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Comparison of Methods to Incorporate Site Response Analysis Results into Probabilistic Seismic Hazard Analysis

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ABSTRACT

In this paper, multiple methods to use Seismic Site Response Analysis (SSRA) results to develop hazard-consistent site-specific hazard curves and/or uniform hazard spectra (UHS) are investigated and compared. Nonlinear SSRA results of a typical high-impedance site (9.1 m of soft soil over bedrock) in Victoria are utilized. The SSRA included three sets of input motions representing the three types of earthquakes that influence the seismic hazard in southwestern BC: crustal, in-slab, and subduction interface sources. From these analyses, three sets of source-specific, period-specific (T) site amplification factors that are dependent on the peak ground acceleration (PGA) of the reference ground condition, $F(T,GA_{ref})$, were obtained.

Four methods were considered to incorporate the SSRA results (source-specific $F(T,PGA_{ref})$ values) to generate site-specific hazard curves and/or UHS. 1) Hybrid method: the simplest method for most engineers to implement by combining deterministic site-specific response information with probabilistic seismic hazard analysis (PSHA) results. It does not require re-running any PSHA – only factoring its output (e.g., total hazard UHS values at a particular hazard level) by the $F(T,PGA_{ref})$ factors associated with the probabilistic PGA_{ref} at that hazard level. 2) Hybrid (Source) method: like the Hybrid method, however the hazard results from each seismic source are modified using their source-specific $F(T,PGA_{ref})$ factors (rather than modifying the total hazard results with the Hybrid method). This means that the PSHA model must be separated and run for each source-type. The hazard curves for each source are then modified by $F(T,PGA_{ref})$ and are then re-aggregated to generate UHS values. 3) Median Intensity Target (MIT) method: involves modifying a UHS by $F(T,PGA_{ref})$ values calculated for the median PGA_{ref} associated with the disaggregated hazard – i.e. the contribution-weighted average of the predicted ground motion intensities corresponding to the individual magnitude-distance (M-R) scenarios. 4) Rigorous method: involves incorporating the $F(T, PGA_{ref})$ factors directly into the ground motion models (GMMs) used in the 6th Generation Seismic Hazard Model of Canada (SHMC-6) and then re-running the full model to generate period-specific hazard curves from which the UHS at a specific hazard level is constructed.

The Rigorous method is the most probabilistically robust method for incorporating site-specific response information into PSHA as it ensures that each event scenario associated with a M-R combination within the hazard model is modified using the SSRA-based $F(T,PGA_{ref})$ value for the corresponding PGA_{ref}. It is shown that the Hybrid and Hybrid (Source) methods provide similar results – however, both underestimate the site-specific hazard, particularity at low annual exceedances rates (AERs). This is because the large PGA_{ref} values associated with low AER at high hazard levels result in lower $F(T,PGA_{ref})$ factors compared to the individual realizations used to generate the aggregated hazard values. The MIT method mitigates this by using median PGA_{ref} values associated with the disaggregated hazard to calculated $F(T,PGA_{ref})$ factors and provides similar results to the Rigorous method with a much lower computational effort.

The results from each method were incorporated into the Seismic Retrofit Guideline (SRG) methodology to develop required resistance (R_m) and probability of drift exceedance (PDE) values for four sample lateral drift resisting system (LDRS) prototypes. For the considered prototypes, a ~10-15% reduction in R_m for the Rigorous method, and a ~0-10% reduction in R_m for the Hybrid (Source) method was observed compared to published *Analyzer* results based on the V_{S30} of the site.

Keywords: Site response analysis, amplification functions, probabilistic seismic hazard analysis.

INTRODUCTION

As described in a companion paper [1], a typical site in downtown Victoria was modelled and analyzed using nonlinear SSRA to develop site amplification factors to obtain amplified surface hazard values by.modifying surface hazard values of a reference ground condition. As described in [1], the site comprises 9.1 m of Victoria Clay with a time-averaged shear wave velocity (V_{S_soil}) of 166 m/s over bedrock with a time-averaged shear wave velocity (V_{S_rock}) of 1100 m/s. The sudden increase in V_S at 9.1 m depth results in a strong impedance contrast that produces a strong resonant amplification response at a linear-elastic site period (T_0) of 0.22 s. The V_{S_rock} = 1100 m/s yields a time-averaged shear wave velocity in the upper 30 m of the site (V_{S30}) of 406 m/s. The analyses were performed with three sets of input motions representing the three types of earthquakes that influence the seismic hazard in southwestern BC: shallow crustal, subduction in-slab, and subduction interface sources. From these analyses, three sets of source-specific, period (T)-specific site amplification factors that are dependent on the peak ground acceleration (PGA) of a rock reference condition (PGA_{ref}) having a V_{S30} = *1100 m/s*, F(T,PGA_{ref}), were obtained as illustrated in Figure 1.

Four methods were considered to incorporate the SSRA results (source-specific F(T,PGA_{ref}) values) to generate site-specific hazard curves and/or UHS: 1) Hybrid method, 2) Hybrid (source) method, 3) Median Intensity Target method, and 4) the Rigorous method. The results from each method were incorporated into the Seismic Retrofit Guideline (SRG) methodology to develop required resistance (R_m) and probability of drift exceedance (PDE) values for four sample lateral drift resisting system (LDRS) prototypes.

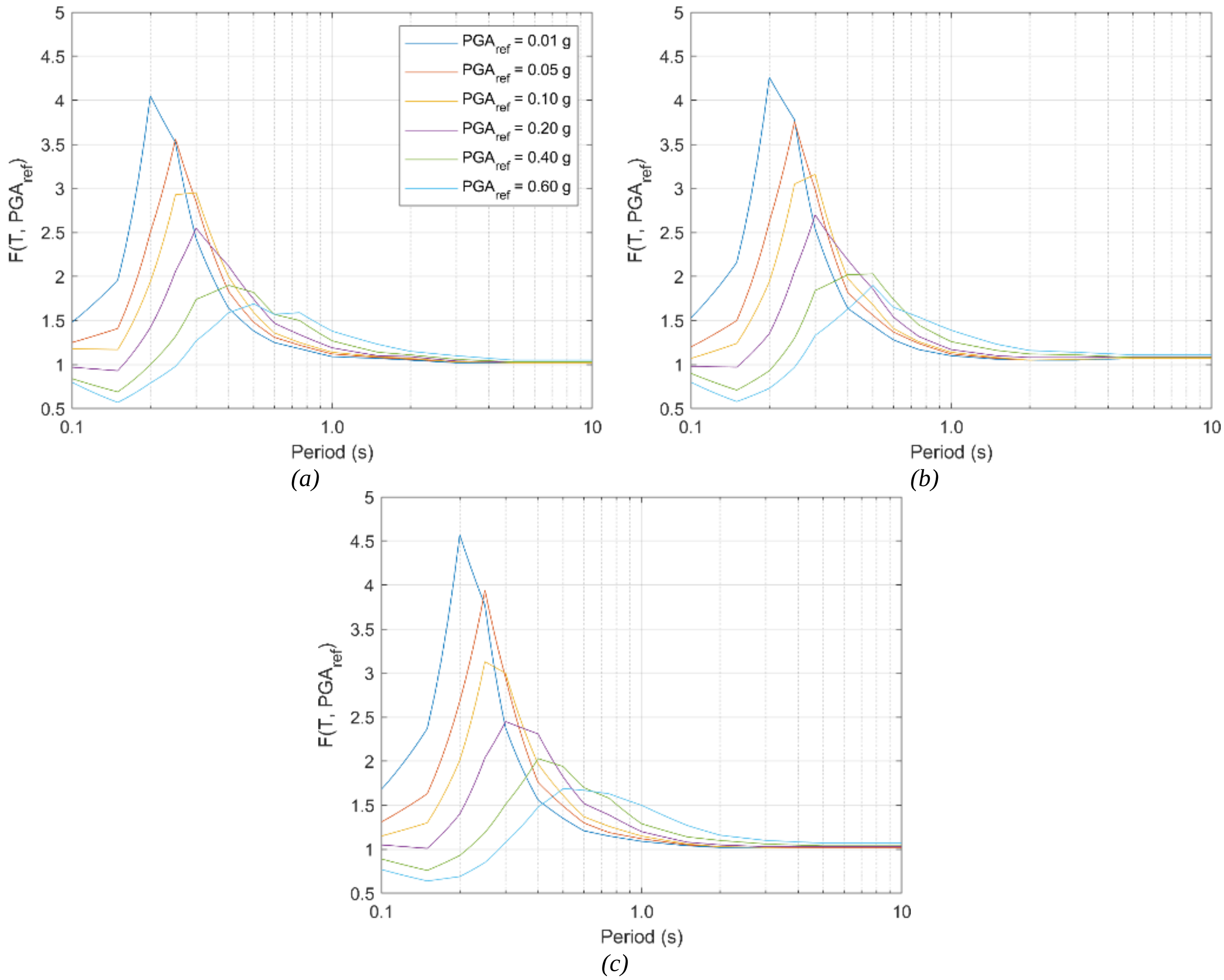


Figure 1: Amplifications functions (F(T,PGA_{ref}) vs. period) for 9.1 m thick Victoria Clay (Vs_soil = 166 m/s) over Bedrock (Vs_rock = 1100 m/s) developed using: a) crustal motions, b) in-slab motions, and c) interface motions [1].

SSRA IMPLEMENTATION METHODOLOGIES

Four methods were considered to incorporate the SSRA results (source-specific F(T,PGA_{ref}) values) to generate site-specific hazard curves and/or UHS: 1) Hybrid method, 2) Hybrid (source) method, 3) Median Intensity Target method, and 4) the Rigorous method. The following sections describe the implementation of these methods.

Hybrid Method

This is the simplest method of combining site-specific response information with PSHA results for most engineers to implement. It is referred to as Hybrid because it combines a probabilistic rock motion with deterministic site amplification. It does not require re-running any PSHA, only factoring its output (e.g., UHS values provided by the Geological Survey of Canada, GSC).

To implement this method, the GSC 6th generation seismic hazard model (used to generate hazard values for the 2020 National Building Code of Canada, NBCC; SHM6) was run for V_{S30} = 1100 m/s [2]. UHS were then developed for different annual exceedance rates (AERs). The 5% damped spectral acceleration, SA(T), values of the reference condition were amplified using the F(T, PGA_{ref}) factors corresponding to the probabilistic PGA_{ref} at the specified AER (the average amplification factors from the three sources were used) according to:

$$SA_{amp}(T) = F\left(T, PGA_{ref}\right) * SA_{ref}(T) \tag{3}$$

where $SA_{amp}(T)$ is the amplified (to the site condition of interest) spectral acceleration for a certain AER, $SA_{ref}(T)$ is the spectral acceleration for V_{S30} = 1100 m/s at the AER, and PGA_{ref} is the PGA for V_{S30} = 1100 m/s at the AER.

Hybrid (Source) Method

This method is similar to the Hybrid method – however the hazard results from each source are modified using their source-specific F(T, PGA_{ref}) factors (rather than modifying the total hazard results with the typical Hybrid method). This means that the PSHA model must be separated and run for each source-type. The hazard curves for each source are then modified by F(T, PGA_{ref}) and are then re-aggregated to generate total hazard UHS values.

Median Intensity Target Method

The Median Intensity Target (MIT) which is referred as Modified Hybrid method by [3] is similar to the Hybrid method, except it computes F(T,PGA_{ref}) values for a ground motion intensity corresponding to the median value of PGA_{ref} (i.e., 0 epsilon) rather than the probabilistic PGA_{ref}(AER). In this approach, amplification is based on the average of the expected level of shaking from all event scenarios (as predicted by the GMMs based on magnitude, distance, etc.) that contributes to the hazard, before considering the epsilon required to obtain a certain AER. The MIT method is more consistent with the approach used by the GMMs to calculate amplification based on the GMM-predicted ground motion intensity associated with individual event scenarios and to use a short-period intensity measure (typically PGA) of a rock reference condition. It is easier to implement than the Rigorous method, as it does not require modifying and re-running the PSHA.

Computing a median PGA_{ref}, med_PGA_{ref} or $PGA_{ref\text{-}med}$, requires four inputs, all readily available from the PSHA for the reference ground condition and its disaggregation: 1) the PGA_{ref}(AER) at a specified hazard level as obtained from the NRCan Seismic Hazard Tool, 2) the contribution of each source to the probabilistic hazard value as obtained from disaggregation of PGA_{ref}(AER), 3) the mean epsilon value for each source as obtained from disaggregation of PGA_{ref}(AER), and 4) the lognormal standard deviation (sigma) describing the aleatoric uncertainty of each GMM used in the PSHA. Then, the median PGA_{ref}, med_PGA_{med}, is computed as:

$$\ln[med\_PGA_{ref}] = \ln\left[PGA_{ref}(AEP)\right] - \sum_{s=1}^{n}\left[cont_s\left(PGA_{ref}\right) * \bar{\varepsilon}_s\left(PGA_{ref}\right) * \bar{\sigma}_s(PGA)\right] \tag{4}$$

where $cont_s$ is the contribution to the hazard at the PGA from the s-th seismic source (i.e., crustal, in-slab, or interface), $\bar{\varepsilon}_s$ is the mean epsilon value for the s-th source, $\bar{\sigma}_s$ is the mean of the lognormal standard deviation of each of the GMMs used in SHMC-6 for the s-th seismic source (average of four GMMs for each seismic source for Western Canada), and n is the total number of seismic sources (up to 3 for Western Canada).

Then, the amplified UHS is calculated using Equation (3) where $F\left(T, PGA_{ref}\right) = F\left(T, med\_PGA_{ref}\right)$ as determined from SSRA conducted on suites of acceleration time histories scaled to med_PGA_{ref}. The factors for each source are weighted based on their contribution to the PGA_{ref} at the AER being amplified. This method has been further explained in detail in the companion paper [1].

Rigorous Method

The most probabilistically robust method for incorporating site-specific response information into PSHA is to incorporate the $F(T,PGA_{ref})$ factors directly into the GMMs used by the PSHA model and then run the model [3] which is also referred as Probabilistic method. This ensures that each event scenario associated with a M-R combination within the hazard model is modified using the appropriate $F(T, PGA_{ref})$ value for the corresponding event-specific estimate of expected PGA_{ref} (before adding the epsilon required to reach a specified AER).

This was done in the developer's version of OpenQuake [4] by replacing the site terms attached to each GMM with lookup tables of source-specific $F(T, PGA_{ref})$ values. For each event scenario in the hazard model, the PSHA calculates the event-specific median SA_{ref} hazard values predicted by each GMM and modifies them by selecting the appropriate $F(T, PGA_{ref})$ from the source-specific lookup table based on the GMM's prediction of event-specific PGA_{ref}, using linear interpolation for intermediate values of PGA_{ref} between the intensity levels considered in the SSRA.

The PSHA combines the GMM-specific amplified median hazard values for each event scenario with the GMM-specific sigma model and the probability of occurrence associated with the mean magnitude-recurrence relationship (in the collapsed version of SHMC-6), to determine the event-specific AER values. The total hazard curves presented below correspond to the summation of all the event-specific AER values for each trial hazard value plotted on the horizontal axis of the AER vs pseudo-spectral acceleration (PSA) plots shown in Figure 2. The model was run for an X1100 site designation, which is consistent with the V_{S30} = 1100 m/s reference condition adopted in the SSRA. The amplified total hazard curves generated using this approach are a function of the GMM sigma values corresponding to the V_{S30} = 1100 m/s reference condition. No attempt was made in this study to modify sigma to account for reduced uncertainty associated with SSRA-based estimates of site amplification as compared to the ergodic V_{s30}-based GMM predictions. Accordingly, the UHS produced using this method are directly comparable to the results of the MIT method.

Comparison of Results

The total hazard curves for PGA and for SA(T) at T = 0.2 s, 0.5 s and 1.0 s, as generated by SHM6 (V_{S30} = 1100 m/s reference) after SRA-derived modification using the Hybrid (Source) and Rigorous methods are shown in Figure 2. The other two methods (the Hybrid and Median Intensity Target methods) amplify the UHS_{ref} at a single AER rather than the complete hazard curves, and thus are not included in Figure 2. The amplified surface UHS from all methods are presented in Figure 3 along with SHM6 results for V_{S30} = 1100 (reference) and 406 m/s (V_{S30} of the site of interest). Most site-specific UHS show a large peak in SA(T) at 0.3 s, which corresponds to the peak amplification at the non-linear site period of the softened soil column when PGA_{ref} is between 0.1g and 0.2g, as shown by the $F(T,PGA_{ref})$ values plotted on Figure 1. The UHS for V_{S30} = 406 m/s obtained directly from SHM6 does not recognize the peak SA(T) due to the fundamental period of the site and significantly underestimates SA(T) at 0.2 s and 0.3 s periods. Above the site period, the site-specific amplified UHS drop below the SHM6-predicted UHS for V_{S30} = 406 m/s.

The Median Intensity Target UHS are similar in shape and amplitude to those from the more robust Rigorous method, indicating that the approximate method of estimating the expected amplification values based on med_PGA_{ref} derived from deaggregation of the total hazard works well. The Hybrid and Hybrid (Source) methods provide similarly shaped UHS but the SA(T) values for T < 0.5 s are much lower than those from the other two methods, especially at the higher hazard levels (e.g., 1/2475 AER). This is because they obtain $F(T,PGA_{ref})$ values using PGA_{ref} values corresponding to the probabilistic aggregation of all event scenario predictions including aleatoric uncertainty (epsilon × sigma), which results in the high AEPs used for engineering design. As seen in Figure 1, $F(T,PGA_{ref})$ tend to decrease with increasing PGA_{ref} and the site period increases as increasing ground accelerations cause increasing nonlinearity in the soil column, which causes reductions in the shear stiffness of the soil and increased damping.

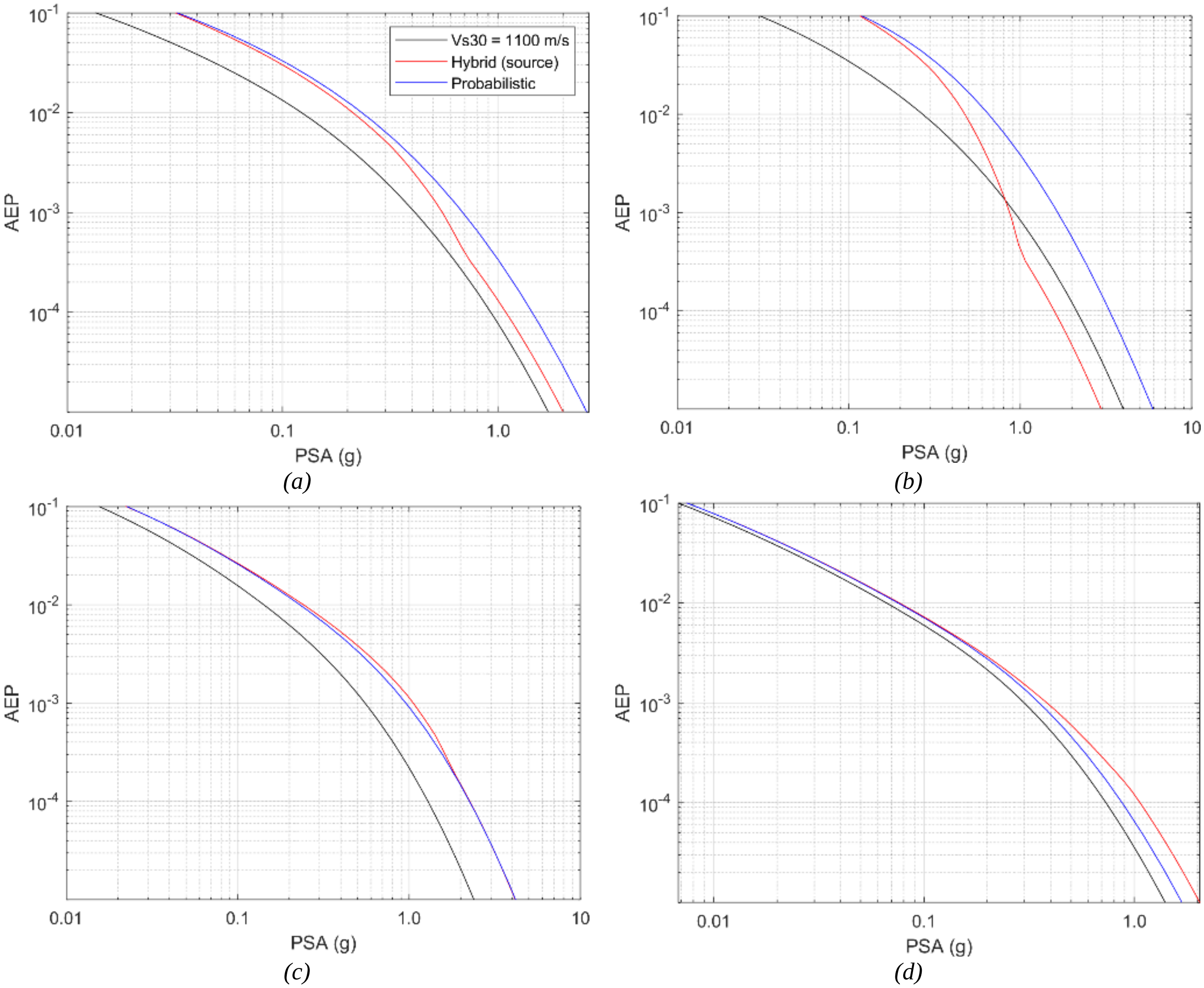
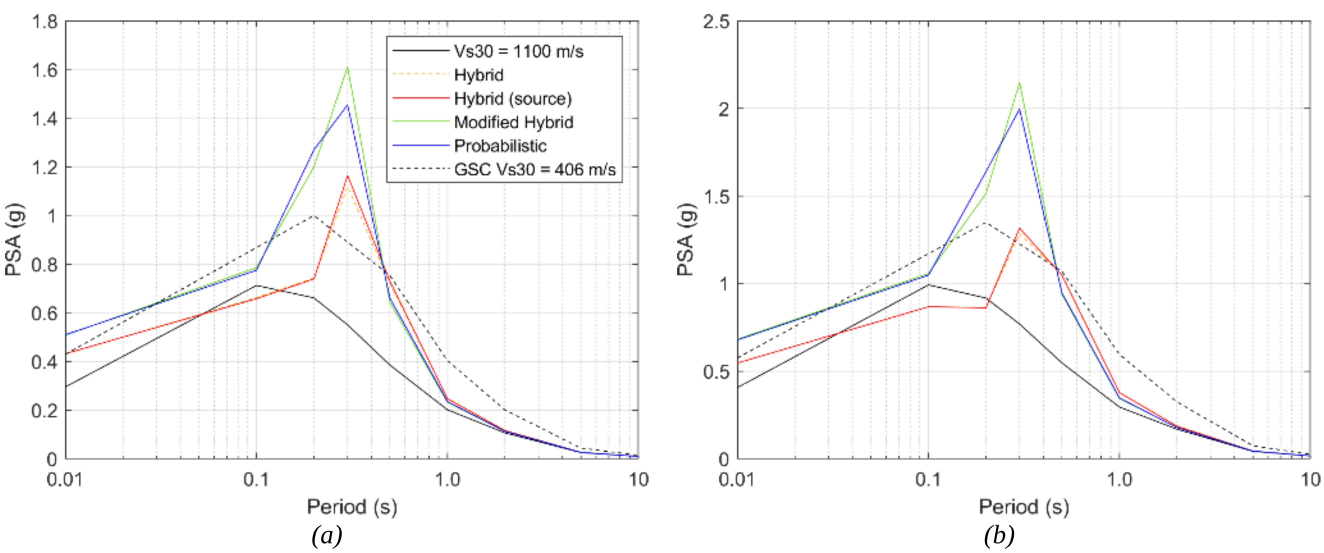
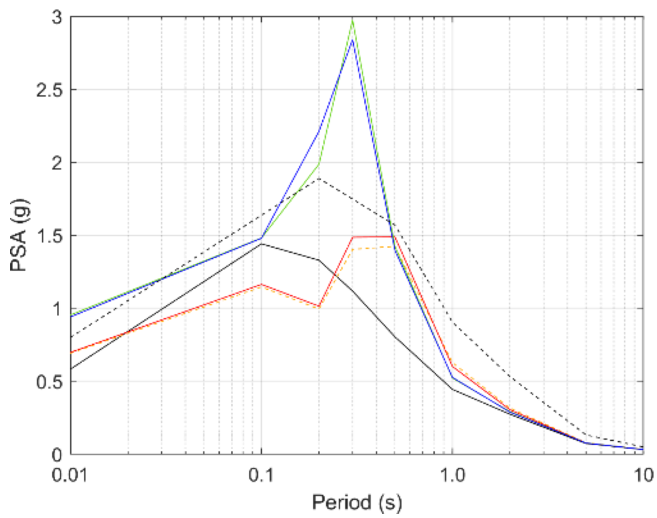


Figure 2: Hazard curves (pseudo-spectral acceleration vs annual exceedance probability) for V_{S30} = 1100 m/s, the Hybrid (Source) method, and Rigorous (Probabilistic) method at: a) PGA; b) T = 0.2 s; c) T = 0.5 s; and d) T = 1.0 s.





(c)

Figure 3: UHS (pseudo-spectral acceleration vs. period) from the SHM6 for V_{S30} = 1100 m/s and V_{S30} = 406 m/s along with the site-specific (V_{S30} = 406 m/s) UHS from each method: Hybrid, Hybrid (Source), Modified Hybrid (Median Intensity Target), and Probabilistic (Rigorous) method for return periods of: a) 475-years; b) 975-years; and c) 2475-years.

IMPLICATION FOR SRG2020 *ANALYZER* VALUES

In this section we implement the resulting hazard curves into the Seismic retrofit Guidelines (SRG) methodology to derive required resistance (R_m) for four sample prototypes commonly used in BC school buildings or for the seismic retrofit of school blocks. Since the Hybrid and Modified Hybrid methods do not produce source-specific amplified hazard curves, they could not be implemented directly into the SRG framework. However, the Hybrid (Source) and the Rigorous methods could be readily incorporated with the existing SRG2020 database results.

SRG Methodology

The SRG methodology is a performance-based methodology which utilizes sophisticated structural models and nonlinear time history analyses to assess the probabilistic performance of structures subjected to seismically induced loads [5]. This methodology uses inelastic deformation, rather than force, to quantify building performance. In the SRG methodology, life safety performance is obtained by defining demand requirements that limit the risk of collapse, or excessive deformation, to an acceptable value in a 50 year period.

In the SRG methodology, the probability of drift exceedance (PDE) of a structural system is determined utilizing incremental nonlinear dynamic analysis (INDA) [6]. Six suites (to represent the three earthquake types that contribute to the seismic hazard in Western BC and two conditioning periods: 0.5 and 1.0 s) comprising 20 conditional spectra (CS) [7] scaled ground motion acceleration time histories, were used perform the INDA for each structural system considering all possible levels of shaking intensity (from 10-250% of the 2% in 50-year hazard). These results were used to generate source-specific fragility curves (i.e., cumulative probability of deformation/drift exceedance as a function of level of shaking).

INDA results are then combined with the hazard curves for a site and integrated over all considered hazard levels to develop drift exceedance rates for each earthquake source type following:

$$\lambda_s(d > D) = \int_{10}^{250\%} CPDE(d > D|SA) * d\lambda_{SA,s} \quad (1)$$

Where $\lambda_s(d > D)$ is the rate that the drift: d, exceeds a certain drift limit: D, for earthquake source s (s = crustal, in-slab, interface); $CPDE(d > D|SA)$ is the conditional probability of drift exceedance given a certain level of shaking: SA, (i.e., the fragility curve from the system obtained from INDA); and $d\lambda_{SA,s}$ is the rate of exceedance of SA for source: s (i.e., the derivative of the hazard curve for the earthquake source and conditioning period being analyzed).

The total annual rate of drift exceedance is then calculated by summing up the rates over all three sources of hazards: crustal, in-slab, and interface. The total probability of drift exceedance: $P(d > D)$, is estimated using a temporal Poisson probability model at given time interval, T (typically 50 years):

$$P(d > D) = 1 - \exp\left(-T * \sum_{s=1}^{3} \lambda_s\right) \tag{2}$$

R_m values for each locality and structural system are obtained by limiting the PDE values to a certain limit (typically 2% in 50-year probability of exceedance) at the systems collapse prevention drift limit (CDL).

Results for each structural system (33 total LDRS are considered in SRG), including R_m values and PDE results for each drift limit, for each locality, are included in a comprehensive database and made available through an online tool: the Seismic Performance Analyzer (*Analyzer*). The *Analyzer* gives its users immediate access to all analysis results without having to perform any probabilistic seismic hazard analysis (PSHA) of INDA. This allows them to efficiently assess the safety of their system and to obtain R_m values for any required retrofit.

Results

Using the Hybrid (Source) and Probabilistic hazard curves (for T = 0.5 and 1.0 s from Figure 2) new Rm_{PDE} values were derived for the prototypes listed in Table 1 for Victoria, with a PDE of 2% in 50 years at each prototypes drift limit. Rm_{CPDE} values were also derived by limiting the conditional probability of drift exceedance (CPDE) to 25% at the drift limit for the governing hazard source. These are compared to the SRG2020 V_{S30} = 1100 m/s results (for reference) and SRG2020 V_{S30} = 406 m/s results, for the four prototypes, in Tables 1, respectively. The code results are also included, for comparison, based on the 2020 NBCC Sa(0.5 s) for V_{S30} = 406 m/s divided by the R_dR_o of each prototype. The results are summarized for each of the four prototypes in Tables 2-5. The R_m vs. PDE for each prototype is shown in Figure 3 for the Hybrid (Source) method, Rigorous method, and *Analyzer* (V_{S30} = 406 m/s) results. For all SRG2020 values, hazard curves from the GSC 6th generation seismic hazard model were used [2].

Table 1: Selected SRG2020 prototypes and information.

Prototype	Description	Height (mm)	R_o	R_d	Drift Limit (%)
W-1	Blocked OSB/plywood	3000	1.7	3.0	4.0
W-2	Unblocked OSB/plywood	3000	1.7	3.0	4.0
C-4	Squat concrete shearwall (shear)	3000	1.3	1.5	2.0
C-6	Moderately ductile concrete shearwall (flexure)	6000	1.4	2.0	1.5

Using the SRA results (source-specific $F(T,PGA_{ref})$ factors) for the high-impedance Victoria site in both the Hybrid (Source) and Rigorous methods resulted in lower required R_m values for the considered prototypes compared to the published *Analyzer* values when the V_{S30} = 406 m/s is used. For the four considered prototypes, a ~10-15% reduction in R_m for the Rigorous method, and a ~0-10% reduction in R_m for the Hybrid (Source) method was observed.

Table 2: R_m result comparison for prototype W-1, height = 3000 mm, PDE = 2%/50 years, governing source CPDE < 25% for 4.0% drift limit

Method	Rm_{PDE} (%W)	Rm_{CPDE} (%W)
SRG2020 Vs30 = 1100 m/s	13.1	12.7
SRG2020 Vs30 = 406 m/s	37.5	35.7
Hybrid (Source)	34.4	36.5
Rigorous (Probabilistic)	32.2	32.6
Code	30.8	

Table 3: R_m result comparison for prototype W-2, height = 3000 mm, PDE = 2%/50 years, governing source CPDE < 25% for 4.0% drift limit

Method	**Rm_{PDE} (%W)**	**Rm_{CPDE} (%W)**
SRG2020 Vs30 = 1100 m/s	13.6	13.5
SRG2020 Vs30 = 406 m/s	38.9	38.3
Hybrid (Source)	35.5	37.7
Rigorous (Probabilistic)	33.0	33.1
Code	30.8	

Table 4: R_m result comparison for prototype C-4, height = 3000 mm, PDE = 2%/50 years, governing source CPDE < 25% for 2.0% drift limit

Method	**Rm_{PDE} (%W)**	**Rm_{CPDE} (%W)**
SRG2020 - Vs30 = 1100 m/s	21.4	20.9
SRG2020 - Vs30 = 406 m/s	49.1	42.2
Hybrid (Source)	46.6	41.0
Rigorous (Probabilistic)	43.2	37.8
Code	80.5	

Table 5: R_m result comparison for prototype C-6, height = 6000 mm, PDE = 2%/50 years, governing source CPDE < 25% for 1.5% drift limit

Method	**Rm_{PDE} (%W)**	**Rm_{CPDE} (%W)**
SRG2020 - Vs30 = 1100 m/s	12.9	14.0
SRG2020 - Vs30 = 406 m/s	35.4	30.7
Hybrid (Source)	33.2	30.7
Rigorous (Probabilistic)	29.4	26.6
Code	56.1	

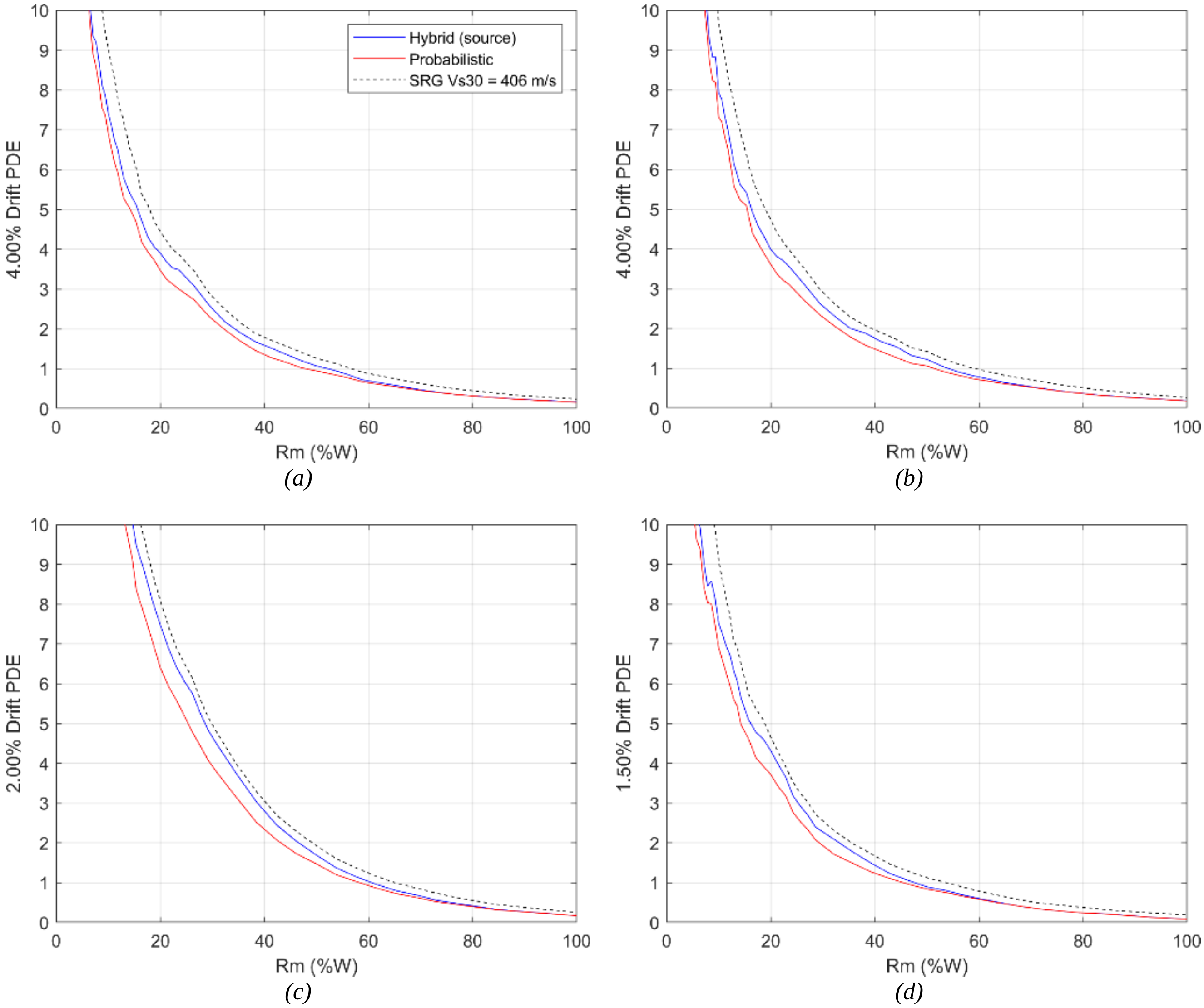


Figure 4: Required resistance (R_m) vs probability of drift exceedance (PDE) for prototypes: a) W-1, height = 3000 mm; b) W-2, height = 3000 mm; c) C-4, height = 3000 mm; and d) C-6, height = 6000 mm.

CONCLUSIONS

In this paper, we compared four methods to combine site response analysis results with probabilistic seismic hazard analysis. The methods included: 1) the Hybrid method, 2) the Hybrid (source) method, 3) the Median Intensity Target (Modified Hybrid) method, and 4) the Rigorous (Probabilistic) method. The two Hybrid methods underestimated hazard values, particularly at low AERs, since they used high PGA_{ref} values associated with the probabilistic aggregation of all event scenario predictions including multiple standard deviations of uncertainty that is included in the probabilistic hazard values at high hazard levels. The Median Intensity Target method mitigated this by using the median of the expected PGA_{ref} values associated with individual event scenarios to compute the amplification factors. This made the Median Intensity Target method comparable to the Rigorous method, in which $F(T,PGA_{ref})$ functions were used directly in the PSHA software to develop the hazard curves.

Since the Hybrid and Median Intensity Target methods do not produce hazard-consistent amplified hazard curves, they could not be implemented directly into the SRG framework. However, the Hybrid (source) (which produced similar results to the Hybrid) and the Probabilistic (which produced similar results to the Median Intensity Target) methods could be. For the four considered prototypes, a ~10-15% reduction in R_m for the Rigorous method, and a ~0-10% reduction in R_m for the Hybrid (source) method was observed. This illustrates the potential benefit that can be obtained by incorporating site-specific response information into performance-based structural analysis, such as the SRG methodology.

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