleration, in cm/s for spectral velocity , and in cm for displacements.

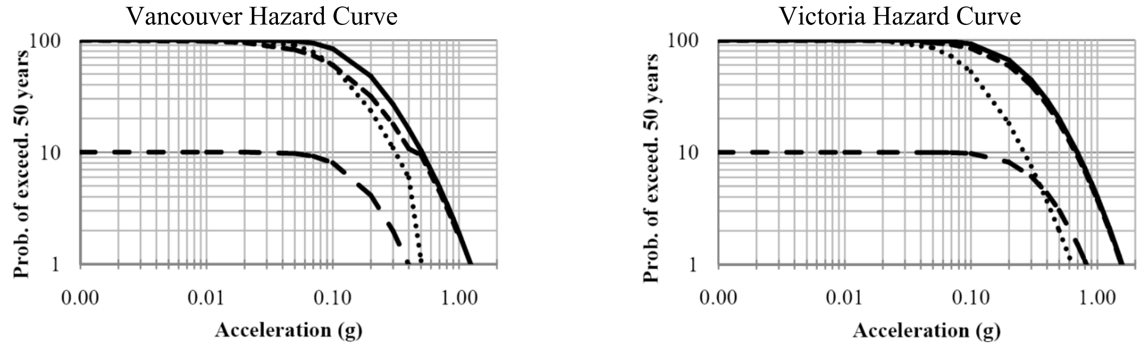
Acceleration Hazard Curves

The hazard curve in this paper is a plot of the intensity of a ground motion parameter associated with different hazard levels for an elastic single-degree-of-freedom (SDOF) with a given period of vibration and damping ratio (5%). The preferred format to present the hazard curve is by specifying the hazard level as an annual frequency of exceedance. To obtain the probability of exceeding a particular hazard level in a given period of time the Poisson model was adopted for the crustal and subcrustal earthquakes.

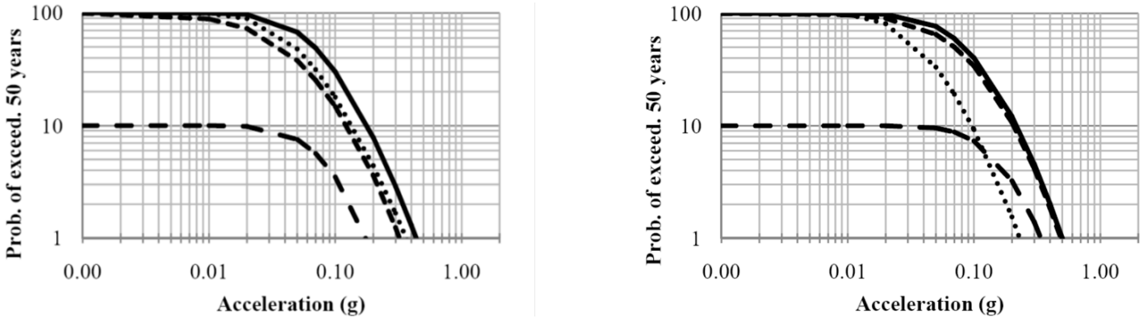
In the GSC Open File 4459 for Cascadia subduction interface earthquake a deterministic model was adopted. The occurrence of the deterministic scenario has a probability of about 10% in 50 years (~600 year recurrence interval). Since the ground motion relationship follows a lognormal distribution, probabilities of exceedance for different levels of ground motion intensity are calculated given a magnitude and distance. For Cascadia interface hazard the probability of exceedance in 50 years is obtained as the product of the event probability (10% in 50 years) and the probability of exceedance of ground motion intensity in the prediction equation.

These hazard curves for Vancouver and Victoria are presented in Fig. 1, for a set of three spectral periods (T = 0.2s, 1.0s and 2.0s) representative of a short period, intermediate and long period structure. Four hazard curves are presented in each figure: (1) the design curve, (2) curve due to crustal earthquakes, (3) curve due to subcrustal earthquakes, (4) due to Cascadia subduction interface earthquake. Following the methodology described above the “hazard curve” for the subduction event was calculated and shown in Fig.1.

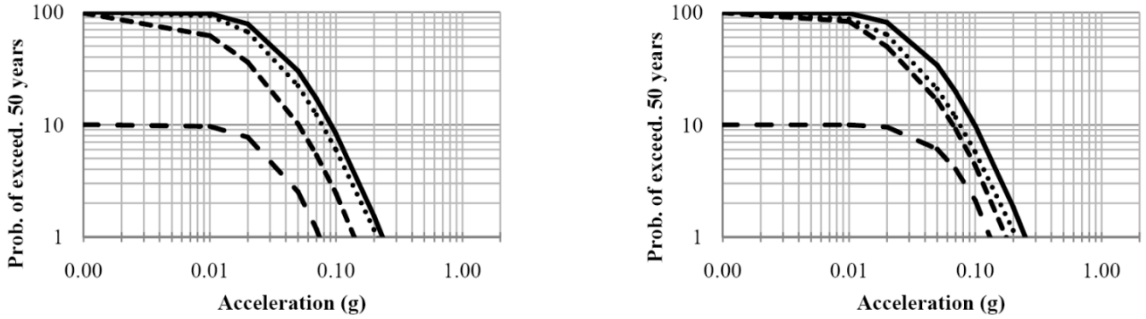
The sensitivity of the ground motion in the hazard curve to the level of probability of exceedance can be qualitatively appreciated through the slope of the curve. In the logarithmic scale a steep slope represents a segment where ground motion is more sensitive to the probability of exceedance than a flat slope.



(a) Spectral period 0.2s
(b) Spectral period 0.2s



(c) Spectral period 1s
(d) Spectral period 1s



(e) Spectral period 2s
(f) Spectral period 2s

Figure 1. Seismic Hazard estimates for Robust model at Vancouver and Victoria at Spectral periods: T=0.2s (a) and (b), T=1.0s (c) and (d), T=2.0s (e) and (f).

Time-dependent model for Cascadia interface earthquake

The Poissonian process estimates the probability of the next event regardless of the time spanned since the last event. For the megathrust earthquake at the interface of North America and Juan de Fuca plates, the earthquake occurrence is evaluated with time-dependent models, which are suitable to describe this regularly recurrent event (Onur, 2004). The results presented in this paper do not include such time-dependent models. The megathrust earthquake is considered to have a recurrence interval of 590±105 years (Adams, 1994) and return period of the corresponding ground motions was not estimated here.

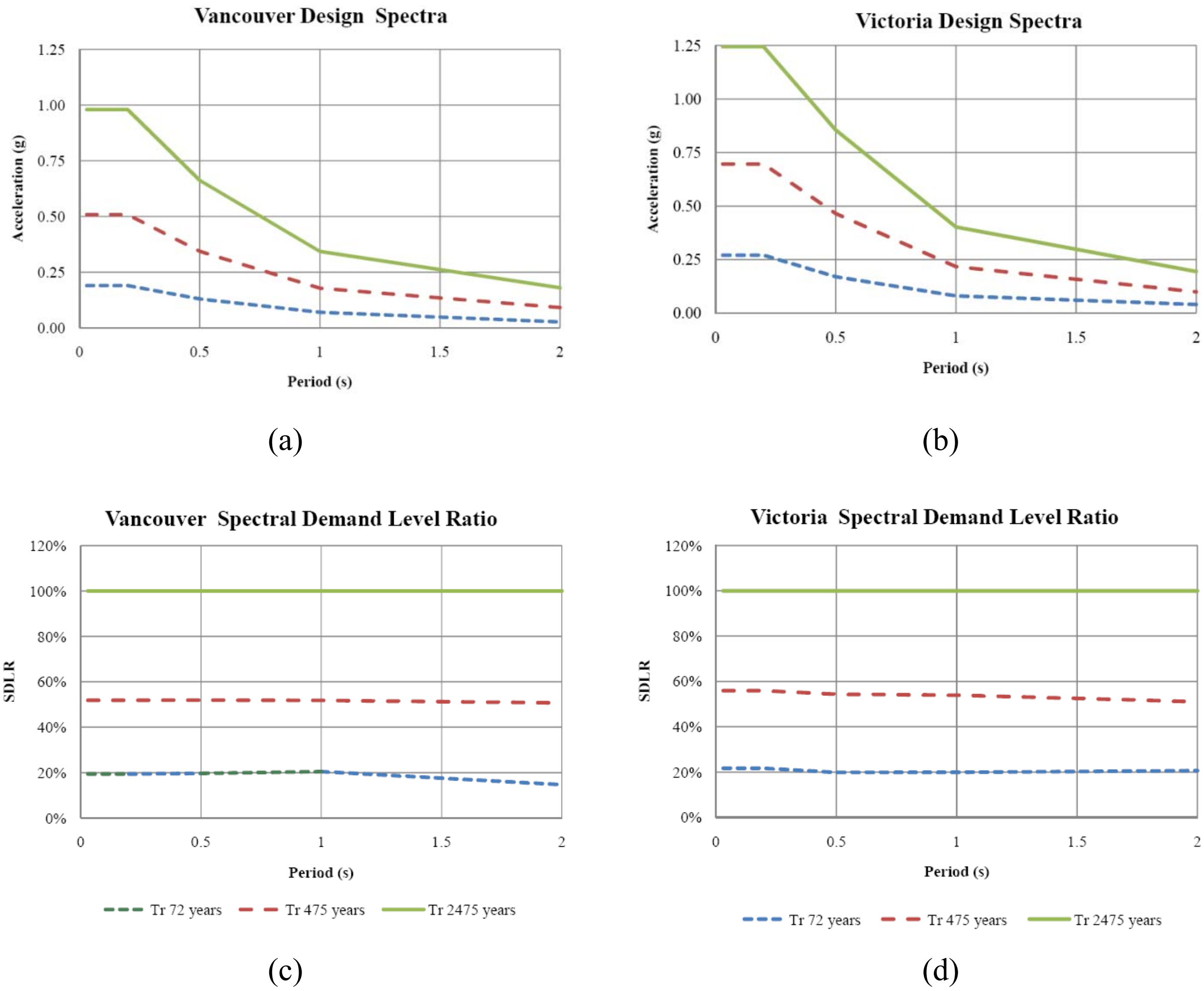
Performance Levels

The spectral demands in the Uniform Hazard Spectra are presented here for three probabilities of exceedance. Using the Poisson model, the probabilities of ground motion exceedance of 50%, 10% and 2% in 50 years correspond to return periods of 72 years, 475 years and 2475 years, respectively.

In applying the Performance-Based Design (PBD) philosophy to the design of ordinary buildings these probabilities of exceedance can be associated with the following performance levels as follows: fully operational level (50 years), life safety level (475 years) and collapse prevention level (2475 years). Since PBD may require the explicit assessment of the building behavior at different levels of demand to satisfy the performance levels listed above, a quantitative estimate to describe how the spectral demands vary across the three levels of shaking is obtained using a 'Spectral Demand Level Ratio' (SDLR). This is the ratio between the spectral ordinate of the design spectrum at any hazard level and the spectral ordinate of the UHS at 2% in 50 years across the period range of interest. The results for periods (T) varying from 0 to 2 sec are presented in Fig. 2, the respective UHS is also shown.

The UHS presented in Fig. 2 allows a comparison of the spectral acceleration demands, which are significantly higher in Victoria than in Vancouver for structures having a period of vibration lower than 1.0 sec. In the long period range the spectral acceleration demands for buildings in Victoria and Vancouver are similar. Given the need to better understand this relation of the demands between Vancouver and Victoria, a detailed comparative study was conducted considering the acceleration, velocity and displacement demands for different earthquake mechanisms.

From the SDLR values shown Fig. 2 it is observed that to satisfy the life safety level, a building would experience spectral demands that oscillate between 52% and 56% of the ground motions having a return period of 2475 years. At the fully operational level a building would experience demands between 19% and 22% of the design ground motion with return period of 2475 years; in this case only a slight drop is observed for the demands posed for long period structures in Vancouver, where they represent a 15% of the design ground motion. These SDLR values indicate that the objectives of the fully operational level may not be met if the design forces are reduced by a ductility factor Rd>=5.5 in Vancouver and Rd>=4.5 in Victoria.



(a) (b)

(c) (d)

Figure 2. Design Spectra from Robust model (a) – (b).
Spectral Demand Level Ratio (c) – (d) for Vancouver and Victoria.

Contributions to the Design Spectra

The contribution to the hazard level in the design spectra is investigated here by weighting the annual frequency of exceedance from each earthquake source to the annual frequency of exceedance of the design hazard level. This accounts for the contribution from the crustal and subcrustal seismic sources, and is obtained directly from the ratio of ordinates in the hazard curves.

As indicated before, an estimate of annual frequency was not carried out for the subduction interface earthquake, and for this reason it is excluded here from the contribution calculation. Still a qualitative estimate of the significance of Cascadia subduction interface ground motions can be observed from the hazard curves in Fig. 1.

The spectral demands for different levels of performance are presented again for Vancouver in part (a), (c) and (e) of Fig. 4; the same is presented for Victoria in part (b), (d) and (f) of Fig. 4. Based on the annual frequency of exceedance, contribution to design spectrum from crustal and subcrustal earthquakes is shown. Although the traditional deaggregation for magnitude and distance gives a clear picture of earthquake scenarios, it does not provide a clear picture of the contribution to hazard from each source of earthquake (e.g. crustal or subcrustal).

Part (a) of Fig. 4 shows that for short period structures the seismic hazard is integrated by similar contributions from crustal and subcrustal sources, but for structures of longer period of vibration dominant contribution comes from crustal sources. In part (c) and (e) the hazard for short period structures exhibits almost a complete contribution from subcrustal sources, demands for long period structures have a dominant contribution from the crustal sources. It is noticeable across the different return periods of the ground motion buildings with a period of vibration between 1.0 and 2.0 sec experience demands integrated in a fairly constant proportion by the crustal and subcrustal sources. Buildings with a period of vibration between 0.2 and 0.5 sec experience demands which contribution from the two seismic sources is more sensitive to the hazard level.

The design spectrum for Victoria in part (b), (d) and (f) of Fig. 4 is largely dominated by subcrustal earthquakes for buildings with vibration period below 2.0 sec. Demands for buildings with vibration period of 2.0 sec or longer are dominated by crustal earthquakes. The demands for long period buildings are attributed to crustal and subcrustal in a fairly constant proportion being dominated by crustal earthquakes.

The spectra have a tendency to be integrated by an increasing contribution from crustal sources as the period of vibration of the structure increases in Vancouver and Victoria, at a different rate for each city.

Sensitivity of Acceleration, Displacement and Velocity Spectra

The UHS for different earthquake mechanisms is presented in Fig. 5 for ground motions corresponding to three return periods including vibration periods between 0 and 2.0 sec. The deterministic (mean+1 standard deviation) for a subduction interface earthquake is shown for comparison purposes. The resulting spectra were obtained for each source of earthquake as the hazard envelope of two probabilistic seismic source zone models adopted by GSC, Historical (H) model and Regional (R) model. This envelope is not quite the same as that from the Robust model implemented in the Open File, because Robust model is defined by the highest values from the four models GSC defined H, R, F and C, where H and R include the contribution from crustal and subcrustal.

The spectra of Fig. 5 are scenario oriented and can be used as an alternative approach of seismic resistant design. Considering the hazard by each source of earthquake separately may lead to less conservative estimate of the demands than those estimated using the NBCC 2005. The seismic risk assessment conducted currently under the seismic retrofit program of schools in the province of British Columbia uses these scenario oriented spectra and calculates the risk probabilistically for each source of earthquake individually (Pina et. al., 2010).

In Fig. 5 it can be observed how the subduction earthquake demands in Vancouver are comparable with those demands of the 475 year crustal and subcrustal earthquake. In the short period region it roughly matches the ground motions caused by the crustal earthquake zone. In the long period region it weaves around the ground motions caused by the crustal and subcrustal earthquakes.

For Victoria, the subduction earthquake demands in Fig. 5 are comparable with the ground motions for the 2475 year return period. The spectral demands from subduction are larger than those posed by the crustal earthquake for vibration periods lower than 1 sec, the opposite occurs for long period buildings. The velocity and displacement demands show the same trend.

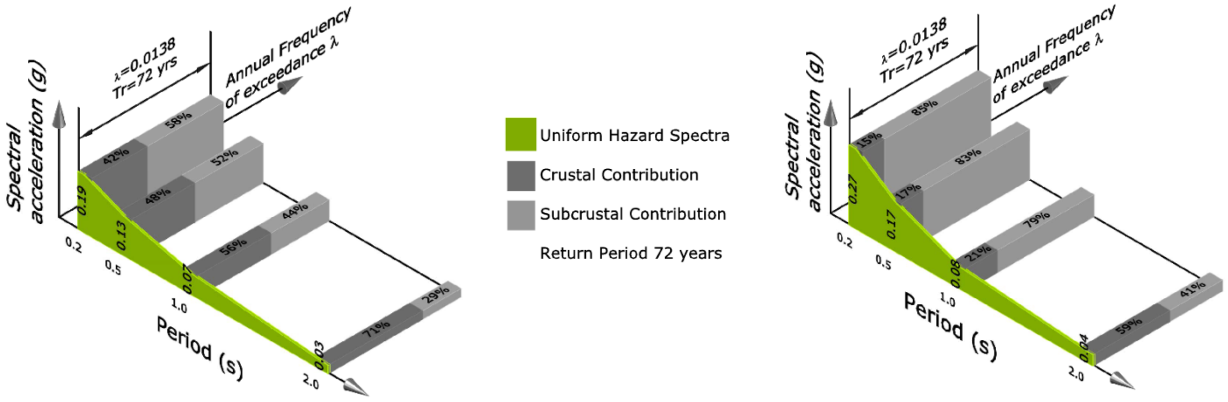
The shape of the spectra for velocity and displacement demands is different for subcrustal earthquakes compared to crustal earthquakes. The subcrustal spectra has a steep dominant rising curve and reaches maximum value at spectral period of 0.5 sec, with a sudden decay in slope through a flat falling curve in the long period range. The demand of subcrustal earthquake requires a building with short period of vibration to be designed for larger demands of acceleration, velocity and displacement than long period buildings.

The spectrum for crustal earthquake has a smooth rising part in the short period range and it flattens in the long period range. The shape of the spectrum for subduction earthquake is quite similar to the subcrustal one but with a smoother transition of demands between raising and falling limbs.

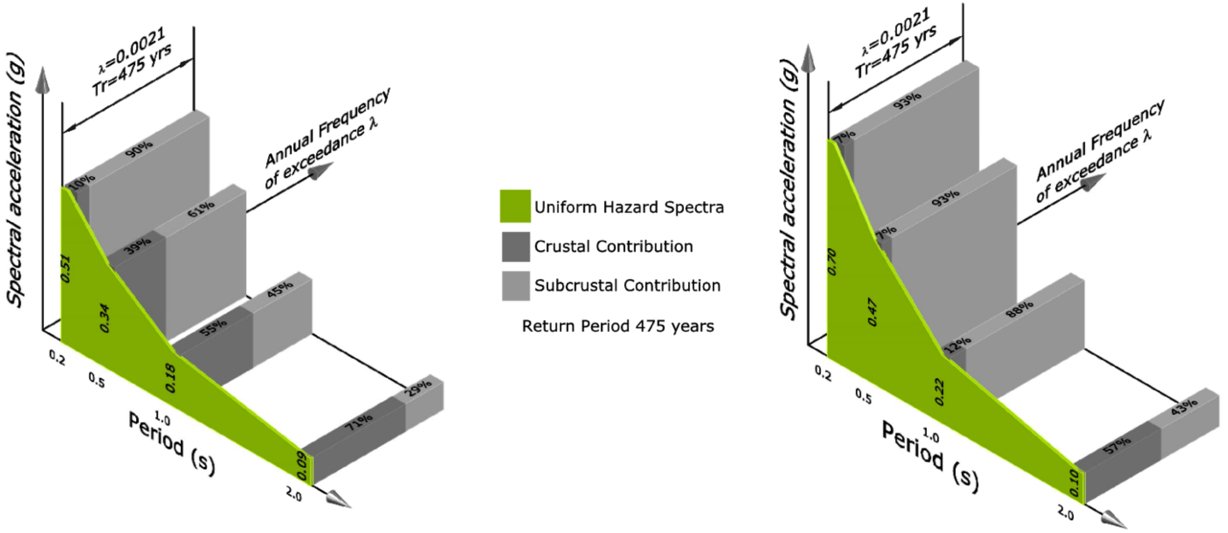
The difference in demands across the crustal and subcrustal earthquake is evaluated quantitatively at the spectral period of 0.5 sec, where subcrustal peak demands occur. In Vancouver the subcrustal demands exceed the crustal demands by a 21%, 45% and 43% for the return periods of 72 years, 475 years and 2475 years, respectively. The same comparison between subcrustal (2475 years) and subduction earthquake yields an exceedance of 133%.

In Victoria the subcrustal demands surpasses the crustal demands in a much significant proportion, where subcrustal exceed crustal demands by 93%, 103% and 87% for the return periods of 72 years, 475 years and 2475 years, respectively. The same comparison between subcrustal (2475 years) and subduction earthquake yields an exceedance of 85%. The subcrustal demands for short period structures in Victoria with a return period of 475 years are very close to the crustal demands with a return period of 2475 years.

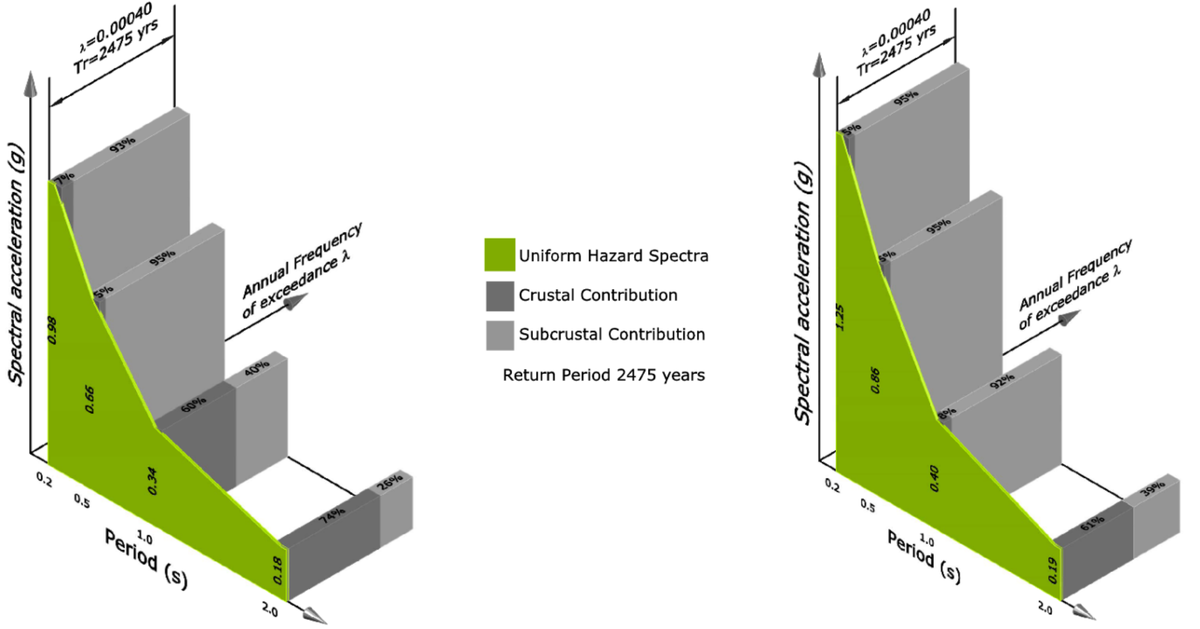
A quantitative comparison of level of demands can also be made between crustal and subcrustal earthquakes for buildings with a period of 2 sec. For spectra in Vancouver the crustal demands are 25% larger than subcrustal demands, and crustal demands (2475 years) are 129% larger than subduction demands. In Victoria the subcrustal demands are 10% larger than crustal demands for the 475 years and 2475 years earthquakes, and subcrustal demands (2475 years) are 35% larger than subduction demands. In Victoria, however the 72 year ground motion is similar for crustal and subcrustal earthquakes in the long period region.



(a) Vancouver (b) Victoria



(c) Vancouver (d) Victoria



(e) Vancouver (f) Victoria

Figure 4. Contributions to uniform hazard spectra.

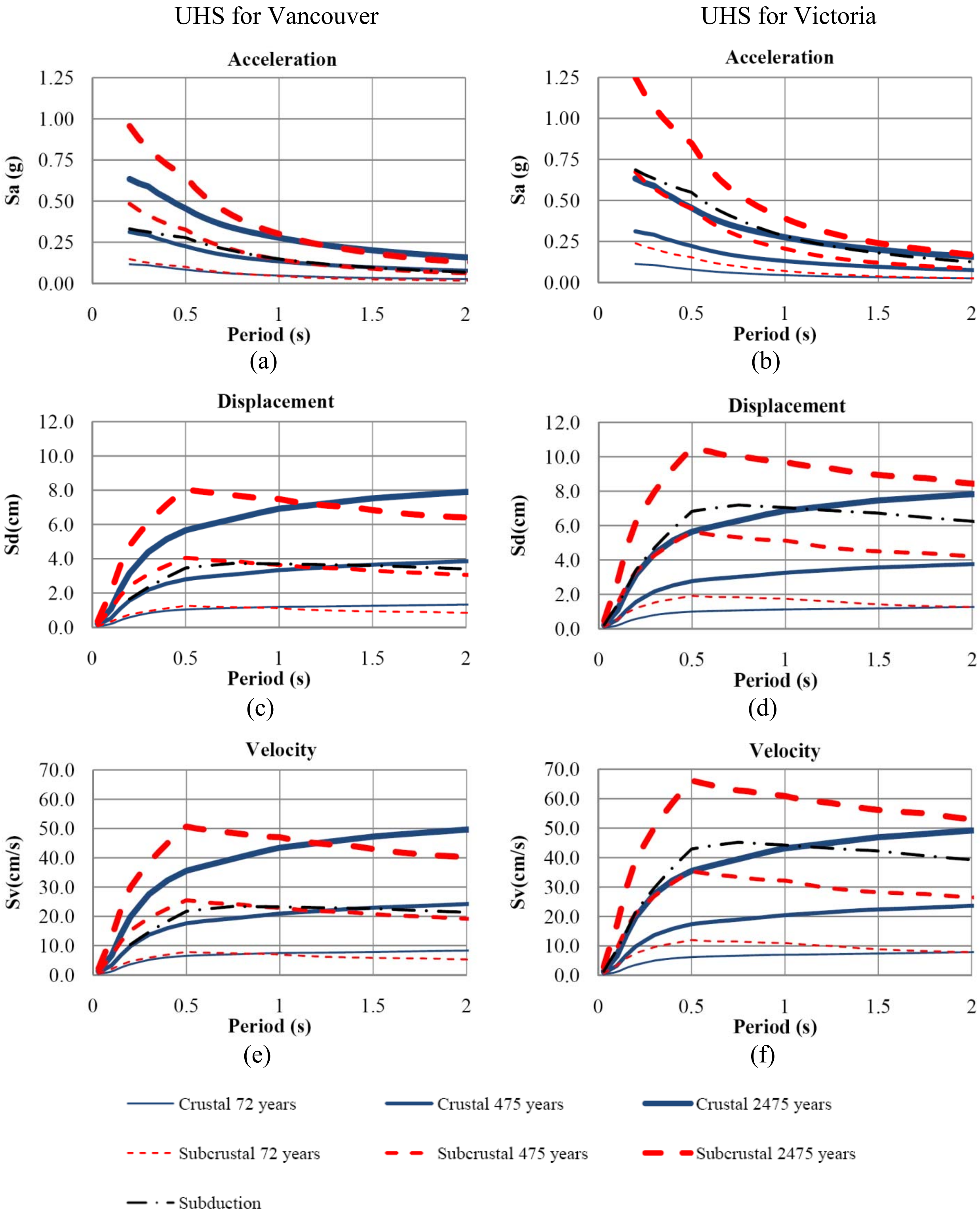


Figure 5. Uniform Hazard Spectra for Vancouver and Victoria: Acceleration Spectra (a) and (b), Velocity Spectra (c) and (d), Displacement Spectra (e) and (f).

Conclusions and Final Remarks

This paper presented a study of the seismic hazard attributed to different sources of earthquakes at several hazard levels for two important cities of British Columbia. The seismic demands given by the NBCC 2005 are attributed mainly to crustal and subcrustal earthquakes. A varying contribution to the hazard from the source of earthquake dependent on the period of vibration is observed. Hazard level for short period buildings is attributed mainly to subcrustal earthquakes and for long period buildings it is governed by crustal earthquakes.

The ground motion at different return periods can be approximately related to the 2% in 50 years demands for Vancouver and Victoria through the 'Spectral Demand Level Ratio'. These values are useful for engineering practice as it is a convenient way to relate demands with different return periods. The study shows how the different earthquake mechanisms in the region affect the acceleration, velocity and displacement spectra.

The GSC and USGS methodology to estimate the Cascadia subduction hazard are different, and the applicability of deterministic approach needs to be further investigated. Because of space limitations the comparison with probabilistic approach is not presented here.

Acknowledgments

The study is part of a project funded by the Ministry of Education of British Columbia for seismic retrofit of school buildings. The Natural Sciences and Engineering Research Council of Canada (NSERC) provided partial financial support for this study.

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