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Non-ergodic Site Response for Hard Rock Correction – a Case Study on the Number of Site-specific Data

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ABSTRACT

In 2012, BC Hydro (BCH) performed a SSHAC Level 3 PSHA that was referenced to a moderate-stiffness rock site condition with V_{S30} =760 m/s. However, many BCH facilities are located on hard rock sites with V_{S30} of 1500 m/s to 2800 m/s. Therefore, the seismic hazards based on V_{S30} = 760 m/s need adjustment, i.e., hard rock correction (HRC). In 2018, BCH initiated a study on an alternate approach that characterizes the HRC factors by estimating the non-ergodic site response at select BCH hard rock sites. The recommended approach comprises four main steps: 1) collect earthquake ground motion data from the site along with the same earthquake event data from nearby Geological Survey of Canada (GSC) stations; 2) perform inversion of the data to derive non-ergodic site terms and their corresponding standard errors in the Fourier amplitude spectra (FAS) domain; 3) convert the site terms to pseudo-spectral acceleration (PSA) domain HRC factors using ground motion simulation; 4) convolve the V_{S30} =760 m/s hazard curves for the site with the PSA domain HRC factors and their standard deviations. Through this approach, epistemic uncertainty (i.e., the standard errors) of the non-ergodic site terms is carried through the procedure, ultimately affecting the resulting hazard curves.

One of the requirements for this approach is that a sufficient number of earthquake ground motion data should be collected from the site to accurately characterize the non-ergodic site terms and limit their standard error. Also, the data must be useable (i.e., have a sufficiently large signal-to-noise ratio) over a wide band of frequencies, particularly at high frequencies, which are often of interest at BCH sites and are most affected by local site noise. Due to this, it can take several years to collect enough high-quality earthquake data at a site.

In this paper, the hazard curves and resulting uniform hazard spectra (UHS) derived using non-ergodic site terms are presented for an example site. The site terms were first computed using approximately 14 months of recorded data, and then with an additional 17 months of data that almost tripled the number of useable data. The non-ergodic site terms were relatively stable and not significantly altered by the additional data; however, the epistemic uncertainty of the non-ergodic site terms was significantly reduced, particularly at the extreme ends of the frequency range. This ultimately resulted in a reduction in the total hazard.

Keywords: Hard rock correction, non-ergodic site response, seismic instrumentation, ground motion simulation, probabilistic seismic hazard analysis.

INTRODUCTION

A probabilistic seismic hazard analysis (PSHA) using the Senior Seismic Hazard Analysis Committee (SSHAC) process [1] was completed in 2012 for BC Hydro dam sites [2]. The PSHA, hereafter referred to as the 2012 BC Hydro PSHA, was conducted for a reference site condition defined by a V_{S30} (time-averaged shear wave velocity in the top 30 m) of 760 m/s. The 2012 BC Hydro PSHA results thus require adjustment or HRC to provide site response and input ground motions for dam sites located on hard rock (i.e., V_{S30} of 1500 to 2800 m/s).

In 2018, a study was initiated by BC Hydro, which involved a panel of experts and BC Hydro Engineering personnel to develop an appropriate method for conversion of the PSHA results from a reference site condition of 760 m/s to the adjusted values for hard rock site conditions in British Columbia (BC), Canada [3]. The first step of the recommended approach involves instrumenting the site(s) of interest with seismic monitoring instruments (3-component broadband seismometers and strong motion accelerometers) and collecting data from small-to-moderate earthquake events in the region (within ~500 km of the site). More details about the site instrumentation are presented in a companion paper [4]. Once enough useable data (i.e., recordings sufficiently high signal-to-noise ratio over a wide frequency band) at the site have been collected, non-ergodic site correction factors can be estimated and used to convolve the V_{S30}=760 m/s hazard curves for the site. Through this approach, epistemic uncertainty (i.e., the standard errors) of the site factors can be quantified and carried through the procedure, ultimately affecting the resulting hazard curves and hard rock corrected uniform hazard spectra (UHS). An increase in the amount of data at a site reduces the uncertainty in the non-ergodic site terms, which can potentially lower the final hazard.

METHODOLOGY

The full background behind the methodology recommended to correct the V_{S30} = 760 m/s hazard curves for an instrumented site is explained by BC Hydro [3, 5]. The main steps can be summarized as: 1) compile earthquake ground motion data from the site along with data for the same events from nearby GSC stations; 2) use this data to derive non-ergodic site terms and their corresponding standard errors in the Fourier amplitude spectra (FAS) domain by performing a generalized inversion of FAS data to derive the non-ergodic site terms in Fourier domain; 3) convert the FAS site terms to pseudo-spectral acceleration (PSA) domain HRC factors using ground motion simulation; 4) convolve the V_{S30} = 760 m/s hazard curves for the site with the PSA domain HRC factors and their standard deviations.

Regional Ground Motion Models

As part of the work in [3], regional ground motion models (GMMs) using a seismological modelling framework referenced to a B.C. generic hard rock site condition (see next section) were developed. These models comprise a source term modeled with a Brune [6] source spectrum, a path term modelled as the summation (in log scale) of a bilinear geometrical spreading and frequency dependent anelastic attenuation models which are earthquake type dependent, and a site term modelled with a crustal amplification and high frequency attenuation κ_0 parameter [7] associated with the selected reference site condition that represent B.C. generic hard rock site condition. The developed GMMs are well-calibrated for empirical observations from **M**2.5–5.5 (moment magnitude) earthquakes recorded at rupture distances of about 50 to 500 km. Outside this range, the models are constrained by the adopted seismological model. Iterative generalized inversions [8] were used to derive the seismological model parameters. Details of the developed GMMs will be presented in a separate journal article. These GMMs can be used to fix the attenuation model within the generalized inversion process.

B.C. Generic Hard Rock Site Condition

The regional GMMs are referenced to a B.C. generic hard rock condition. A total of 12 reference stations are selected within the inversion process for the GMM development to represent the B.C. generic hard rock site condition.

To develop a shear-wave velocity profile for the B.C. generic hard rock site condition, the Cascadia velocity model (CVM) [9] was used to extract the shear-wave velocity up to a depth of 8 km within 5 km of the reference stations. The near-surface shear-wave velocity profiles adopted from the CVM model were constrained using the measured shear-wave velocities at selected BC Hydro facilities with similar bedrock geology. The V_{S30} of the proposed generic profile is about 2285 m/s. A density model is adopted for the generic V_S profile by adjusting the Boore (2016) [10] density model to match the measured surface bedrock density at selected BC Hydro facilities. Crustal amplification for the generic shear-wave velocity profile is calculated using the square-root-impedance ratio method (SRI) [11]. The B.C. generic hard rock site amplification, as a function of frequency, is shown in Figure 1a.

For the B.C. generic hard rock site condition, a κ_0 value was estimated within the inversion process of the observed ground motion data by fitting the high frequency of the adjusted source terms (removing the crustal amplification), which is equal to 0.0136 s ± 0.0005 s (standard error).

Characterization of the V_{S30} = 760 m/s Site Condition

The 2012 BC Hydro PSHA model was developed with V_{S30} = 760 m/s as the reference site condition. The model used the NGA-West 1 GMMs for crustal earthquakes and used a GMM developed for subduction interface and inslab events, commonly referred to as the "BC Hydro subduction GMM" [12].

The V_{S30} = 760 m/s reference site condition of the selected GMMs was characterized in terms of crustal amplification and κ_0 values. The methodology developed by Al Atik and Abrahamson (AA21) [13] was used to derive 1D shear wave velocity profiles, crustal amplification, and κ_0 values compatible with the GMMs used in the 2012 BC Hydro PSHA model. This methodology is based on the SRI method and employs inverse random vibration theory (iRVT; e.g., [14]) to convert predicted PSA values from the GMMs to Fourier amplitudes.

Figure 1b and c show the corresponding crustal amplification of the V_S profiles for the four NGA West 1 GMMs and the BC Hydro subduction GMM, respectively. Average κ_0 values estimated for the NGA West 1 GMMs and BC Hydro subduction GMMs are 0.040s (±0.002 s, standard deviation) and 0.047s (±0.001 s), respectively.

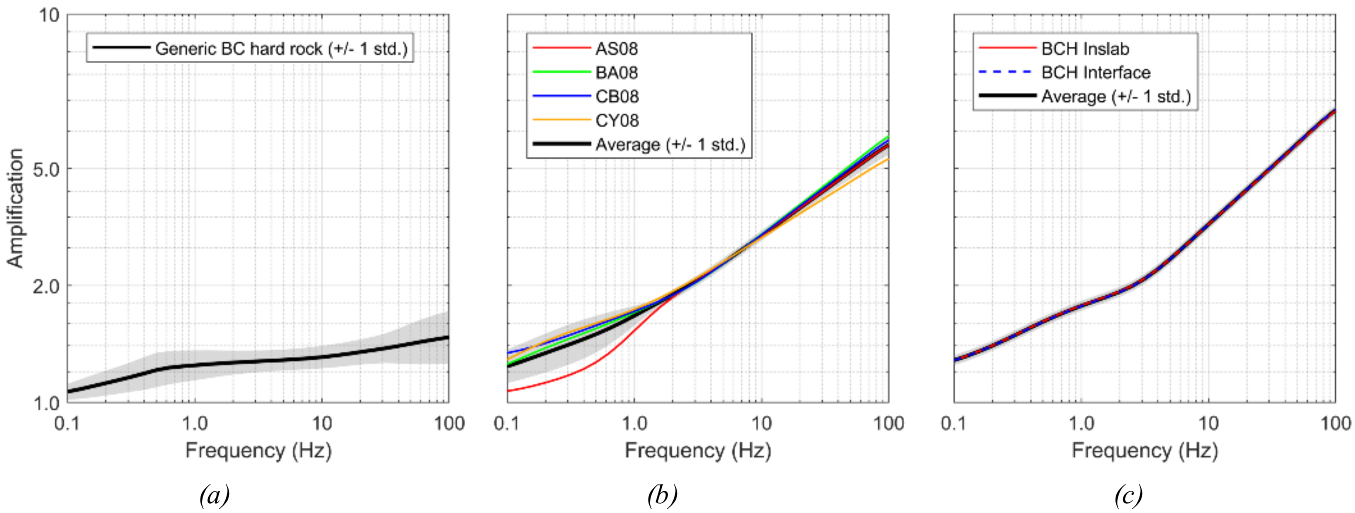


Figure 1. Crustal amplification (± 1 standard deviation) for: a) the generic B.C. hard rock site condition; b) the NGA West 1 GMMs; and, c) the BC Hydro subduction GMMs for V_{S30} = 760 m/s.

COMPILATION OF GROUND MOTION DATA

In 2020, two seismic stations were installed at the example site of interest, herein referred to as BCH1 and BCH2. The stations began operation early in 2020 and have been collecting ground motion data continuously since then. Each station comprises side-by-side three-component force-balance broadband (BB) seismometer and strong motion accelerometer (SMA) sensors installed within a surface metal vault anchored to a concrete pad, which was cast directly on and anchored to clean, exposed bedrock [4].

The first non-ergodic HRC was performed using data collected over the first ~14 months of the stations' operation. The initial database comprised 73 unique earthquake events including: 63 shallow continental crustal events, 6 deep inslab events in the Juan de Fuca plate, and 4 shallow transition events in the Juan de Fuca plate at the edge of the continent. Available data from these events recorded at nearby Geological Survey of Canada (GSC) stations was also compiled. The complete database contained 2354 records from 27 stations, including the site of interest. The magnitudes and distances of earthquake events used in the initial database, separated based on type, are presented in Figure 2 (top), for BCH1 and BCH2. Although the two stations are in proximity, there is more background noise at the BCH1 location – thus, less high-quality recordings were available from BCH1. Only 34 of the 73 events provided useable recordings for the BCH1 station.

The analyses were redone using an additional ~17 months of earthquake data (31 months total). The updated database comprised 211 events from 188 crustal events, 16 inslab events, 6 transition events, and 1 offshore event. The complete database, combined with available GSC data, contained 8926 records from 48 stations. The magnitudes and distances of earthquake events used in the updated database are presented in Figure 2 (bottom).

For each record, the total duration was estimated based on magnitude and distance using the PEER NGA-West2 equations for source and path terms [15]. An equal amount of pre-event noise was also retrieved for each record. This noise was used to compute a frequency-dependent signal-to-noise ratio (SNR) for each record by dividing the signal FAS by the noise FAS. Useable frequencies for each record were defined by the frequency band with SNR > 2. Records with less than 30% useable frequencies (computed at 271 log-spaced frequencies from 0.1-50.12 Hz) were considered unusable and excluded from the database. Also, records that appeared erroneous were excluded.

For the selected records, effective amplitude spectrum (EAS) is calculated for the horizontal component acceleration Fourier amplitude spectra (FAS_1 and FAS_2) to derive a rotation independent measure [16]:

$$EAS(f) = \sqrt{1/2(\,FAS_1(f)^2 + FAS_2(f)^2)} \tag{1}$$

Outliers with respect to the BC Hydro EAS GMM ($EAS_{predicted}$) were removed [3]. These are records with EAS(1 Hz) > $EAS_{predicted}$(1 Hz)*$10^{1.3}$ *and* EAS(5 Hz) > $EAS_{predicted}$(5 Hz)*$10^{1.3}$ or EAS(1 Hz) < $EAS_{predicted}$(1 Hz)*$10^{-1.3}$ *and* EAS(5 Hz) < $EAS_{predicted}$(5 Hz)*$10^{-1.3}$.

The total amount of useable data as a function of frequency at the site of interest for the two analysis cases is summarized in Figure 3. The update to the database nearly tripled (~2.9x) the amount of useable data, and significantly increased the amount of data at the extreme frequency ends for each station. The significant increase in the amount of useable data in the high frequency range was due to the addition of many low magnitude, close distance, recordings (particularly at BCH1, which had a relative lack of these type of events in the original database; see: Figure 2 and Figure 3). Several large magnitude, large distance, recordings added additional low frequency useable data at each station.

The database EAS values plotted vs. the BC Hydro EAS GMM for **M**2.5-3 and **M**3.5-4 events in Figure 4 for frequencies of 1.0 and 10 Hz.

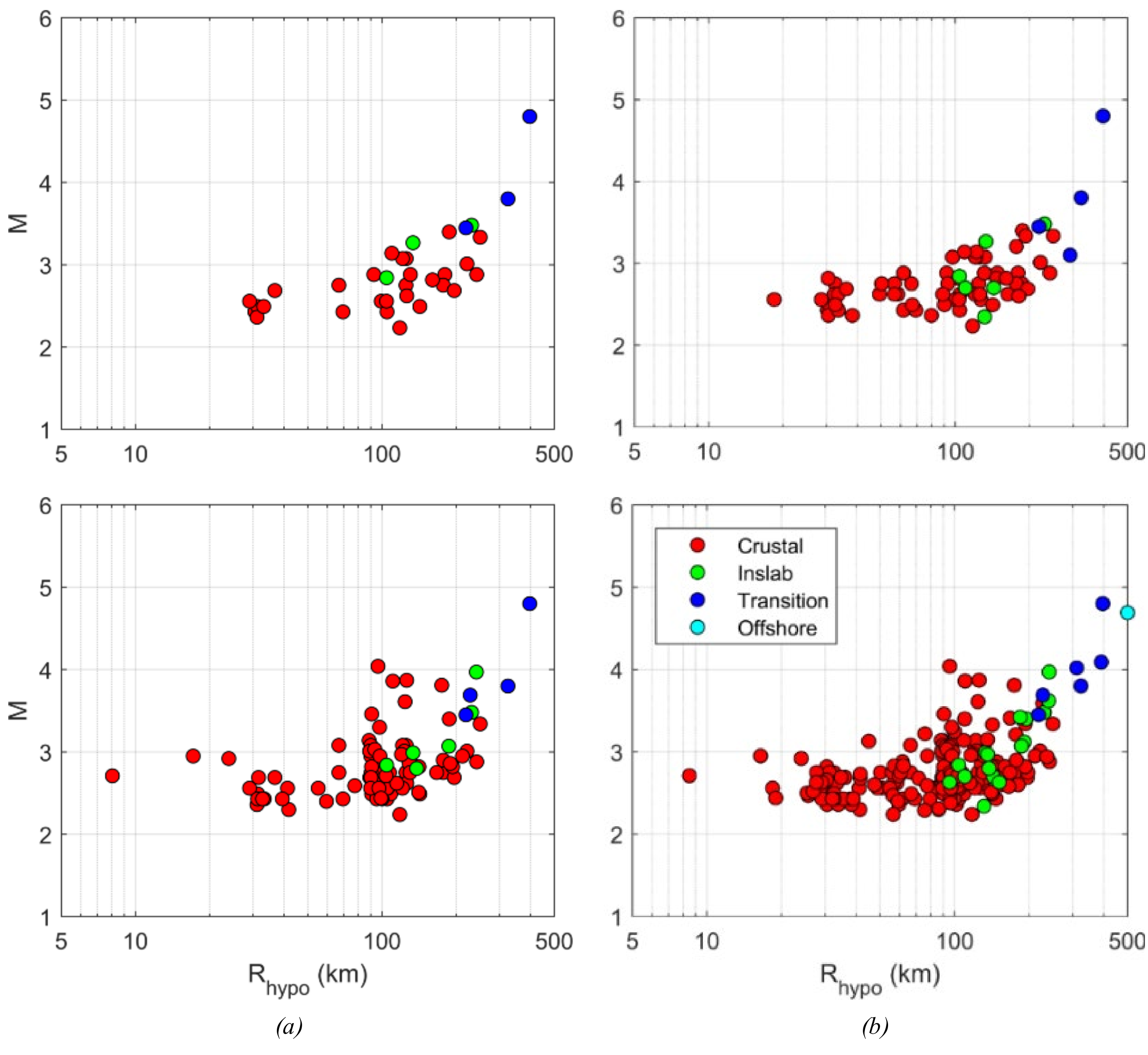
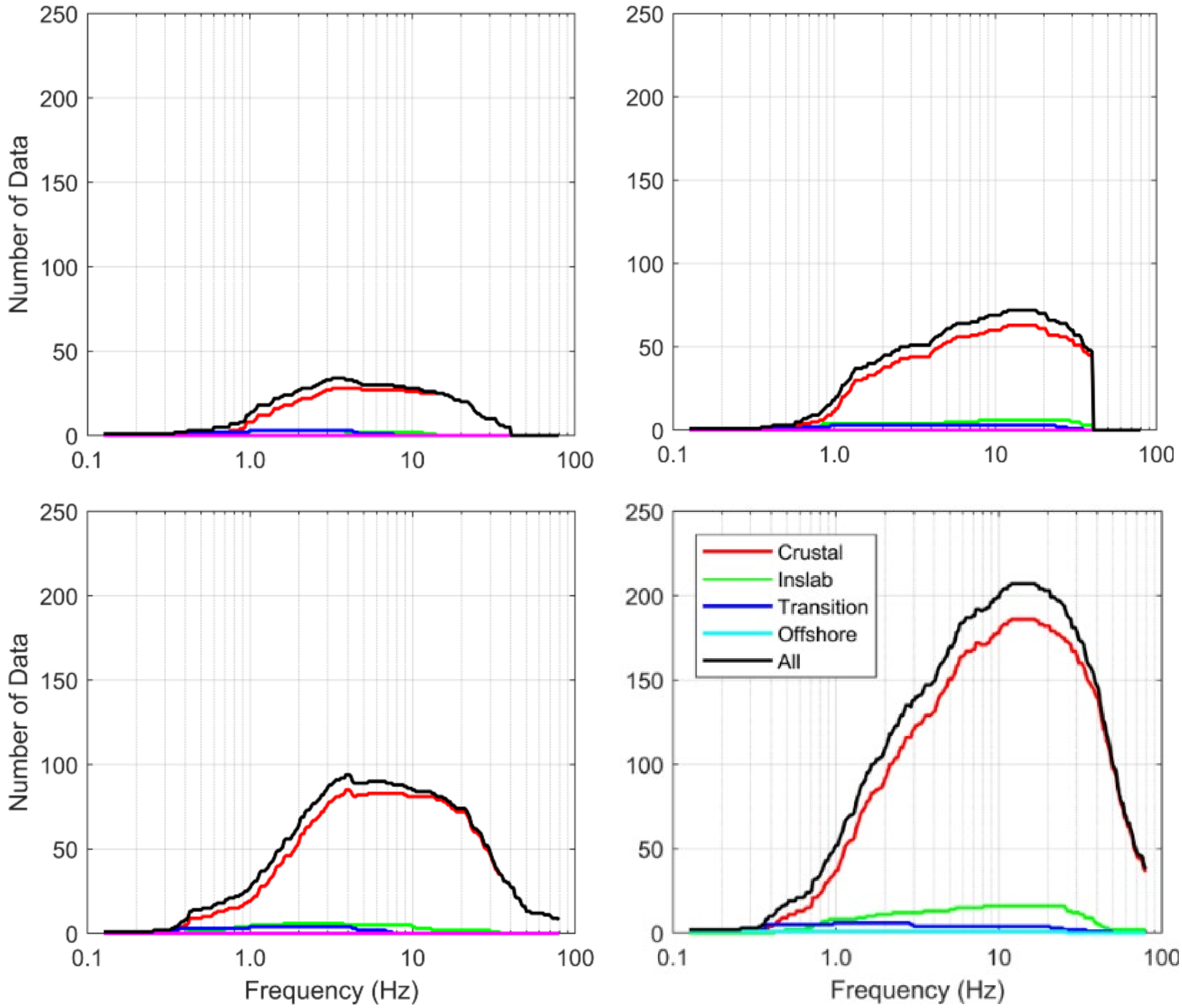


Figure 2. Magnitude-distance plots for the events in the two databases: a) station BCH1; b) station BCH2. Top: the initial 14 months of data; bottom: the total 31 months of data.



(a) *(b)*

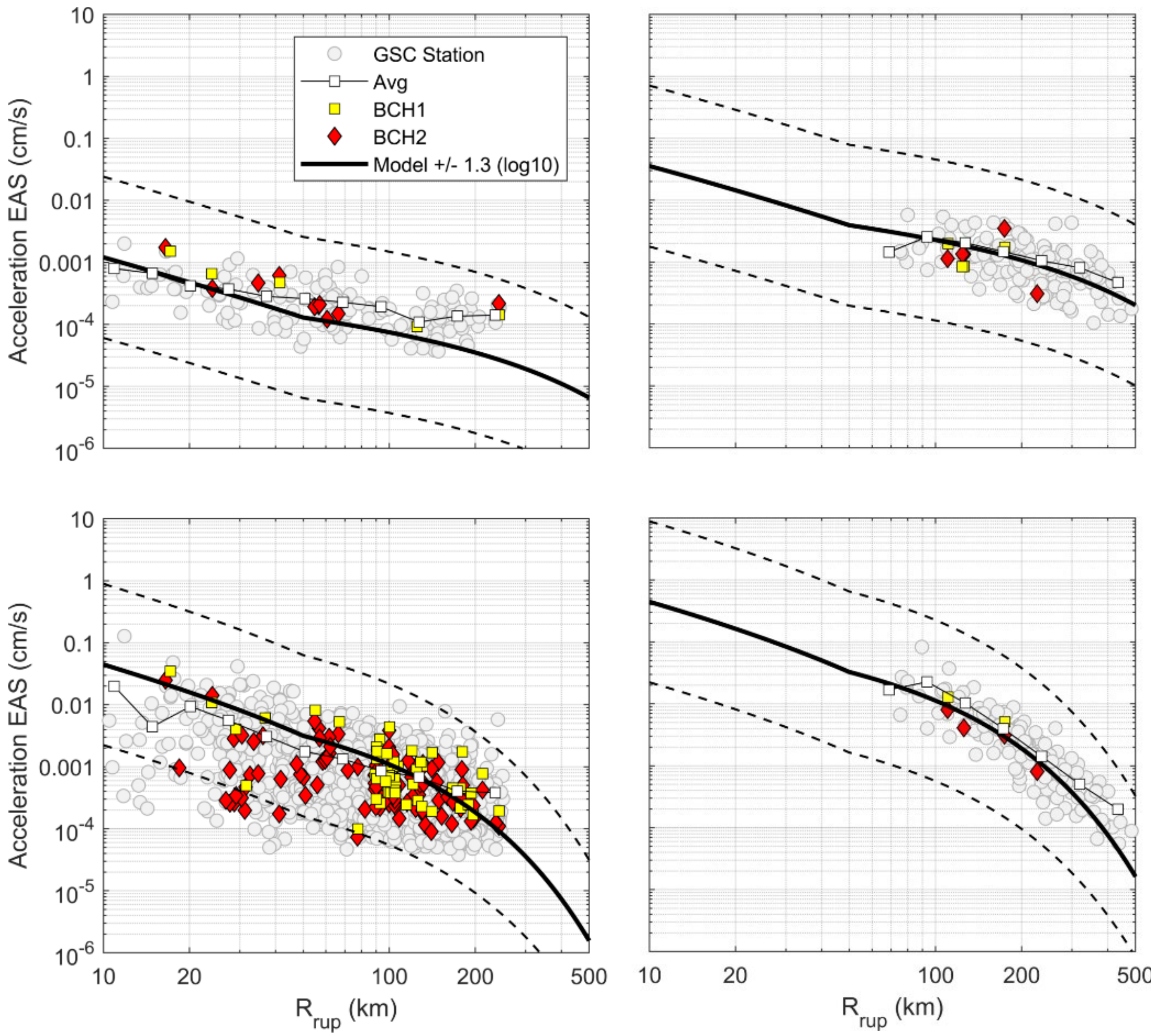
Figure 3. Number of useable data for each frequency, filtered by earthquake type: a) station BCH1; b) station BCH2. Top: the initial 14 months of data; bottom: the total 31 months of data at the site of interest. Useable frequencies are defined as frequencies with SNR > 2.

GENERALIZED INVERSION TO ESTIMATE SITE TERMS

The site-specific ground motion data recorded at the site was used to derive non-ergodic site terms in FAS domain [5]. The main advantage of this approach is that the non-ergodic site term can be estimated directly from site-specific ground motion recordings by performing an inversion/residual analysis - without the need to perform ground response analysis (GRA) (e.g., [18]), which requires assumptions regarding GRA models and their associated input parameters including shear-wave velocity profile, high-frequency attenuation: κ_0, and damping. Additionally, in this approach, the epistemic uncertainty of the site response is equal to the standard error of the non-ergodic site term estimated from generalized inversion or residual analysis, which is easily quantifiable.

Using the compiled database, a generalized inversion was performed to estimate the non-ergodic site terms for each station at the site of interest. In this approach, the EAS of each recording is adjusted for attenuation effects using the attenuation model of the BC Hydro EAS GMM [3] and is written as the sum (in log-space) of a source, site, and error term. The inversion scheme by Andrews [8] is used to simultaneously solve the system of equations for all source, site, and error terms. The trade-off between source and site terms is solved by choosing reference sites and fixing the site terms for these stations. 7 out of the 12 reference stations identified earlier are in the compiled database. Of these sites, 6 were selected and used as reference sites along with their corresponding site terms that are estimated as part of the regional GMM development process.

The estimated site terms at BCH1 and BCH2, and their corresponding standard errors (epistemic uncertainty of the non-ergodic site terms), are shown for the analyses performed with both databases in Figure 5. Note that these site terms are relative to the reference site condition of the inversion (BC hard rock site). The mean site terms are relatively stable between the two analyses; however, their standard errors were significantly reduced with the additional data, especially at the extreme frequency ends (> 15 Hz and < 1.0 Hz). The additional low-frequency data also allowed the terms to be estimated to lower frequencies (below 0.4 Hz).



(a) *(b)*

Figure 4. Ground motion amplitude (EAS) for the crustal records compared to the BC Hydro EAS GMM (± 1.3 log10 units) [3] for: a) ***M****2.5-3.0 (model predictions for* ***M****2.75); b)* ***M****3.5-4.0 (model predictions for* ***M****3.75). Top: frequency = 1.0 Hz. Bottom: frequency = 10 Hz.*

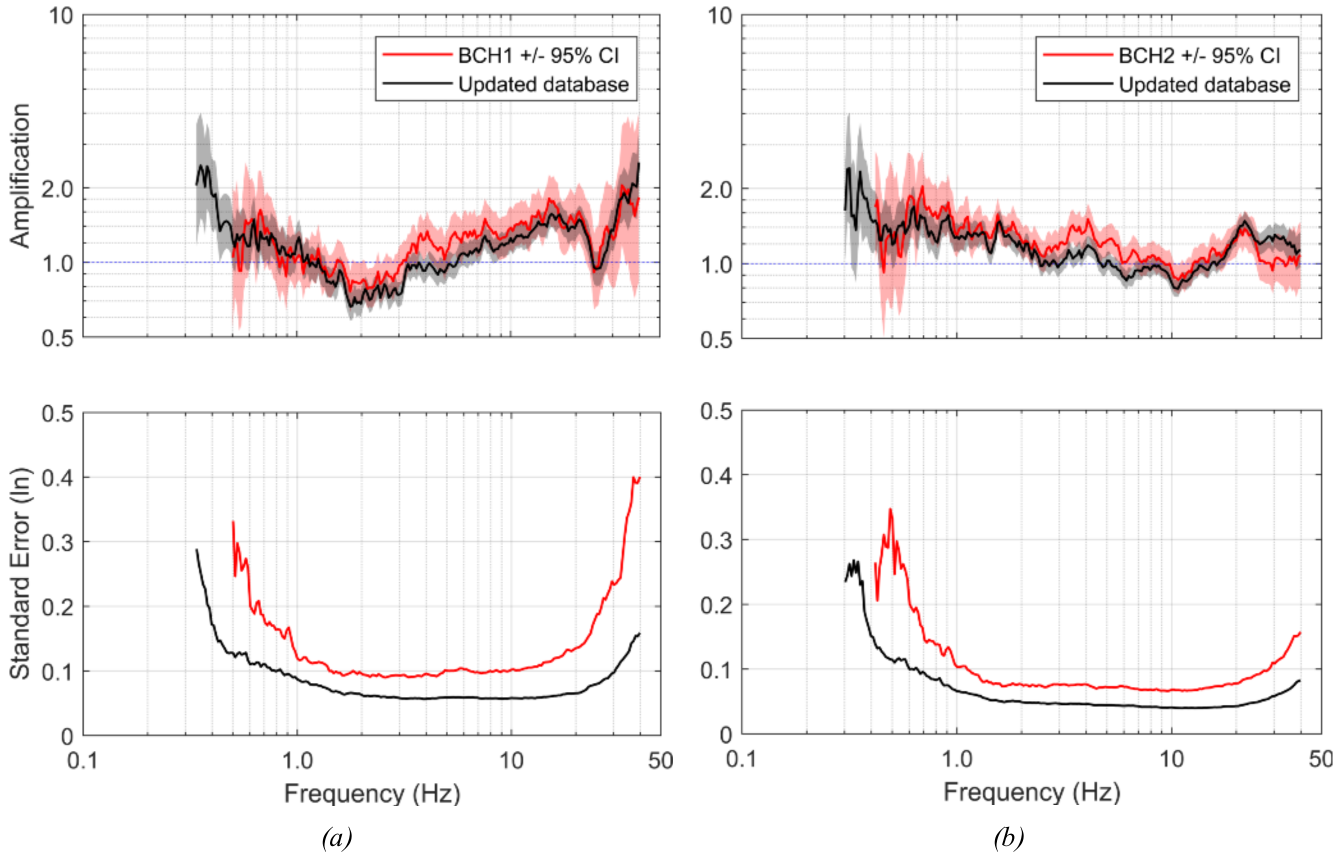


Figure 5. Site terms from the inversions: a) station BCH1; b) station BCH2. Top: mean +/- 95% confidence interval (CI), bottom: standard error.

DERIVATION OF HARD ROCK CORRECTION FACTORS IN PSA DOMAIN

PSA domain hard rock amplification factors (AF) are derived by finding the ratio of Target (i.e., site of interest) to Host (i.e., reference site condition of the 2012 BC Hydro PSHA model, V_{S30} = 760 m/s site) site PSA values derived from ground motion simulations. SMSIM simulations [19] are used for crustal and inslab earthquake scenarios to derive the simulated PSA values. EXSIM is used to perform finite-fault stochastic simulations for the interface earthquake scenarios [20-22]. The simulations are performed for scenarios based on the deaggregation results at the 1/10000 annual exceedance frequency (AEF) hazard level at the site of interest. The modal magnitude and modal distance crustal earthquakes for a 1/10000 AEF are **M**7.2 and 2.5 km (rupture distance), respectively; the modal magnitude and modal distance inslab earthquakes are **M**6.9 and 125 km, respectively; and the modal magnitude and modal distance interface earthquakes are **M**9-9.2 and 175 km, respectively.

There are three main sources of epistemic uncertainty in the hard rock correction process: 1) uncertainty in the non-ergodic site terms estimated relative to the BC generic hard rock site condition; 2) uncertainty in the BC generic hard rock site condition (κ_0 and crustal amplification); and 3) uncertainty in the Host site condition (V_{S30} = 760 m/s) (κ_0 and crustal amplification) as implied by the GMMs used in the 2012 BC Hydro PSHA model. A 5-level logic tree with 3 branches at each level is used to capture this epistemic uncertainty, as illustrated in Figure 6. Each branch of the logic tree discretizes the standard error using a three-point approximation to a normal distribution (weight of 0.63, 0.185, and 0.185 to the mean, the mean + 1.645 standard errors, and the mean -1.645 standard errors, respectively) [23].

The simulation input parameters are based on those from BC Hydro [3] and are the same for Host and Target site conditions except for the values of κ_0 and the crustal amplification. The Host crustal amplification and κ_0 are based on the soft rock site condition implied by the 2012 BC Hydro PSHA GMMs (see: Figure 1 b, c). The Target κ_0 is based on a generic BC hard rock value estimated from GSC recordings at stations located on hard rock sites (mean +/- 1.645σ = 0.0136 +/- 0.0008 s). The Target crustal amplification is the generic BC hard rock crustal amplification (see: Figure 1a) modified by the non-ergodic site terms from the previous section (see: Figure 5). The site terms from Figure 5 were extrapolated below the range with sufficient data to estimate the terms (~0.5 Hz) by assuming a linear decrease to 1.0 at 0.01 Hz (very low frequency), which is consistent with the theoretical site transfer function [24]. Above ~40 Hz the terms were extrapolated by fitting a $\Delta\kappa_0$ function to the amplification curves using an $\exp(-\pi\Delta\kappa_0 f)$ functional form (fit for frequencies >5 Hz). The standard error at these low and high frequencies are assumed to be equal to the standard error as estimated at ~0.4 Hz and the high frequency cut-off of ~40 Hz, respectively.

Figure 7 and Figure 8 show the weighted average non-ergodic hard rock correction factors derived for BCH1 and BCH2, respectively, and their corresponding standard deviations (epistemic uncertainty). The site-to-site variability (ϕ_{S2S}) of the 2012 BC Hydro PSHA model for crustal and subduction earthquakes is also shown [2]. As seen in Figure 7 and Figure 8, the epistemic uncertainty of the non-ergodic hard rock correction factors from both analyses are significantly smaller than ϕ_{S2S} where sufficient site-specific ground motion data are available (~0.4-40 Hz). The additional data has effectively reduced the epistemic uncertainty, especially at the extreme frequency ends. Outside the range where sufficient useable data is available, the epistemic uncertainty is adjusted to converge to ϕ_{S2S} at 0.1 and 100 Hz.

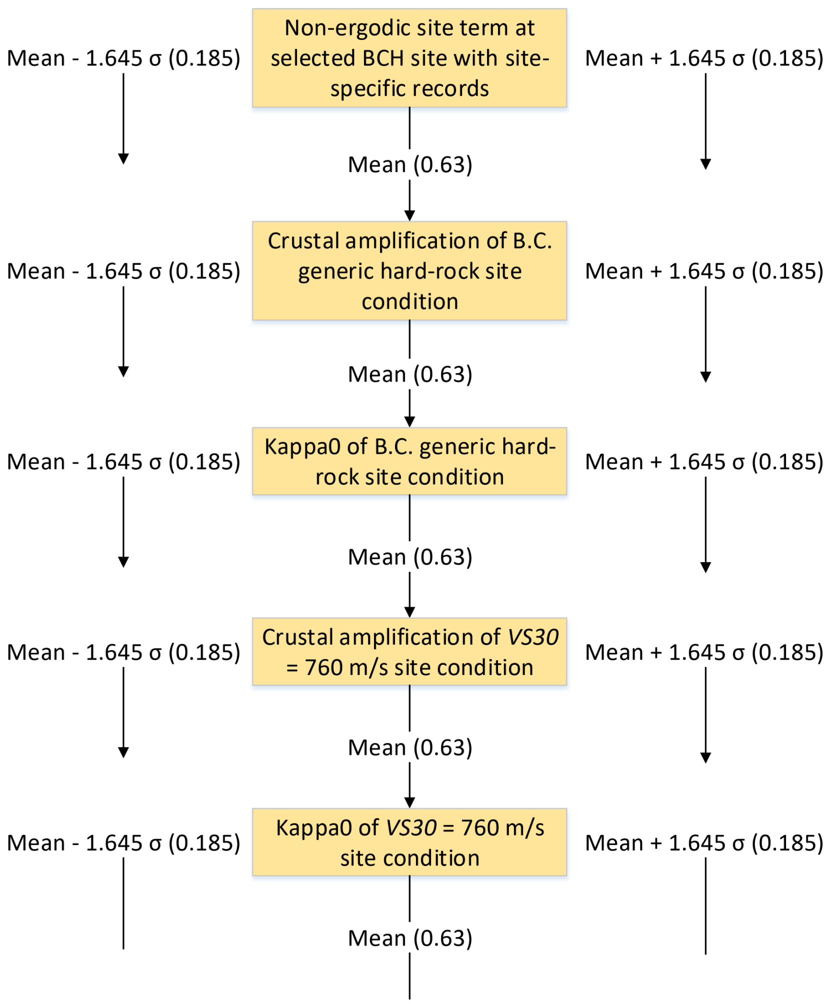


Figure 6. Schematic view of the 5-level logic tree used to quantify the epistemic uncertainty of the non-ergodic hard rock correction factors [3].

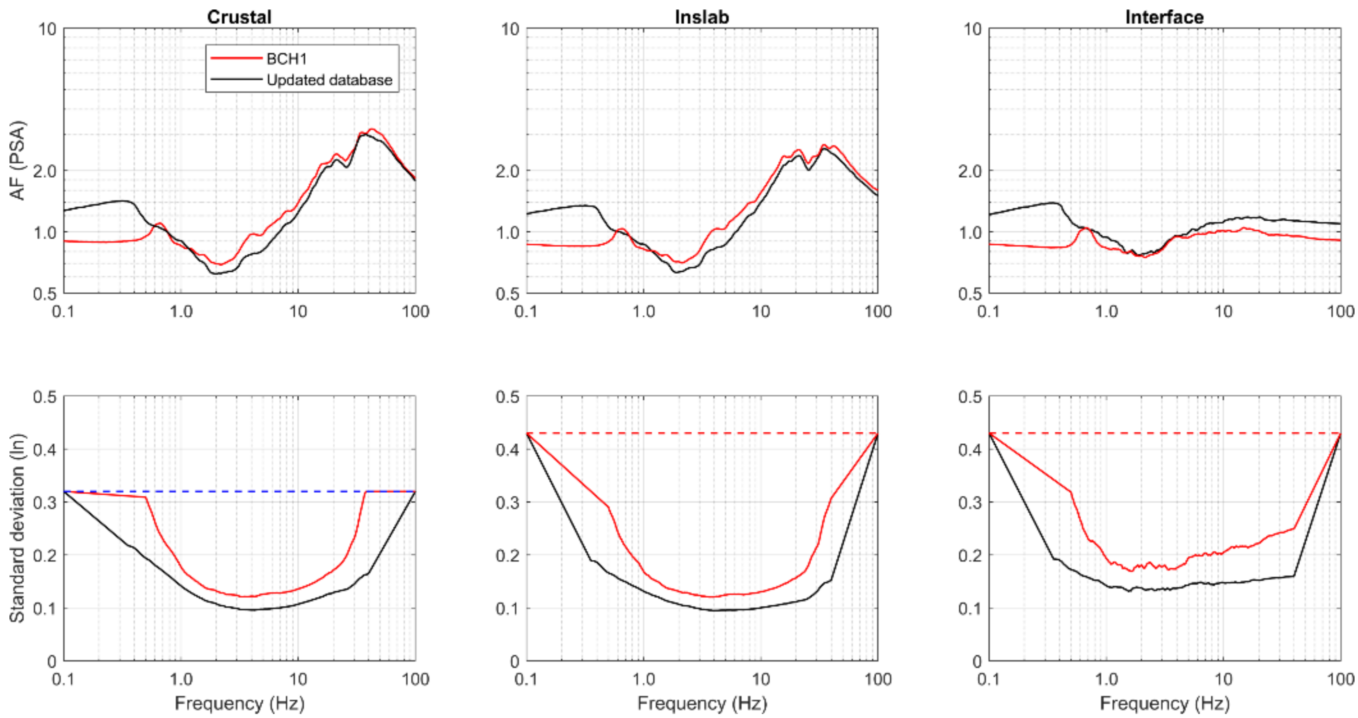


Figure 7. Top: weighted average non-ergodic hard rock correction amplification factors (AF) as a function of oscillation frequency for crustal, inslab and interface earthquake scenarios for BCH1. Bottom: weighted standard deviation of the hard rock correction factors. Also shown are the ϕ_{S2S} used in the 2012 BC Hydro PSHA model for crustal (dashed blue line) and subduction (dashed red line) earthquakes.

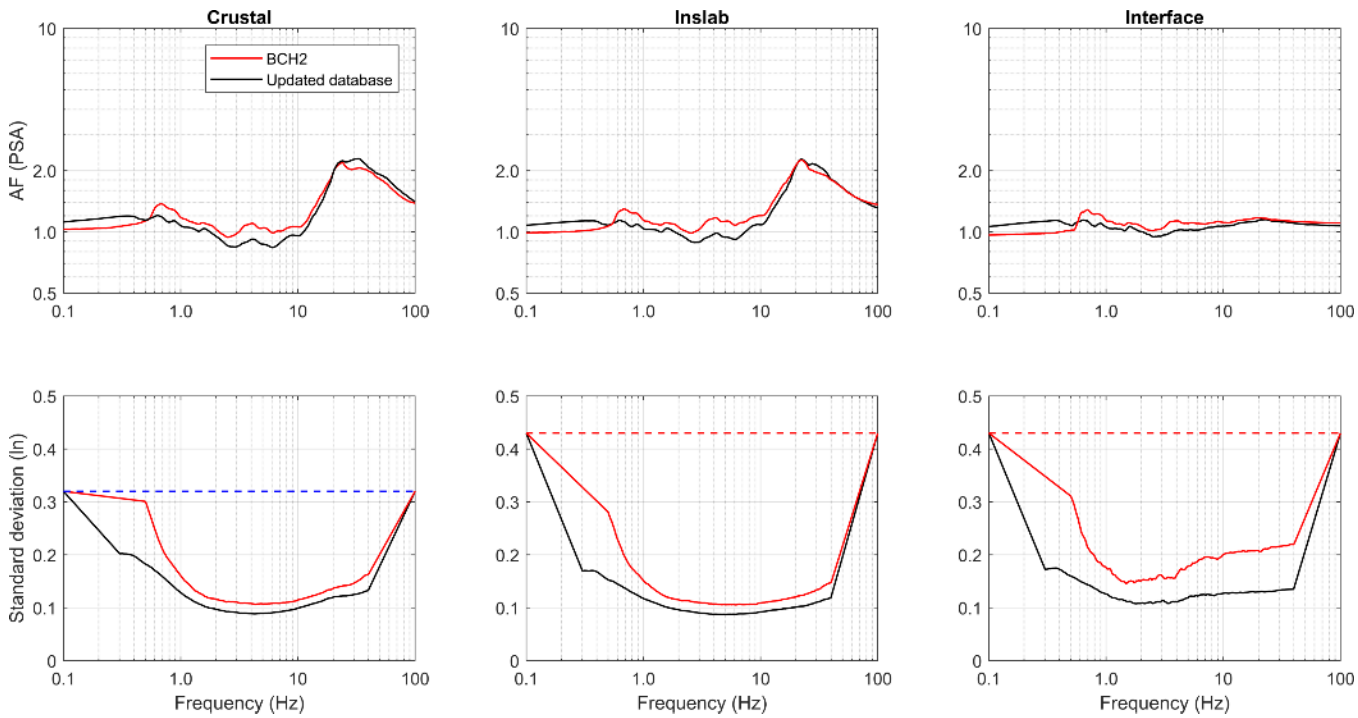


Figure 8. Top: weighted average non-ergodic hard rock correction amplification factors (AF) as a function of oscillation frequency for crustal, inslab and interface earthquake scenarios for BCH2. Bottom: weighted standard deviation of the hard rock correction factors. Also shown are the ϕ_{S2S} used in the 2012 BC Hydro PSHA model for crustal (dashed blue line) and subduction (dashed red line) earthquakes.

HARD ROCK ADJUSTED HAZARD CURVES

To derive hard rock hazard curves, the source-specific PSA domain hard rock correction factors (and associated standard deviations; see: Figure 7 and Figure 8) are convolved with the single-station sigma (SSS) V_{S30} = 760 m/s hazard curves for each of the three earthquake sources affecting the seismic hazard at the site of interest. Approach 3, proposed by McGuire et al. [25], was used for the convolution. This can be written as [26, 27]:

$$\lambda_T(z) = \sum_{x_j} \mathrm{P}\left[AF > \frac{z}{x_j}\middle|x_j\right] P_{SA}\ (x_j) \tag{2}$$

in which λ_T is the adjusted hazard for the Target site condition, z is the ground-motion level at the Target site condition, AF is the amplification function (amplification of the Target site condition with respect to the Host site condition, e.g., hard rock correction factors), $\mathrm{P}[AF > z/x_j\,|x_j]$ is the probability that AF is greater than z/x_j conditioned such that $SA = x_j$, where SA is the spectral acceleration at the Host site condition and $P_{SA}(x_j)$ is the annual probability of occurrence for $SA = x_j$, which can be approximated using the hazard curves of the Host site condition (e.g., integrating over the hazard curves). Assuming that AF has a lognormal distribution, $\mathrm{P}[AF > z/x_j\,|x_j]$ can be written as:

$$\mathrm{P}\left[AF > \frac{z}{\mathrm{x}}\middle|\mathrm{x}\right] = 1 - \Phi\,\left(\frac{\ln\left[\frac{z}{x}\right] - \mu_{\ln AF|x}}{\sigma_{\ln AF|x}}\right) \tag{3}$$

where $\mu_{\ln AF|x}$ is the mean value of $\ln(AF)$ given $SA = x$ and $\sigma_{\ln AF|x}$ is the standard deviation of $\ln(AF)$ given $SA = x$, which represents the epistemic uncertainty of the correction factors.

Figure 9 shows the resulting UHS at BCH1 and BCH2 as a function of oscillation period for 1/10000 and 1/475 AEF hazard levels, together with the corresponding UHS for the site from the original 2012 BC Hydro PSHA model for the V_{S30} = 760 m/s site condition when the SSS and the total variability, including site-to-site (S2S) variability are used in the PSHA calculations.

As seen in Figure 9, the non-ergodic hard rock corrected UHS show smaller amplitudes at oscillation periods larger than ~0.1 s, compared to the corresponding amplitudes from the UHS of the original hazard curves for V_{S30} = 760 m/s. This difference is due to two factors: 1) the correction factors are < 1 from ~0.1-1 s (10-1 Hz), and 2) relatively smaller standard deviation (epistemic uncertainty) with respect to the 2012 BC Hydro PSHA S2S variability model (see: Figure 7 and Figure 8). At periods less than ~0.1 s, the effect of large correction factors appears in the hard rock corrected UHS, and the hard rock corrected UHS amplitudes at both stations are larger than the corresponding values from the original hazard curves (V_{S30} = 760 m/s).

At BCH2, there was a reduction of ~10-20% in the UHS from ~0.1-1.0 s due to the increase in the number of useable data. Since the amplification functions were relatively stable between the two databases (see: Figure 8), the reduction in hazard is due primarily to the reduction in epistemic uncertainty of the non-ergodic site terms (bottom panel in Figure 8). The difference is more drastic for BCH1, which – due to having fewer initial data – had a larger relative increase in data, particularity, useable high-frequency data. At BCH1, there was a similar 10-25% reduction in the UHS from ~0.1-1.0 s due to the increase in the number of useable data. However, there was also up to a 20% reduction in the short period hazard (< 0.1 s), that was not observed at BCH2.

CONCLUSIONS

In this paper, a non-ergodic site correction was performed and used to generate hazard curves and UHS for an example BCH site using two sets of data. The site terms used for the correction were first computed using approximately 14 months of recorded site-specific data, and then updated with an additional 17 months of recording time that almost tripled the number of useable data. The non-ergodic site terms were relatively stable between the two databases; however, the epistemic uncertainty of the non-ergodic site terms was significantly reduced, particularly at the extreme ends of the frequency range (low magnitude, close distance, events adding to the amount of useable high frequency data; higher magnitude, larger distance, events adding to the amount of useable low frequency data). The significant reduction of epistemic uncertainty and slightly modified hard rock correction factors ultimately resulted in a hazard reduction of up to 25%.

Based on these results, it appears that ~1-1.5 years of data, recorded in an active seismic region, (around 70 useable earthquake events) is suitable to estimate non-ergodic site terms at a site over most frequencies (more or less time may be required based on the noise level at the site). Although note that a site in a region with lower seismicity might need longer duration to record enough usable data. An additional 17 months of recording data did not significantly modify the original terms other than refining the terms at the extreme frequency ends. Updating the database with nearly triple the amount of useable data (around 210 useable earthquake events) did, however, lower the epistemic uncertainty corresponding the site terms, especially at the extreme frequencies. This reduction in uncertainty was carried through the analysis and ultimately lowered the resulting UHS at the site. This is important to consider when determining how long to plan to record site-specific data at a site for use in non-ergodic hard rock correction – especially if the structure is sensitive to high-frequency ground motion, which is particularly difficult to capture due to background site noise, and thus, may see a large reduction in epistemic uncertainty from the additional data.

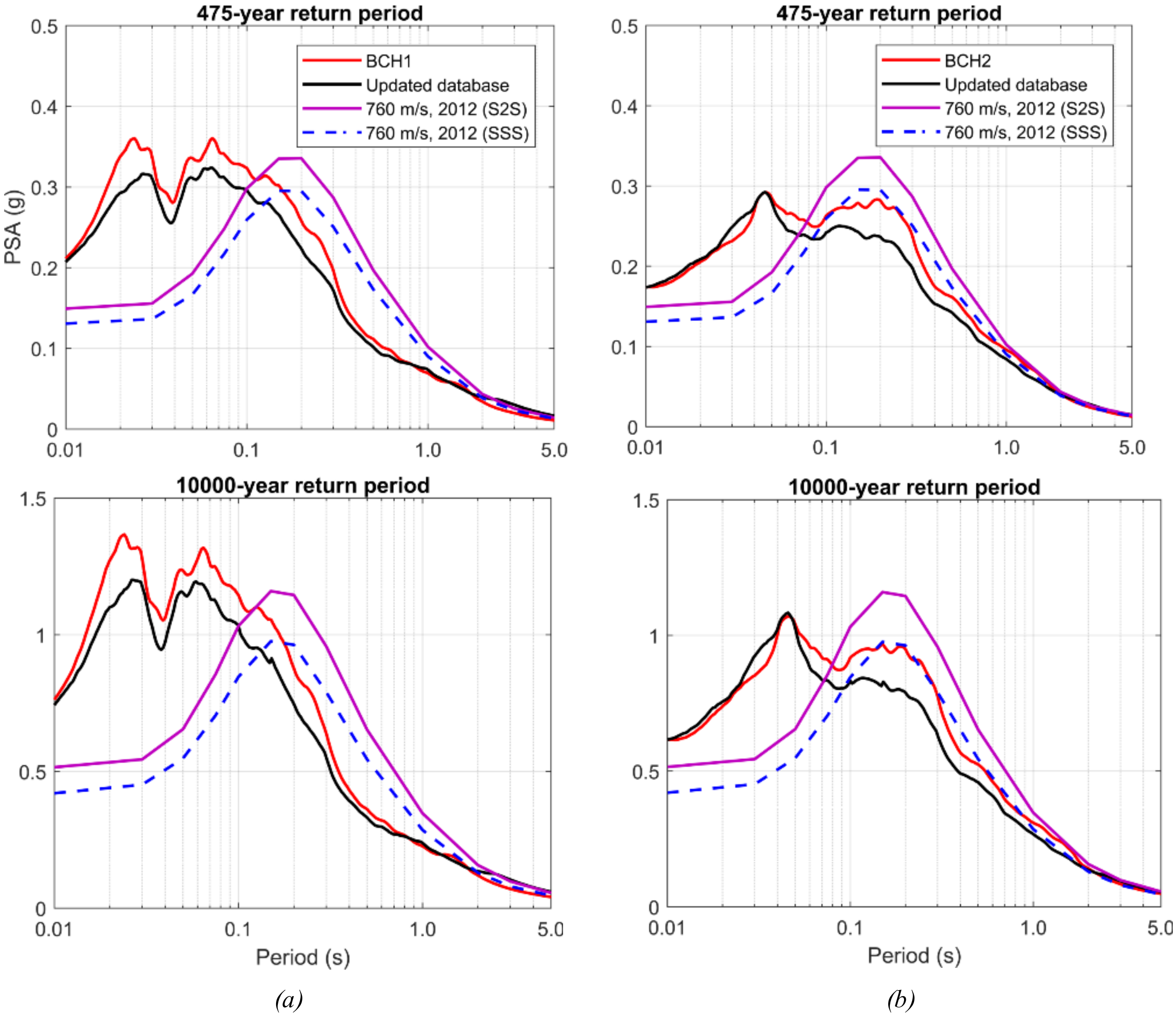


Figure 9. Non-ergodic hard rock adjusted UHS as a function of oscillation period for: a) station BCH1; b) station BCH2. Top: 1/10000 AEF hazard level; bottom: 1/475 AEF hazard level. UHS are also shown for the original 2012 BC Hydro PSHA model for the V_{S30} = 760 m/s site condition when both the SSS and the total variability (including S2S variability) are used in the PSHA calculations.

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