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Effect of Horizontal Component Definition on the Characterization of Vertical Ground Motions: Application to Eastern Canada

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Abstract: In this paper, ground motions recorded on rock sites in eastern Canada are studied in order to characterize their vertical acceleration components. Emphasis is placed on the sensitivity of vertical-to-horizontal spectral ratios to: (i) inter-component intensity correlations, and (ii) the use of geometric mean horizontal components at each site instead of considering them individually. Four different definitions of horizontal components are investigated. Vertical-to-horizontal spectral ratios are compared with the findings of other researchers. We illustrate how the results can be used to evaluate vertical acceleration demands on rock sites in eastern Canada.

Key words: Earthquakes; Vertical accelerations; Eastern Canada ground motions; Vertical-to-Horizontal spectral ratios; Intraplate earthquakes; Ground motion correlations; Principal directions.

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1 Introduction

The question of whether or not to explicitly include the vertical component in seismic design and safety evaluation of structures is one that has recently gained renewed interest. This is mainly due to the availability and increasing popularity of advanced and efficient modeling and computational tools, combined with the emergence and requirements of performance-based approaches. The characterization of vertical ground motions in a given region is a first crucial step to ensure the appropriate selection of seismic input for multidirectional time-history or modal response spectrum analyses. Ambraseys and Simpson [1996] studied historical records from European, Western US (WUS), New Zealand, and Nicaragua events. They observed high vertical-to-horizontal spectral ratios in excess of 1.5 for near-field events in short period ranges. Bozorgnia et al. [1998] investigated the dependence of vertical-to-horizontal spectral ratios of the 1994 Northridge earthquake records on period and source-to-site distance. They mainly found that near-field low period ratios exceeded 1. They proposed an approximate vertical spectrum obtained by shifting the horizontal acceleration response spectrum to shorter periods by a period shift factor of about 2 and reducing it by applying distance-dependent vertical-to-horizontal spectral ratios. Christopoulos et al. [2003] studied the vertical components from a database of 45 historical ground motions recorded on rock and stiff soil sites from Western North America (WNA), Eastern Europe and Japan. They concluded that the $2/3$ value commonly recommended by codes worldwide [Shrestha, 2009] is generally a good approximation of the ratio of vertical-to-horizontal PGAs, but is inadequate to describe the relationship between horizontal and vertical spectral accelerations because of differences in frequency content between both components. Christopoulos et al. [2003] recommended shifting and reducing the horizontal spectrum to obtain vertical accelerations, and suggested a shift factors from 1.55 to 1.60 towards shorter periods and reduction factors from 0.55 to 0.8 depending on the ratio of peak ground acceleration to velocity. The coefficients proposed by Christopoulos et al. [2003] were used later by Wanitkorkul and Filiatrault [2005] to simulate vertical ground motions for seismic fragility evaluation of nonstructural components in hospitals in Eastern North America (ENA). Malhotra [2006] studied the smooth spectra of horizontal and vertical ground motions based on the analysis of 63 records from 33 rock and 30 soil sites. He confirmed that the vertical-to-horizontal spectral ratio is frequency-dependent and found that this dependence is more pronounced for soil sites than for rock sites. Malhotra [2006] also showed that the short-period vertical-to-horizontal ratios are roughly 0.55 and 0.75 for rock and soil sites, respectively, and that they decrease to approximately 0.4 and 0.3 at a period of 1 s, respectively. Lopez et al. [2006] investigated the response spectra characteristics of the principal components of 97 near- and far-fault ground motions recorded on rock and soil sites during 25 historical earthquakes that occurred in California, Chile, Japan, and Taiwan. In particular, they determined the principal response spectra and their ratios and studied the influence of source to site distance on the obtained principal response spectra. They found that principal vertical accelerations could be either greater than or less than major principal horizontal accelerations, but that in far-fault sites, vertical acceleration spectra were below both major and minor principal horizontal acceleration spectra, with ratios varying between 0.34 and 0.69. In the short period range of near-fault sites, they reported ratios between vertical and major principal horizontal acceleration spectra between 0.3 and 1.33.

It is common practice to obtain vertical acceleration demands by scaling code-prescribed design or uniform hazard spectra for horizontal accelerations. This scaling can be based on frequency-independent or frequency-dependent spectral ratios as mentioned previously. In the former case, the conventional average $V/H = 2/3$ is usually adopted. It is important however to relate the suitability of the applied spectral ratio to the type of measure used to determine the horizontal accelerations of the particular code-prescribed design or uniform hazard spectrum considered. In previous studies characterizing vertical-to-horizontal spectral ratios V/H, the effect of horizontal components recorded along each horizontal direction taken separately were generally considered. The effect of intensity correlations between three ground motion components recorded at a given site on the assessment of vertical seismic hazard did not receive much attention in the literature. The influence of considering the geometric mean of horizontal components instead of individual components has not been investigated either. Such information is however important since geometric mean measure is commonly used to define horizontal spectral demands in GMPEs [Boore et al. 2006; Campbell and Bozorgnia 2007] and code prescribed UHS [Stewart et al. 2011]. We note that H/V Fourier spectra ratios and V/H response spectra ratios are also usually studied to determine site response. For example, Nakamura's H/V technique can be used to determine site amplification, resonant frequency, and empirical transfer functions [Lermo and Chavez-Garcia, 1993; Zhao et al., 2006; Nakamura, 2008; Ghofrani et al., 2013]. These ratios are strongly dependent on site conditions and vary with soil type and depth to bedrock. In this work however, we focus on the characterization of V/H ratios on rock sites due to the limited number of available recordings within magnitude and distance ranges of interest to structural engineering applications in eastern Canada.

2 Scope and objectives

Although eastern Canada is situated in a stable intra tectonic plate region, it has been shaken by several moderate to strong historical earthquakes [Mitchell et al. 1990 ; Adams et al. 1995 ; Lamontagne et al. 2008]. The investigation of these events has revealed two principal trends: (i) a higher frequency content than in WNA, and (ii) a slower attenuation of ground motions. Most of the studies characterizing or modeling ENA seismic hazard focused on horizontal components of ground motions [Atkinson and Boore 1995 ;Campbell 2003 ;Atkinson 2008 ;Pezeshk et al., 2011]. McGuire et al. [2001] proposed a predictive model of vertical-to-horizontal spectral ratios as part of a process to develop seismic design ground motions for nuclear facilities in the US. This model included several assumptions to account for seismological regional differences between rock sites in western US (WUS) and central and eastern US (CEUS). Their study revealed that CEUS V/H spectral ratios could be estimated by: (i) shifting the WUS V/H ratios towards higher frequencies, and (ii) scaling up the low frequency WUS V/H ratios. Siddiqqi and Atkinson [2002] compiled mean horizontal-to-vertical, i.e. H/V, Fourier spectra computed using digital three-component seismograms of events of magnitude $2 \leqslant M < 5$, recorded between 1993 and 1998 on rock sites in Canada. Their study revealed that average spectral ratios H/V

for rock sites do not vary significantly across Canada, and that they are weakly frequency-dependent, globally decreasing from a value in the range of 1.2 to 1.6 at 0.1 s to near unity at 2 s.

Previous research clearly shows that there is still a need for additional results to reduce the uncertainty associated with vertical ground accelerations in Eastern Canada, namely by considering new data recorded recently during stronger events such as Rivière-du-Loup (2005) and Val-des-Bois (2010) earthquakes. This work aims to characterize near- and far-field vertical ground motions recorded on rock sites during the $M_{\mathrm{W}}\,4.9$ Miramichi (1982), $M_{\mathrm{W}}\,6.8$ Nahanni (1985), $M_{\mathrm{W}}\,5.9$ Saguenay (1988), $M_{\mathrm{W}}\,4.3$ La Malbaie (1997), $M_{\mathrm{W}}\,4.9$ Cap Rouge (1997), $M_{\mathrm{W}}\,3.3$ La Malbaie (2003), $M_{\mathrm{W}}\,3.7$ Thurso (2006), $M_{\mathrm{W}}\,3.8$ Baie-Saint-Paul (2006), $M_{\mathrm{W}}\,4.7$ Rivière-du-Loup (2005), $M_{\mathrm{W}}\,3.6$ Rivière-du-Loup (2008), and $M_{\mathrm{W}}\,5.2$ Val-des-Bois (2010) events. A particular attention will be devoted to investigating the sensitivity of vertical-to-horizontal spectral ratios to: (i) inter-component intensity correlations of the studied ground motions, and (ii) the use of geometric mean horizontal components at each site instead of considering them individually. More specifically, the effects of using four different definitions of horizontal components are investigated herein: (i) horizontal recorded components taken independently; (ii) geometric mean of recorded components at each recording station; (iii) principal horizontal components taken independently; and (iv) geometric mean of principal horizontal components at each recoding station. The relationship to code-prescribed horizontal seismic demands in Eastern Canada is also illustrated.

3 Ground motions studied

3.1 Recorded data

For each of the eleven earthquakes described above, we investigate the time histories of ground accelerations a_X, a_Y and a_Z recorded at different sites along instrument horizontal axes X and Y, and vertical axis Z, respectively. The studied accelerograms were obtained from different sources [LDEO 2007, GSC 2011, Atkinson 2011]. Table 1 contains the main characteristics of the selected ground motions, including the name of the recording site, the date and time of the event, the moment magnitude M_{W}, the station coordinates, the type of subsoil, the epicentral distance r_{E}, the hypocentral depth h_{F}, and the Peak Ground Accelerations (PGAs) a_X^*, a_Y^* and a_Z^* along the orthogonal components X, Y and Z, respectively. The distribution of magnitudes from $M_{\mathrm{W}}\,3.3$ to $M_{\mathrm{W}}\,6.8$ as a function of epicentral distances ranging from 0.8 to 150 km is illustrated in Fig. 1 for the seismic data studied herein. We note that moment magnitude scale was used for all the earthquakes studied for consistency and comparison purposes. The moment magnitudes reported in Table 1 were obtained from Bent [2009] and USGS [2012] when available, or using conversion expressions proposed by Macias-Carrasco et al. [2010] otherwise.

3.2 Uncorrelated data

The accelerations recorded along the three orthogonal components of an earthquake are naturally correlated, considering that they result from the same ground motion source and same seismic waves traveling through the same medium from source to site. The correlation between the three ground motion components recorded at each station can be investigated by examining the individual contributions of each component to the total energy released during the shaking. Penzien and Watabe [1975] showed that the three-component accelerations recorded at a given site can be stochastically uncorrelated to obtain three principal components corresponding to maximum, intermediate and minor directions along which maximum, intermediate and minor earthquake energy is released, respectively. These directions and corresponding accelerations can be obtained as the eigenvectors and eigenvalues of the tensor I of earthquake intensities defined by Arias [1970] as

$$I_{ij} = \frac{\pi}{2\mathrm{g}} \int_{t_0}^{t_\mathrm{f}} a_i(t)\, a_j(t)\, \mathrm{d}t \qquad i, j = X, Y, Z \tag{1}$$

where g is the acceleration due to gravity, a_i is the acceleration along direction i, and t_0 and t_f denote the first and last times of the interval of interest of the shaking duration, respectively. In this work, we use a Trifunac-Brady duration [Trifunac and Brady 1975] corresponding to a time interval $\Delta t_\mathrm{TB} = t_\mathrm{f} - t_0$ during which the earthquake releases between 5% and 95% of its Arias intensity [Arias 1970]. In what follows, the results related to the principal components will be referred to as *uncorrelated*, while those corresponding to the original data will be referred to as *recorded*.

4 Ratios of vertical-to-horizontal PGAs of the studied ground motions

One way to estimate the amplitude of the vertical component of an earthquake consists of relating it to that of the horizontal component through the ratio η_0 of vertical-to-horizontal PGAs. This ratio has been investigated by several researchers, such as Newmark [1973], Lew [1992], Perea and Esteva [2004], and Kalkan and Gülkan [2004], Collier and Elnashai [2001] and Bommer et al. [2011], using data from different regions. It was generally found that this ratio decreases gradually with increasing rupture distance, suggesting the higher severity of the vertical component of near fault ground motions.

Fig. 2 (a) presents the variation of the vertical-to-horizontal PGA ratios η_0 of the ground motions studied, obtained as a^*_Z/a^*_X and a^*_Z/a^*_Y at each recording site. As expected, large vertical-to-horizontal PGA ratios characterize near field ground motions, such as those of Miramichi and Nahanni at epicentral distances less than $10\,$km. However, η_0 ratios larger than 1 are also observed for ground motions at higher epicentral distances around 45 to $60\,$km, i.e. some recording stations of Val-des-Bois (2010) and Rivière-du-Loup (2005). A linear trend is obtained for data decreasing from around $\eta_0 = 0.95$ at the very near field to $\eta_0 = 0.5$ at $r_\mathrm{E} = 160\,$km. η_0 ratios less than 0.5 are obtained for some ground motions at epicentral distances from the near to the far field. Fig. 2 (a) also reveals that the mean of η_0 ratios are 0.82, higher than the commonly adopted assumption of $\eta_0 = 2/3$.

Vertical-to-horizontal PGA ratios η_0 of the uncorrelated ground motions are computed as $a^*_V/a^*_{H_1}$ and $a^*_V/a^*_{H_2}$ at each site, where $a^*_{H_1}$, $a^*_{H_2}$ and a^*_V denote the PGAs along principal directions H_1, H_2 and V, respectively. Fig. 2 (b) illustrates the effect of correlation of ground motions on vertical-to-horizontal

PGA ratios. We observe that the η_0 ratios of uncorrelated ground motions are generally slightly higher than the recorded ones in both the near and far field. This can be clearly seen from the linear trend, now decreasing from around $\eta_0 = 0.98$ at the very near field to around $\eta_0 = 0.6$ at epicentral distance $r_{\mathrm{E}} = 160$ km. As previously, the mean of η_0 ratios are larger than $2/3$, and are equal to 0.86, practically the same values as for recorded data.

Geometric mean is commonly used to define horizontal spectral demands in GMPEs [Boore et al. 2006; Campbell and Bozorgnia 2007] and code prescribed UHS [Stewart et al. 2011]. It is therefore important to evaluate the effect of using geometric mean of horizontal components on vertical-to-horizontal PGA ratios. For this purpose, vertical-to-horizontal PGA ratios $\bar{\eta}_0$ are determined at each site as $a_Z^*/\sqrt{a_X^*\, a_Y^*}$ and $a_V^*/\sqrt{a_{H_1}^*\, a_{H_2}^*}$ for recorded and uncorrelated ground motions, respectively. Figs. 2 (c) and (d) illustrates the obtained results. It is seen that the mean of $\bar{\eta}_0$ ratios for recorded data is 0.81. This value increases to 0.82 for uncorrelated data. We note that the mean $\bar{\eta}_0$ ratios are slightly closer to $2/3$ than η_0 ratios. The slope of the linear slightly decreasing trend of $\bar{\eta}_0$ is also similar to that of η_0, with a linear variation from around $\bar{\eta}_0 = 0.93$ (respectively $\bar{\eta}_0 = 0.90$) at the very near field to around $\bar{\eta}_0 = 0.5$ (resp. $\bar{\eta}_0 = 0.6$) at $r_{\mathrm{E}} = 160$ km for recorded data (resp. uncorrelated data).

To better illustrate the differences between the trends observed in Figs. 2 (a) to (d), they are plotted in Figs. 3 (a) and (b), along with their 95% confidence limits. We remark that the slight variations observed between η_0 ratios corresponding to recorded and uncorrelated PGA ratios, for both three component and two component geometric mean analyses, are negligible when compared with their 95% confidence limits. This suggests that decorrelation has little to no influence on η_0 ratios of the rock site ground motions studied herein. Figs. 3 (a) and (b) also clearly illustrate that η_0 ratios corresponding to recorded and uncorrelated accelerograms exhibit a slightly decreasing trend as epicentral distance increases. As previously discussed, this behavior was also observed by other researchers such as Collier and Elnashai [2001] and Bommer et al. [2011].

The V/H ratios are generally variable over the frequency spectrum, the 5%-damped horizontal and vertical acceleration response spectra of the previously described recorded and uncorrelated accelerograms are computed and investigated hereafter.

5 Frequency-dependent vertical-to-horizontal ratios of the studied ground motions

To further characterize the frequency-dependence of the relationship between horizontal and vertical spectral accelerations, we consider the following ratios defined at each period T as

$$\eta(T) = \left\{ \frac{A_Z(T)}{A_X(T)}, \frac{A_Z(T)}{A_Y(T)} \right\}; \qquad \bar{\eta}(T) = \frac{A_Z(T)}{\sqrt{A_X(T)\, A_Y(T)}} \tag{2}$$

for recorded accelerograms, and

$$\eta(T) = \left\{ \frac{A_V(T)}{A_{H_1}(T)}, \frac{A_V(T)}{A_{H_2}(T)} \right\} ; \qquad \bar{\eta}(T) = \frac{A_V(T)}{\sqrt{A_{H_1}(T)\, A_{H_2}(T)}} \tag{3}$$

for uncorrelated accelerograms.

These ratios are studied next for periods T up to 2 s. A larger period range is considered for comprehensive identification of global trends, although spectral ratios for periods $T \geqslant 1$ s should be interpreted with care because of the generally vanishing spectral accelerations at these periods as well as possible long-period noise due to analog-to-digital conversions.

Fig. 4 presents recorded and uncorrelated frequency-dependent η and $\bar{\eta}$ ratios obtained for all the studied records. Figs. 4 (a) and (b) show that the mean values of η spectral ratios are bracketed between $2/3$ and 1 approximately for recorded and uncorrelated data. The mean values of η slightly exceed 1 over a period range between 0.4 s and 1.3 s. The same remarks can be made for $\bar{\eta}$ as can be seen from Figs. 4 (c) and (d).

Fig. 5 presents the mean values of η and $\bar{\eta}$ spectral ratios with their 95% confidence limits. The results confirm that η and $\bar{\eta}$ spectral ratios are practically similar for recorded and uncorrelated data, with only minor variations visible, which suggests that uncorrelating accelerograms does not have a significant effect on the vertical-to-horizontal characterization of the studied ENA ground motions. Comparing Fig. 5 (a) to Fig. 5 (b) reveals that frequency-dependent characterization of vertical-to-horizontal acceleration spectral ratios is practically insensitive to using two horizontal components separately or a single geometric mean horizontal component, when either recorded or uncorrelated data are used. Finally, the previous analyses confirm that the studied ENA ground motions obey the common observation that maximum vertical spectral accelerations are generally lower than maximum horizontal ones.

The obtained mean values of vertical-to-horizontal spectral ratios are compared next to results from other researchers. Fig. 6 (a) compares the frequency-dependent vertical-to-horizontal spectral ratios proposed by McGuire et al. [2001] for CEUS rock sites to the mean values of η ratios. McGuire et al. [2001] recommend three series of frequency-dependent V/H spectral ratios for three ground motion categories differing by expected maximum horizontal PGAs: PGA < 0.2 g, 0.2 g $\leqslant$ PGA $\leqslant 0.5$ g and PGA > 0.5 g. We note that although most of the ground motions studied in the present work have PGAs less than 0.2 g, the ratios corresponding to the two other categories are also shown in Fig. 6 (a) for comparison purposes. It is seen that the obtained mean η ratios: (i) agree with the increasing and then decreasing trend of the predictive model of McGuire et al. [2001] over the short period range from 0 to about 0.1 s, (ii) is generally higher or equal to those proposed by McGuire et al. [2001] for PGA < 0.2 g over the same short period range, and (iii) vary differently from the constant ratios predicted by McGuire et al. [2001] for $T > 0.1$ s, i.e. $2/3$ for ground motions with PGA < 0.2 g. Most of the predictions however fall within the 95% confidence limit, with only a small section falling slightly outside it. We note that the model suggested by McGuire et al. [2001] to predict V/H ratios for CEUS ground motions was developed based on a point-source computational predictive model for WUS records. The original WUS model was validated against rock site records from the 1989 M6.9 Loma Prieta earthquake. This model was then extended using generic CEUS crustal conditions to account for differences between WUS and CEUS seismic hazard characteristics. The results mainly showed that CEUS V/H spectral ratios could be estimated by: (i) shifting the WUS V/H ratios towards higher frequencies, and (ii) scaling up the low frequency WUS V/H ratios by about 50%, i.e. a factor of 1.5. Although such a simple point-source model provides a basis for comparison of the impact of different generic crustal conditions on V/H spectral ratios, it is associated with a fair amount of uncertainty as it includes several assumptions and was not validated against other models [McGuire et al., 2001; Silva and Costantino, 2002]. Because of this, and also for practical purposes, the recommended CEUS V/H spectral ratios were smoothed in the low frequency range as described by McGuire et al. [2001], thus yielding the flattened curves after 0.1 s in Fig. 6 (a).

The mean values of the horizontal-to-vertical, i.e. H/V, Fourier spectra ratios obtained by Siddiqqi and Atkinson [2002] are first inverted and then compared to the mean η ratios in Fig. 6 (a). Spectral ratios corresponding to all rock sites from all over Canada considered by Siddiqqi and Atkinson [2002] as well as those only from eastern Canada are depicted. We observe a very good agreement between mean η ratios and Fourier spectral ratios corresponding to eastern Canada rock sites for periods 0.05 s $\leqslant T \leqslant 0.2$ s. After this period range, increasing trends are observed for both types of results until 0.4 s, but higher η mean values are observed. This is followed by a continuously increasing trend of mean Fourier spectral ratios, while η mean values decrease until they join up at a value of 1 at 2 s. We remark that the V/H Fourier spectra ratios corresponding to eastern Canada fall entirely within the 95% confidence limits of the obtained mean η ratios.

To characterize vertical-to-horizontal principal accelerations, Lopez et al. [2006] studied the spectral ratio

$$\hat{\eta}(T) = \frac{A_V(T)}{A_{H_1}(T)} \tag{4}$$

and proposed predictive equations based on the results corresponding to near fault and far fault ground motions recorded from 25 earthquakes that occurred in California, Chile, Japan, and Taiwan. Fig. 6 (b) compares the predictions of these equations to the $\hat{\eta}$ ratio mean values obtained in this work. It is clearly seen that the predictions do not match the spectral ratios of the eastern Canada records studied, except for very short periods where a good agreement is found. In particular, the $\hat{\eta}$ mean values do not exhibit the pronounced bell-shaped variations between 0.02 s and 0.3 s nor the troughs after this period, but rather only slight variations between 0.02 s and 0.3 s followed by an increase after this period. These particular trends are in line with those discussed above for η spectral ratios. It is important to remind that the records studied by Lopez et al. [2006]: (i) originate from other regions than

ENA, (ii) have PGA's much higher, on average, than those of ENA ground motions considered in the present work, and (iii) were recorded on rock and soil sites, practically in a proportion of 50%/50%. The equations proposed by Lopez et al. (2006) were calibrated using results from the analysis of the whole set of selected ground motions regardless of their classification in terms of PGA's or rock and soil sites. These factors contribute to the differences observed in Fig. 6 (b).

6 Relationship to code-prescribed horizontal seismic acceleration demands

In this section, we estimate vertical seismic demands based on code-prescribed horizontal seismic accelerations, such as those given in NBCC 2010 UHS [NRCC 2010]. This UHS is generated based on the geometric mean of horizontal spectral acceleration components A_X and A_Y recorded along orthogonal axes X and Y [NRCC 2010]. Vertical spectral demands A_Z can then be estimated by scaling the UHS by the spectral ratio $\bar{\eta}$ defined by Eq. (3). For this purpose, the $\bar{\eta}$ ratios for recorded ground motions are reevaluated as a function of period ranges that characterize the response of typical structures, from very stiff to very flexible. The following period ranges are considered: $[0\,\mathrm{s}-0.1\,\mathrm{s}]$; $[0.1\,\mathrm{s}-0.4\,\mathrm{s}]$; $[0.4\,\mathrm{s}-0.6\,\mathrm{s}]$; $[0.6\,\mathrm{s}-1\,\mathrm{s}]$ and $[1\,\mathrm{s}-2\,\mathrm{s}]$. The obtained mean $\bar{\eta}$ ratios are given in Table 2 and illustrated in Fig. 7 (a). The eight stacks of bars represent the eight period intervals described previously. Each bar corresponds to a triplet of two horizontal and one vertical acceleration components at each site, organized by ascending epicentral distances, the shortest period corresponding to the leftmost stack of bars. We note that no clear trend concerning the effect of epicentral distance could be identified from Fig. 7 (a). Fig. 8 shows the UHS for a rock site (type A) in Montreal according to NBCC 2010 as well as the resulting rock vertical spectrum envelope corresponding to the mean $\bar{\eta}$ ratios in Table 2. It is clearly seen that the resulting vertical acceleration demands are higher than the commonly adopted $V/H = 2/3$ vertical spectrum.

It is also possible to define principal spectral vertical accelerations using the ratio $\hat{\eta}$ given by Eq. (4) provided that major principal horizontal acceleration demands A_{H_1} are available. For example, Hong and Goda [2010] developed GMPEs along the principal axes of records from intraplate California earthquakes, and concluded that scaling factors to obtain major principal acceleration demands from a standard UHS range from 1.13 to 1.17. The obtained mean $\hat{\eta}$ ratios reevaluated per period range, are given in Table 2 and shown in Fig. 7 (b). For illustration purposes, Fig. 8 shows the envelope of principal vertical spectral accelerations A_V determined assuming a scaling factor of 1.15 to obtain major principal accelerations from the NBCC 2010 UHS. We remark that vertical spectra A_V and A_Z obtained using $\bar{\eta}$ and $\hat{\eta}$ are practically similar.

Another interesting approach is to estimate principal vertical spectral accelerations V when the geometric mean of recorded horizontal spectral acceleration components A_X and A_Y are provided. For this purpose, the following frequency-dependent spectral ratio γ is introduced

$$\gamma(T) = \frac{A_V(T)}{\sqrt{A_X(T)\,A_Y(T)}} \tag{5}$$

The γ spectral ratios are computed per period range and the results are given in Table 2 and illustrated in Fig. 7 (c). Comparison with the results of spectral ratios $\bar{\eta}$ and $\hat{\eta}$ in Figs. 7 (a) and (b), respectively, shows only small differences in the shape, although the mean values are different, with $\bar{\eta}$, $\hat{\eta}$, and γ mean ratios being the highest, the lowest and intermediate, respectively. The γ ratios can be applied directly to scale the code-prescribed spectrum to obtain an estimation of the principal vertical spectral accelerations A_V as illustrated in Fig. 8. It can be seen that these principal spectral vertical accelerations are slightly lower than the vertical spectra A_Z and A_V defined previously using the vertical spectral ratios $\bar{\eta}$ and $\hat{\eta}$, however they are still larger than $2/3$.

7 Summary and conclusions

In this paper, we investigated the characteristics of the vertical components of historical ground motions recorded on rock sites in Eastern Canada. Three axes instrument-recorded components of 50 near and far-field records were studied as well as the corresponding uncorrelated principal accelerograms to investigate the influence of inter-component intensity correlations. Vertical-to-horizontal PGA and spectral acceleration ratios were studied. The results first confirmed that the studied records obey the common observation that maximum vertical spectral accelerations are generally lower than horizontal ones. We investigated the sensitivity of vertical-to-horizontal spectral ratios to four different definitions of horizontal components, namely: (i) horizontal recorded components taken independently; (ii) geometric mean of recorded components at each recording station; (iii) principal horizontal components taken independently; and (iv) geometric mean of principal horizontal components at each recording station. We mainly showed that frequency-dependent characterization of vertical-to-horizontal acceleration spectral ratios is practically insensitive to using two horizontal components separately or a single geometric mean horizontal component when either recorded or uncorrelated data are used. We also found that uncorrelating ground motions, and relating the principal vertical acceleration component to only the major horizontal acceleration component provides a more constrained characterization of vertical seismic demands. Obtained frequency-dependent vertical-to-horizontal spectral acceleration ratios were compared against results from other researchers when available and the particular trends exhibited by the studied ENA ground motions were highlighted. An illustration of the obtained vertical-to-horizontal spectral acceleration ratios to estimate vertical spectral acceleration demands on rock sites from code-prescribed horizontal seismic demands in eastern Canada was also presented. Overall, these results are believed to contribute to reduce the uncertainty associated with the evaluation of vertical seismic demands on rock sites in eastern Canada. The methodology presented can also be used to evaluate the effect of horizontal component definition on the characterization of vertical ground motions considering other site conditions or regions.

List of symbols

Abbreviations

CEUS	Central and Eastern United States
ENA	Eastern North America
GMPE	Ground motion prediction equation
GSC	Geological survey of Canada
LDEO	Lamont-Doherty Earth Observatory
NBCC	National Building Code of Canada
NRCC	National Research Council of Canada
PGA	Peak ground acceleration
UHS	Uniform hazard spectra
USGS	United States Geological Survey
WNA	Western North America
WUS	Western United States

Symbols

a_i	Ground acceleration along direction i
a_X, a_Y, a_Z	Ground accelerations recorded along instrument axes X, Y and Z, respectively
a_{H_1}, a_{H_2}, a_V	Ground accelerations along principal axes H_1, H_2 and V, respectively
$a^*_{H_1}$, $a^*_{H_2}$, a^*_V	Peak ground accelerations along principal directions H_1, H_2 and V, respectively
a^*_X, a^*_Y, a^*_Z	Peak ground accelerations recorded along instrument axes X, Y and Z, respectively
A_{H_1}, A_{H_2}, A_V	Acceleration response spectra along principal directions H_1, H_2 and V, respectively

Symbols cont'd

A_X, A_Y, A_Z	Acceleration response spectra along principal directions X, Y and Z, respectively
g	Acceleration due to gravity
h_{F}	Hypocentral depth
I	Tensor of earthquake intensities
M	Magnitude
M_{W}	Moment magnitude
r_{E}	Epicentral distance
t_0, t_{f}	First and last times of the interval of interest of the shaking duration
T	Period
γ	Vertical-to-horizontal spectral ratio defined by Eq. (5)
Δt_{TB}	Trifunac-Brady duration
η_0	Ratio of vertical-to-horizontal PGAs calculated considering the two horizontal components separately
$\bar{\eta}_0$	Ratio of vertical-to-horizontal PGAs calculated considering the geometric mean of the two horizontal components
η	Vertical-to-horizontal spectral ratio defined by Eqs. (2) or (3)
$\bar{\eta}$	Vertical-to-horizontal spectral ratio defined by Eqs. (2) or (3)
$\hat{\eta}$	Vertical-to-horizontal spectral ratio defined by Eq. (4)

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Table 1
Recorded ground motions analyzed.

Event name Site, date and time	Mag.	Lat. / Long.	Subsoil	r_E (km)	h_F (km)	Comp.	PGA (g)
Miramichi							
Mitchell Lake Rd.	M_W 4.9	47.03 N /	Bedrock	4.8	5	X	0.152
31/03/1982		66.61 W				Y	0.236
21 h: 02 min						Z	0.582
Nahanni							
Iverson	M_W 6.8	62.20 N /	Bedrock	6.8	6	X	1.101
23/12/1985		124.37 W				Y	1.345
05 h: 16 min						Z	2.367
Iverson	M_W 4.9	62.20 N /	Bedrock	6.8	10	X	0.228
23/12/1985		124.37 W				Y	0.089
05 h: 48 min						Z	0.112
Slide Mountain	M_W 4.3	62.23 N /	Bedrock	5.6	10	X	0.382
09/11/1985		124.17 W				Y	0.460
04 h: 46 min						Z	0.254
Battlement Creek	M_W 6.8	62.13 N /	Bedrock	22.2	6	X	0.194
23/12/1985		123.83 W				Y	0.186
05 h: 16 min						Z	0.181
Battlement Creek	M_W 5.2	62.13 N /	Bedrock	19.7	10	X	0.105
25/12/1985		123.83 W				Y	0.089
15 h: 42 min						Z	0.074
Saguenay							
Saint-Ferréol	M_W 5.9	47.12 N /	Bedrock	113.1	28	X	0.121
25/11/1988		70.83 W				Y	0.097
23 h: 46 min						Z	0.062
Québec	M_W 5.9	46.78 N /	Bedrock	149.9	28	X	0.051
25/11/1988		71.27 W				Y	0.051
23 h: 46 min						Z	0.020

Table 1
Recorded ground motions analyzed (Continued).

Event name Site, date and time	Mag.	Lat. / Long.	Subsoil	r_E (km)	h_F (km)	Comp.	PGA (g)
Saguenay							
La Malbaie	M_W 5.9	47.65 N /	Bedrock	92.8	28	X	0.124
25/11/1988		70.15 W				Y	0.060
23 h: 46 min						Z	0.068
St-Pascal	M_W 5.9	47.52 N /	Bedrock	122.5	28	X	0.046
25/11/1988		69.80 W				Y	0.056
23 h: 46 min						Z	0.037
Rivière-Ouelle	M_W 5.9	47.47 N /	Bedrock	113.7	28	X	0.040
25/11/1988		69.99 W				Y	0.057
23 h: 46 min						Z	0.023
Chicoutimi-Nord	M_W 5.9	48.49 N /	Bedrock	43.7	28	X	0.107
25/11/1988		71.01 W				Y	0.131
23 h: 46 min						Z	0.102
St-André-du-Lac	M_W 5.9	48.32 N /	Bedrock	64.5	28	X	0.156
25/11/1988		71.99 W				Y	0.091
23 h: 46 min						Z	0.045
La Malbaie							
St-Roch-des-Aulnaies	M_W 4.3	47.24/	Hard rock	52.3	11.3	X	0.0012
28/10/1997		-70.19				Y	0.0011
11 h: 44 min						Z	0.0006
Rivière-Ouelle	M_W 4.3	47.47/	Hard rock	23.4	11.3	X	0.0177
28/10/1997		-70.00				Y	0.0181
11 h: 44 min						Z	0.0126
St-André	M_W 4.3	47.47/	Hard rock	16.9	11.3	X	0.0273
28/10/1997		-69.69				Y	0.0183
11 h: 44 min						Z	0.0247

Table 1
Recorded ground motions analyzed (Continued).

Event name Site, date and time	Mag.	Lat. / Long.	Subsoil	r_E (km)	h_F (km)	Comp.	PGA (g)
La Malbaie							
Misère	M_W 4.3	47.45/	Hard rock	44.6	11.3	X	0.0012
28/10/1997		-70.41				Y	0.0011
11 h: 44 min						Z	0.0016
Sainte-Mathilde	M_W 4.3	47.69/	Hard rock	13.7	11.3	X	0.0594
28/10/1997		-70.09				Y	0.0623
11 h: 44 min						Z	0.0154
Saint-Siméon	M_W 4.3	47.82/	Hard rock	17.5	11.3	X	0.0111
28/10/1997		-69.89				Y	0.0292
11 h: 44 min						Z	0.0165
Cap Rouge							
St-Roch-des-Aulnaies	M_W 4.9	47.24 N /	Hard rock	105.0	22	X	0.00167
06/11/1997		70.19 W				Y	0.00207
2 h: 34 min						Z	0.00117
Rivière-Ouelle	M_W 4.9	47.47 N /	Hard rock	130.5	22	X	0.00259
06/11/1997		70.00 W				Y	0.00296
2 h: 34 min						Z	0.00240
La Malbaie							
Rivière-Ouelle	M_W 3.3	47.47/	Hard rock	26.3	11.1	X	0.0086
13/06/2003		-70.00				Y	0.0071
11 h: 34 min						Z	0.005
St-André	M_W 3.3	47.47/	Hard rock	30.0	11.1	X	0.0027
13/06/2003		-69.69				Y	0.0029
11 h: 34 min						Z	0.002
Misère	M_W 3.3	47.45/	Hard rock	36.3	11.1	X	0.0015
13/06/2003		-70.41				Y	0.0014
11 h: 34 min						Z	0.0019

Table 1
Recorded ground motions analyzed (Continued).

Event name Site, date and time	Mag.	Lat. / Long.	Subsoil	r_E (km)	h_F (km)	Comp.	PGA (g)
La Malbaie							
Sainte-Mathilde	M_W 3.3	47.69/	Hard rock	0.8	11.1	X	0.0243
13/06/2003		-70.09				Y	0.0286
11 h: 34 min						Z	0.0178
Saint-Siméon	M_W 3.3	47.82/	Hard rock	20.4	11.1	X	0.0116
13/06/2003		-69.89				Y	0.0149
11 h: 34 min						Z	0.0083
La Malbaie	M_W 3.3	47.54/	Hard rock	24.5	11.1	X	0.0045
13/06/2003		-70.32				Y	0.0039
11 h: 34 min						Z	0.0055
Rivière du Loup							
St-André	M_W 4.7	47.70 N /	Hard Rock	6.0	13	X	0.0775
06/03/2005		69.69 W				Y	0.0711
6 h: 17 min						Z	0.0839
Saint-Siméon	M_W 4.7	47.82 N /	Hard Rock	14.8	13	X	0.0355
06/03/2005		69.89 W				Y	0.0353
6 h: 17 min						Z	0.0184
Sainte-Mathilde	M_W 4.7	47.69 N /	Hard Rock	27.7	13	X	0.0648
06/03/2005		70.09 W				Y	0.0524
6 h: 17 min						Z	0.0293
Rivière-Ouelle	M_W 4.7	47.47 N /	Hard Rock	37.4	13	X	0.0307
06/03/2005		70.00 W				Y	0.0187
6 h: 17 min						Z	0.0125
La Malbaie	M_W 4.7	47.54 N /	Hard Rock	50.1	13	X	0.0262
06/03/2005		70.32 W				Y	0.0170
6 h: 17 min						Z	0.0114

Table 1
Recorded ground motions analyzed (Continued).

Event name Site, date and time	Mag.	Lat. / Long.	Subsoil	r_E (km)	h_F (km)	Comp.	PGA (g)
Rivière du Loup							
Misère	M_W 4.7	47.45 N /	Hard Rock	60.7	13	X	0.0162
06/03/2005		70.41 W				Y	0.0100
6 h: 17 min						Z	0.0201
St-Roch-des-Aulnaies	M_W 4.7	47.24 N /	Hard Rock	66.6	13	X	0.0081
06/03/2005		70.19 W				Y	0.0084
6 h: 17 min						Z	0.0057
Thurso							
Alfred	M_W 3.7	45.62/	Rock	27.0	20	X	0.00860
25/02/2006		-74.88				Y	0.00700
01 h: 39 min						Z	0.00530
Glen Almond	M_W 3.7	45.70/	Hard rock	20.2	20	X	0.01470
25/02/2006		-75.48				Y	0.00670
01 h: 39 min						Z	0.00360
Ottawa	M_W 3.7	45.39/	Hard rock	47.4	20	X	0.00410
25/02/2006		-75.72				Y	0.00400
01 h: 39 min						Z	0.00200
Baie-Saint-Paul							
St-Roch-des-Aulnaies	M_W 3.8	47.24/	Hard rock	25.0	24.5	X	0.00230
07/04/2006		-70.19				Y	0.00380
08 h: 31 min						Z	0.00230
St-André	M_W 3.8	47.47/	Hard rock	68.2	24.5	X	0.00210
07/04/2006		-69.69				Y	0.00160
08 h: 31 min						Z	0.00058
Misère	M_W 3.8	47.45/	Hard rock	9.3	24.5	X	0.00900
07/04/2006		-70.41				Y	0.00800
08 h: 31 min						Z	0.00920

Table 1
Recorded ground motions analyzed (Continued).

Event name Site, date and time	Mag.	Lat. / Long.	Subsoil	r_E (km)	h_F (km)	Comp.	PGA (g)
Baie-Saint-Paul							
Sainte-Mathilde	$M_W\, 3.8$	47.69/	Hard rock	44.6	24.5	X	0.00370
07/04/2006		-70.09				Y	0.00220
08 h: 31 min						Z	0.00220
Saint-Siméon	$M_W\, 3.8$	47.82/	Hard rock	65.5	24.5	X	0.00210
07/04/2006		-69.89				Y	0.00160
08 h: 31 min						Z	0.00150
La Malbaie	$M_W\, 3.8$	47.54/	Hard rock	21.3	24.5	X	0.01410
07/04/2006		-70.32				Y	0.00990
08 h: 31 min						Z	0.00570
Rivière du Loup							
Rivière-Ouelle	$M_W\, 3.6$	47.47/	Hard rock	36.0	13.3	X	0.0020
15/11/2008		-70.00				Y	0.0018
10 h: 52 min						Z	0.0016
St-André	$M_W\, 3.6$	47.47/	Hard rock	5.5	13.3	X	0.0530
15/11/2008		-69.69				Y	0.0716
10 h: 52 min						Z	0.0212
Misère	$M_W\, 3.6$	47.45/	Hard rock	59.5	13.3	X	0.0016
15/11/2008		-70.41				Y	0.0012
10 h: 52 min						Z	0.0023
Saint-Siméon	$M_W\, 3.6$	47.82/	Hard rock	14.9	13.3	X	0.0191
15/11/2008		-69.89				Y	0.0201
10 h: 52 min						Z	0.0056

Table 1
Recorded ground motions analyzed (Continued).

Event name Site, date and time	Mag.	Lat. / Long.	Subsoil	r_E (km)	h_F (km)	Comp.	PGA (g)
Val des Bois							
Ottawa	M_W 5.2	45.39/	Bedrock	58.7	22	X	0.0426
23/06/2010		-75.71				Y	0.0391
13 h: 41 min						Z	0.0303
Ottawa	M_W 5.2	45.40/	Thin soil	57.5	22	X	0.0468
23/06/2010		-75.69				Y	0.0632
13 h: 41 min						Z	0.0299
Ottawa	M_W 5.2	45.39/	Bedrock	58.7	22	X	0.0333
23/06/2010		-75.71				Y	0.0315
13 h: 41 min						Z	0.0262

Table 2
Mean values and corresponding stand deviations of $\bar{\eta}$ ratios (recorded accelerograms), $\hat{\eta}$ ratios, and γ ratios considering different period ranges.

Ratios		Period ranges (s)				
		< 0.1	$0.1 - 0.4$	$0.4 - 0.6$	$0.6 - 1$	$1 - 2$
$\bar{\eta}$	Mean	0.80	0.89	1.02	1.02	0.95
	Sd. dev.	0.35	0.34	0.41	0.44	0.39
$\hat{\eta}$	Mean	0.64	0.75	0.93	0.94	0.88
	Sd. dev.	0.34	0.42	0.49	0.49	0.47
γ	Mean	0.74	0.82	0.99	0.98	0.92
	Sd. dev.	0.36	0.31	0.42	0.39	0.37

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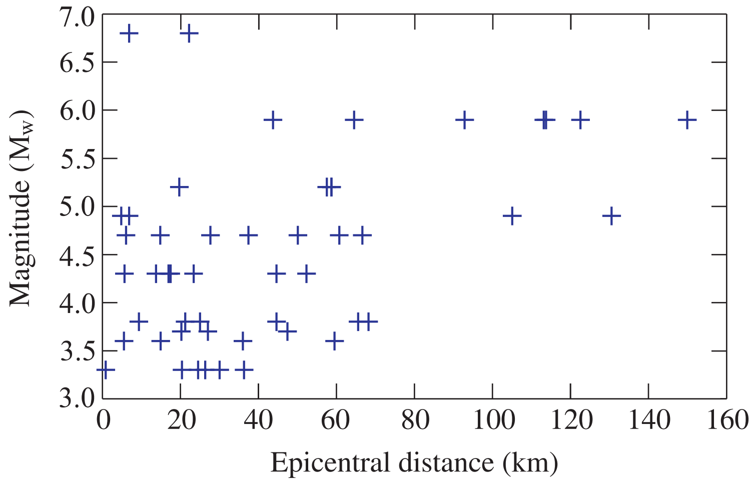

Figure 1. Magnitudes and epicentral distances of the ground motions studied.

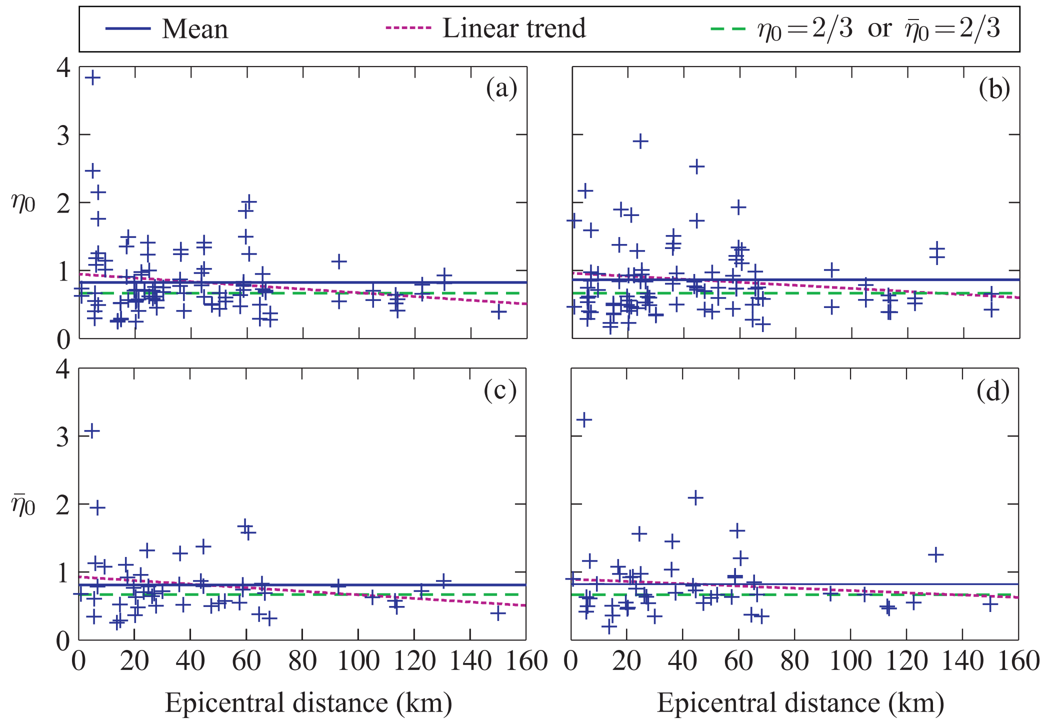

Figure 2. Variation of vertical-to-horizontal PGA ratios η_0 and $\bar{\eta}_0$ as a function of epicentral distance: (a) Recorded 3 component data; (b) Uncorrelated 3 component data; (c) Recorded geometric mean data; (d) Uncorrelated geometric mean data.

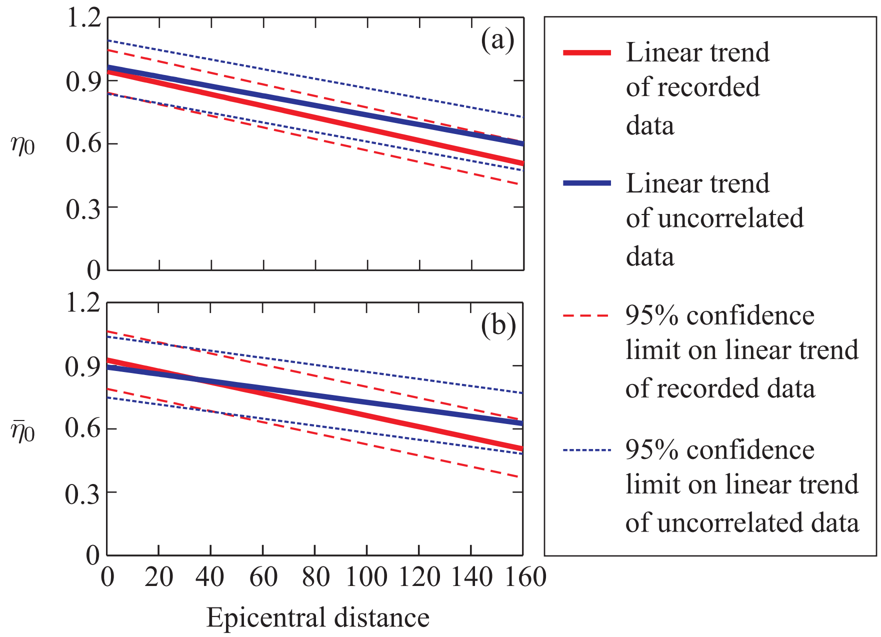

Figure 3. Variation of vertical-to-horizontal PGA ratio trends η_0 and $\bar{\eta}_0$ as a function of epicentral distance: (a) Recorded and uncorrelated 3 component data; (b) Recorded and uncorrelated geometric mean data.

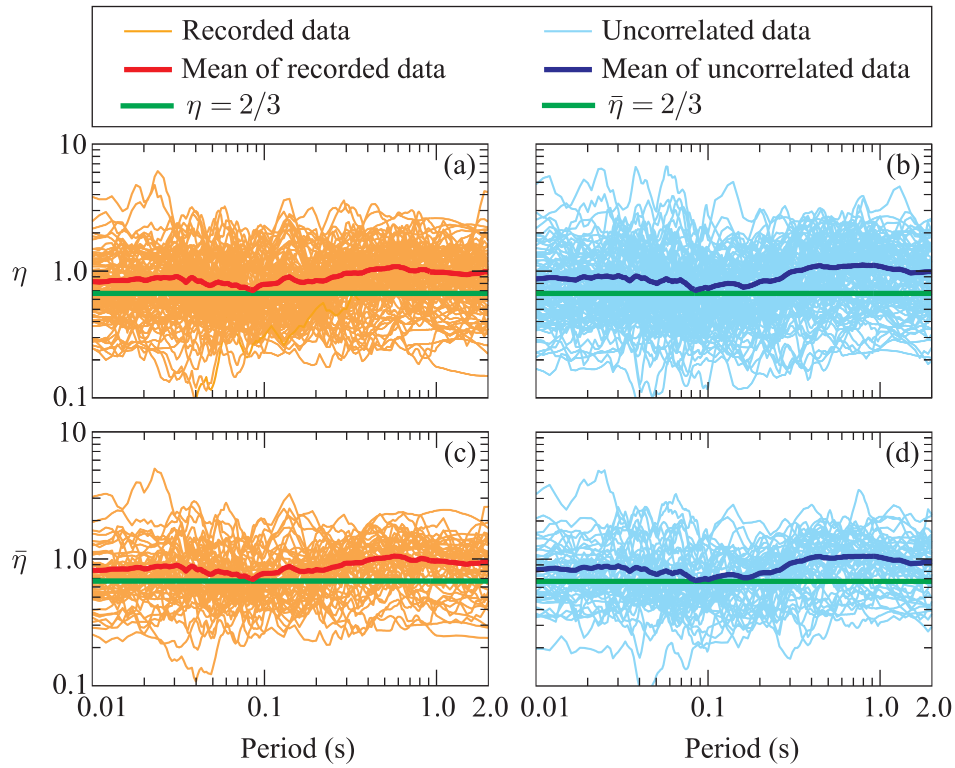

Figure 4. Variation of frequency dependent vertical-to-horizontal response spectra ratios η and $\bar{\eta}$: (a) Recorded 3 component data; (b) Uncorrelated 3 component data; (c) Recorded geometric mean data; (d) Uncorrelated geometric mean data.

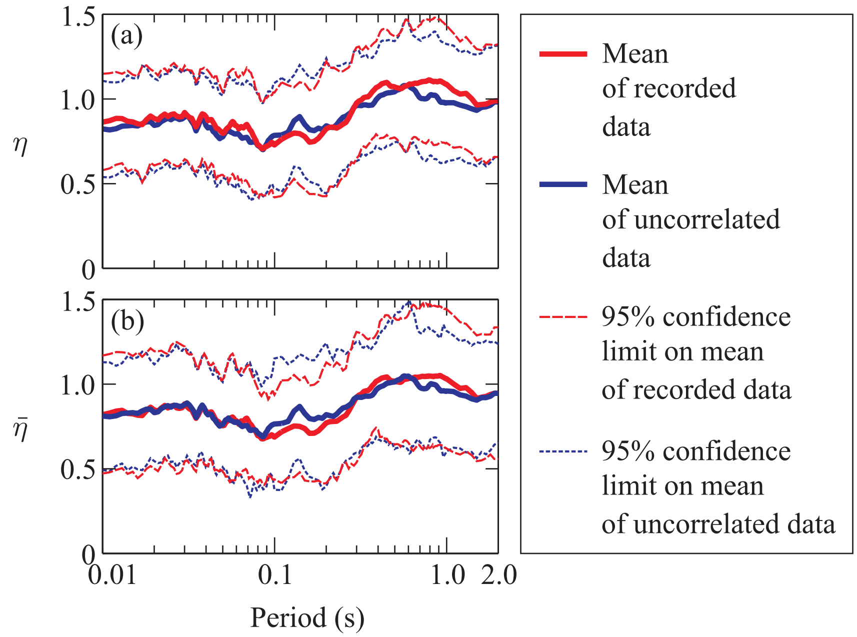

Figure 5. Variation of mean frequency dependent vertical-to-horizontal response spectra ratios η and $\bar{\eta}$: (a) Recorded and uncorrelated 3 component data; (b) Recorded and uncorrelated geometric mean data.

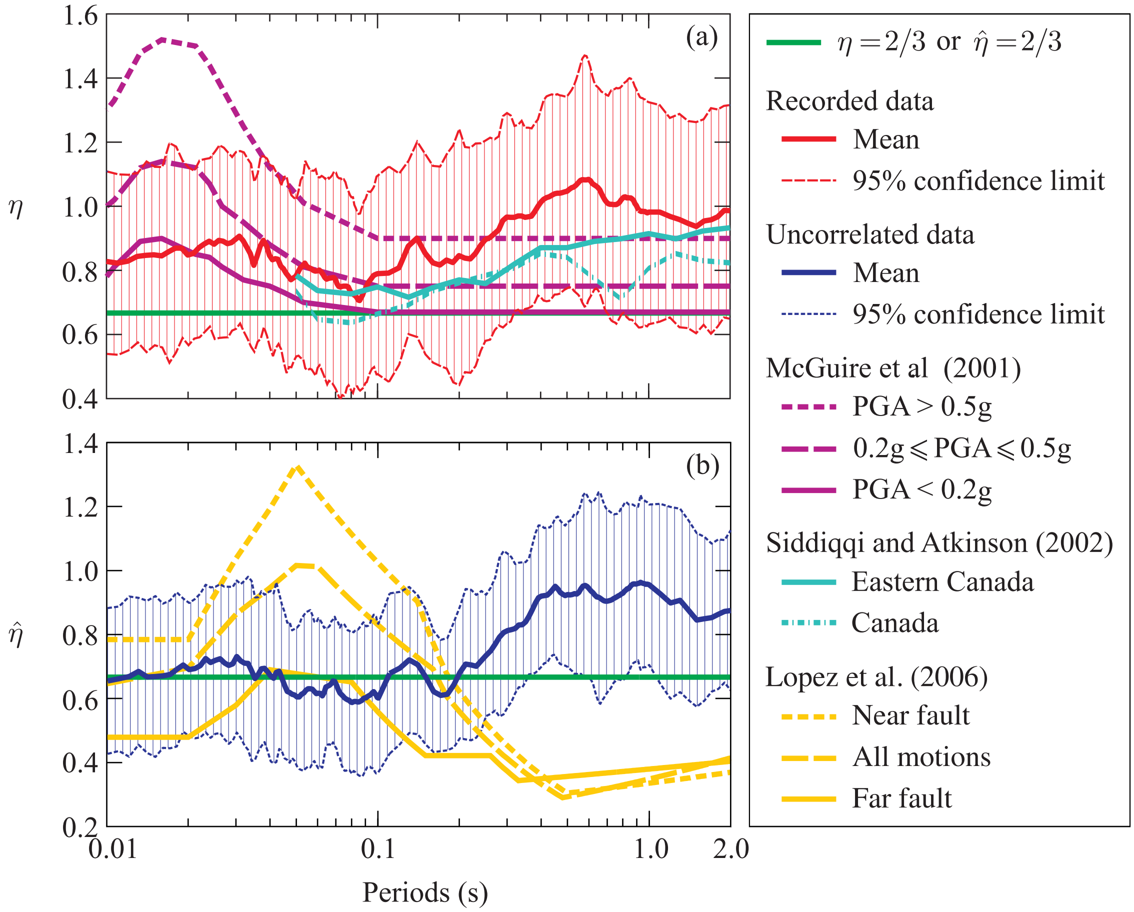

Figure 6. Mean values of η and $\hat{\eta}$ spectral ratios with 95% confidence limit error bars: (a) Recorded η ratios, mean PGA<0.2 g, comparison to McGuire et al. (2001) predicted V/H ratios and Siddiqqi and Atkinson (2002) observed Fourier vertical-to-horizontal spectral ratios; (b) $\bar{\eta}$ ratios, comparison to Lopez et al. (2006) observed $\hat{\eta}$ ratios.

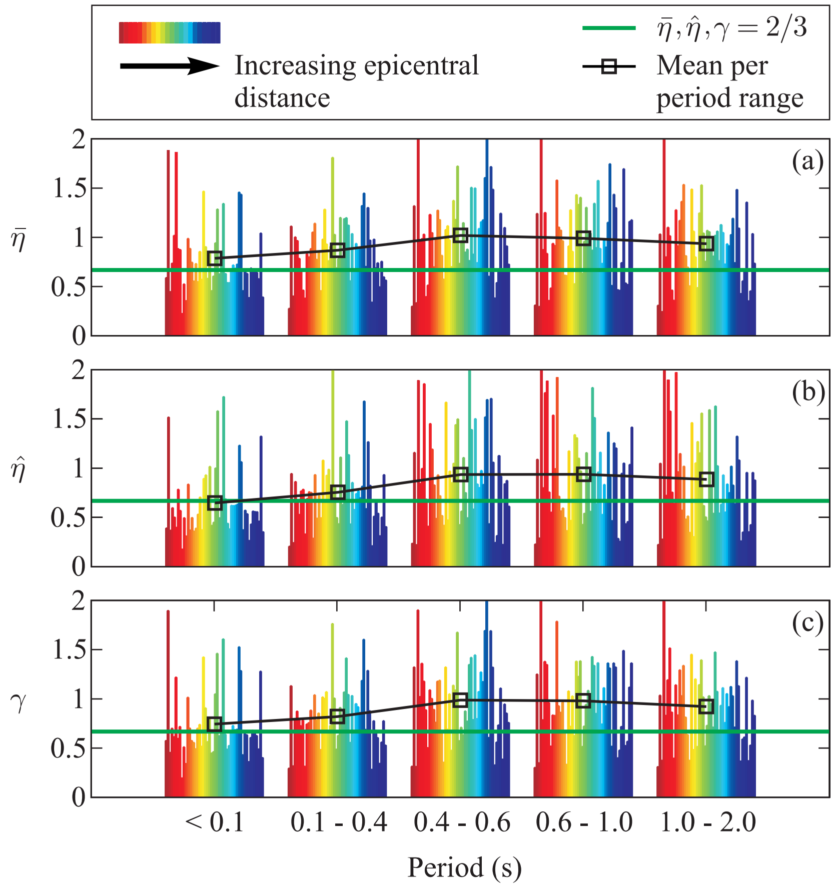

Figure 7. Variation of spectral ratios as a function of typical period ranges: (a) $\bar{\eta}$ ratios corresponding to recorded accelerograms; (b) $\hat{\eta}$ ratios corresponding to uncorrelated accelerograms; (c) γ ratios relating recorded to uncorrelated accelerograms.

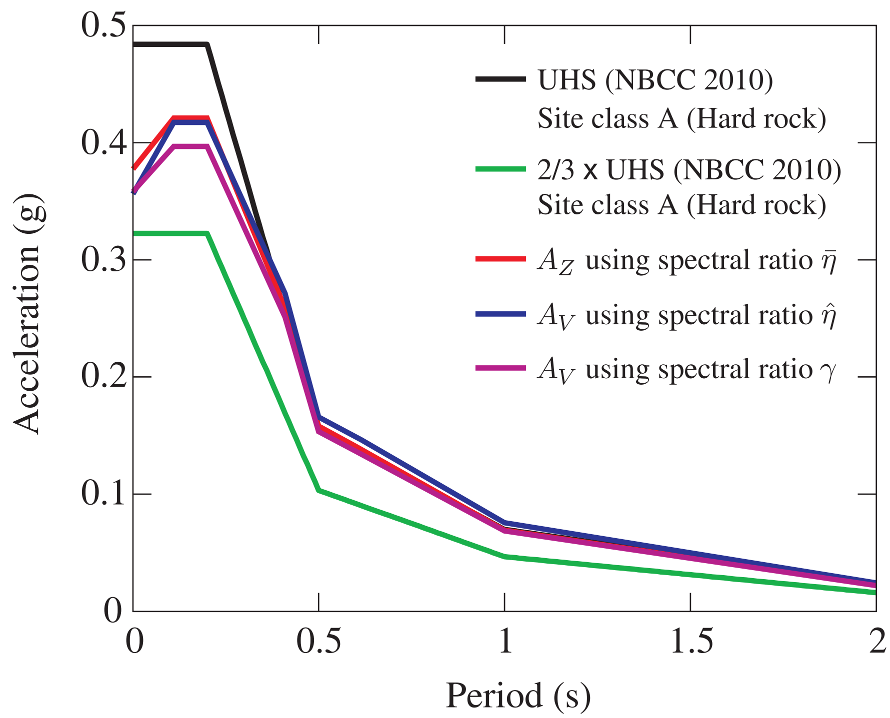

Figure 8. UHS for class A (Hard rock) in Montreal according to NBCC 2010 and corresponding vertical spectral acceleration demands.