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SELECTION OF GROUND MOTIONS FOR THE SEISMIC RISK ASSESSMENT OF BRITISH COLUMBIA SCHOOL BUILDINGS FOR THE PROPOSED 2015 NBCC GROUND MOTIONS

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ABSTRACT: The province of British Columbia (BC) is located in a region with a unique seismic setting including three potential high risk sources of seismic activity including crustal, subcrustal, and subduction sources. As a part of a major seismic mitigation project towards low- and mid-rise BC school buildings, incremental dynamic analysis is being used to characterize the risk of these buildings to the life safety of their occupants based on their seismic setting. This project: the Seismic Retrofit Guidelines (SRG), is now moving towards its next version, the 3rd edition, to be released in 2017 (SRG3).

With this update, however, also comes an update in the predicted seismic hazard of Western Canada. This update, proposed for the 2015 National Building Code of Canada (NBCC 2015), includes major revisions of the seismic hazard across Canada, with a drastically different assessment of the seismic demand on the West Coast of Canada including Southwestern B.C. and Vancouver Island. This required a necessary revision in the earthquake catalogue for the 3rd edition of the SRG. The new catalogue of ground motions was chosen to represent the three main types of earthquakes that dominate the seismic hazard in B.C. and have been selected from many sources with similar tectonic settings to that of Southwestern B.C. This paper summarizes how these records are selected and scaled and introduces how these selected records are used in the seismic risk assessment methodology of the SRG.

1. Introduction

The province of British Columbia (BC), Canada, is located in a highly seismic region near along the Western Coast of Canada. Its two largest cities, Vancouver and Victoria, are also close to the Cascadia Subduction Zone, which is capable of generating mega-thrust earthquakes of up to magnitude 9 or greater (Goldfinger et al., 2012). As part of a province wide seismic mitigation project, the British Columbia Ministry of Education is evaluating the seismic risk of its public schools. For this evaluation, incremental nonlinear dynamic analysis (INDA) has been adopted to estimate seismic risk (Vamvatsikos and Cornell, 2002).

INDA typically requires a unique set of ground motions selected for a site with specific characteristics such as soil conditions (site class) and mean magnitude and distance (coming from probabilistic seismic hazard analysis). The ground motions will then typically be modified to match a certain target demand, which may come from a code-based uniform hazard spectrum (UHS), a conditional mean spectrum (CMS), or conditional spectrum (CS). This modification may include simple linear scaling and/or modification of the frequency content of the input record to match a range of target spectral ordinates. Matching will be done either at a single period (i.e. fundamental period of the structure of interest) or over a range of periods chosen to represent the period range that defines the response of the structure (including higher mode effects and period lengthening due to damage if modeled nonlinearly). By choosing and matching records based on ground motion parameters (i.e. spectral ordinates) and geophysical parameters (i.e. moment magnitude, distance, site characteristics, etc.) the records should ideally define the most probable structural damage scenario.

This paper summarizes the methodology chosen for selecting and scaling records for the seismic assessment and retrofit of BC school buildings – most of which are low-rise (1-3 stories) and located in a region with seismic hazard coming from multiple earthquake sources. Input motions were chosen for each source (crustal, subcrustal, and subduction) based on spectral shape, geophysical parameters, and diversity. Records were then scaled and selected to match a target CS representative of the earthquake-type hazard for the different localities in BC.

2. Tectonic Setting of South-Western British Columbia

BC has a unique seismic setting that includes hazards from three sources: crustal, which occur along shallow faults in the Earth's crust; subcrustal, which occur deep within tectonic plates; and subduction, which are caused by slip between subducting tectonic plates. Geophysical parameters and structural response can vary substantially between these types of earthquakes. Therefore, the definition of seismic hazards for each type of earthquake is an important for the selection of ground motions in this seismic risk assessment project.

The seismicity in South-Western BC, which is where most of the major population centers in BC are located, is dominated by the subduction of the oceanic Juan de Fuca plate beneath the continental North America plate occurring about 100km west of Southern Vancouver Island (Ristau, 2004) – also called the Cascadia Subduction Zone (See Fig. 1). Large mega-thrust 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). Subcrustal earthquakes can occur deep below the surface in faults along the Juan de Fuca plate. Shallow crustal earthquakes, typically less than 20km deep, have been recorded in the North American plate. Currently, the faulting in the North American and Juan de Fuca plates, which causes these two types of earthquakes, is not known, but there is past evidence the proves either of them may occur.

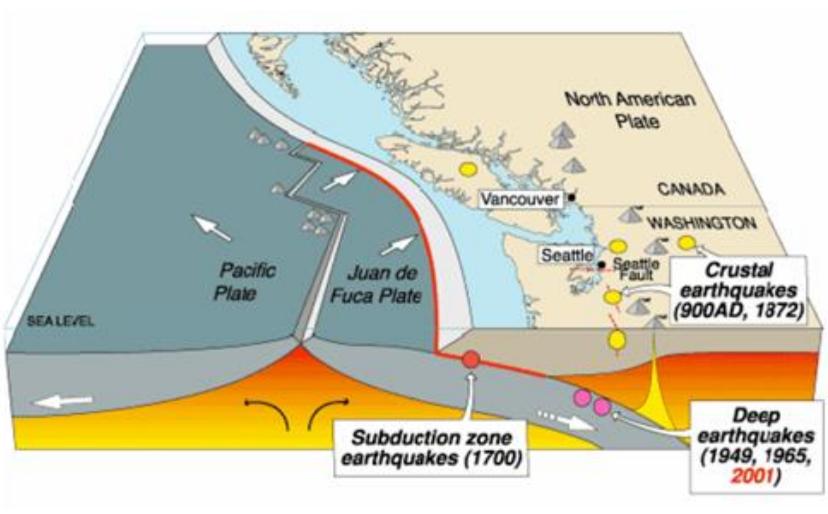
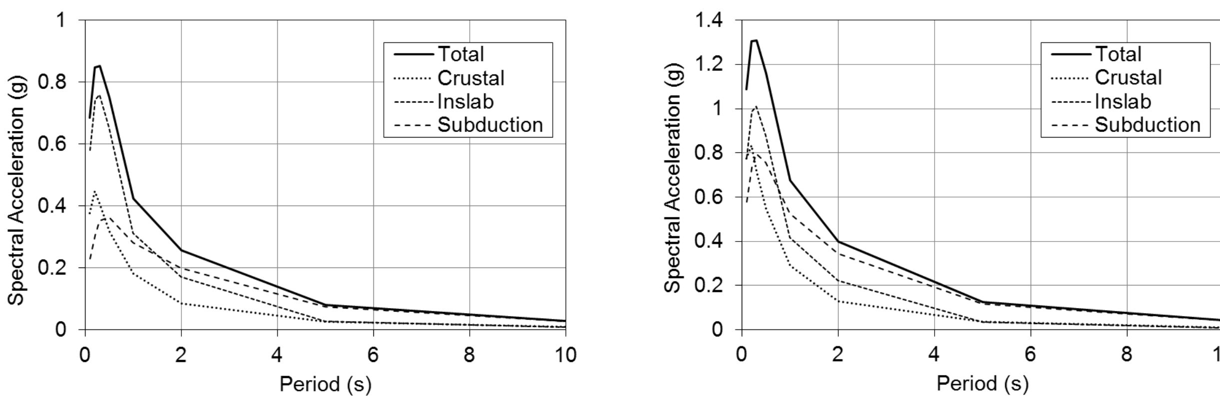


Fig. 1 – South-western BC Earthquake Sources (from the United States Geological Survey)

3. 2015 Seismic Hazard

In early 2014, the Geological Survey of Canada (GSC) released an open file report to the public containing Canada's 5th Generation seismic hazard model that was implemented to develop seismic hazard values proposed for the 2015 National Building Code of Canada (NBCC2015) (Halchuk et al., 2014). The GSC 2015 hazard model had significant changes compared to the previous 2010 model which was used to generate hazard values for the NBCC2010 code. Some of the major revisions to the model include: the Cascadia Subduction zone is now treated probabilistically and included with the rest of the sources – previously it was analyzed deterministically and analyzed separately from the other sources; the maximum expected magnitude of the Cascadia Subduction zone was increased (M8.2 to M9.0); and updated magnitude-reoccurrence and ground motion prediction equations (GMPEs) were implemented (Atkinson and Adams, 2013). The changes have drastic effects on the seismic hazard in BC, including significant increases on BC's South-western coast, which is heavily influenced by the Cascadia Subduction zone and also includes the provinces largest population zones.

The 2015 GSC South-western Canada seismic hazard model was implemented in the EZ-FRISK software (Risk Engineering, 2008), which was used to generate seismic hazard data for each type of earthquake. The crustal, subcrustal, and subduction sources were all treated probabilistically, similar to the approach used by the GSC. The seismic sources, magnitude-reoccurrence relationships, and attenuation relationships were selected based on the GSC report (Halchuk et al., 2014). Spectral accelerations were chosen as the criteria for selection and scaling of ground motions. Fig. 2a and b present the Vancouver and Victoria Site Class C acceleration spectra with a probability of exceedance of 2% in 50 years (2475-year return period), respectively, including the individual spectra for each earthquake source.



(a) **(b)**

Fig. 2 – Site Class C 5% Damped Spectral Accelerations for (a) Vancouver and (b) Victoria for Aggregated Sources (UHS) and for Each Earthquake Type

4. Seismic Hazard by Region

For SRG3 it is proposed to use five seismic hazard regions. These seismic hazard regions would be selected based on their overall hazard level as well as the earthquake source contribution to the total hazard. For example, a Very High region would be assigned to localities on the West Coast of Vancouver Island and Queen Charlotte Island, since these areas have a high total hazard dominated by relatively close, large magnitude (M_w = 8-9) subduction earthquakes. Another region would be the lower mainland, including Vancouver and nearby cities; this area has a moderate seismic hazard with large contributions from crustal and subcrustal sources in the short periods, and large contributions of large but distant subduction sources in the longer period range.

Fig. 3 illustrates the total spectral acceleration and spectral acceleration for each source over BC at a period of 1.0 second. Based on this hazard distribution, it is proposed to divide BC cities into five distinct seismic hazard zones: Very High, High, Moderate I, Moderate II, and Low. Each of these zones is characterized by its overall seismic hazard (as denoted by its name) as well as the source contribution.

Records will be selected for each seismic zone and scaled to each city in the corresponding zone. Table 1 summarizes the source contributions of the five seismic zones.

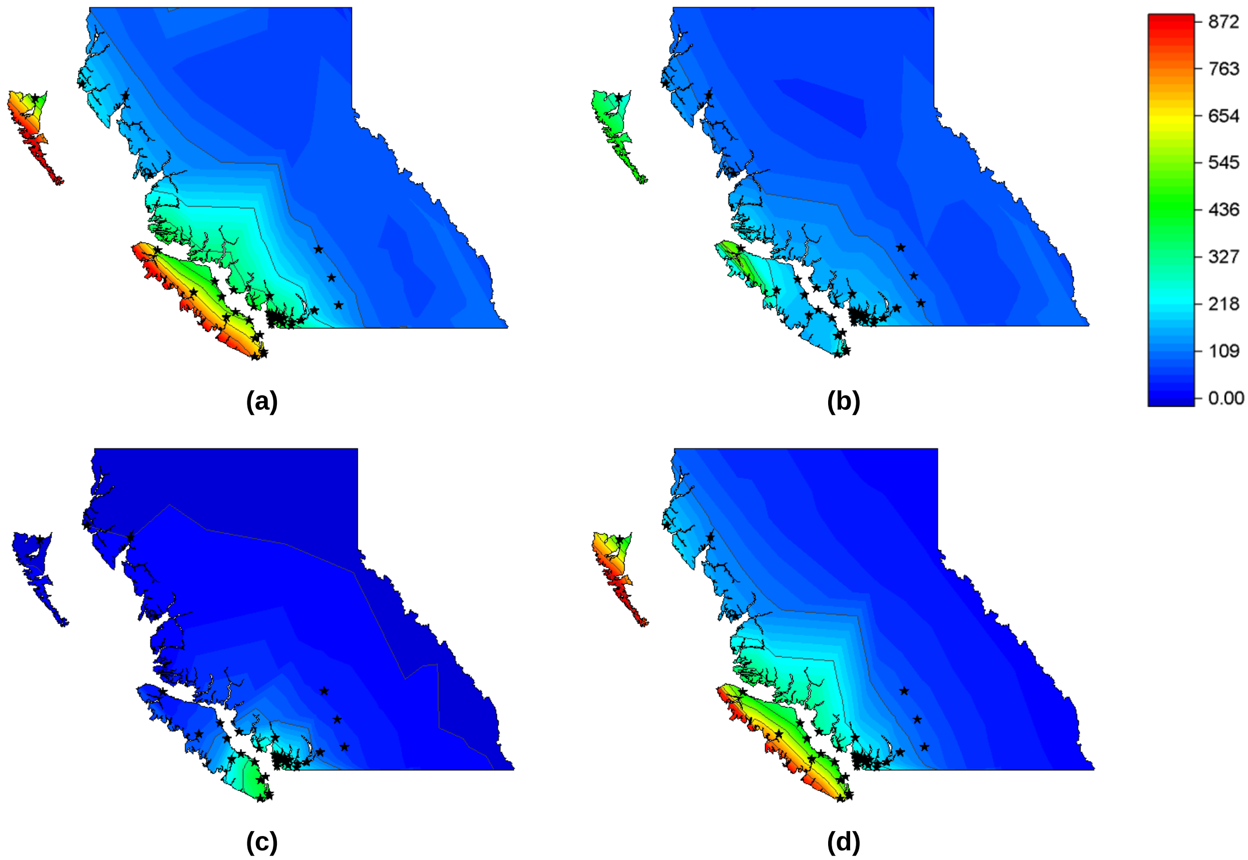


Fig. 3 – Spectral Accelerations Based on GSC 2015 Hazard Model (cm/sec^2) at T = 1.0 (sec) for: (a) Total, (b) Crustal Sources, (c) Subcrustal Sources, and (d) Subduction Sources

Table 1 – Seismic Zone Source Contributions

	Crustal Contribution	Subcrustal Contribution	Subduction Contribution	Location
Very High	Low	Very Low	Very High	Queen Charlotte Island/West Vancouver Island
High	Moderate	High	High	South Vancouver Island
Moderate I	Moderate	High	Moderate	Lower Mainland
Moderate II	Moderate	Very Low	High	North Vancouver Island/Western BC
Low	Very High	Very Low	Very Low	BC Interior

5. Target Hazard: Conditional Spectra

For SRG3, it is proposed to use CS, rather than UHS, as target spectra for selecting and scaling ground motions for BC. Because CS are derived using epsilon correlations from observed ground motions (Baker and Jayram, 2008), their shape better resembles the spectral shape of realistic ground motions compared to a UHS (it is extremely unlikely that a ground motion record produces spectral accelerations with a uniform probability of exceedance at all periods). Due to this, the CS provides a more realistic target spectrum which facilitates easier ground motion selection and scaling, and forgoes some of the conservatisms built into a UHS (NEHRP, 2011). For more information and background about CS development and implementation, the reader is referred to Lin et al. (2013a and b) and NEHRP (2011).

Additionally, because selecting records to match a CS involves matching mean spectral values as well as their variance, proper record-to-record variability is accounted for, which makes it a more probabilistically robust method (NEHRP, 2011), and better suited for the SRG probabilistic methodology.

Matching records to a target CS involves selecting a suite of individually scaled ground motion records with a mean that closely matches the CMS values, while also representing the variance (or standard deviation) about that mean. CMS are "anchored" to (match) a UHS (in this case with a 2% in 50 year probability of exceedance) at a single period, a "conditioning period", but fall below the UHS at other periods based on epsilon correlation coefficients observed in past earthquakes. The required variance about that mean is computed using the standard deviations associated with the ground motion prediction equations (GMPEs) that were used to derive the conditional mean spectrum (Baker and Cornell, 2006).

Because most of BC has seismic hazard contributions from three earthquake sources (crustal, subcrustal, and subduction), CMS for each source are derived separately, as illustrated in Fig. 4. All CMS are developed using the epsilon correlation coefficients developed by Baker and Jayram (2008).

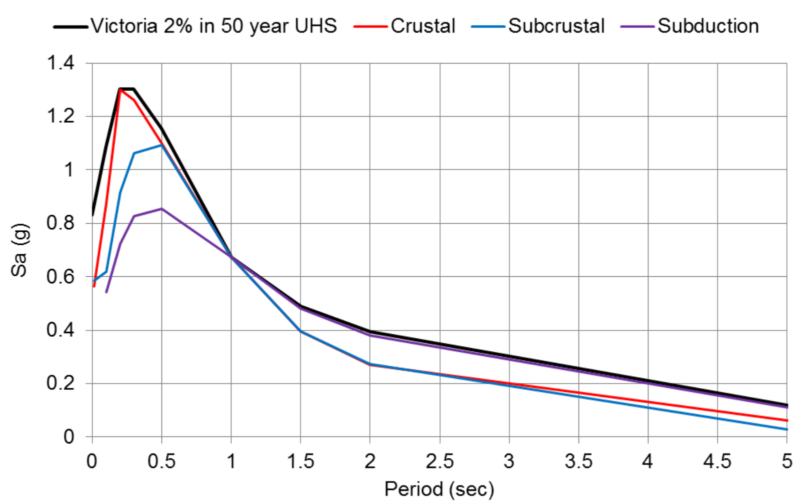


Fig. 4 – Victoria 2% in 50 Year UHS and CMS for Crustal, Subcrustal, and Subduction Sources Conditioned at 1.0 second

It should be noted that the epsilon correlation coefficients developed by Baker and Jayram (2008) were based on a database of shallow crustal earthquakes – subcrustal and subduction events were not included. However, a study conducted by Jayram et al. (2011) showed that these correlations do work well for Japanese recorded crustal and subduction motions. However, the largest earthquake in the dataset considered in this study was the 2003 M_w = 8.0 Tokachi-oki subduction earthquake. The preliminary results of another study indicates that these correlations may also be suitable for larger Japanese subduction earthquakes, including the 2011 Mw = 9.0 Tohoku earthquake (Bebamzadeh et al. 2015). Based on these results it is deemed reasonable to extend the use of the Baker and Jayram (2008) epsilon correlation coefficients to subcrustal and large (M_w > 8.0) subduction events.

CS are developed for conditioning period of 0.5 seconds and 1.0 seconds. The 0.5 second CS will be used to analyze stiffer prototypes (i.e. concrete shearwall), while the 1.0 second CS will be used for more flexible prototypes (i.e. woodframe structures).

6. Record Database

For this project, an extensive database of crustal, subcrustal, and subduction earthquake recordings was developed. The database includes records from events that have occurred in a tectonic setting similar to that of BC, mainly at the interface of subducting plates, in subducting plates, and in the overlaying crust. These types of settings are found in Japan, the North Pacific of the United States, the West coasts of Central and South America, and Southern Europe. Many of the crustal events were from recordings in the United States, specifically, California.

The majority of crustal records were downloaded from the PEER-NGA database (Chiou et al., 2008). These records were already filtered and baseline corrected, and thus, required no further processing. Japanese earthquakes, which made up a large part of the subcrustal and subduction records, were downloaded from K-NET (Kinoshita 1998) and KiK-net (Aoi et al. 2000). These recording were uncorrected, and thus, were baseline corrected with a linear function and filtered with a 4-th order band-pass Butterworth filter with cut-off frequencies of 0.10 and 25 Hz (cut-off periods of 10s and 0.04s). Other subcrustal and subduction records were retrieved from the COSMOS database (Archuleta et al. 2006). These records came from a variety of sources, and some of them required additional filtering and baseline correction. Where it was required, these records were processed in a similar fashion as the Japanese records.

7. Selection Criteria

The selection of viable records from the database was constrained by a range of magnitudes and distances to the source. Ranges were determined from the results of deaggregated probabilistic seismic hazard analysis using the EZ-FRISK implementation. The ranges were selected from the sources that had the largest contribution to the spectral accelerations with a 2% in 50 year probability of exceedance at a period of 1.0 second. Since the fault types and locations in BC are not well known, no restrictions were put on the type of faulting and direction of the records. As an example, Table 2 summarizes the selection criteria for each source for the Southern Vancouver Island hazard zone.

Table 2 – Example Distance and Magnitude Ranges for Selection of Records for Southern Vancouver Island

	Subduction	**Subcrustal**	**Crustal**
Hypocentral Distance (km)	-	50-150	0-80
Closest Distance to Rupture (km)	50-150	-	-
Moment Magnitude (Mw)	8+	6-7.5	5.5-7.5

8. Selection of Records

Once a target CS has been developed and appropriate record selection criteria have been defined, a suite of records can be selected from the database to best match the mean and variance of the CS. Ten records are selected and scaled for each source (crustal, subcrustal, and subduction). The records are individually scaled to match the target spectrum at the conditioning period using a linear scaling factor applied at all periods. To avoid excessive scaling, these linear scale factors are limited from 0.25 to 4.0 for all cases. If no suitable records can be found these constraints will be incrementally extended until a proper suite of records is found.

Fig. 5 illustrates 10 example records selected for Southern Vancouver Island for a CS conditioned at 1.0 second. The majority of the records were from Japanese sources (Tohoku 2011, M_w = 9.0 and Hokkaido

2008, M_w = 8.0), with others from Michoacán, Mexico, 1985 (M_w = 8.1) and El Maule, Chile, 2010 (M_w = 8.8).

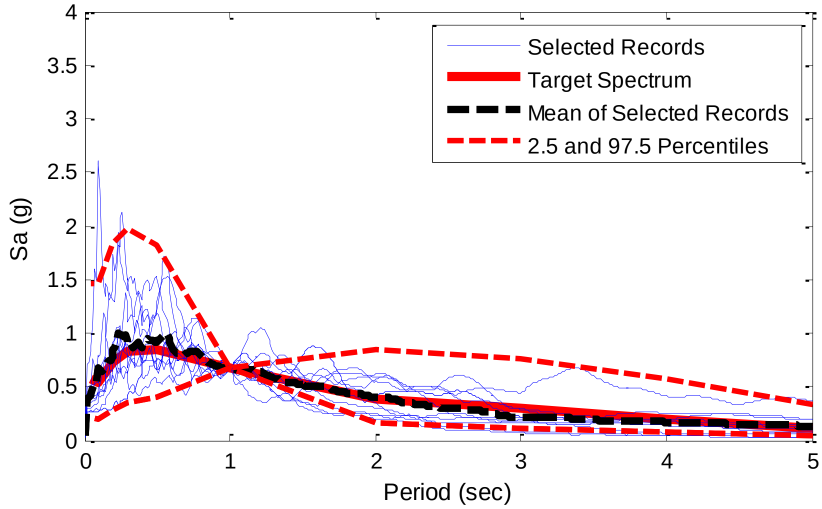


Fig. 5 – Selected Subduction Records for Southern Vancouver Island for a 1.0 second Conditioning Period

9. Demand Examples

The SRG3 methodology employs incremental nonlinear dynamic analysis (INDA) to assess the performance of different buildings types. Deformations of the nonlinear models (namely, interstory drift) are used to predict damage and define performance. Thus, it was necessary to see how the use of CS would affect the performance, and ultimately, the required resistance (R_m) for an example building prototype, compared to UHS or even CMS scaled ground motions.

As an example, 4.5m concrete flexural shearwall prototype was considered. This prototype was analyzed for Victoria, Site Class C, for suites of motions scaled to seven different spectra: UHS; CMS conditioned at 0.5, 1.0, and 1.5 seconds; and CS conditioned at 0.5, 1.0, and 1.5 seconds. The difference between the CMS and CS selected motions is that CMS only considers the mean spectrum, while CS accounts for mean and variance. A period range of 0.2-2.0 seconds was selected for matching the mean of the records to the UHS and CMS and for matching the mean and variance for the CS.

The results are illustrated in Fig. 6. This figure plots the resistance, expressed as a percentage of the total weight (W) of the structure, required to achieve a 2% in 50 year probability of drift exceedance, for different drift levels. The results show the CMS and CS scaled motions provide require lower R_m values at all drift levels. However, the CS selected motions, because they also express the required variance, require slightly large R_m values compared to the CMS selected motions for all conditioning periods considered.

Because this is a stiff concrete shearwall prototype, the CS and CMS conditioned at 0.5 seconds have the largest demands and will govern the required R_m factors. At a life safety drift limit of 1.0% drift (this is the drift level where the prototype starts to lose resistance) the UHS requires an R_m of 29.5%W to limit the probability of drift exceedance to 2% in 50 years. The 1.0 second conditioned CS drops this value about 10% to 27.1%W.

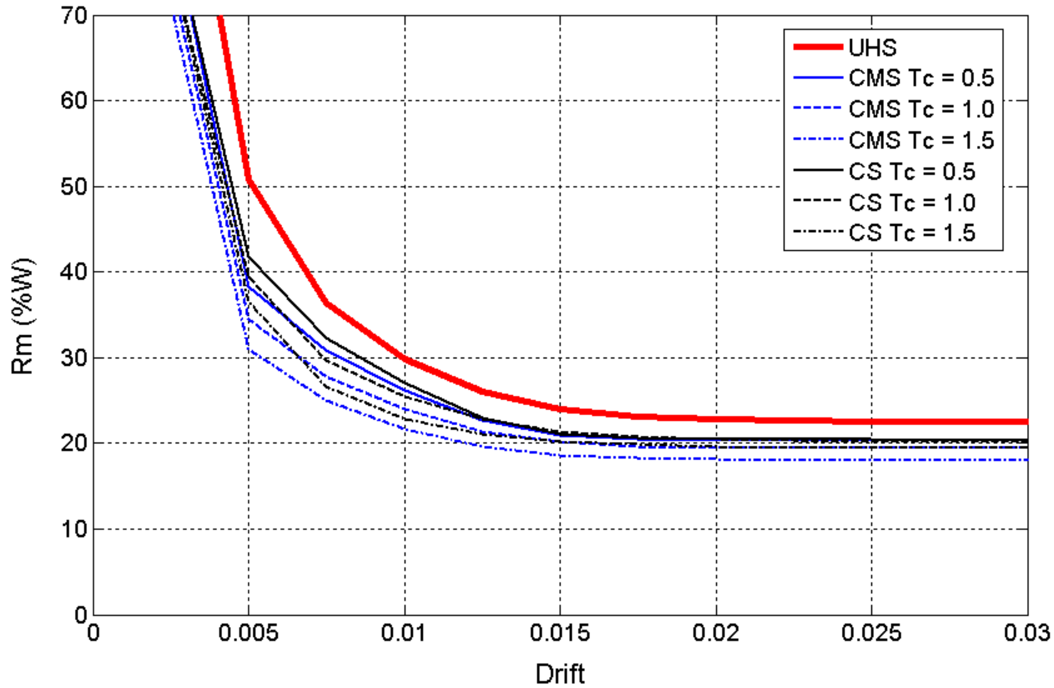


Fig. 6 – R_m vs. Drift Results for a 4.5m Concrete Flexural Shearwall Prototype with Ground Motions Scaled to UHS, CS, and CMS Conditioned at 0.5, 1.0, and 1.5 seconds for Victoria, Site Class C.

In order to determine the sensitivity of the choice of conditioning period (T_c), 10 different SRG prototypes were ran with motions scaled to a CS conditioned at 0.2, 0.5, and 1.0 seconds. The prototypes comprised blocked OSB/plywood shearwalls (W-1), steel frames (S-1: moderately ductile concentrically braced frame; S-5: limited ductility concentrically braced frame; S-7: eccentrically braced frame; and S-8: moderately ductile moment resisting frame), ductile reinforced concrete moments frames (C-1), concrete shearwalls (C-4 for squat walls and C-6 for moderately ductile flexural walls), reinforced masonry walls (M-3), and rocking elements (R-2: for modeling the rocking of stiff walls with medium aspect ratios).

Table 3 –R_m Values for Different SRG Prototypes for UHS, and CS conditioned at 0.2, 0.5, and 1.0 seconds Required for PDE=2% in 50 year at the DDL and CPDE<25% for Victoria, Site Class C.

	UHS		T_c = 0.2 sec		T_c = 0.5 sec		T_c = 1.0 sec	
Prototype/Height (mm)	**3000**	**4500**	**3000**	**4500**	**3000**	**4500**	**3000**	**4500**
W-1	27.8	-	25.4	-	24.6	-	25.5	-
S-1	51.2	-	36.6	-	47.0	-	42.0	-
S-5	37.0	-	29.3	-	35.0	-	32.3	-
S-7	36.7	-	26.1	-	30.7	-	29.5	-
S-8	48.5	-	33.9	-	39.2	-	37.7	-
C-1	19.3	-	16.5	-	18.7	-	17.8	-
C-4	36.0	-	27.5	-	29.7	-	30.1	-
C-6	-	29.5	-	25.5	-	27.1	-	25.4
M-3	42.4	-	31.6	-	32.6	-	33.5	-
R-2	25.9	-	18.5	-	23.8	-	27.4	-

All R_m values in Table 2 were determined to limit the probability of drift exceedance (PDE) at the design drift level (DDL) to 2% in 50 years considering all possible earthquake sources and shaking levels, and to limit the conditional probability of drift exceedance (CPDE) to 25% at a design level earthquake (2% in 50 years), according to the SRG2 methodology. The more flexible prototypes, i.e. W-1 and R-2 tended to be governed by the 1.0 second CS matched motions, while the other, stiffer prototypes were governed by the 0.5 second CS matched motions.

10. Conclusion

This paper introduced a methodology for the selection and scaling of ground motion time-history records for use in INDA to assess the risk of BC school buildings. BC has a complex seismic background with hazard contributions coming from crustal, subcrustal, and subduction sources – thus, records need to be selected for each source from regions with similar seismic settings. BC will be divided into five seismic hazard zones based on the total seismic hazard as well from source contribution. Records will be selected for each seismic hazard zone to match ground motion parameters (i.e. spectral ordinates) and geophysical parameters (i.e. moment magnitude, distance, site characteristics, etc.) in order define the most probable structural damage scenario.

Conditional spectra are proposed for targets for ground motion selection and scaling. Since CS are developed to have representative spectral shapes compared to recordings from historic earthquakes, the use of CS facilitates easier ground motion selection and is less conservative compared to a UHS. Since variance is properly accounted for, the use of CS is a more probabilistically valid method opposed to scaling to a UHS.

This paper also presented an example of record selection and scaling for Southern Vancouver Island (Victoria) and showed how it affected the INDA results for a flexural concrete shearwall. In this example, records scaled to a CS showed moderately lower demand requirements compared to UHS-selected motions due to the conservatism built into a UHS. The sensitivity of the conditioning period for a range of SRG prototypes was also investigated. It was found that stiffer prototypes (i.e. concrete shearwalls) tended to be governed by CS conditioned at 0.5 seconds, while more flexible prototypes (i.e. wood shearwalls, rocking elements) were governed by CS conditioned at 1.0 second. This is important to note because it will save a significant amount of analysis time by only having to run each prototype for its governing record set.

11. Acknowledgements

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