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Performance-Based Seismic Retrofit of School Buildings in British Columbia, Canada – 2020 Edition

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ABSTRACT

The province of British Columbia (BC) possesses a unique seismic setting, with three potential high-risk sources of seismic activity: shallow crustal, deep subduction in-slab, and subduction interface earthquake events. Approximately 750 BC schools are situated in regions with a high seismic hazard, necessitating proactive measures to address their seismic vulnerability. In response, the BC Ministry of Education (EDUC) has allocated over $1.9B since 2004 to evaluate and quantify the seismic risk associated with the province's at-risk school buildings. A dedicated seismic mitigation program, in collaboration with Engineers and Geoscientists British Columbia (EGBC) and the University of British Columbia (UBC), has been initiated to expedite the seismic upgrading of the most vulnerable schools. The partnership between EDUC, EGBC, and UBC aims to develop and implement a comprehensive seismic upgrade program that prioritizes the safety and cost-effectiveness of BC schools. Central to this effort is the development of seismic assessment tools and guidelines for performance-based seismic evaluation and retrofit. These guidelines, known as the Seismic Retrofit Guidelines (SRG), are continuously evolving and are currently progressing towards their 4th edition, SRG2020, scheduled for publication in September 2023. The SRG2020 edition will further enhance the seismic assessment and retrofit practices for BC schools, ensuring the continuous improvement of safety standards.

This paper presents the performance-based methodology developed for the assessment and retrofitting of school buildings in British Columbia (BC) and provides an overview of the province-wide retrofit program's current status. The upcoming 4th edition of the Seismic Retrofit Guidelines (SRG2020) introduces significant methodology enhancements. Notably, the seismic hazard has been revised to align with the seismic hazard for the 2020 National Building Code of Canada (NBCC 2020), which incorporates substantial revisions to seismic demand along the West Coast of Canada. Site classification will no longer be used in NBCC 2020. Instead, 30m time-averaged shear wave velocity (V_{s30}) values are now input directly into the Ground Motion Models (GMMs) used in the probabilistic seismic hazard analysis (PSHA) to derive the hazard values for different site conditions. This paper explains how these changes were incorporated into the SRG performance-based methodology. Comparisons with SRG3 (which used NBCC 2015 hazard values) are also presented for major BC localities for several construction types.

Several new building prototype models will be added to the SRG2020 catalogue, and many existing prototype models will be improved based on recent testing program results. These tests provide novel data on the effect of long duration subduction interface motions, particularly on wood-frame construction. The updated guidelines will continue to provide safe and cost and time efficient retrofit solutions for BC's at-risk school buildings.

Keywords: seismic risk assessment, schools seismic retrofit, performance-based design; long duration earthquakes.

INTRODUCTION

British Columbia (BC), located on the West Coast of Canada, is a region known for its high seismic hazard. In 2004, the BC Ministry of Education introduced the Seismic Mitigation Program (SMP) to prioritize the safety of public elementary and secondary schools. To date, the Ministry of Education has spent more than $1.9 billion to successfully carry out seismic retrofit projects targeting high-risk school buildings across the province. In its ongoing commitment to safety, the Ministry has allocated an additional $1,098 million in its three-year capital plan for further high-risk seismic projects.

The BC Ministry of Education oversees approximately 1600 provincial public schools, of which approximately 750 are located in regions with a high seismic hazard. Among these schools, 497 have been classified as high-risk and are included in the seismic mitigation program (SMP). As of April 2023, 43% of these schools have successfully completed seismic mitigation, while 3% are currently under construction, and 1% have entered the construction phase. For the remaining high-risk schools, the business case for 4% is being developed, and the rest are categorized as future priorities (Figure 1).

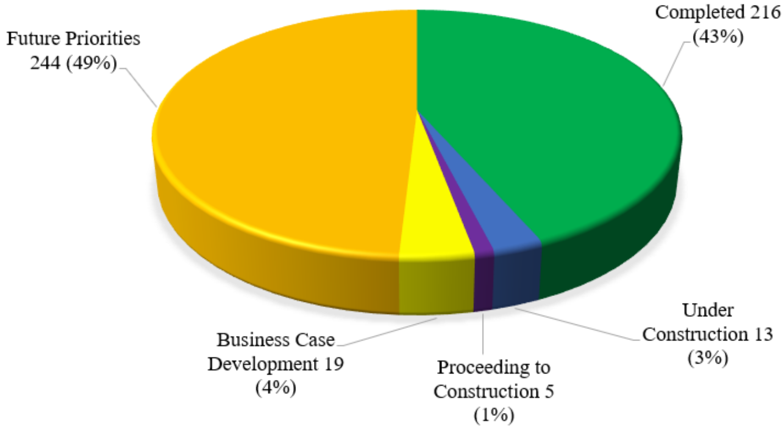

Figure 1. SMP Status of BC School Buildings – April 2023.

SEISMIC RETROFIT GUIDELINES

As part of SMP program, a set of novel performance-based technical guidelines have been developed for structural engineers to assess seismic risk and to design retrofit solutions for school buildings. UBC, under a contract with EGBC, has led the development of the performance-based Seismic Retrofit Guidelines (SRG) through an extensive applied research program.

To ensure the quality and reliability of the guidelines, each draft has undergone rigorous peer review. A BC peer review committee, consisting of experienced local consulting engineers, as well as an external peer review committee composed of prominent California consulting engineers and researchers, have provided valuable input and feedback. This collaborative approach has led to the evolution of the guidelines over time, incorporating enhancements and improvements with each edition.

The continuous refinement of the guidelines reflects the commitment to delivering state-of-the-art guidance for seismic risk assessment and retrofit design. The following overview presents a summary of the guidelines, highlighting their development and key features.

- 2006, the interim Bridging Guidelines for the Performance-based Seismic Retrofit of BC Schools were created to provide consistent and rational retrofit methodologies for Engineers and Geoscientists BC members who were undertaking work on the seismic assessment and retrofit of BC schools.
- May 2011, The Seismic Retrofit Guidelines, 1st Edition (SRG1), replaced the Bridging Guidelines [1].
- November 2013, The Seismic Retrofit Guidelines, 2nd (SRG2) Edition, were introduced. SRG2 applied the same performance-based methodology used in the previous editions, but also included enhanced information on seismicity by community and common school construction types, prioritizing structural elements that are at greatest risk, as well as a complementary web-based tool (*Seismic Performance Analyzer*) which allows practitioners to instantly generate seismic resistance criteria for specific types of construction [2].
- June 2017, SRG3 comprised 11 volumes and considered the effects of adjusted ground motions developed for the National Building Code of Canada 2015 (NBCC 2015) [3] and additional prototypes. In addition, enhancements to the *Seismic Performance Analyzer* web-based tool were incorporated into the *Seismic Performance Analyzer 1* version 3.0 [4].

These updates aim to equip engineers with the most current and effective tools for seismic risk assessment and retrofit design. By embracing a commitment to ongoing improvement, the guidelines remain at the forefront of seismic retrofit practices. They allow engineers to effectively enhance the safety and resilience of school buildings in British Columbia, reflecting the latest advancements in the field.

The SRG guidelines are currently undergoing revisions for their 4th edition (SRG2020), scheduled for publication in September 2023. This paper focuses on the revisions made in SRG2020 to accommodate the changes in seismic hazard outlined in the 2020 National Building Code of Canada (NBCC) [5]. Furthermore, the enhancements in the SRG2020 *Seismic Performance Analyzer* and updates to the building prototype catalogue are also discussed.

SRG METHODOLOGY

The SRG introduced a unique approach compared to current practice regarding the utilization of capacity (C) and demand (D) values in the seismic engineering process [6]. Unlike the traditional prescriptive C/D ratio approach, the SRG employs a probabilistic risk assessment for individual block elements. This assessment determines the probability that the element's peak drift, which indicates damage, will exceed the allowable drift limit over a specified time period (e.g., 50 years). This methodology deviates from the code-based approach commonly used in current practice for seismic retrofitting of low-rise buildings: instead of relying on force or base shear force, the methodology focuses on quantifying building performance through inelastic deformation.

The SRG methodology encompasses two essential steps in the retrofit process: Risk Assessment and Retrofit Design. The Risk Assessment helps determine whether a building meets the desired performance objective, while the Retrofit Design aims to identify the most cost-effective retrofit solution to achieve the performance objective. The key elements of the nonlinear performance-based methodology implemented in the SRG include:

- Building performance is quantified using inelastic deformations instead of forces.
- Probabilistic analysis is conducted to estimate the likelihood of surpassing selected maximum deformation levels for each building system, considering different earthquake sources (crustal, in-slab, and subduction interface) as well as factors such as distance from potential earthquakes and local soil conditions.
- Nonlinear characteristics are developed for the predominant structural systems found in the province, along with new construction systems suitable for retrofitting purposes.

UPDATES TO NBCC 2020 HAZARD

Southwestern BC features a unique seismic setting encompassing hazards from three distinct sources: crustal earthquakes, occurring along shallow faults in the Earth's crust; in-slab earthquakes, deep within subducting tectonic plates; and subduction interface earthquakes, resulting from slip between subducting tectonic plates. The geophysical parameters and structural response exhibit significant variations among these earthquake types. Therefore, it is necessary to define the seismic hazard associated with each type of earthquake. This definition plays a vital role in the selection of suitable ground motions for conducting nonlinear dynamic analysis, which in turn facilitate accurate calculation of probabilities of damage exceedance during the SRG seismic risk assessment and retrofitting processes.

The seismic hazard data employed in SRG is derived from Canada's 6^{th} generation seismic hazard model (SHM6) [5]. It is important to note that the seismic hazard models utilized for generating the seismic hazard data in SRG2020 were based on the SHM6 trial version using Open File 8629 [7], whereas the hazard models employed for NBCC 2020 are based on the final version of SHM6 using Open File 8630 [8]. A comparative analysis between SHM6 trial and final versions reveals that there is only a difference of less than 5% in hazard values across British Columbia and different soil types. The SHM6 utilized in NBCC 2020 and SRG2020 incorporates significant modifications in comparison to the previous Canada's 5^{th} generation of seismic hazard model (SHM5) used in NBCC 2015 and SRG3:

- The Cascadia catalogue was expanded with the inclusion of four additional earthquakes, resulting in a reduced return period from approximately 1/500 to approximately 1/420 [5].
- Ground motion models (GMMs) and have been updated [9] to align with the latest findings in the scientific literature.
- Several new discrete faults have been incorporated, including the Leech River Valley fault near Victoria [10].
- The in-slab source zone beneath the Strait of Georgia has been redefined [5].
- The hazard assessment for different site classes now relies on direct input of the top 30m shear wave velocity (V_{s30}) values into the GMMs [9]. Consequently, soil amplification factors are no longer employed in NBCC 2020, marking a departure from their usage in NBCC 2015.

As a consequence of these modifications, there has been a slight increase in Sa(T=0.5 s) and Sa(T=1.0 s) in the Lower Mainland, estimated at approximately 5-10% (Figure 2a). Most Vancouver Island localities experienced a moderate increase of around 10-20%. Near Victoria (Figure 2b) and the West Coast of Vancouver Island, a significant change has been observed, with an increase of approximately 20-30% for V_{s30} = 450m/s. Considering these changes, a comprehensive review of the current SRG methodology and database was conducted, as elaborated in the subsequent sections.

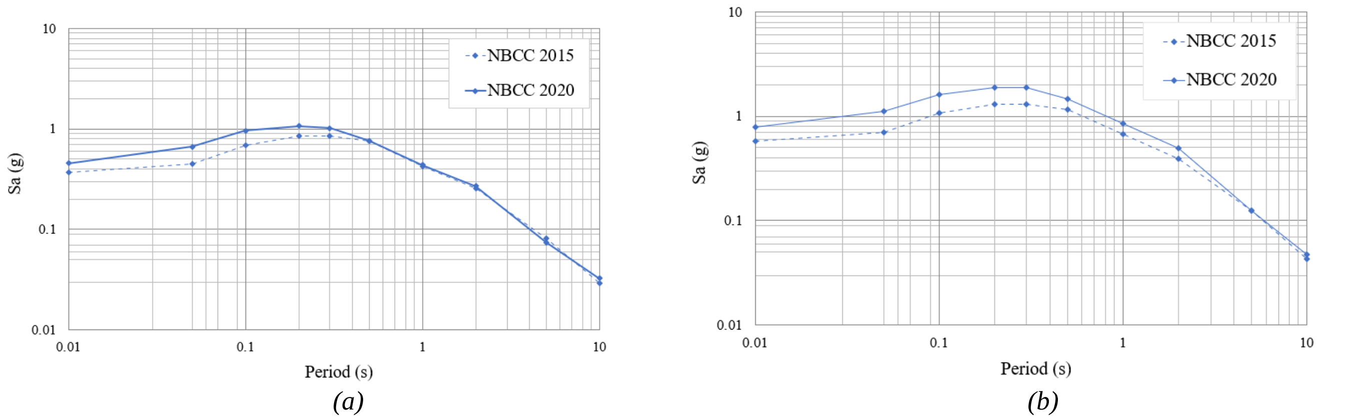

Figure 2. Comparison of NBCC 2020 and NBCC 2015 design UHS in (a) Vancouver and (b) Victoria using V_{s30} = 450m/s.

UPDATES TO SRG 2020 DATABASE

Within SRG3, an extensive database was constructed encompassing 33 lateral drift resisting systems (LDRS), 6 diaphragm systems, and 4 out-of-plane (OP) rocking systems. This comprehensive database was constructed to include damage fragility functions derived from Incremental Dynamic Analysis (IDA) results using properly scaled ground motions. In light of the seismic hazard variations across BC, two hazard levels were taken into account: "High" and "Moderate". For each hazard level, a representative locality was carefully chosen to reflect the hazard associated with each seismic source (crustal, in-slab, and interface). For each of the two hazard levels and three seismic sources, two sets of 20 conditional spectra (CS) scaled motions were developed, considering two conditioning periods (T_c) of 0.5 and 1.0 s [11]. The IDA was performed using the 20 CS motions at various levels of shaking, spanning from 10% to 250% of the 2% in 50-year shaking level.

To obtain fragility curves for the remaining localities, the IDA results from one of the selected representative localities were scaled to match the hazard level at the selected locality. These scaled results were then combined with the hazard curves for the selected locality to generate drift exceedance values. These values were subsequently used to define the required resistance (R_m) values for the given localities. The existing SRG3 database was utilized to generate SRG2020 values through the same procedure. The step-by-step procedure to generate SRG2020 values using the existing database is outlined as follows:

1) Execute the 2020 seismic hazard model for each SRG locality and record the Sa(0.5) and Sa(1.0) values, along with the corresponding hazard values for each period (0.5 and 1.0 s) and seismic source (Figure 3a).
2) Determine the hazard level (Moderate or High) based on the seismic source and the Sa(T) value obtained for that source.
3) Access the SRG3 IDA results specific to the representative source and hazard level (Figure 3b).
4) Scale the SRG3 IDA results (fragility curves) according to the 2020 Sa(T) value in comparison to the Sa(T) value of the representative locality from 2015 (Figure 3c).
5) Integrate and combine the scaled IDA results with the 2020 hazard values for each seismic source to obtain the drift exceedance rates corresponding to each source.

$$\lambda_i(d > D) = \int CPDE(d > D|_{Sa}) \bullet d\lambda_{Sa} \tag{1}$$

where $\lambda_i(d > D)$ is the rate of drift exceedance of a specified drift limit: D, and each seismic source: i; $CPDE(d > D|_{Sa})$ is the conditional probability that the drift exceeds D at a particular level of shaking (the fragility curve); and $d\lambda_{Sa}$ is the annual frequency of ground motions with intensity Sa (the hazard curve).

6) Calculate the Probability of Drift Exceedance (PDE) values for all seismic sources combined using a temporal Poisson probability model with a time period (T) of 50 years and index (i) ranging from 1 to 3 for each seismic source including crustal, in-slab, and interface (Figure 3d):

$$PDE(d > D) = 1 - \exp(-T \bullet \sum \lambda_i) \tag{2}$$

7) This process is carried out for each conditioning period, resistance value, and specified drift limit, D.
8) The required resistance (R_m) is then selected to limit the PDE to 2% in 50 years for the governing period (0.5 or 1.0 s motions).

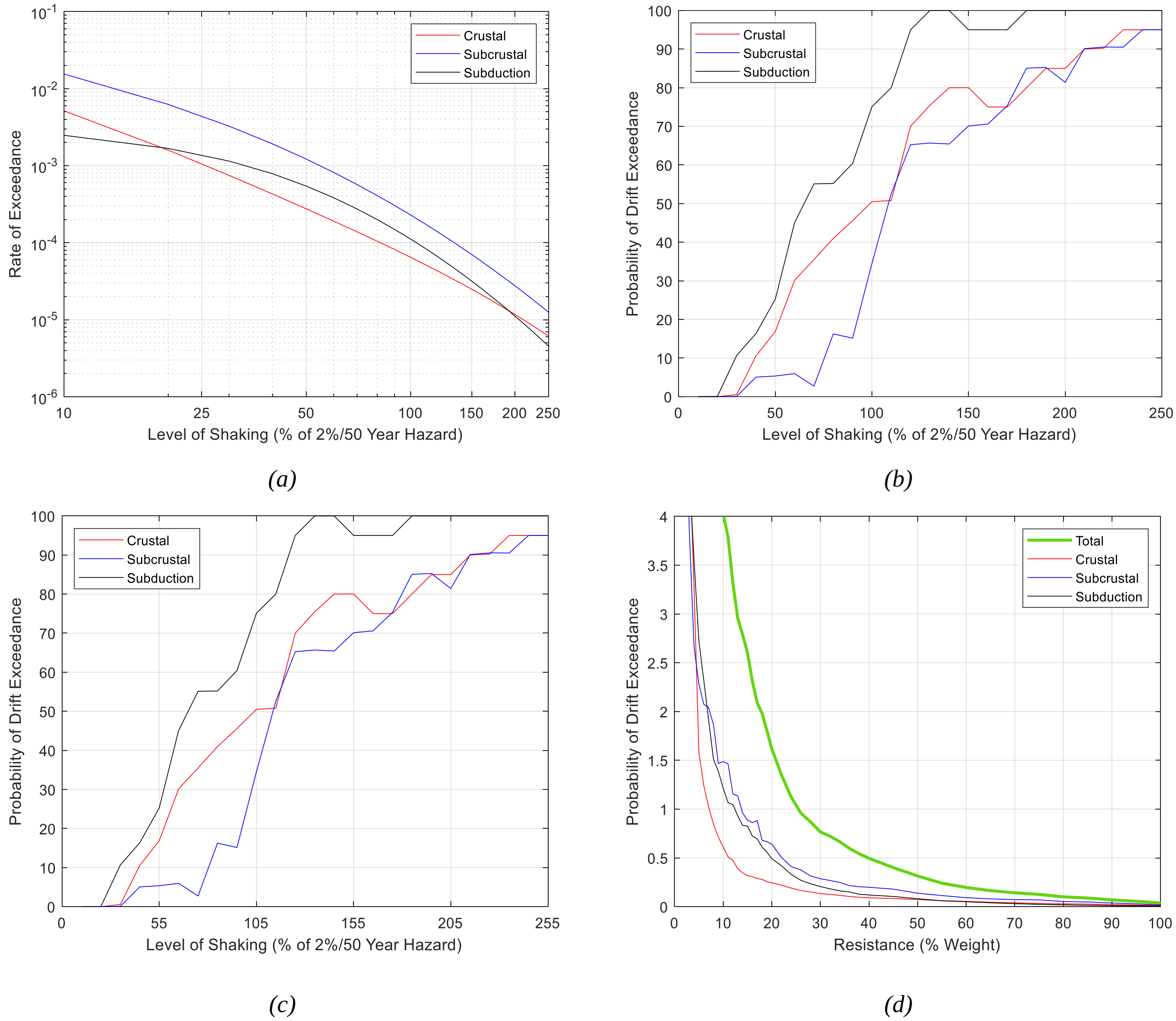

Figure 3. Procedure to compute required resistance: a) 2020 hazard curve for T=0.5 s for the three sources; b) fragility curve for W-1 prototype (Height = 3000 mm, drift = 4.0%) from SRG3 database; c) fragility curve scaled to 2020/2015 hazard at T=0.5 s; and, d) individual source and combined 50 year probability of drift exceedance curves.

COMPARISON OF SRG3 AND SRG2020

Figure 4 and Figure 5 illustrate the R_m ratio for SRG2020 compared to SRG3 R_m for a site with V_{s30} = 450 m/s across various structural prototypes. In Figure 4, for the Vancouver Lower Mainland region with V_{s30} = 450 m/s, there is an observed increase in R_m values ranging from 0% to 20%. Conversely, Figure 5 demonstrates that in Victoria and surrounding areas, the increase in R_m values can range from 30% to 60%, depending on the specific structural prototype. This significant increase in R_m values in Victoria, and surrounding localities, is attributed to change in NBCC 2020 hazard values for those locations. In the remaining parts of Vancouver Island with V_{s30} = 450 m/s, the increase in R_m values ranges from 20% to 40%. Notably, the increase in R_m values is more pronounced for sites with softer soil conditions, specifically V_{s30} < 360 m/s.

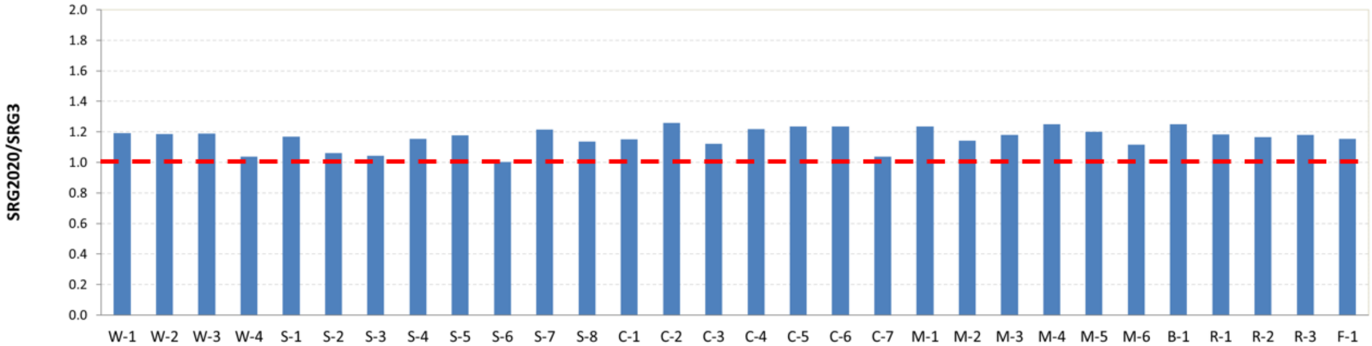

Figure 4. SRG2020 to SRG3 R_m ratio for various structural prototypes for Vancouver, height = 3000m, V_{s30} = 450 m/s.

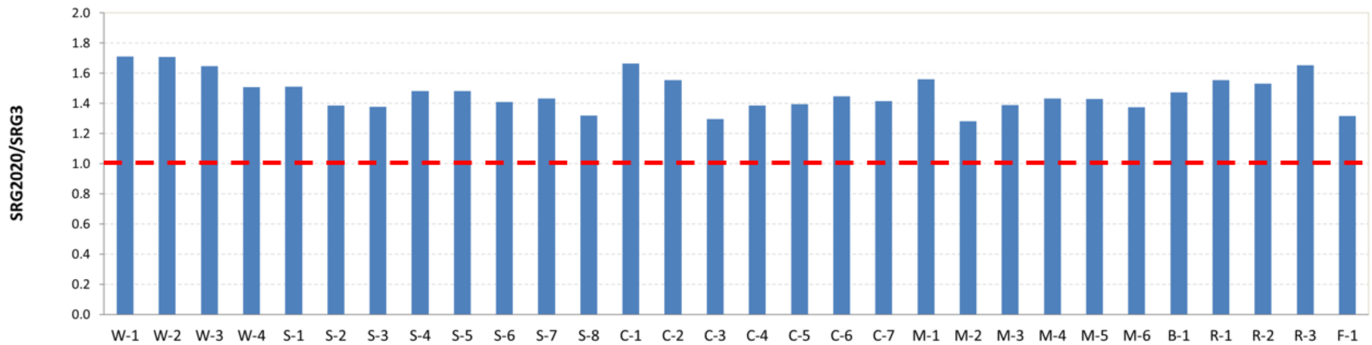

Figure 5. SRG2020 to SRG3 R_m ratio for various structural prototypes for Victoria, height = 3000m, and V_{s30} = 450 m/s.

SITE V_{S30} INTERPOLATION PROCEDURE

For the NBCC 2020, a significant change introduced in the 6th generation of the seismic hazard model is the direct computation of seismic hazard considering different site conditions using representative soil V_{s30} values [5, 9]. The seismic hazard is evaluated at 11 specific V_{s30} values, namely 140, 160, 180, 250, 300, 360, 450, 580, 760, 910, and 1100 m/s. For intermediate V_{s30} values, a log-log interpolation technique is employed to obtain the corresponding hazard data.

Extensive sensitivity analysis conducted in SRG2020 has confirmed that the required resistance (R_m), probability of drift exceedance (PDE), and conditional probability of drift exceedance (CPDE) values exhibit a linear relationship with V_{s30} when plotted on a log-log scale. This allows for the adoption of interpolation techniques. In order to enhance computational efficiency, rather than conducting analyses at 11 specific V_{s30} values, SRG2020 focuses on five key V_{s30} values: 140, 250, 450, 760, and 1100 m/s. Through the implementation of log-log interpolation, R_m, PDE, and CPDE values can be generated for intermediate V_{s30} values.

Figure 6 presents the R_m values for W-1 (height = 3000 mm at 4.0% drift) computed for 11 distinct V_{s30} values ranging from 140 to 1100 m/s. When these results are plotted on a log-log scale, they exhibit a nearly linear relationship. This finding serves as evidence to support the application of log-log interpolation for generating results for intermediate V_{s30} values.

To further evaluate the suitability of this procedure for seismic assessment, 2%/50-year PDE values were extracted for W-1 at different V_{s30} values in Vancouver. Specifically, this analysis focused on the SRG2020 Site Class C, utilizing V_{s30} = 450 m/s at the design R_m for a 4% drift limit. The outcome of this assessment are presented in Figure 7. Once again, the results confirm the appropriateness of log-log interpolation when estimating values between V_{s30} data points.

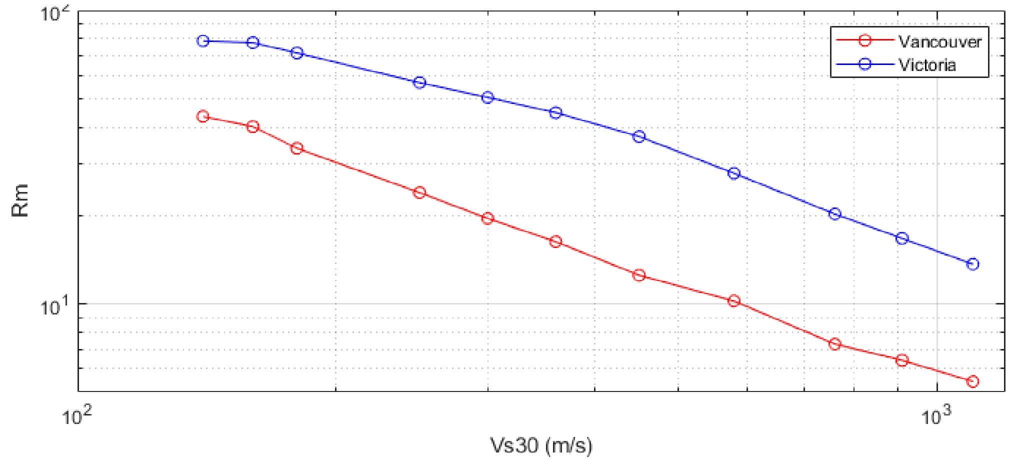

Figure 6. Required resistance (R_m,%W) for W-1, Height = 3000mm, Drift = 4%, and various V_{s30}

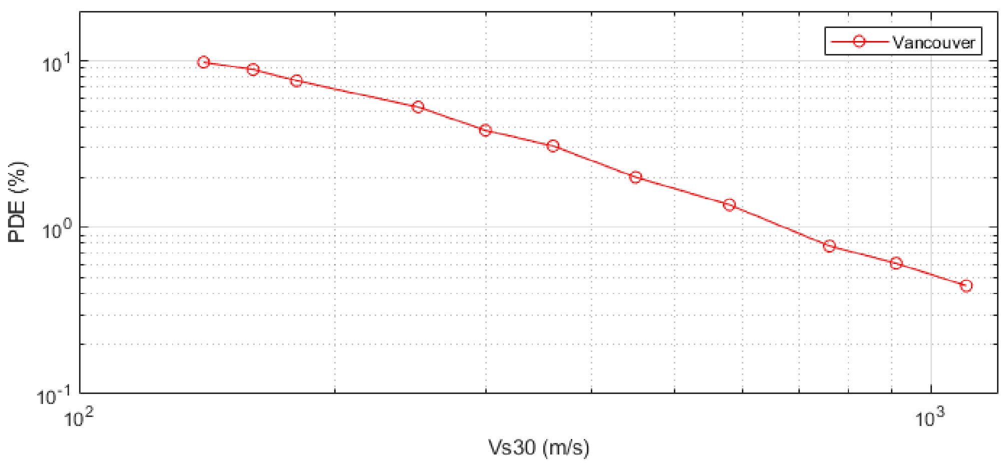

Figure 7. PDE (%) for W-1, R_m = 12.5%, Height = 3000mm, Drift = 4%, and various V_{s30} in Vancouver.

UPDATE TO THE *SEISMIC PERFORMANCE ANALYZERA*

The *Seismic Performance Analyzer*, known as the *Analyzer*, serves as the primary analytical tool utilized in accordance with the SRG Guidelines. It offers immediate access to the comprehensive SRG peer-reviewed analytical database, as shown in Figure 8. This powerful tool enables experienced engineers to combine their practical knowledge and expertise with over 40 million IDA results. By utilizing the *Analyzer*, engineers can accurately assess the risk associated with specific building blocks and devise cost-effective retrofit solutions.

The *Analyzer* allows engineers to efficiently analyze three critical building elements with analytically complex behavior: lateral deformation resisting systems, walls rocking out-of-plane, and diaphragms. For each of these elements, the *Analyzer* facilitates risk assessments and retrofit designs. The entire SRG2020 *Analyzer* (Version 4.1) database has been updated to reflect the seismic hazard revisions outlined in NBCC 2020. Additionally, instead of selecting a soil site class, users can directly input soil V_{s30} values into the SRG2020 *Analyzer* to calculate the probability of drift exceedance (PDE) and the required resistance (R_m) for achieving life safety standards.

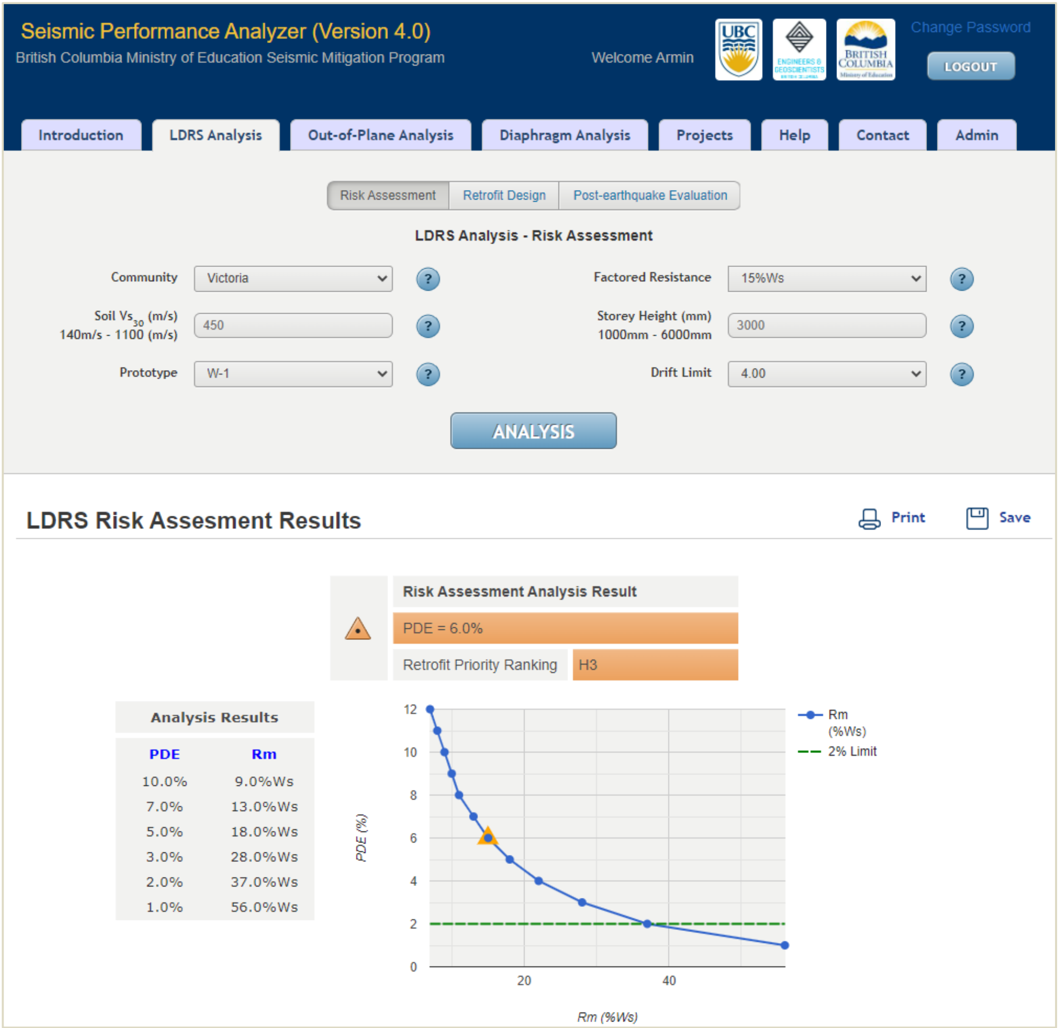

Figure 8. Screenshot of the Seismic Performance Analyzer.

SEISMIC SITE RESPONSE ANALYSIS

Seismic Site Response Analysis (SSRA) has been undertaken to take advantage of opportunities to mitigate soil amplification effects in shallow soil sites on Vancouver Island. The unique characteristics of these shallow soil sites, characterized by soil columns less than 30 meters deep on top of stiff rock, often require a customized SSRA approach to accurately assess soil amplification effects. The conventional NEHRP classifications and V_{s30} values may not provide an accurate representation of the site response in many of these cases. To address this, multiple methods for incorporating SSRA results have been investigated and compared to develop site-specific hazard curves and uniform hazard spectra (UHS). A companion paper [12] presents a comprehensive comparison of different approaches to integrate SSRA into probabilistic seismic hazard analysis, while [13] provides a practical SSRA methodology consistent with SHM6. Notably, [12] demonstrates that for certain structural prototypes on shallow sites, conducting SSRA results in an observed reduction of approximately 10-15% in R_m compared to the published *Analyzer* results based solely on the site's V_{s30}.

CONCLUSION

Through SRG methodology, a considerable number of schools (497) in BC have been assessed, with approximately 216 schools successfully retrofitted and others prioritized for future retrofitting. One notable aspect of the SRG methodology is its ability to relieve engineers from the need to conduct complex nonlinear analyses for individual buildings, while still benefiting from the advantages of a probabilistic performance-based design approach. Engineers can utilize their conventional engineering knowledge to assess and retrofit structures, relying on the SRG *Analyzer* to provide essential parameters for their designs.

This paper outlined several major changes that will be incorporated into the Seismic Retrofit Guidelines, 4^{th} Edition (SRG2020). These updates aim to ensure that SRG2020 continues to offer cost-effective retrofit solutions and user-friendly guidelines, while incorporating the latest advancements in the understanding of the seismic hazard in BC. Additionally, the paper introduced other components of the program, such as The *Seismic Performance Analyzer* and Seismic Site Response Analysis, highlighting their relevance and contribution to the overall framework.

Overall, the SRG methodology, along with the upcoming SRG2020, presents a significant advancement in seismic retrofit practices, contributing to improved structural resilience and safety in BC school buildings. By integrating advanced knowledge and providing engineers with practical tools, the SRG program continues to enhance seismic design and retrofit practices, ultimately ensuring the well-being of students and occupants in seismic-prone regions of BC.

ACKNOWLEDGEMENT

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