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Ground-Motion Amplification at Rock Sites across Canada as Determined from the Horizontal-to-Vertical Component Ratio

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Abstract We determine the frequency-dependent amplification inherent in hard-rock sites across Canada under the assumption that it can be estimated from the ratio of the horizontal-to-vertical (H/V) components of ground motion. The use of H/V as an estimate of amplification was originally proposed by Nakamura (1989) for microtremors and then generalized to earthquake ground motions by Lermo and Chavez-Garcia (1993). The H/V method was applied to a Fourier spectra database compiled from 424 earthquakes of magnitude greater than or equal to 2, recorded on 32 three-component stations of the Canadian National Seismograph Network (CNSN), all sited on rock (shear-wave velocity $>$ 1500 m/sec); in each case we analyzed the *S*-wave portion of the seismograms, including the direct *S* and other strong *S* phases such as *Lg*.

The average amplification (H/V) for rock sites does not vary significantly across the country. It is weakly frequency dependent, increasing from a factor near unity at 0.5 Hz to a maximum in the range from 1.2 to 1.6 at 10 Hz. This amplification is consistent with what would be expected from a gradual decrease in shear-wave velocity as the seismic waves approach the surface, due to factors such as near-surface weathering. The interpretation of the H/V ratio as a measure of site response is consistent with the general geological conditions of the recording sites. In particular, the 5 Hz H/V ratio can be correlated with local geological conditions. The central Canada sites have the lowest estimated site amplification; this is consistent with competent hard-rock site conditions with high near-surface shear-wave velocities. There are two stations that show anomalous H/V ratios that suggest significant local site effects; these are EDM near Edmonton, which may be influenced by topographic amplification, and A61, a station in the Charlevoix seismic zone.

Introduction

It is well known that soil deposits amplify ground motion. The amount of amplification depends on several factors, including layer thickness, degree of compaction, and age. These factors also influence the shear-wave velocity, density, and damping characteristics of the soil. By contrast, it is often assumed or observed that hard-rock sites do not amplify ground motion (Bard and Thomas, 2000). However, the results of previous studies indicate that rock sites may also have significant amplification due to their shear-wave velocity gradient (e.g., Steidl *et al.,* 1996; Beresnev and Atkinson, 1997; Boore and Joyner, 1997). In this study, we investigate site response associated with hard-rock seismograph sites in Canada as estimated from the ratio of the horizontal-to-vertical (H/V) component of the Fourier spectrum of ground motions. For this purpose, an earthquake database was compiled based on digital seismograms obtained from the Geological Survey of Canada (GSC). In total, 61 earthquakes of magnitude 4–6 from 1993 to 1996 and 363 earthquakes of magnitude 2–5 from 1998 to 1999 were analyzed. Thirty-two broadband three-component Canadian National Seismographic Network (CNSN) seismograph stations recorded these events. The *S*-wave part of the seismograms, including the direct *S* and other strong *S* phases such as *Lg,* was windowed from the time series of each component of each record. The Fourier spectrum was calculated, and the ratio of the horizontal-to-vertical component determined as a function of frequency (H/V).

According to Nakamura (1989) and Lermo and Chavez-Garcia (1993), the H/V ratio is a measure of site amplification. Lermo and Chavez-Garcia (1993) found that it is possible to estimate the dominant period of the site response and the overall amplification factor based on the H/V ratio, for most site geologies. They observed that the method gives a good estimate of the frequency and amplitude of the first resonant mode of the site, though the higher modes do not appear. Duval *et al.* (1995) developed amplification maps for the region of Nice, France, based on microtremor observations; by using the H/V ratios, they determined the spatial distribution of the amplification peak. Bour *et al.* (1998) performed microzonation using Nakamura's method in the plain near Rhone Delta in Southern France. With their results, they produced maps to characterize amplification effects of the region. These included a resonance frequency map and maps of amplification amplitudes as a function of frequency range, leading to a seismic microzonation for the region. The H/V ratios determined in this study for Canada are correlated with the general geological conditions of the sites and compared with the findings of previous studies (Atkinson, 1993; Atkinson and Cassidy, 2000).

Database and Processing

Digital three-component broadband time series of events of $M \geq 4$ from 1993 to 1996, recorded on at least three stations at distances less than 500 km, were obtained from the Geological Survey of Canada (GSC) archives. These data were supplemented by recent well-recorded small events (M 2–5, 1997–1998) available through the GSC autodrm facility (an electronic archive request facility accessed by e-mail to *autodrm@seismo.nrcan.gc.ca*). The digital seismograms are sampled at 40 samples/sec and have a flat velocity response over the entire frequency range of the study (0.1–20 Hz). The data were processed to obtain the Fourier spectra of the *S*-wave and noise windows. The *S*-wave window contains the strongest part of the shaking and was typically about 60 sec in length. The noise window is a pre-event sample, normalized to the same length as the signal window. The Fourier transforms of the signal and noise windows were smoothed over log-frequency increments of 0.1 units by taking the log-average value of all spectral values within frequency bins with central values of $\log f = -1, -0.9, -0.8, \ldots, 1.2$. For all frequencies for which the signal-to-noise ratio exceeded 2, the H/V ratio was calculated. Note that the division of H/V has the effect of removing the instrument response from the record (since the horizontal and vertical components have the same instrument response). The resulting H/V values were tabulated over the frequency range from 0.1 to 20 Hz.

Analysis of Results

Mean H/V ratios are plotted for each station in Figures 1–5; the 90% confidence limits about the mean are also shown. For all regions, H/V increases slowly with frequency, having a value near unity (0 log units) at 0.5 Hz, and typical values range from 1.2 to 1.6 (0.1–0.2 log units)

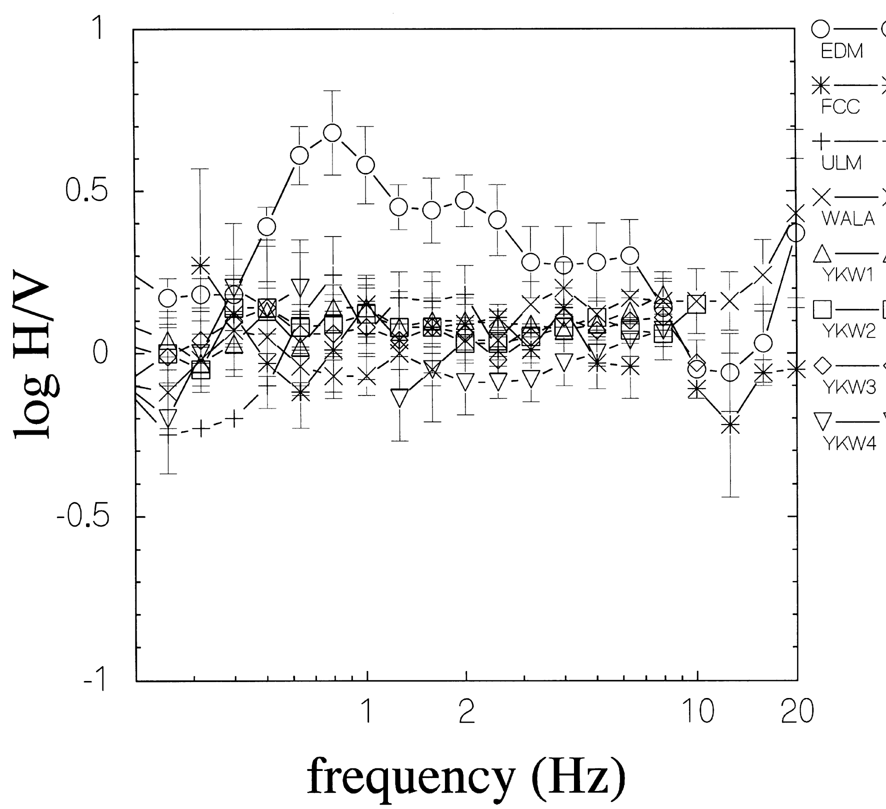

Figure 1. Mean H/V for stations in central Canada (log units). Error bars show 90% confidence limits on mean.

at 10 Hz. No significant regional variations in H/V are apparent. However, two stations, EDM (Edmonton, in central Canada) and A61 (in the Charlevoix seismic zone) show anomalous H/V values, suggesting site amplification by as much as a factor of 4.

Geological Aspects

The recording stations of the Canadian National Seismographic Network (CNSN) are located on rock sites, with typical shear-wave velocities greater than 1500 m/sec (Beresnev and Atkinson, 1997; Atkinson and Cassidy, 2000); in regions where softer materials predominate, stations are located on rock outcrops. Rock sites include igneous, sedimentary, and metamorphic rock types; the most competent rock conditions within the region are generally sought when siting seismographic stations. Information on the CNSN stations and their locations can be obtained at *www.seismo.nrcan.gc.ca* Geological Survey of Canada (2000). The dominant site condition in the area surrounding the recording sites, according to surficial geology maps of the Geological Survey of Canada, was compared to the H/V ratios obtained at frequencies of 1 and 5 Hz. At 1 Hz, the H/V ratios are generally near unity (about a factor of 1.1). However, for station EDM (Edmonton) the 1 Hz H/V ratio attains a value of nearly a factor of 4, suggesting significant site response. The H/V ratio at EDM decreases with frequency to a factor of about 2 at 5 Hz. A likely reason for this type of response is that there is a topographic amplification effect. The station EDM is located on the flank of a river valley, where the topography is relatively steep compared to a gentle relief of the rest of the area (the elevation changes about 30 m over a distance of 1 km in the vicinity of EDM).

At the frequency of 5 Hz, we noticed an apparent correlation between the H/V ratio and the surficial geology of the area in which the site is located. Table 1 lists the 5-Hz H/V values in ascending order, along with the surficial geology of the area as listed on the regional surficial geology maps. (H/V ratios are presented as multiplicative factors in this table, e.g., not in log units.) We note that surficial geology for sites near the top of Table 1 (e.g., with low to moderate H/V values) are mostly listed as rock or shallow till. Stations listed farther down Table 1, showing amplifications of more than 1.4, are mostly listed as marine, thick till, or colluvial. This apparent relationship between the regional surficial geology and the 5-Hz H/V ratios suggests that even though the selected sites appear to be on rock, they may nevertheless be subject to amplification effects due to the overall type of surficial geology in the area in which the rock outcrop is situated.

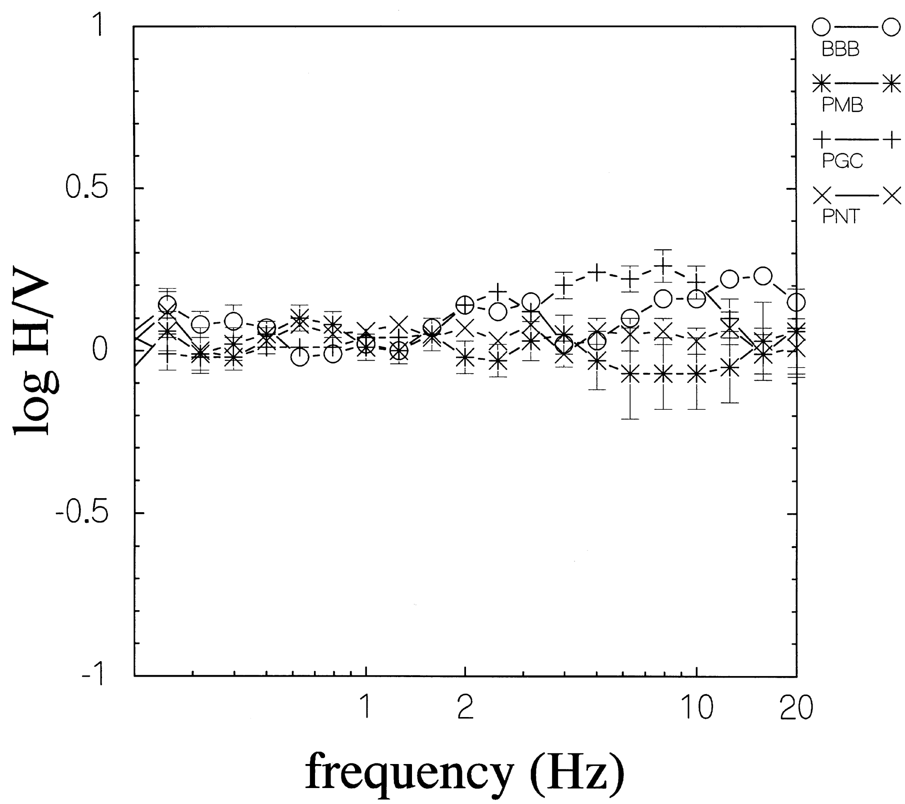

Figure 2. Mean H/V for stations in southwestern Canada (log units). Error bars show 90% confidence limits on mean.

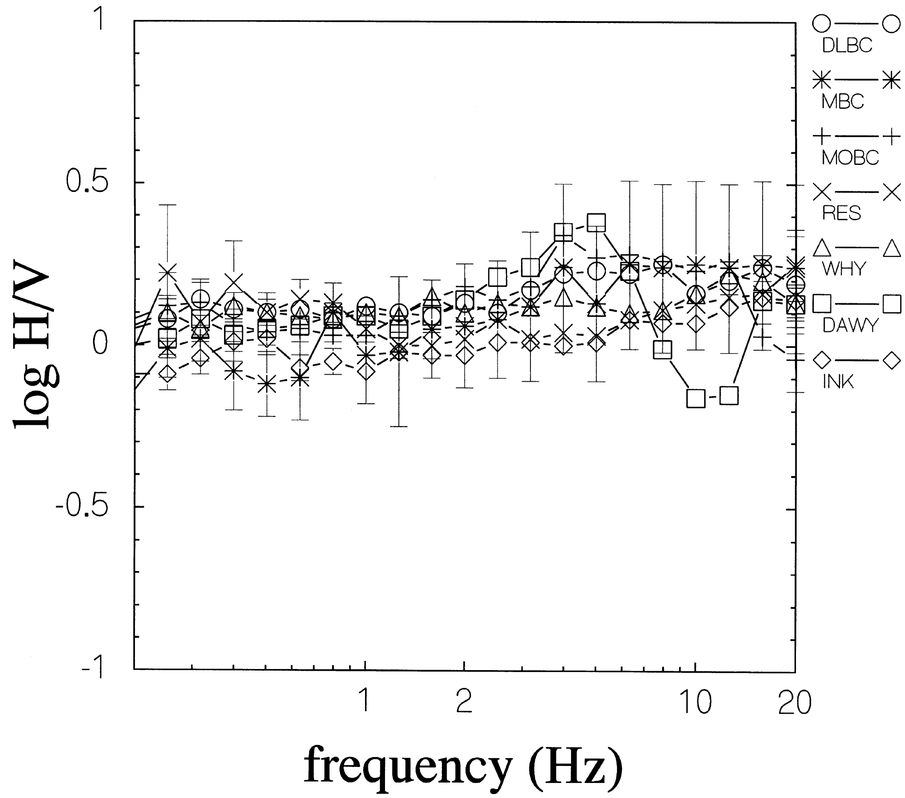

Figure 3. Mean H/V for stations in northwestern Canada (log units). Error bars show 90% confidence limits on mean.

Significant high-frequency amplification, about a factor of 4, is obtained from the H/V ratio for the station A61 (Charlevoix array). The surficial geology map indicates that A61 lies within a pocket of marine material composed of silt and clay with stones. By contrast, the surrounding three stations in Charlevoix (A64, LMQ, and A54) are within an environment that is characterized as mostly till blanket (with H/V of 1.3, 1.3, and 1.2 respectively). Thus the amplification for A61 might have been strongly influenced by the local geological conditions (marine materials).

Seismological Properties

A number of studies support the hypothesis of Lermo and Chavez-Garcia (1993), which asserts that the observed H/V ratios are a measure of the amplification of seismic ground motions due to their transit through the crustal and/or near-surface velocity gradient. For example, Atkinson and Cassidy (2000) showed that the H/V ratio for rock sites in western British Columbia (B.C.) matches the amplification that would be expected based on the regional shear-wave velocity gradient. The expected amplification was calculated from the regional shear-wave velocity profile, using the quarter-wavelength approximation (Boore and Joyner, 1997) to estimate the amplification as a function of frequency. Atkinson and Cassidy (2000) also studied ground motions for soft soil sites in the Fraser Delta, B.C., that amplify weak motions 3–5 times in the frequency range from 0.3 to 4 Hz, and concluded that observed amplifications were consistent with the H/V ratios. Chen (2000) reported a correlation between H/V (averaged over sites within a region) and the expected amplification from the regional shear-wave velocity profile for California, Mexico, Japan, and Turkey.

Beresnev and Atkinson (1997) conducted a shear-wave refraction survey at seismographic sites in eastern Canada and determined that near-surface velocities (β_1) are generally in the range from 2000 to 3000 m/sec in the upper 50 m, sometimes overlain by a shallow weathered layer with velocities from 500 to 700 m/sec. Based on these typical profiles, they concluded that near-surface amplification based on the impedance contrast should be about a factor of 1.3 for hard-rock eastern stations. Specifically, given a shear-wave velocity (β_2) of 3800 m/sec at seismogenic depths (about 10 km), the amplification due to seismic impedance contrasts, $\sqrt{[(\rho_2\,\beta_2)/(\rho_1\,\beta_1)]}$, should be in the range from 1.1 to 1.4 (assuming no significant change in density, ρ). This range of amplification agrees well with the H/V ratios observed at rock sites across all regions of Canada.

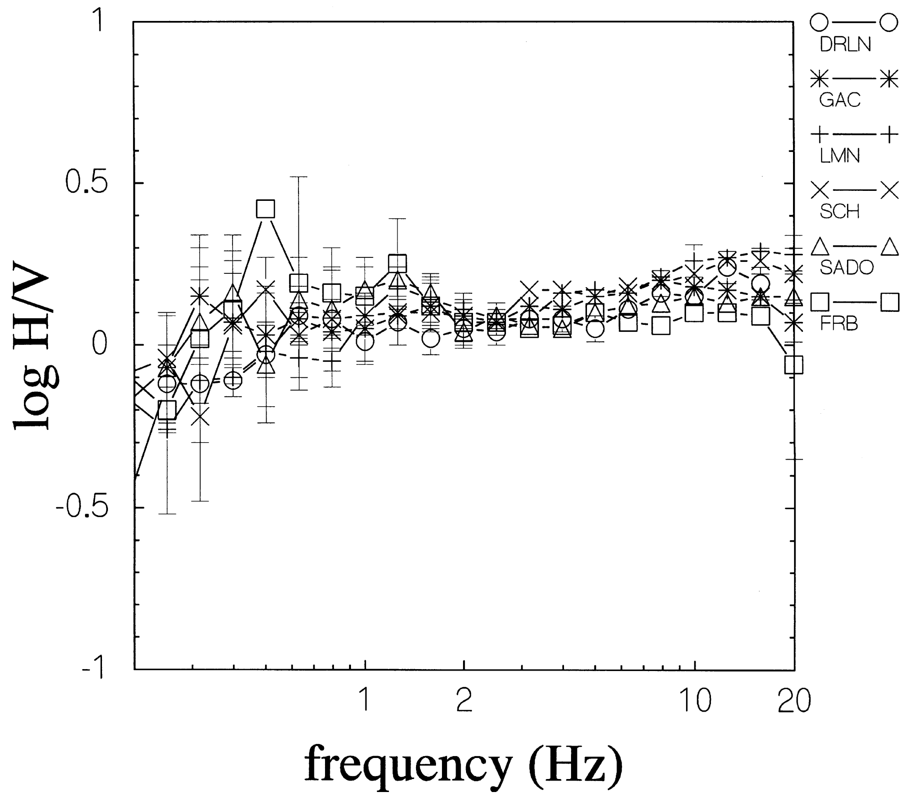

Figure 4. Mean H/V for stations in eastern Canada (log units). Error bars show 90% confidence limits on mean.

Regional Variability of Rock Amplification

Tables 2–5 present the mean H/V values and their 90% confidence limits for stations within the various regions of Canada. The results are consistent with previous H/V results for eastern and western Canada (Atkinson, 1993; Atkinson and Cassidy, 2000). The results suggest that the amplification of ground motions at rock sites in southwestern Canada is 1.1 and 1.2 for 1 and 5 Hz, respectively (excluding the anomalous A61 station). For northwestern Canada, the rock amplifications are 1.1 and 1.5 for 1 and 5 Hz, respectively. The average amplification factors for central Canada are biased by the high response at EDM. If EDM is excluded from the average, then the amplification levels at both 1 and 5 Hz are 1.16. The relatively low H/V ratios at 5 Hz in central Canada imply slightly higher near-surface shear-wave velocities than is typical in other regions of Canada, which is consistent with the highly competent Canadian Shield rock conditions.

Figure 6 compares the mean H/V ratios for the five regions, where the 90% confidence interval on the regional mean is also shown. The anomalous stations EDM and A61 have been excluded from the means. It is concluded that regional variation in H/V is not significant. The average H/V for typical rock sites is 1.1 ± 0.1 at 1 Hz, increasing to 1.2 ± 0.1 at 10 Hz (also shown on Fig. 6). It is important to note that all of the Canadian rock sites were scoured by glaciation about 10,000 yr ago. The results of this study would not be expected to apply to rock sites in regions that were not subjected to recent glaciation. Specifically, amplification for rock sites in regions such as California would be expected to be greater (Boore and Joyner, 1997).

Conclusions

The following conclusions are drawn from the results of this study.

1. The H/V ratios for rock sites (including all rock types) in Canada are in accord with expected amplification values due to the near-surface shear-wave velocity gradient and with previous H/V estimates for rock sites.
2. There appears to be a weak correlation between H/V ratios at 5 Hz and the general surficial geology of the area in which the recording station is located. Although all sites are rock or rock outcrops (with typical shear-wave velocities > 1500 m/sec), H/V ratios are generally higher where the local geological conditions indicate relatively soft conditions (e.g., widespread surficial soil deposits) predominate surrounding the site.

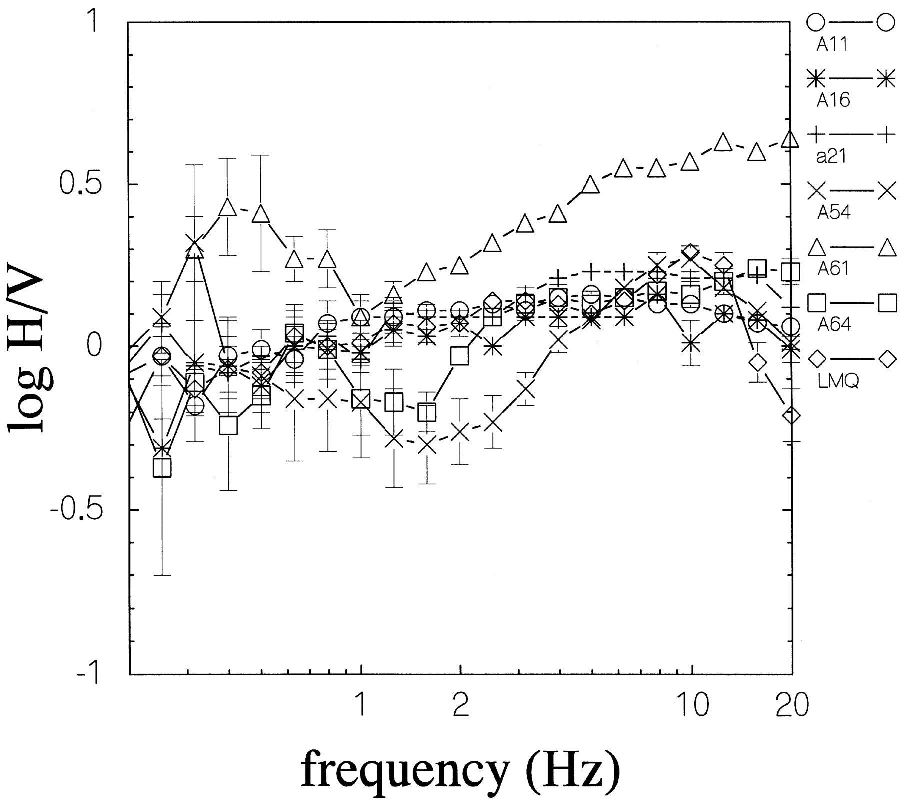

Figure 5. Mean H/V for stations in Charlevoix region, Quebec (log units). Error bars show 90% confidence limits on mean.

3. The average H/V for typical rock sites in Canada is 1.1 ± 0.1 at 1 Hz, increasing to 1.2 ± 0.1 at 10 Hz, with little apparent regional variability. It is important to note, however, that most of Canada's surface was scoured by glaciation about 10,000 yr ago.
4. There appear to be significant local site effects at sites EDM (Edmonton) and A61 (Charlevoix).

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Table 1

Amplification and Geologic Conditions

Station	Mean 5-Hz H/V	90% Confidence Interval (C.I.)	Geology
FCC	0.94	0.78–1.12	Marine
PMB	0.94	0.77–1.16	Rock
YKW4	1.00	1.10–0.91	Till Veneer
INK	1.03	0.99–1.07	Till Veneer
BBB	1.06	1.02–1.10	Rock
RES	1.07	1.02–1.13	Colluvial
DRLN	1.13	1.03–1.24	Till Veneer
PNT	1.15	1.06–1.25	Till Veneer
YKW3	1.18	1.09–1.26	Till Veneer
A54	1.21	1.15–1.28	Till Blanket
A16	1.22	1.13–1.32	Marine
YKW1	1.24	1.15–1.33	Till Veneer
FRB	1.25	1.18–1.33	Till Veneer
SADO	1.26	1.18–1.35	Rock
LMQ	1.27	1.21–1.33	Till Veneer
YKW2	1.29	1.17–1.44	Till Veneer
WALA	1.31	1.16–1.49	Rock
WHY	1.33	1.29–1.37	Till Blanket
A64	1.33	1.23–1.45	Till Blanket
MBC	1.36	0.79–2.33	Colluvial
GAC	1.40	1.32–1.48	Till Veneer
SCH	1.40	1.32–1.49	Till Veneer
A11	1.44	1.39–1.50	Marine
LMN	1.48	1.39–1.57	Rock
DLBC	1.71	1.63–1.78	Till Blanket
A21	1.71	1.64–1.79	Marine
PGC	1.72	1.59–1.86	Marine
MOBC	1.88	1.79–1.98	Colluvial
EDM	1.89	1.45–2.46	Till Blanket
DAWY	2.37	2.30–2.45	Colluvial
A61	3.18	3.10–3.27	Marine

Table 2

Amplification Factors for Southwestern Canada

Station	1 Hz* Mean H/V	90% C.I. Range	5 Hz† Mean H/V	90% C.I. Range
PNT	1.14	1.07–1.21	1.15	1.06–1.25
PMB	1.02	0.93–1.13	0.94	0.77–1.16
PGC	1.09	1.04–1.13	1.72	1.59–1.86
BBB	1.04	0.99–1.09	1.06	1.02–1.10

*Average regional amplification at 1 Hz = 1.07; standard deviation = ±0.05.

†Average regional amplification at 5 Hz = 1.22; standard deviation = ±0.29.

Table 3

Amplification Factors for Northwestern Canada

Station	1 Hz* Mean H/V	90% C.I. Range	5 Hz† Mean H/V	90% C.I. Range
DLBC	1.30	1.23–1.38	1.71	1.63–1.78
WHY	1.26	1.20–1.32	1.33	1.29–1.37
MOBC	1.08	1.01–1.16	1.88	1.79–1.98
MBC	0.93	0.66–1.32	1.36	0.79–2.33
INK	0.83	0.78–0.90	1.03	0.99–1.07
DAWY	1.23	1.16–1.31	2.37	2.30–2.45
RES	1.11	1.00–1.22	1.07	1.02–1.13

*Average regional amplification at 1 Hz = 1.11; standard deviation = ±0.16.

†Average regional amplification at 5 Hz = 1.54; standard deviation = ±0.45.

Table 4

Amplification Factors for Eastern Canada

Station	1 Hz* Mean H/V	90% C.I. Range	5 Hz† Mean H/V	90% C.I. Range
FRB	1.42	1.16–1.74	1.25	1.18–1.33
GAC	1.11	0.86–1.43	1.40	1.32–1.48
SADO	1.49	1.20–1.86	1.26	1.18–1.35
DRLN	1.02	0.90–1.16	1.13	1.03–1.24
SCH	1.22	1.07–1.38	1.40	1.32–1.49
LMQ	1.02	0.86–1.20	1.27	1.21–1.33
LMN	1.23	1.07–1.41	1.48	1.39–1.57
A11	1.24	1.09–1.40	1.44	1.39–1.50
A16	0.95	0.87–1.04	1.22	1.13–1.32
A21	0.91	0.82–1.00	1.71	1.64–1.79
A54	0.67	0.45–1.00	1.21	1.15–1.28
A61	1.23	1.05–1.44	3.18	3.10–3.27
A64	0.69	1.86–0.90	1.33	1.23–1.45

*Average regional amplification at 1 Hz = 1.09; standard deviation = ±0.24.

†Average regional amplification at 5 Hz = 1.48; standard deviation = ±0.51.

Table 5

Amplification Factors for Central Canada

Station	1 Hz* Mean H/V	90% C.I. Range	5 Hz† Mean H/V	90% C.I. Range
WALA	0.85	0.97–0.74	1.31	1.16–1.49
YKW1	1.36	1.11–1.67	1.24	1.15–1.33
YKW2	1.31	1.07–1.61	1.29	1.17–1.44
YKW3	1.21	1.47–1.00	1.17	1.09–1.26
YKW4	0.81‡	N/A	1.00	1.10–0.91
FCC	1.41	1.15–1.74	0.94	0.78–1.12
EDM	3.84	2.90–5.08	1.89	1.45–2.46
ULM	1.14	0.83–1.55	N/A	N/A

*Average regional amplifications at 1 Hz = 1.49; standard deviation = ±0.91. Average except EDM at 1 Hz = 1.16; standard deviation = ±0.22.

†Average regional amplifications at 5 Hz = 1.26; standard deviation = ±0.29. Average except EDM and ULM at 5 Hz = 1.16; standard deviation = ±0.14.

‡Value for mean extrapolated from data.

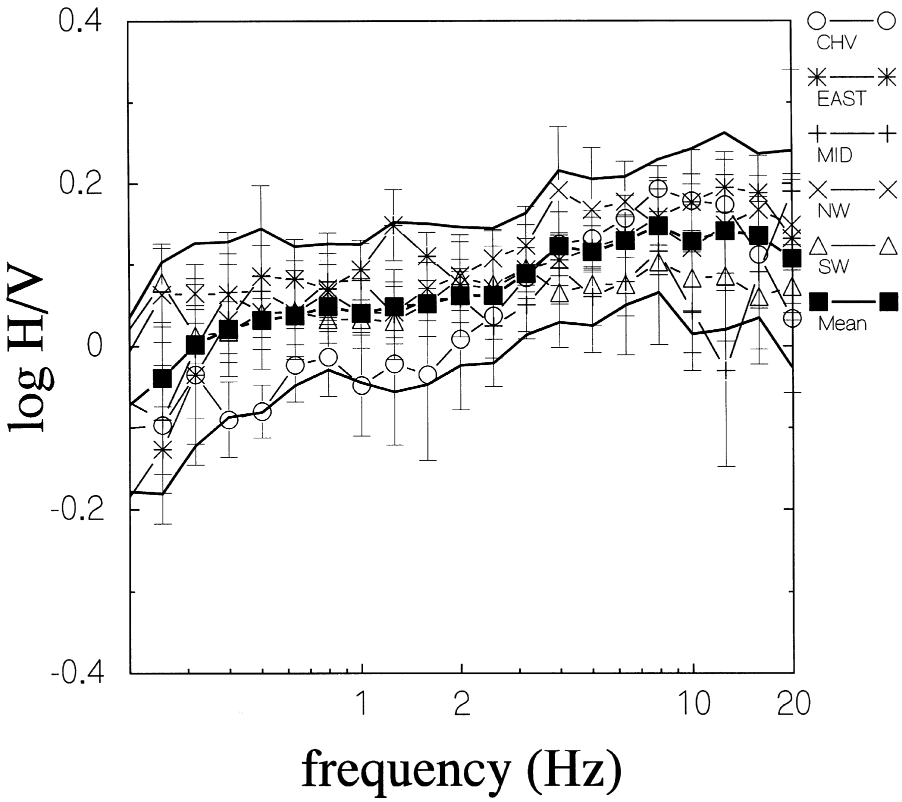

Figure 6. Mean H/V (symbols) and its 90% confidence limits (error bars) within each of the subject regions (circles, Charlevoix; stars, eastern Canada; plus, central Canada; x, northwestern Canada; triangles, southwestern Canada). The mean H/V averaged over all stations (including all regions) is also shown (solid squares), along with the standard deviation of H/V (heavy lines).